CONVENTIONAL HYDROGEOLOGICAL, HYDROCHEMICAL AND ENVIRONMENTAL ISOTOPE STUDY OF THE SANDSPRUIT RIVER CATCHMENT, BERG RIVER BASIN, SOUTH AFRICA

by

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Submitted in fulfilment of the academic
requirements for the degree of
Master of Science in the
School of Geological Science,
University of KwaZulu-Natal
Durban

February 2012

As the candidate's supervisor I have/have not approved this thesis/dissertation for submission.

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Abstract

The Sandspruit River catchment, found within the heart of the Swartland region is infamous for wheat and wine production. Variable groundwater quality and low productivity is encountered within the folded and fractured Malmesbury Group aquifer, whilst the most productive and better quality groundwater is found within the Table Mountain Group sandstone. The Sandspruit catchment (a tributary of the Berg River) represents a drainage system, whereby saline groundwater with TDS up to 10870 mg/l, and EC up to 2140 m*S*/m has been documented. The catchment belongs to the winter rainfall region with precipitation seldom exceeding 400mm/yr, as such, groundwater recharge occurs predominantly from May to August. Recharge estimation using the catchment water-balance method, chloride mass balance method, and qualified guesses produced recharge rates between 8-70 mm/yr.

To understand the origin, occurrence and dynamics of the saline groundwater, a coupled analysis of major ion hydrochemistry and environmental isotopes ($\delta^{18}O$, $\delta^{2}H$ and ^{3}H) data supported by conventional hydrogeological information has been undertaken. Research data were collected in three seasonal field sampling campaigns within the study catchment. These spatial and multi-temporal hydrochemical and environmental isotope data provided insight into the origin, mechanisms and spatial evolution of the groundwater salinity. These data also illustrate that the saline groundwater within the catchment can be attributed to the combined effects of evaporation, salt dissolution, and groundwater mixing. The geology together with the local and regional faults control the chemistry of the groundwater, whereby relatively fresh groundwater can be observed in certain direct recharge areas. The salinity of the groundwater tends to vary seasonally and evolves in the direction of groundwater flow.

The stable isotope signatures further indicate two possible mechanisms of recharge; namely, (1) a slow diffuse type modern recharge through a relatively low permeability material as explained by heavy isotope signal and (2) a relatively quick recharge prior to evaporation from a distant high altitude source as explained by the relatively depleted isotopic signal and sub-modern to old tritium values. A conceptual hydrogeological model based on the hydrogeological, hydrochemical, and environmental isotope data was developed for the Sandspruit catchment. This model, together with statistical and groundwater quality analysis has lead to the development of a proposed local optimized monitoring scheme for the catchment.

Preface

This MSc dissertation is based on research undertaken from May 2009 to May 2010 within the Sandspruit River catchment located in the Berg River basin, Western Cape. The analysis and interpreted work described in this dissertation was carried out in the School of Geological Science, University of KwaZulu-Natal, Durban, under the supervision of Doctor Molla Demlie.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

Declaration - Plagiarism

I, Sivashni Naicker declare that:

1. The research reported in this dissertation, except where otherwise indicated, is my original research.
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Acknowledgements

My utmost gratitude to the following people/organisations:

- The Water Research Commission (WRC) for funding
- Mr. Paddy Ewer from the School of Mathematics at the University of KwaZulu-Natal for the National Research Foundation (NRF) funding
- iThemba labs in Johannesburg for the environmental isotope analysis
- Ms. Anita Moodley for the anion analysis in the School of Chemistry, University of KwaZulu-Natal
- Mrs. Janine Naicker for the cation analysis in the School of Geological Science, University of KwaZulu-Natal
- Mr. Mukesh Seyambu for the thin-section preparation in the School of Geological Science, University of KwaZulu-Natal
- The X-ray diffraction (XRD) and X-ray fluorescence team at the School of Geological Science, University of KwaZulu-Natal

I shall save the best for last, and sincerely thank my supervisor, Dr. Molla Demlie for the opportunity given to me to do my MSc, and my family and friends for their relentless support. A special thank you goes out to Mr. Revash Singh for his assistance during difficult times.

List of principal symbols and acronyms

ACRU Agricultural Catchments Research Unit
C runoff coefficient
Cl_p chloride concentration in precipitation [mmol/l]
Cl_{sw} chloride concentration in soil water [mmol/l]
CMB chloride mass balance
CRD cumulative rainfall departure
D recharge [mm/month]
D_d dry chloride deposition [mg/l]
dr inverse relative distance Earth-Sun
DO dissolved oxygen [ppm]
DWA Department of Water Affairs
DEA Department of Environmental Affairs
DTWL depth to water-level [m.bgl]
EC electrical conductivity [m*S*/m]
Eh reduction potential [mV]
e°(T) saturation vapour pressure at air temperature T [kPa]
e_s saturation vapour pressure for a given time period [kPa]
e_a actual vapour pressure [kPa]
e_s- e_a saturation vapour pressure deficit
ETo reference crop evapotranspiration
ETc crop evapotranspiration under standard conditions [mm day^{-1}]
FAO Food and Agriculture Organisation
G soil heat flux [MJ m^{-2} day^{-1}]
GCTA Greater Cape Town Area
GRAI Groundwater Resource Assessment Phase I
GRAII Groundwater Resource Assessment Phase II
GMWL global meteoric water-line
HP Harvest Potential [m^3/yr]
IAEA International Atomic Energy Agency
I thermal index
I_r intensity of rainfall [mm/hr]
IC ion chromatograph
ICP-MS inductively coupled mass spectrometry
J number of day in the year
Kc crop coefficient

Kc ini crop coefficient during the initial growth stage

Kc mid crop coefficient during the mid-season growth stage

Kc end crop coefficient at end of the late season growth stage

LMWL local meteoric water-line

m^3/a cubic meter per annum

N maximum possible sunshine duration in a day, daylight hours [hour]

Nm latitude correction factor

n actual duration of sunshine in a day [hour]

ORP oxygen reduction potential [mV]

P precipitation [mm/month]

PPC Pretoria Portland Cement

Q peak runoff rate [m^3/s]

q monthly runoff [mm]

QA quality assurance

QC quality control

Ra extraterrestrial radiation [MJ m^{-2} day^{-1}]

Rn net radiation [MJ m^{-2} day^{-1}]

Rnl net longwave radiation [MJ m^{-2} day^{-1}]

Rns net solar or shortwave radiation [MJ m^{-2} day^{-1}]

Rs solar or shortwave radiation [MJ m^{-2} day^{-1}]

Rso clear-sky solar or clear-sky shortwave radiation [MJ m^{-2} day^{-1}]

ra aerodynamic resistance [s m^{-1}]

rl bulk stomatal resistance of well-illuminated leaf [s m^{-1}]

Rs/Rso relative solar or relative shortwave radiation

RH relative humidity [%]

RO surface runoff [mm]

SAR sodium adsorption ratio

T air temperature [°C]

TAL total alkalinity [mg/l]

TDS total dissolved solids [ppm]

TMG Table Mountain Group

USEPA United States Environmental Protection Agency

V-SMOW Vienna standard mean ocean water

WMA Water Management Area

XRD X-ray diffraction

XRF X-ray fluorescence

u2 wind speed at 2 m above ground surface [m s^{-1}]

γ psychrometric constant [kPa °C^{-1}]

∆ slope of saturation vapour pressure curve [kPa °C^{-1}]

∆s change in soil water storage [mm/month]

δ(ETo estimation) solar declination [rad]

$\delta^{18}O$ 18-oxygen stable isotope [‰]

$\delta^{2}H$ 2-hydrogen stable isotope [‰]

^{3}H 3-hydrogen radioactive isotope [TU]

ρa mean air density [kg m^{-3}]

σ Stefan-Boltzmann constant [4.903 10^{-9} MJ K^{-4} m^{-2} day^{-1}]

φ latitude [rad]

ωs sunset hour angle [rad]

CHAPTER 1 – INTRODUCTION

1.1. Background and rationale

Sustainable development of the Greater Cape Town Metropolitan Area (GCTMA) and adjacent towns, as well as the agricultural needs of the Western Cape, makes the efficient utilisation of available water resources a necessity. Rapid population growth, industrial development, improving living standards and the needs of irrigation have severely taxed the water resources of the GCTMA and the surrounding environment (Palmer *et al*., 2004). Therefore, the optimum utilisation of the water resources on a regional basis is necessary for the sensible planning of the development of the region.

A pilot Delphi survey, conducted by Adams (2009) of the WRC, has revealed that amongst the main groundwater themes requiring urgent research attention is groundwater pollution and protection. The underlying issue regarding the above mentioned theme is the limited monitoring of the variables/parameters required to enhance and advance our understanding of groundwater quality.

The term water quality describes the physical, chemical, biological and aesthetic properties of water which determine its fitness for a variety of uses and for protecting the health and integrity of aquatic ecosystems (Bartram and Ballance, 1996). Many of these properties are controlled or influenced by constituents which are either dissolved or suspended in water.

The National Water Act No.36 of 1998 legislates the way in which all of South Africa's surface and groundwater resources are protected, used, developed, conserved, managed and controlled, to ensure that there is enough water of good quality available for distribution to municipalities, water boards, water user associations and other water service institutions (DWA, 2007). The Sandspruit catchment was selected as the demo catchment for the project based on feasibility in terms of logistics and size, in addition, the Department of Water Affairs (DWA) has a long record of water quality data at the Sandspruit weir and the catchment is already used in two other research projects (WRC projects No. K5/1503 and No. K5/1516). The Sandspruit catchment has a relatively complex geology, land use is predominantly agricultural and it is critical in terms of salt load discharge into the Berg River (Adams, 2009). Hydrochemical and isotope data are needed to assess the water quality within the catchment, and provide insight towards the origin of the groundwater salinity, which further helps in developing strategies to improve the water quality within the catchment.

de Clerq et al., (2010) published the WRC K5/1503 report on land use impacts on salinity in Berg River water. The report surmised that the regolith in this semi-arid coastal region

contains an abundance of stored salts of marine origin that have accumulated meteorically over a very long period. During this period the climate was drier than at present and/or a vegetation cover prevailed that allowed less water to be discharged from catchments than currently occurs under the prevailing land use (mainly winter wheat), because of greater water extraction and/or smaller surface runoff.

In the WRC project K5/1516, Rossouw and Gorgens (2005) generated a knowledge review of modelling pollution in agriculture. Their conclusions amongst the five papers discussed, were to address certain needs for a long term-research programme programme. The needs included the development of fundamental research to prioritize the primary NPS (non-point source) processes e.g. groundwater salinity; evaluation of models that describe primary NPS processes; research into integrative tools to configure and verify NPS models at a catchment scale using data collected for the project ;and management support research to test the field scale and catchment scale models.

Interpreted data from monitoring points or networks, serves as a guide to aid policy making at local and regional scales. Monitoring is primarily based on physical and chemical variables to characterise the resource and to detect trends/changes of the resource. Groundwater hydrochemical and isotope monitoring is core to any groundwater management strategy as actions to maintain or improve overall groundwater quality depends solely on a good monitoring network, and database. However, groundwater characteristics can change over relatively short temporal and spatial scales. It is thus necessary to understand what, how and when a resource should be monitored.

Salinization of water resources is one of the most extensive processes that degrades water quality and endangers future water exploitation. Salinization of land and water is brought about by physical and chemical processes that increase concentrations of salt in soil and water (Salama *et al*., 1999). The processes responsible for the development of saline land and water are complex and intimately related to the transport of dissolved mass in various groundwater flow systems (Salama *et al*., 1999). Countries that are affected by salinization are mainly located in arid and semi-arid regions and include areas in North and South America, Australia, China, India, regions in the Mediterranean and Middle East, and south-east Asia (Salama *et al*., 1999). The world loses about 0.1 km^2 of arable land every minute, 0.03 km^2 of which is lost by salinization (Ghassemi *et al*., 1995).

In South Africa, salinity problems are encountered in several river basins, e.g. the Great Fish, Sundays, Berg, and Breë Rivers (Hall and Gőrgens, 1978). Flugel (1995) proposed the concept of dryland salinity for the Sandspruit catchment, a process whereby a rise in

groundwater level is brought upon by the removal of natural vegetation and replacement of cultivated crops. It was shown by Kamish (2008), that the salt load of the lower Berg River could be attributed to the contribution of salt loads from the very saline tributaries, viz Sandspruit River, Matjies River, and the Moorreesburg Spruit. The fundamental relationships between $\delta^{18}O$ and $\delta^{2}H$ and between $\delta^{18}O$ and salinity have been used to identify different salinization pathways (Gaye, 2001). Monitoring and identifying the origin of the salinity are crucial for both water management and remediation.

1.2. Location of study area

The study catchment (Figure 1.1) is located within the Berg River basin approximately 100 km north-east of Cape Town in the Western Cape. It is called the Sandspruit catchment (named after the Sandspruit River) a tributary of the Berg River and is represented by the quaternary catchment G10J. Moorreesburg and Riebeek-West are the main towns situated north-east and south of the catchment respectively.

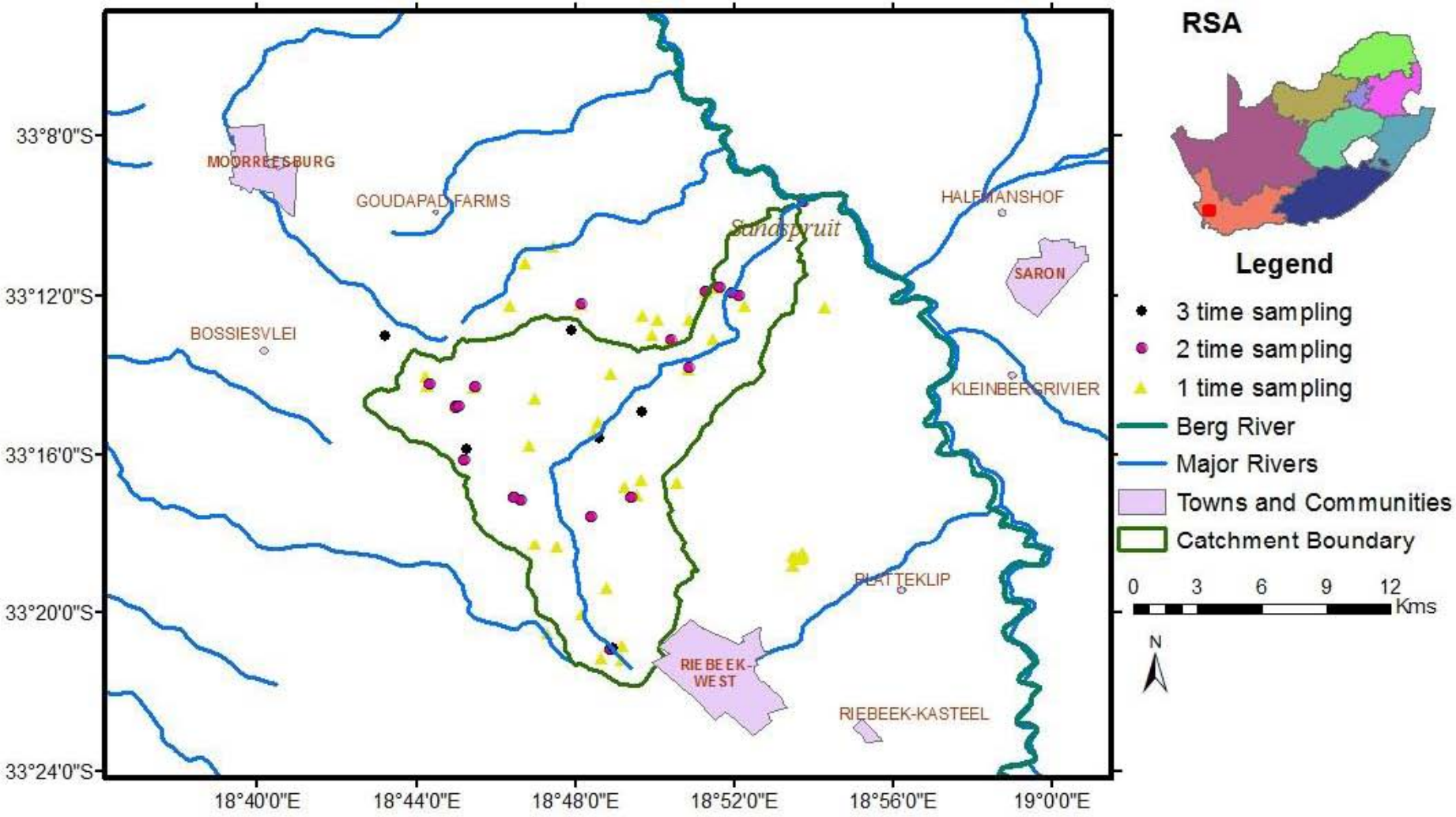


Figure 1.1: Location of Sandspruit catchment illustrating surface and groundwater sampling points

1.3. Aims and objectives

The main objectives of this M.Sc. research project are the following:

- Characterise groundwater occurrence, movement and hydrochemistry: hydrochemical evolution patterns and its implication on circulation, flow, transfer and quality of groundwater within the study catchment
- Conduct a water-balance study for the catchment, using different methods.
    - Quantifying the main components of the water balance (such as recharge, evapotranspiration and runoff)
- Investigate the temporal changes of water quality with respect to time i.e. seasonality
- Study the origin of groundwater salinity using integrated conventional hydrogeological, hydrochemical and environmental isotope techniques (isotopes of oxygen, hydrogen and tritium)
- Developing a conceptual hydrological model of groundwater occurrence and circulation within the study catchment
- Establish an optimized catchment scale groundwater model monitoring network using the water quality data, environmental isotope analysis and conceptual hydrogeological framework

1.4. Thesis outline

This thesis comprises six chapters, and the various chapters are set-up as follows:

- Chapter one outlines the study background and rationale, aims/objectives. An introduction of the study is addressed.
- Chapter two provides a literature review, discussing methods used to analyse the hydrogeological, hydrochemical and isotope data, as well as applying multivariate statistics to explain data variance. A background into the concept of groundwater salinity and mineralisation of South African surface water and groundwater is also presented. Lastly, the development of an optimized monitoring network at a local catchment scale is reviewed.
- Chapter three discusses the methodology used to obtain, analyse and present the hydrogeological, hydrochemical, and isotope data.
- Chapter four gives the outline of the study area in terms of the demography and economic development; physiography and drainage; hydrological and hydrometeorological aspects and geology. The geological characteristics are described through lithology, stratigraphy and structure.

- Chapter five outlines the main results and discussion i.e. discussion on the different hydrogeologic units within the Sandspruit catchment, recharge estimation and water balance, hydrochemical and environmental isotope results, the state of water quality and the degree and origin of groundwater salinity.
- Chapter six presents the main conclusions and recommendations emanating from the research. Presentation of a summary of the main results, conceptual hydrological model, as well as recommendation for optimized groundwater monitoring within the Sandspruit catchment using the hydrogeological, water quality, environmental isotope data and the conceptual hydrological model.
- All scientific papers referred and cited during this study, are listed as references.
- The results of XRD, XRF, groundwater flow diagrams, recharge rate, runoff and evapotranspiration, hydrochemical data from DWA, as well as original hydrochemical, water quality and environmental isotopic data are listed as appendix to this thesis.

CHAPTER 2 – LITERATURE REVIEW

2.1. Hydrogeology

Through qualified guesses, Enslin (1970) and Vegter (1995) estimated sustainable groundwater yields in South African aquifers of 2 500 x 10^6 m^3/a, and 5 400 x 10^6 m^3/a respectively. Based on the national hydrogeological mapping work of Vegter (1995), Baron et al., (1998) produced a Harvest Potential (HP) Map of South Africa, this was based mainly on storage and recharge estimates to provide a sustainable groundwater yield in $m^3/km^2/a$ (Baron et al., 1998), their estimate was 19 x 10^9 m^3/a. Haupt (2001) took this map a step further by recognizing that aquifer transmissivity was the main limiting factor in determining the so-called HP. He applied a factor to the HP based on borehole yield categories and came up with an estimate of groundwater availability of 10 x 10^9 m^3/a (Haupt, 2001).

The DWA completed its Phase 1 Groundwater Resources Assessment (GRAI) in 2003 after the publication of a series of 21 hydrogeological maps at a scale of 1:500 000 which was basically an aquifer classification project. In late 2003 DWA initiated Phase 2 Groundwater Resources Assessment Project (GRAII), the main aim of which was to quantify South Africa's groundwater resources (DWA, 2005). The project comprised the following sub-tasks (DWA, 2005):

- Quantification (basically of aquifer storage)
- Planning Potential
- Recharge
- Groundwater/Surface Water Interaction
- Aquifer Classification and
- Groundwater Use

Algorithms were developed for the estimation of key parameters, including storage, recharge and base-flow to generate the best estimate to date of the amount of groundwater that can be abstracted on a quaternary catchment basis. The GRAII project produced the above mentioned relevant hydrogeological sub-tasks for the Sandspruit catchment (component of quaternary catchment G10J), presented in Table 2.1.

Table 2.1: Groundwater Resource Assessment Phase ll results for Quaternary catchment G10J (after DWA, 2005)

QUAT	Area (km^2)	MAP (mm)	Ave Water-level (m.bgl)	Saturated Thickness (m)		Specific Yields of WZ	Volume of water stored in aquifer($x10^3$ m^3/km^2)	Mean Annual potential recharge (m^3/km^2)	
				Weathered Zone (WZ)	Fractured Zone (FZ)			Wet season	Dry season
G10J	868	447	10.9	41	125	3.63E-0^4	16335	17534000	11966100

Table 2.1: Continued...

QUAT	Mean annual contribution to river baseflow (m^3/km^2)	Average groundwater exploitation potential (m^3/a)		Utilisable groundwater exploitation potential (m^3/a)	
		Normal AGEP	Dry AGEP	Normal UGEP	Dry UGEP
G10J	5207820	6251310	3873390	2422470	101513

2.1.1. Major aquifers within study catchment

Aquifers within the study catchment are the fractured rocks of the Malmesbury Group and Table Mountain Group (TMG), fractured and intergranular rocks of the Cape Granite Suite, and the intergranular sediments of the Springfontyn Formation.

The Malmesbury phyllite and greywacke aquifers produce yields of between 0.9-2 l/s. Groundwater exploitation in the Malmesbury Group is often problematic due to the largely argillaceous nature of many of the lithological units (Meyer, 2001).

The TMG aquifer, notably the often fractured arenaceous components, is largely anisotropic, and thus does not display uniform aquifer characteristics. The TMG remains as the most groundwater exploited aquifer, with yields in the sandstones reaching an average of 2.28 l/s with increased yield up to 4 l/s located at major discontinuities (Meyer, 2001). Weaver *et al*., (2002) estimated hydraulic conductivity (K) of the TMG to be ranging from 0.002 to 1.99 m/d. Weaver *et al*., (1999) also found that the storage coefficients (S) of 0.001 was a good representation of the storativity of the Peninsula (encountered within the study area) and Nardouw formations.

Aquifers of the Cape Granite Suite have variable grain size with varied composition, with diverse weathering forms diverse groundwater implications (Meyer, 2001). Porphyritic granite, containing abundant phenocrysts of feldspar is likely to weather to produce a clay rich material, which often impedes infiltration. Weathered medium-grained granite with a more balanced composition is likely to be a better aquifer, with yields of 0.5-5 l/s (Meyer, 2001).

Both unconfined and confined aquifers exist within the research area. Table 2.2 provides a summary of processes affecting the groundwater level within these aquifers, these are classified according to whether they are natural or man-induced, whether they produce fluctuations in confined or unconfined aquifers, and whether they are short-lived, diurnal, seasonal, or long-term in their frame time (Freeze and Cherry, 1979). Those checked in the “confined” column produce fluctuations in hydraulic head at depth. Those checked in the “unconfined” column produce fluctuations in water-table elevation near the surface (Freeze and Cherry, 1979). Understanding the mechanisms that influence the water-level can serve as a guideline for the prediction of future water-level fluctuations.

Table 2.2: Summary of mechanisms that lead to fluctuations in groundwater levels (after Freeze and Cherry, 1979)

Factors/ Processes	**Unconfined**	**Confined**	**Natural**	**Man-induced**	**Short-lived**	**Diurnal**	**Seasonal**	**Long-term**	**Climatic influence**
Groundwater recharge (infiltration to the water-table)	√		√				√		√
Air entrapment during groundwater recharge	√		√		√				√
Evapotranspiration and phreatophytic consumption	√		√			√			√
Bank-storage effects near streams	√		√				√		√
Tidal effects near oceans	√	√	√			√			
Atmospheric pressure effects	√	√	√			√			√
External loading of confined aquifers		√		√	√				
Earthquakes		√	√		√				
Groundwater pumpage	√	√		√				√	
Deep-well injection		√		√				√	
Artificial recharge; leakage from ponds, lagoons, and landfills	√			√				√	
Agricultural irrigation and drainage	√			√				√	√
Geotechnical drainage of open pit mines, slopes, tunnels, etc.	√			√				√	

2.2. Groundwater recharge estimation

Quantification of groundwater recharge rate provides the basis for efficient groundwater resource management. It is particularly important in regions with large demands for groundwater supplies, where such resources are the key to economic development. However, the rate of aquifer recharge is one of the most difficult factors to measure in the evaluation of groundwater resources (Sun, 2005). The techniques used in this study are the water-balance, chloride mass balance, and qualified guesses approaches. Rainfall is the principal means for replenishment of moisture in the soil water system and recharge to groundwater. Moisture movement in the unsaturated zone is controlled by capillary pressure and hydraulic conductivity (Sun, 2005). Two principal types of recharge are recognised, categorised here (Figure 2.1.) as direct and indirect (FAO, 1981; Lloyd, 1986). Direct recharge is best described as water added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone (Lloyd, 1986). Indirect recharge results from percolation to the water-table following runoff and localisation in joints, as ponding in low lying areas and lakes, or through the beds of surface water (Lerner et al., 1990). Two distinct categories of indirect recharge are thus evident i.e. that associated with surface water, and a second localised form resulting from surface concentration of water in the absence of well-defined surface drainage.

Recharge is governed by the intricate balance between several components of the hydrologic cycle, each of which is a function of several controlling factors (Xu and Beekman, 2003):

- Rainfall: (intensity, frequency, variability, spatial distribution)
- Evapotranspirative losses: (temperature, wind, humidity)
- Discharge losses: (interflow, springs, base-flow, lateral flow and artificial discharge)
- Catchment: (soil type, thickness, spatial distribution, topographical features, vegetation)
- Geology: (rock types, structural geology and igneous intrusions)

Variations in geomorphology reflect differences in topography, vegetation, and soil type, which can affect recharge. The impact of topography on local and regional groundwater flow paths was demonstrated by Tóth (1963). Recharge is generally considered to occur in topographic highs and discharge in topographic lows in humid regions, whereas in arid regions recharge is usually focused in topographic lows, such as valleys. The concept of hydrogeomorphic units was originally described by Tóth (1963) and Meyboom (1966, 1967). Delineation of hydrogeomorphic settings on the basis of topographic attributes, including

slope classes, slope beaks, curvature, and elevation is greatly facilitated by the use of geographic information systems (GIS) and digital elevation models (Salama *et al*., 1994; Hatton, 1998) as a decision support system. Vegetation cover is important in assessing the recharge potential at a site. Recharge is generally greater in non-vegetated than in vegetated regions (Gee *et al*., 1994) and greater in areas of annual crops and grasses than in areas of trees and shrubs (Prych, 1998). Irrigated areas should also be identified because irrigation return flow often contributes significant amounts of artificial recharge. Soil texture and permeability are important because coarse-grained soils generally result in higher recharge rates than fine-grained soils (Scanlon *et al*., 2002).

There are as many methods available for quantifying groundwater recharge, as different sources and processes of recharge are largely site specific. They are (a) direct versus indirect, (b) water-balance (c) Darcyan physical methods, (d) chemical, isotopic and gaseous tracer methods (Lerner *et al*., 1990; Kinzelbach *et al*., 2002). Each of the methods has its own limitations in terms of applicability and accuracy. Geographic information system approach is used to calculate the water-balance in the current research.

Recharge is very difficult to estimate reliably, and more than one method is often used. The recharge estimation carried out in this study focuses mainly on the water-balance method and is therefore discussed in detail. The water-balance method is commonly used to estimate recharge because of its relative simplicity (Sun, 2005). The advantages of water-balance methods are that they can usually be estimated from readily available data (e.g. rainfall, runoff, water-levels) and therefore efficient to apply, and they account for all water entering and leaving the system (Lerner *et al*, 1990). The different recharge estimation methods used in this study are discussed in the following sections (sections 2.2.1, 2.2.2, and 2.2.3).

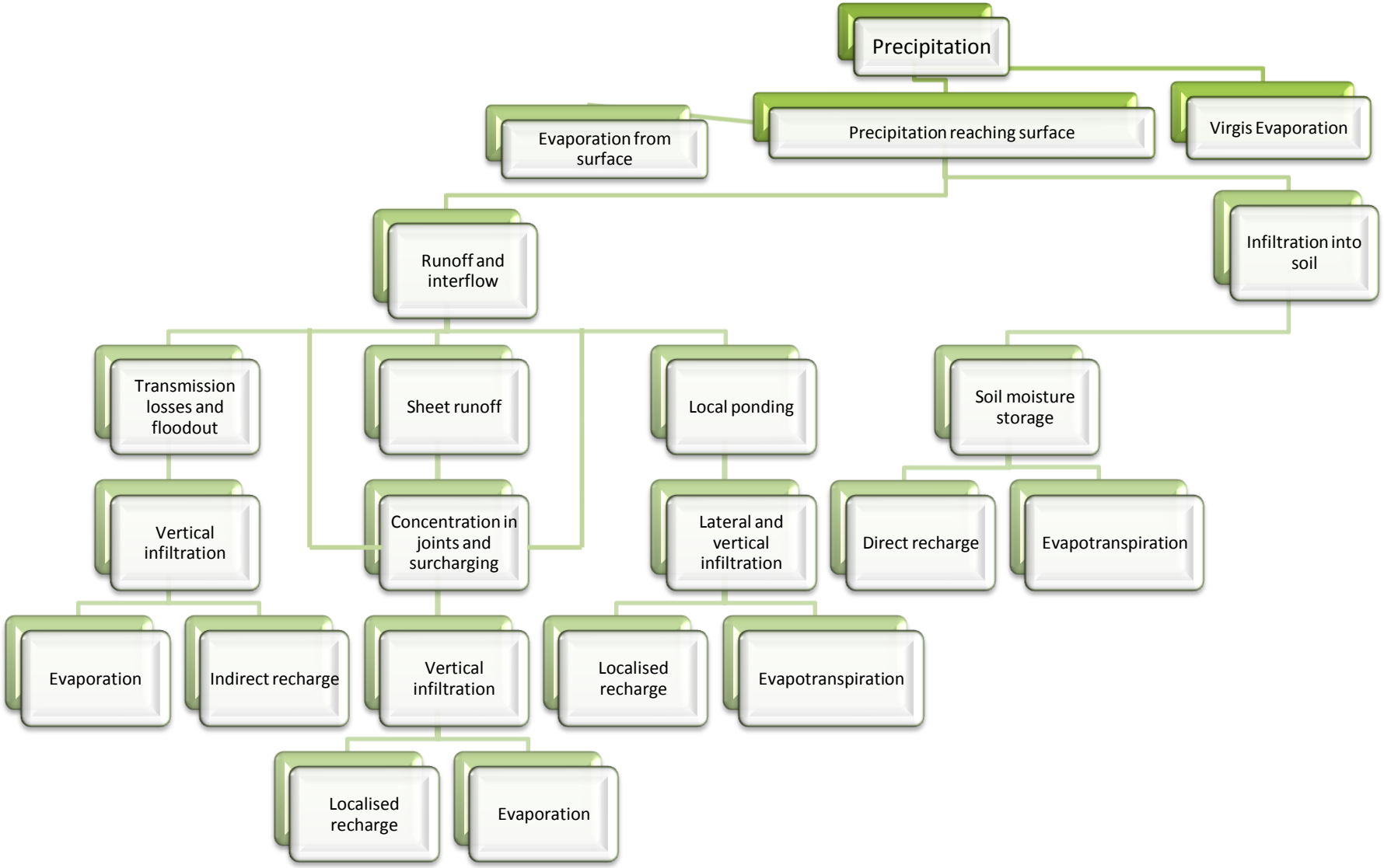


Figure 2.1: The various elements of recharge in an arid area (adapted from Lloyd, 1986)

2.2.1. Catchment water-balance

The concept of the water-balance provides a framework for studying the hydrological behaviour of a catchment and it can be used to identify and predict changes in water-balance components. The water-balance for a catchment can be written as (Zhang *et al*., 1999):

$$P = ETc + RO + D + \Delta S \quad (2.1)$$

where P is precipitation, ETc is crop evapotranspiration, RO is surface runoff measured as streamflow, D is recharge to groundwater, and ΔS is the change in soil water storage.

Precipitation is the largest term in the water-balance equation and it varies both temporally and spatially. Evapotranspiration (loss of water by evaporation from both the soil and plant) is the second or third largest term in the water-balance equation. In arid and semi-arid regions, evapotranspiration often exceeds precipitation (Zhang *et al*., 1999). Surface runoff is also an important component of the water-balance and it can be generated when the soil is saturated with water or when rainfall intensity exceeds infiltration capacity of the soil. Surface runoff is affected by the presence of vegetation through rainfall interception and evapotranspiration (Zhang et al., 1999). Annually, surface runoff will generally show a good correlation with annual precipitation, particularly in areas with winter dominant precipitation (Budyko, 1974). The last term in the water-balance equation is the change in soil water storage. Over a long period of time (i.e. 5 to 10 years), it is reasonable to assume that changes in soil water storage is zero (Zhang *et al*., 1999). Recharge and change in soil water storage is often just 5 to 10 % of the annual water-balance. Therefore, it is expected that a change in annual surface runoff associated with land use changes such as afforestation, deforestation and land development should be reflected in the annual evapotranspiration (Zhang *et al*., 1999).

For determining the reference crop evapotranspiration (ETc), the reference evapotranspiration (ETo) should first be estimated. Doorenbos and Pruitt (1977) defined ETo as "*the rate of evapotranspiration from an extensive surface of green grass cover in uniform height, actively growing, completely shading and no shortage of water*". Among the more than 50 empirical formulas used for estimating ETo, the Food and Agriculture Organization (FAO) recommended the Penman-Monteith equations as the international standard for estimating ETo (Allen *et al*., 1998). The Penman-Monteith method requires many input meteorological variables, which may not be readily available for all weather stations. On the other hand, the Thornthwaite (1948) equation requires only air temperature that is measured in all weather stations.

2.2.1.1. The Thornthwaite method

The Thornthwaite (1948) method is generally used in humid regions where air temperature is the only input data. The Thornthwaite monthly ETo is determined with the equation proposed by Thornthwaite (1948) for a standard month of 30 days and days with 12 hour photoperiod, by using the monthly mean temperature and is as follows:

$$ET_m = 16Nm(10/I)^{a} \qquad 0℃ \leq T \leq 26℃ \qquad (2.2)$$

$$I = \sum_{n=1}^{12}(0.2T)^{1.514} \qquad T > 0℃ \qquad (2.3)$$

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.7912 \times 10^{-2} I + 0.49239 \qquad (2.4)$$

where ET_M is the monthly ETo in mm mon^{-1}; Nm the latitude correction factor (40^o for the project area); I is the thermal index; a is the exponent of Equation (2.2) given by Equation (2.4) and T is the monthly mean temperature in ^oC. This method underestimates monthly ETo under dry and arid climates because the equation does not consider the saturation vapour deficit of the air (Pelton *et al*., 1960; Pruitt 1964; Doorenbos and Pruit 1977; Hashemi and Habibian 1979; Malek 1987).

2.2.1.2. The Penman-Monteith Method

The Penman-Monteith form of the combination equation is (Allen *et al*., 1998):

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \qquad (2.5)$$

where R_n is the net radiation, G is the soil heat flux, $(e_s - e_a)$ represents the vapour pressure deficit of the air, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapour pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances. From the original Penman-Monteith equation (Equation 2.5), including aerodynamic and surface resistance, the FAO modified Penman-Monteith method to estimate ETo can be derived (Equation 2.6) (Allen *et al*., 1998):

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad (2.6)$$

Where ETo is the reference evapotranspiration [mm day^{-1}], R_n the net radiation at the crop surface [MJ m^{-2} day^{-1}], G the soil heat flux density [MJ m^{-2} day^{-1}], T represents the mean daily air temperature at 2 m height [°C], u_2 the wind speed at 2 m height [m s^{-1}], e_s the

saturation vapour pressure [kPa], e_a the actual vapour pressure [kPa], e_s-e_a the saturation vapour pressure deficit [kPa], Δ the slope of the vapour pressure curve [kPa °C^{-1}] and γ the psychrometric constant [kPa °C^{-1}]. The reference crop evapotranspiration represents the evapotranspiration from a standardized vegetated surface. Experimentally determined ratios of ETc/ETo, called crop coefficients (Kc), are used to relate ETc to ETo or:

$$ETc = Kc*ETo. \quad (2.7)$$

The crop coefficient integrates the effect of characteristics that distinguish a typical field crop from the grass reference, which has a constant appearance and a complete ground cover (Allen *et al*., 1998). Consequently, different crops will have different Kc coefficients. The changing characteristics of the crop over its specific growing season will also affect the Kc coefficient.

2.2.1.3. Runoff

Runoff is another important component of the catchment water-balance whereby the excess precipitation flows on the surface along streams and rivers. Impact of factors on the runoff is similar to the evapotranspiration in a certain degree, but the formation mechanism of the runoff is totally different from that of evapotranspiration. The runoff coefficient, C, represents the percentage of rainfall that becomes runoff (Tripathi and Singh, 1998). The magnitude of runoff varies on the basis of precipitation and land surface and is heavily influenced by vegetation, soil type and degree of disturbance, catchment slope and the number and nature of watercourses in the catchment (Anon, 1997). Tripathi and Singh (1998) conducted studies on small basins in India and developed the following relationship for the estimation of peak discharge:

$$Q = 1/360\ CI_rA_{ha} \quad (2.8)$$

Where Q is peak rate of runoff [m^3/s] for a given frequency of rainfall; C is the runoff coefficient; A_{ha} is the area of the basin [ha]; and I_r *is* the intensity of rainfall [mm/h] for design frequency for duration equal to time of concentration. The above equation was modified to take monthly precipitation into account, and to determine the monthly runoff rate, and not the recharge volume, thus providing:

$$q_{(t)} = 1/360\ CP_{(t)} \quad (2.9)$$

Where q is runoff rate (mm), C is the runoff coefficient, and P is the precipitation (mm), for a given time (t).

2.2.2. The chloride mass balance (CMB) method

The environmental tracer chloride (Cl^-) has been extensively used for the estimation of groundwater recharge, the CMB technique developed by Eriksson and Khunakasem (1969) is simple to estimate, inexpensive, and the most universal for recharge estimation. Chloride is used for recharge estimation because of its conservative nature and its relative abundance in rainfall. Application is based on comparison of the chloride (dry) deposition rate at the soil surface with the concentration in the groundwater (Allison *et al*., 1984). Chloride concentration increases relative to the concentration of rainfall as a result of interception, soil evaporation and/or root water uptake by vegetation. The total (wet and dry) chloride deposition and the total precipitation depth determine the chloride concentration of the rainwater at the soil surface (Allison *et al*., 1984). Subsequent evapotranspiration can then be estimated from the increase in chloride concentration, providing that no other major sources of chloride exist.

Chloride increases in the root zone under diffusive or piston flow conditions, until a constant value is reached (Allison, 1988). Under steady-state conditions of piston flow, the chloride flux at the surface is equal to the chloride flux below the active root zone, and conservation of mass leads to Equation (2.10) (Eriksson and Khunakasem, 1969):

$$P\,Cl_p = D\,Cl_{sw} \qquad (2.10)$$

where P and D are mean annual precipitation and recharge (mm/a), and Cl_p and Cl_{sw} are mean Cl^- concentrations (mmol/l) in precipitation and soil water, respectively.

Chloride mass balance can also be used to determine moisture fluxes and recharge rates in the unsaturated zone. These mass balances assume steady state conditions and conservation of mass between the atmospheric Cl^- input and the Cl^- flux in the subsurface (Selaolo, 1998). For deep infiltration below the root zone, downward moisture flux *R* (mm/a) is determined by (Edmunds *et al*., 1988; Sharma, 1989):

$$R = \frac{PCl_{\mathrm{p}}+D_{\mathrm{d}}}{Cl_{\mathrm{sw}}} \qquad (2.11)$$

P is the precipitation (mm/a), Cl_p is the Cl^- content of in precipitation (mg/l), D_d is the dry deposition (mg/m^2/a) and Cl_{sw} is the Cl^- concentration (mg/l) in the soil moisture. Limitations

arising with the application of chloride as a tracer in the unsaturated zone, including (Selaolo, 1998):

- When recharge rates are based on tracer estimates in the root zone, tracer techniques can overestimate recharge until the tracer has moved well below the root zone (Tyler and Walker, 1994).
- The movement of chloride through the soil can be influenced by anion exclusion in various lithologies (Bresler, 1973). A further complicating factor is channelling of water in soils with a well-defined structure. Tyler and Thomas (1981) observed that the maximum in chloride breakthrough in an undisturbed, structured sequence was far ahead of one pore volume, indicating that majority of the chloride moved through the larger pores, bypassing part of the soil matrix. This phenomenon is equivalent to what other researchers describe as the presence of mobile and immobile water in the soil matrix (Gvirtzman and Magaritz, 1986).
- Cl^- is present in the tissues of all plants (Feth, 1981).
- The mineralogical composition of sediments might contribute chloride to the soil water or groundwater through dissolution or weathering, evaporate minerals are particularly disruptive (Dettinger, 1989).
- Other sources of chloride that may disrupt the mass-balance approach are anthropogenic input by means of, for example, irrigation return flow.

2.2.3. Qualified Guesses

The maps of Vegter (1995), ACRU, Groundwater component of River Base flow and Harvest Potential are used to determine the groundwater recharge rate. The qualified guesses for recharge from the soil/vegetation and geology are from expert options and general equations proposed by Bredenkamp *et al*. (1995) and Kirchner *et al*. (1991).

2.3. Hydrochemistry and water quality

2.3.1. Composition of natural water

The chemical composition of groundwater varies mostly due to the natural quality of the aquifer, and to a lesser extent, precipitation, recharge rate, meteorological aspects, saline water and flow patterns (Aastrup and Axelsson, 1984). The natural chemical composition of groundwater is mostly determined by the (Aastrup and Axelsson, 1984):

- reaction velocity between water and minerals in sediment or rock
- residence time of water within the aquifer
- contact area between water and minerals

The reaction velocity between the groundwater and minerals is determined by the weathering capacity of the rock material contained in the soil (Aastrup and Axelsson, 1984). The topography, together with the grain size distribution of the soil, determines the residence time of water within the aquifer, i.e. the rate of chemical interaction between water and solid material (Aastrup and Axelsson, 1984). Moreover the chemical composition of groundwater changes temporally. Reasons for natural variations may include (Aastrup and Axelsson, 1984):

- Supply of groundwater from different regions of the aquifer in connection with changes in groundwater level
- Changes in groundwater level which cause changes in the redox situation, effecting ions involved in the redox processes (SO_4, Fe, Mn)
- Changes in the chemical composition of rainfall

Understanding the above processes, and being able to make reliable quantitative statements about them, requires the application of theoretical analysis to develop tentative models. These hypotheses are often referred to as “conceptual models” (Aastrup and Axelsson, 1984). Essential data used in the determination of water quality are obtained by the hydrochemical analysis of water samples in the laboratory or onsite sensing of chemical properties in the field.

2.3.2. Illustration of hydrochemical data

2.3.2.1. Piper diagram

The diagnostic chemical properties of water are presented by various methods, of which the hydrochemical facies, e.g. the Piper (1944) trilinear diagram method, is the most common. The Piper diagram is useful in screening and filtering large volumes of chemical data, which makes interpretation easier. Furthermore, a Piper diagram can define the patterns of spatial

change in the water chemistry among geological units, along a line of section or along a flow line (Raji and Alagbe, 1997; Domenico and Schwartz, 1998). On these diagrams the milliequivalent percentages of the major cations and anions are plotted, to which the point at which an analysis plots is of considerable diagnostical value (Hem, 1985).

2.3.2.2. Schoeller diagram

The Schoeller diagram consists of vertical axes on which the concentrations in mg/l of various cations and anions are plotted. The axes are displaced vertically so that the concentrations can also be read in milliequivalents on the two outer scales (Hem, 1985). Points for each ion are connected by straight lines. The diagram displays the ion ratios between points joined by straight lines. Identical ion ratios with different concentrations plot as parallel lines. The Schoeller diagram also allows the classification of water samples (Hem, 1985).

2.3.3. Groundwater salinity

Salinization is the process whereby the concentration of dissolved salts in water and soil is increased due to natural or anthropogenic processes (Salama *et al*., 1999). Salinity of surface and groundwater within the Sandspruit catchment has been vastly documented by Flugel (1995), and Kamish (2008). It is thus important to characterise the origin of the salt load within these waters.

2.3.3.1. Mechanisms of groundwater salinity

The spatial distribution of saline land and water in a catchment is related to the hydrogeomorphology (e.g., topography and hydrostratigraphy) and associated groundwater flow systems (Flugel, 1995). The physical and chemical processes responsible for the development of saline soils involve the mineralisation of the groundwater, the physical transport of dissolved salts, the discharge of saline baseflow into streams and lakes, and the precipitation of salts within the soil zone. Most of the salt in the groundwater system comes from input loading, which includes air-borne salts, salt dissolved in the water recharging the system, and salt contributed from mineral dissolution within the groundwater flow system (Salama *et al*., 1999). The most important process that adds salt to groundwater is mineral dissolution reactions in the subsoil.

Soil salinization occurs in areas of groundwater discharge or a rising water-table when mineralised interstitial pore water at or near the ground surface continually evaporates and causes minerals to precipitate (Salama *et al*., 1999). A critical factor controlling the amount of evaporation is the depth of the water-table below the surface. In general, evaporation is

minimal when the water-table is below 3.0 m depth (Salama *et al*., 1999) and rising water-tables can lead to the development of saline soils in recharge areas. Groundwater discharge areas are commonly sites of the most active soil salinization, because salt fluxes facilitated by continuous upward movement of dissolved salts (Salama *et al*., 1999).

2.3.3.2. Sodium and chloride (salinity) enrichment in groundwater

Sodium is retained by adsorption on mineral surfaces, especially by minerals having high cation-exchange capacities such as clays (Hem, 1985). Clarke (1924) estimated that about 60% of igneous rock in the Earth's outer crust consists of feldspar. The common feldspars are orthoclase and microcline, and the plagioclase (albite to anorthite). Some sodium may be present, substituting for potassium in orthoclase and microcline. In resistate (principally composed of residual unaltered fragments of a precursor rock body) sediments, sodium may be present in unaltered mineral grains, as an impurity in the cementing material, or as crystals of readily soluble sodium salts deposited with the sediments or left in them by saline or brackish water (Hem, 1985). The soluble salts go into solution and are removed from coarse-grained sediments after environmental changes, such as faulting and upliftment of land surfaces or a decline of sea level imposing a freshwater leaching regimen. During the early stages of the leaching process, the water leaving the sediments may have high concentrations of sodium in solution. The remaining traces of marine salt or connate water may persist for long periods where circulation of water is impaired (Hem, 1985). Chloride may be present in resistates as the result of inclusion of connate brine water and in cementing material and is to be expected in any incompletely leached deposit laid down by the sea or in a closed drainage basin. When porous rocks are submerged by the sea after their formation, they become impregnated with soluble chloride salts. Fine-grained marine shale might retain some of this chloride for very extensive periods (Hem, 1985).

In hydrolyzate (characterized by elements such as aluminum, potassium, or sodium which are readily hydrolyzed) sediments, the particles normally are very fine grained, and the circulation of water through the material is impaired. The hydrolyzates typically include clay minerals having large cation exchange capacities. Water trapped in the hydrolyzate sediment when it was deposited may be retained with its solute load for long periods (Hem, 1985).

2.3.3.3. Concept of dryland salinity

In Australia, widespread replacement of deep-rooted perennial native vegetation (often Eucalyptus species) with shallow-rooted annual plants, which not only use but also tend to intercept less water, has led to the development of dryland salinity (Peck and Williamson

1987). It is the concept “excess” net recharge that is responsible for salinity formation in arid/semi-arid areas (Salama *et al*., 1999). For example, in the southern part of the Australia, saline soils and seeps that existed prior to settlement were the result of additional moisture formed by natural conditions, such as ponding and above-average annual precipitation (Salama *et al*., 1999). Secondary salinization is caused by human-induced actions, such as summer fallow, irrigation, dam construction, and clearing of native vegetation. Dryland salinity in a catchment is the hydrogeological response to the clearing in the landscape and the replacement of native vegetation with shallow-rooted cultivated crop (Salama *et al*., 1999). Groundwater recharge rates increase and water-tables rise or the pressures in confined aquifers increase, causing an upward leakage to the phreatic aquifers (Salama *et al*., 1999). The fundamental cause of dryland salinity is that the full impact of changed water-balance is generally not experienced by those responsible for the imbalance and the resulting excess recharge of groundwater (Hayes, 1997). The additional water available on catchments converted to dryland farming is estimated to be 20–100 mm/a (Holmes and Talsma, 1981).

2.3.3.4. Mineralisation in South African surface waters and groundwaters

Water quality considerations are important in the management of most South African river systems. Mineralisation i.e. the contamination of surface waters with inorganic salts is a significant water quality problem in rivers such as the Great Fish and Sundays Rivers in the Eastern Cape and the Berg and Breë Rivers in the Western Cape (Hall and Gőrgens, 1978). The tributaries within the Berg River basin which have their origin in the mountainous areas where the rocks are relatively inert (Table Mountain Group sandstone) and where precipitation often exceeds 1 000 mm per annum typically have total dissolved solids (TDS) concentrations of about 60 mg/l in the winter rainy season (Fourie and Steer, 1971). In contrast, tributaries having their origin in the low-lying Malmesbury Shale formations where the rainfall is low (usually 400 to 500 mm per annum) typically have winter TDS concentrations of about 3 500 mg/l (Fourie and Steer, 1971).

An implication of the increased utilization of the Berg River resources is further progressive salinization (Hall and Gorgens, 1978). One of the major causes of this increased salinization is increased irrigation return flow. The salt concentrations at the Misverstand Weir have TDS values which frequently exceed 500 mg/l, this would reduce the value of this water for Saldanha water supply and at times fail to meet water quality standards (Hall and Gorgens, 1978).

Fey and de Clercq (2004) performed a pilot study on dryland salinity impacts on the rivers of the Western Cape. Their analysis included the identification of saline scolds (*brak kolle* – patches devoid of vegetation due to high soil salinity) and modelling of likely runoff on Rooihoogte farm, a farm a few kilometres north-east of the Sandspruit catchment, under different vegetation scenarios (winter wheat and *Renosterveld*). Their hypothesis, which stated that a switch from perennial deep-rooted *Renosterveld* to annual shallow-rooted wheat would result in less water use and therefore enhanced discharge of salts into the river system was confirmed at Rooihoogte, ACRU calculations predicted that under *Renosterveld*, water use by vegetation reduces annual runoff to a meagre 1 mm. This increases to 18 mm or more (up to 60 mm) under winter wheat. The proportional increase in runoff from *Renosterveld* to wheat is much less in higher rainfall parts of the catchment, and the increase in contribution to catchment salt load would be smaller still, because less salt is stored in high rainfall catchments. This suggests that with increasing aridity, there is an increase both in the salt trapping effect from atmospheric deposition under natural vegetation and in the sensitivity of the catchment to releasing a substantial salt load into the river system when wheat replaces *Renosterveld*.

Fey and de Clercq (2004) have also reported signs of soil salinity become progressively more evident in the lower, more northerly parts of the Berg River basin. Further upstream of the Sandspruit catchment, the Berg River drains largely from a higher rainfall region with quartzitic rocks and a non-saline regolith, resulting in low salinity.

Flugel (1995) has undertaken a drilling and soil mapping program in the Sandspruit catchment. The results revealed that the salt distribution in the catchment is associated with topographic location. A considerable increase of soil salinity was found in the sandy alluvial deposits on the valley floor of the Sandspruit River. Flugel (1995) further observed that that there was a distinct difference between the summer and winter seasons. The first rain in May and June filled up the shallow soils on the slopes. Consequent rain storms in July and August saturate the soils and create surface runoff and interflow generating steep hydrograph limbs. Rainfall on the slopes infiltrates and recharges the fractured shale aquifer. Groundwater level rises into the alluvial soils of the valley floor and base-flow was established by continuous seepage into the river. Salts from recharge areas at the slopes were leached from the soils and the weathered shale into the groundwater. The salts are also transported in the unsaturated zone to the valley floor and percolate through the soils into the groundwater. From there, it seeps into the Sandspruit River. Consequently, during the summer season without rainfall, subsurface water is consumed by evapotranspiration. At the valley floor, salts are transported upwards by capillary rise from the shallow saline groundwater and crystallize in the unsaturated soil zone and on the soil surface. The

topographical distribution of the different soil classes reflects the hydro-saline dynamics. Due to salt leaching during winter, soils at the slopes are less saline and tend to be only moderate or medium solonetzic (soils associated with a vegetative cover of grass and forbs). Whereas, solonetz soils in the valley floor are developed. In 1986, the Sandspruit catchment had rainfall (325 mm) close to average, of which only 3.5% (11 mm) was discharged as runoff into the Berg River, along with 8000 tons of salt from a catchment area of about 150 km^2 (i.e. about 50 kg/ha). Only about 1800 tons of salt (<15 kg/ha) could be accounted for by atmospheric deposition. This means that for the year there was a leaching loss of salt of about 35 kg/ha.

Wiplinger (1980) stated that much of the regolith within the study area and groundwater salts are a legacy of past inundation by the sea and subsequent incomplete weathering and leaching, the output of salts might simply be described as a natural phenomenon that would have occurred with the same intensity under *Renosterveld* vegetation.

In the study by Fourie (1976), water samples were taken during the winter rainy season in 1973 at approximately 180 points along tributaries of the Berg River. While geological factors contribute to the distribution of salts in the landscape (and here particular cognisance should also be taken of Wiplinger's (1980) comments that the salts possibly resulted from oceanic submergence of the coastal plain), a compelling case through Fourie's (1976) results can be made for a climatic effect that is strong enough to override these geological factors.

2.4. Multivariate statistical analyses

Geological and hydrogeological processes are generally complicated, and this complexity is illustrated by the random distributions of many field measurements. Physical and chemical data may contain this information, but the data are mingled with major and minor trends so it is difficult to extract a direct interpretation of the governing process from the raw data (Suk and Lee, 1999). The basic behavioural and conceptual model is the necessary framework upon which more sophisticated interpretations are to be built. It is in those early stages that multivariate analysis comes into play as an essential tool (Suk and Lee, 1999). Multivariate statistical analysis aims to interpret or disclose the governing processes through data reduction and classification. Factor analysis can be undertaken to identify the most important factors contributing to the data structure and the similarities between the factors (Suk and Lee, 1999).

2.4.1. Factor analysis

Factor analysis is a statistical approach that can be used to analyze interrelationships amongst large numbers of variables and to explain these variables in terms of their common dimensions (factors) (Suk and Lee, 1999). The statistical approach involves condensing the information contained in a number of original variables into a smaller set of dimensions (factors) with a minimum loss of information (Hair et al., 1992). The primary objectives of a factor analysis are to determine (DeCosta, 1998):

- The number of common factors influencing a set of measures
- The strength of the relationship between each factor and each observed measure
- Identify the nature of the factors in a specific content area
- Demonstrate the dimensionality of a measurement scale. Researchers often wish to develop scales that respond to a single characteristic
- Determine what features are most important when classifying a group of variables

Factor analysis combines variables that are correlated into clusters in order of the amount of variance explained (Lawrence and Upchurch, 1982). Regionally distributed, lithologically-controlled variables generally are extracted first, and then the more local, flow-controlled variables are identified (Lawrence and Upchurch, 1982). Prior to factor analysis, data is normalized according to criteria presented by Howarth and Earle (1979). This is necessary since the first step in the factor analysis is computation of a correlation coefficient matrix, which requires normal distributions in all variables. Entry with a correlation matrix causes the factor analysis to compare variables according to linear correlation coefficients. True factor analysis allows for an error term, with Kaiser normalization and Varimax rotation (Nie *et al*., 1975). Davis (1973) and Klovan (1975) explain the mathematics of the solution. The general procedure solves the equation:

$$Z_{kj} = a_{1j}F_{k1} + a_{2j}F_{k2} + \ldots + a_{mj}F_{krn} + a_jE_{kj} \qquad (2.12)$$

The a's are factor loadings, coefficients that reflect the importance of each variable, j, in the factors represented by the aF terms. Thus, where factor loadings are high, it can be assumed that the variable contributes to that factor. The F's are factor scores. The scores indicate the importance of each factor with respect to each sample, k. Z's are original variables in standard form (Lawrence and Upchurch, 1982). The sum of squares of factor loadings within each factor before rotation or other manipulation to maximize loadings is the eigenvalue for that factor. The eigenvalue of each cluster divided by the total number of variables represents the proportion of the total data variability accounted for by each cluster (Lawrence and Upchurch, 1982). Factor analysis was thus performed using a varimax

rotation in a correlation matrix by applying principal component analysis, communality values are listed in Table 5.8.

2.5. Environmental isotopes

Isotopes of the same chemical element have almost identical physical and chemical properties. However, due to the small mass differences, isotopes have different reaction rates and different abundances in two chemical compounds or phases that are in isotopic exchange (Geyh, 2000). Physical processes such as diffusion, evaporation, condensation, melting, etc. produce isotopic differentiation. Variations in the isotopic composition, produced by chemical or physical processes, in compounds or phases, present in the same system, are called isotopic fractionation (Geyh, 2000).

The most important atomic constituents of the water molecule are ^{16}O and ^{18}O and ^{1}H and ^{2}H (deuterium), and ^{3}H (tritium). These have the widest field of application in groundwater studies, for instance, tracing the origin of the water, the mode of recharge of groundwater, determining the age of groundwater (Geyh, 2000). The relationship between $\delta^{2}H$ and $\delta^{18}O$ in fresh waters correlate well on a global scale (Craig, 1961). This relationship is described as the Global Meteoric Water Line (GMWL) and is expressed by the equation (Craig, 1961):

$$\delta^{2}H = 8\delta^{18}O + 10 \quad (2.13)$$

The GMWL is an average of many regional and local meteoric water lines (LMWL) that differ from the GMWL in slope and/or intercept as a result of different climatic and geographic factors (Clark and Fritz, 1997). Deuterium excess (d-excess) is a measure of the deviation of a given data point from a line with a slope of 8 going through V-SMOW and is defined by the equation (Dansgaard, 1964):

$$\text{d-excess} = \delta^{2}H - 8\,\delta^{18}O \quad (2.14)$$

The d-excess value globally is approximately +10‰, as global atmospheric water vapour forms from seawater with an average humidity slightly greater than 85% and produces precipitation that is displaced from seawater by approximately +10‰ for $\delta^{2}H$ (Clark and Fritz, 1997). The value of d-excess is a function of the mean relative humidity of the atmosphere above the ocean water (Merlivat and Jouzel, 1979). Evaporation from surface water may cause the slope to be as low as 4. The slope can be as low as 2 for groundwater in the unsaturated zone (Athanasopoulos, 2009). If the isotopic signature of the groundwater deviates from the LMWL, it indicates various processes of isotopic exchange and fractionation. The best known examples are departures due to evaporation observed in brines from sedimentary marine aquifers, exchange of oxygen between water molecules,

and mixing between meteoric groundwater's and connate residual brines in crystalline rocks (Athanasopoulos, 2009).

The radioactive hydrogen isotope, tritium, has a half-life of 12.43 years (Fetter, 2001). The tritium activity is given in tritium units [TU]. One TU corresponds to one ^{3}H atom to 10^{18} hydrogen atoms. ^{3}H acts as a conservative tracer. The natural cosmogenic level of ^{3}H in precipitation is a few TU. Since the 1950's the level in precipitation rose up to about 2000 TU due to nuclear weapons testing primarily in the northern hemisphere until 1963/1964. After the atom bomb explosion, it dropped exponentially to about 10 TU in the northern hemisphere at present (Geyh, 2000). In the southern hemisphere the time course of the ^{3}H levels was similar though on a much lower level and retarded by about 2 years (Geyh, 2000). In order to record this change of ^{3}H in precipitation, the IAEA (2011) established a global network of about 125 stations to collect precipitation for isotope analysis. The measured isotopic abundances have regularly been published in the IAEA Technical Reports Series since 1969 (IAEA 1969 - 1994). This database provides sufficiently reliable input curves for extrapolation to nearly any site on the globe. There is a pronounced continental effect, whereby higher ^{3}H levels are found inland than in coastal areas (Geyh, 2000). It is assumed that groundwater consists of water of different aged components (from different aquifer systems) whose proportions decrease exponentially with increasing age (Geyh, 2000).

2.6. Groundwater quality monitoring strategies

The South African Strategic Framework for National Water Resource Quality Monitoring (DWA, 2004) defines water resource quality monitoring (Figure 2.2) as the "*acquisition of data, management and storage of data, and the generation and dissemination of information on the physical, chemical, biological and ecological attributes of the water resource*". Various components fall into the scope of monitoring, i.e. the terms "monitoring program", "monitoring system" and "monitoring network" are often used in an overlapping manner. Sanders *et al*., (1983) defines a "monitoring network" as "*the means through which data is acquired*". A "monitoring system" or operational monitoring system is the component within the monitoring program where the actual monitoring is done and information is generated on a continual basis. The monitoring system comprises all three main functions, namely the monitoring network, data storage and management, and information reporting. The term "monitoring program" includes all aspects of monitoring, including the monitoring system

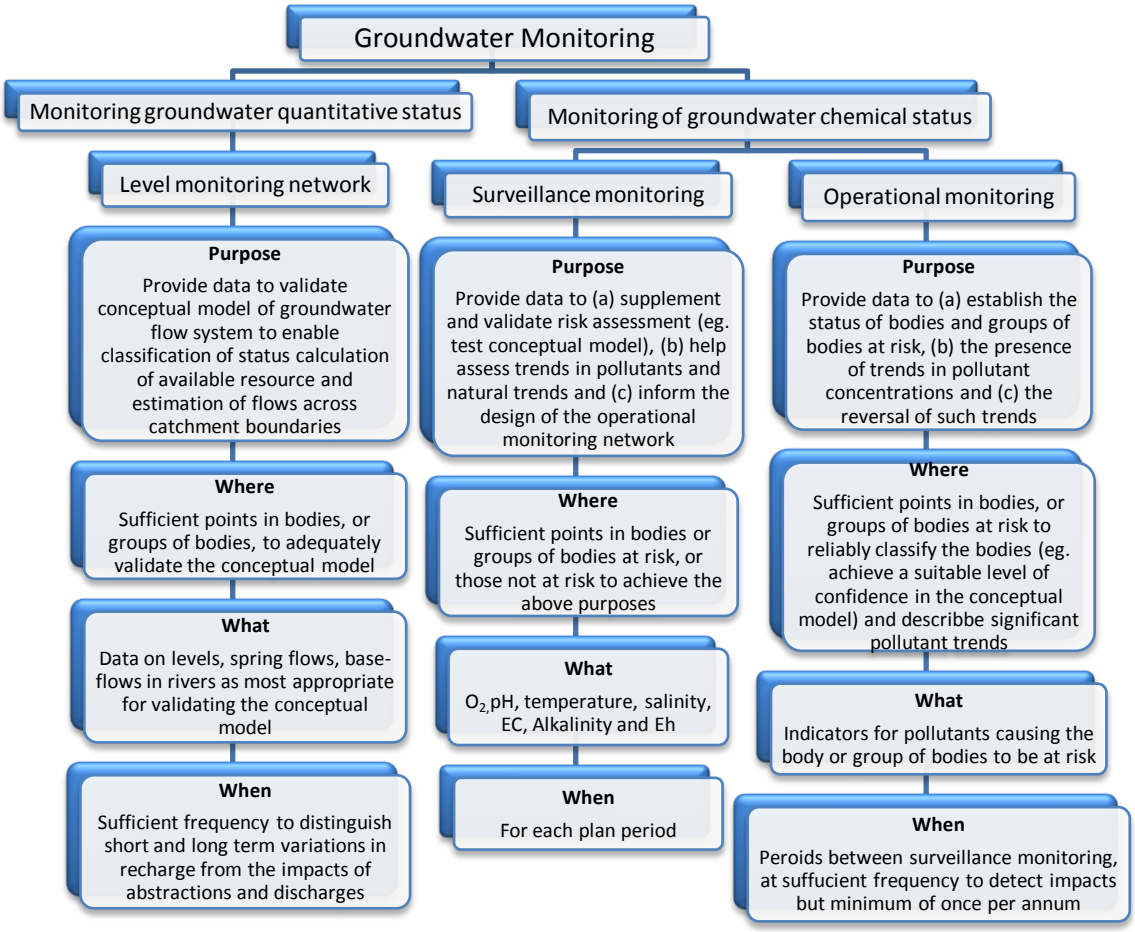


Figure 2.2: Groundwater monitoring (adapted from Quevauviller, 2005)

2.6.1. Objectives of a water quality monitoring system

Monitoring of groundwater hydrochemistry and isotope is the long-term, standardized measurement, evaluation and reporting of the groundwater environment in order to define status and trend (Seward, 2006). Groundwater quality monitoring and assessment should be seen in the wider context of the management of groundwater resources, comprising both aspects of quality and quantity. Many authors (Nacht, 1983; Chapman, 1992) have emphasized the need to define clearly the objective of a groundwater monitoring programme before beginning any monitoring network design so as to get adequate information. Generally, groundwater hydrochemistry and its isotopic composition are monitored to determine its quality and how the quality varies temporally (i.e. water pollution), residence time, flow velocity and understand and quantify the rate of its replenishment.

A number of different specific objectives for a groundwater quality and isotope programme can be recognised (Bartram and Ballance, 1996):

- To develop an understanding of regional groundwater quality as an aid to better understand the groundwater regime for optimal management of groundwater resources
- To determine long-term trends in groundwater quality and relate observed trends to human activities as a basis for informed decision making
- To identify and monitor the locations of major pollutant sources and the movement of the pollutant in the aquifer, in relation to the design of aquifer restoration
- To determine compliance with local and international regulations and standards
- To assess the effectiveness of pollution control measures, such as groundwater protection zones
- To determine regional groundwater quality variation for studying natural processes
- To study groundwater recharge using natural tracers, such as chloride and the isotopes of oxygen and hydrogen, including tritium
- To determine the quality of groundwater particularly with respect to its possible use as a source of drinking water, industry, irrigation etc
- To determine the groundwater quality in the vicinity of public water supply sources, threatened by point source pollution or saline intrusion, to protect the integrity of the supply and maintain its use
- To calibrate and validate groundwater quality models which may have been developed for pollution control or resource management, for example saline intrusion, contaminant migration, prediction of nitrate trends etc

2.6.2. Groundwater monitoring network design

Groundwater quality monitoring network design is a representation of sampling points and (temporal) sampling frequency to determine physical, chemical, and biological characteristics of groundwater. Steps in monitoring site selection include:

- Collection of appropriate hydrogeochemical, and hydrogeological (aquifer type, thickness and lithology, borehole logs, yield, hydraulic conductivity, transmissivity, storativity and water-level) and isotopes (^{2}H, ^{3}H and ^{18}O)
- Development of conceptual model with existing data
- Identification of sites based on models
- Identification of groundwater recharge and discharge areas
- Identification of areas with poor water quality according to SAWQ (1996)/WHO (2011) and areas with high aquifer vulnerability (Table 2.3)

- Identification of areas that meet the above three criteria that coincide with existing boreholes, such boreholes can then become monitoring boreholes
- If there is not any existing borehole present, drilling of new boreholes in the selected areas should be done in locations most convenient for transport, safety, etc.

Temporal monitoring is dependant on the:

- Vulnerability of the aquifer and;
- Trends observed in the chemical analyses

Table 2.3: Qualitative monitoring network optimization decision logic (USEPA, 2005)

Reasons for retaining or adding a well in a monitoring network	**Reasons for removing a well from a monitoring network**
Well is needed to further characterize the site or monitor changes in contaminant concentrations through time.	Well provides spatially redundant information with a neighbouring well (e.g. same constituents, and/or short distance between wells).
Well is important for defining the lateral or vertical extent of contaminants.	Well has been dry for more than two years, and there is no expectation for the water levels to recover in the foreseeable future.
Well is needed to monitor water quality at a compliance point or receptor exposure point (e.g. sentinel well for municipal wells).	Contaminant concentrations are consistently below laboratory detection limits or cleanup goals.
Well is important for defining background water quality.	

2.6.3. Optimized long term monitoring at local scale

Qualitative long term monitoring evaluations (Table 2.3) rely on the use of professional judgment to assess the adequacy of the monitoring network and sampling frequency (USEPA, 2005). All approaches to the design, evaluation, and optimization of effective groundwater monitoring programs must review and account for the dynamic nature of groundwater systems, as affected by natural phenomena (e.g., changes in groundwater levels) and anthropogenic changes (e.g., changes in pumping rates, contaminant behaviour) (Everett, 1980).

In a qualitative evaluation, the number and location of wells and frequency of sample collection are determined in the context of site-specific conditions. The final configuration of

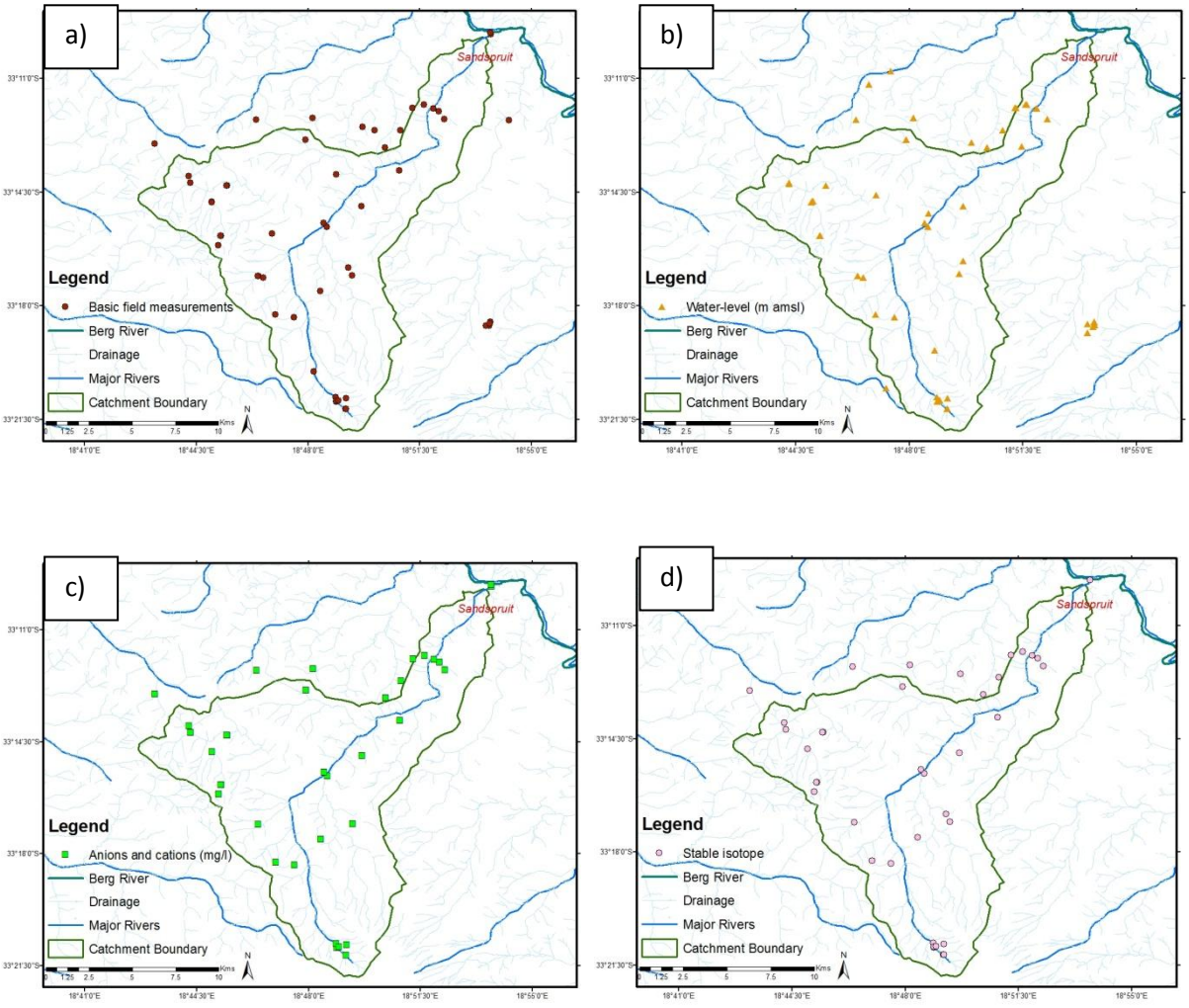
the monitoring program, including the location of wells and frequency of monitoring, is subject to the investigator's understanding of (Everett, 1980):

- The properties and behaviour of the various aquifer systems,
- The ways in which these properties influence the movement and fate of contaminants, and the resultant contaminant plume, and
- What constitutes an "optimal" monitoring program, given the monitoring objectives, probable contaminant pathways, and travel times (USEPA, 2005).

CHAPTER 3 - METHODOLOGY

3.1. Fieldwork

A total of 110 groundwater and surface water data were gathered within the catchment and surroundings (Figure 3.1), of which 73 water sites were field tested with respect to its EC, TDS, pH, temperature, DO, Eh and salinity; the water-level at 69 groundwater points were measured; 48 new water samples were collected and tested for major, minor, and trace elements; 56 water samples were collected for $\delta^{18}O$ and $\delta^{2}H$ analysis and 35 samples were analyzed for tritium (^{3}H) measurements. Rock samples representing the various lithologies present within the catchment were sampled at five locations.



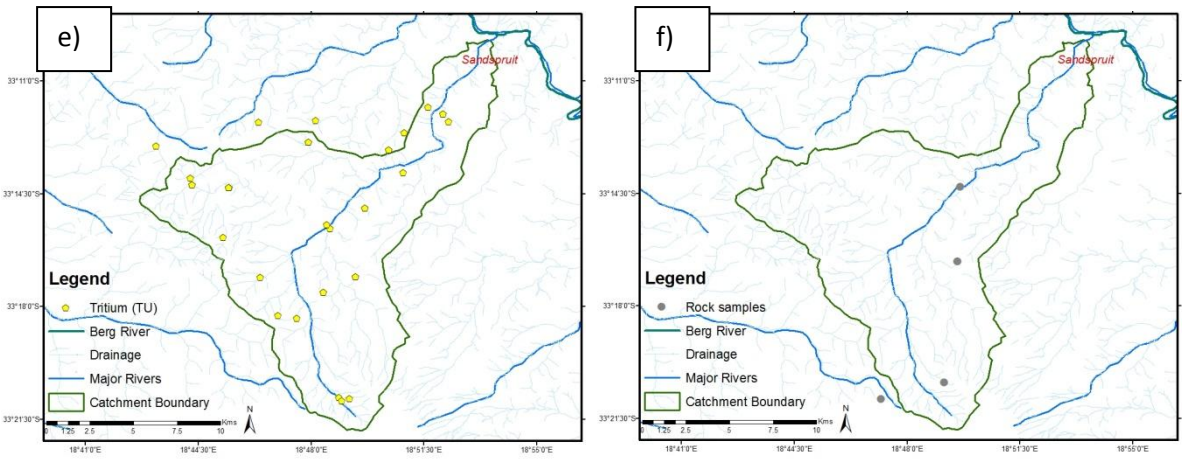


Figure 3.1: a) New field measurements, b) Water-level measurements, c) Samples taken for anion and cation analyses, d) Samples taken for stable isotope analyses, e) Samples taken for tritium analysis, f) Rock sampling areas

3.1.1. Field water sampling procedure

- All field testing and sampling equipment was 'cleaned' and calibrated before use.
- A dip meter was used, in cases where the depth to groundwater could be measured. The 101 Solinst Canada water-level meter (dip meter) which is marked in millimetres, centimetres, capable of measuring up to 100m was used in field sampling campaigns one and two. The 107 TLC Solinst Canada, a combination water-level meter & well profiler – rugged instrument for checking water-levels and for profiling conductivity and temperature (up to depths of 100m), was used in the third sampling campaign.
- The boreholes were purged and field measurements with a multiparameter electrode meter were taken until readings were constant. The Hanna HI 9828 multi-parameter water quality meter was used to test for EC, pH, TDS, DO, Eh and temperature.
- Water samples were titrated on site using a 0.02M HCl solution to determine total alkalinity and bicarbonate content. If the pH of the sampled water is >7, the procedure was such that initially a few drops of phenolphthalein indicator is added into a 100ml water sample and stirred turning the solution pink. The 0.02M HCl is added drop by drop into the phenolphthalein water solution, until the sample turns colourless and the volume of acid used is noted. If the water sample pH is <7, few drops of bromocresol green indicator is added and the colour turns from blue to yellow once the solution is titrated, once again the volume of acid used to titrate the solution is noted. To determine total alkalinity (TAL) and HCO_3^-, the following equations were used:

$$\text{TAL (mg/l } CaCO_3) = \frac{\text{Amount of HCL used in titration (ml)} \times 0.02 \times 50000}{100} \quad (3.1)$$

$$HCO_3^- \text{ (mg/l)} = \frac{\text{TAL}}{50.04} \times 61.02 \quad (3.2)$$

- Cation and anion samples were filtered using 0.45 µm filter into polyethylene bottles with polyseal capping and screw type lid. Cation samples were preserved using ultrapure acid (30% HNO_3) to a pH<2. Acidification to below pH 2 has become standard practice for the preservation of samples for major cations and trace metal analysis. The function of this step is to prevent adsorption of metals onto the container walls by minimising ion exchange effects. Acidification prior to filtration will result in the release of metals bound to particulates and this will contribute to the results upon analysis and is not recommended.
- All isotope samples remained unfiltered, and were also contained in polyethylene bottles.
- Samples were kept cool during transportation and storage.

3.2. Data collection

- Review of existing literature pertaining to study catchment.
- Analysis of existing hydrometrological, hydrological, hydrogeological and hydrochemical data (DWA).

3.3. Laboratory work

3.3.1. Hydrochemical and environmental isotope analyses

All major anions (Cl^-, PO_4^{3-}, SO_4^{2-}) were analyzed using the Dionex ICS-90 Ionpac® AS14 apparatus at the instrumental laboratory (School of Chemistry, University of KwaZulu-Natal).

All major, minor and trace cations were analyzed using the ELAN 6100, Perkin Elmer Inductively coupled plasma mass spectroscopy (ICP-MS) apparatus at the School of Geological Sciences, University of KwaZulu-Natal)

In ICP-MS, ions generated in inductively coupled plasma are used to determine elemental abundance or isotopic ratios by mass spectroscopy (UCT, 2011a). It is a quick, simple and cost-effective method for water analysis. A set of calibration standards of known concentration is prepared. The ELAN system then uses the known concentration of the standards as a reference to construct a calibration curve of signal intensity versus concentration for each element of interest (UCT, 2011b). The standard calibration curve is then used to calculate the concentration of the unknown samples by comparison of signal

intensities. This result is then displayed as a spreadsheet of signal intensities and concentration for each sample (UCT, 2011b).

Stable isotope ($\delta^{2}H$ and $\delta^{18}O$) were analyzed using a Los Gatos Research (LGR) DT-100 Liquid Water Isotope Laser Analyser at the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal. Tritium was analyzed using a Liquid Scintillation Counter Mass Spectrometer at the Environmental Isotope laboratory (iThemba Labs) in Gauteng.

Stable isotope sample preparation included filtration and equilibration of samples. Vials of samples were then capped with septa and stacked into an autosampler tray. A set of three standards were placed in the autosampler tray before every 5 samples to be analyzed as well as after the last 5 sample set. A V-SMOW (IAEA) water sample was placed in the last 5-sample set to make up four, 5-sample sets. The spectrum of the analyzer was verified and the sub-sampling of the autosampler programmed. Each sample and standard was sub-sampled and analyzed 6 times using the LGR DT-100 analyzer. Tritium samples were distilled and subsequently enriched by electrolysis. For liquid scintillation counting samples are prepared by directly distilling the enriched water sample from a highly concentrated electrolyte. 10 ml of the distilled water sample is mixed with 11 ml Ultima Gold and placed in a vial in the analyzer and counted 2 to 3 cycles of 4 hours. Detection limits are 0.2 TU for enriched samples.

3.3.2. Rock sample and thin-section analyses

Thin-sections were produced for all rock samples (L1 – L5) collected during the field campaign. This was analyzed using the Olympus BX41 microscope at the School of Geological Sciences, University of KwaZulu-Natal. All rock samples also underwent whole rock analysis using the Philips XUnique II XRF at the School of Geological Sciences, University of KwaZulu-Natal. X-ray Fluorescence (XRF) Spectroscopy using both energy and wavelength modes has for some time been used as the method of choice for determining percentage levels of metals in inorganic matrices such as alloys and cement. XRF yields an average bulk analysis of the sample. The instrument is calibrated using standards of known composition (GC, 1993).

Rock samples (L2 and L3) underwent mineral analysis using the Phillips PW 1710 XRD at the School of Geological Sciences, University of KwaZulu-Natal. X-ray diffraction is able to determine which phases are present and at what concentration levels, and what are the amorphous content of the sample. The majority of samples studied here were analyzed using 6 mineral phases (i.e., quartz, mica, anorthite, orthoclase, chlorite, illite).

3.4. Data interpretation tools

- Systematic hydrogeological database development for the research basin and organization of all pertinent hydrogeological data in GIS environment for further spatial analysis.
- Analysis of hydrogeological and hydrochemical data using appropriate software. Hydrological, hydrometerological, hydrogeological, and hydrochemical analyses was performed using various software:
  - GIS (Geographical Information System) ArcMap™
    - GIS is important decision making software that provides spatial and temporal analysis in groundwater studies. The aim of a Geographical Information System (GIS) is to store geographically references data as different layers. These different data layers may be manipulated and visually accessed as output data.
  - Surfer™
    - Surfer™ is a contouring and 3D surface mapping program. It quickly and easily converts your data into outstanding contour, 3D surface, 3D wireframe, vector, image, shaded relief, and post maps(Golden software, 2010).

  - Aquachem™
    - AquaChem™ is a software package developed specifically for graphical and numerical analysis and modelling of water quality data. It features a database of physical and chemical parameters and it provides a comprehensive selection of analysis tools, calculations and graphs for interpreting water quality data (Aquachem, 1998).
    - These powerful analytical capabilities are complemented by a comprehensive selection of commonly used plotting techniques to represent the chemical characteristics of water quality data. The plot types available in AquaChem™ include (Aquachem, 1998):
      - Correlation plots: X-Y Scatter, Ludwig-Langelier, and Wilcox
      - Summary plots: Box and Whisker, Frequency Histogram, and Schoeller
      - Trilinear plots: Piper, Durov, Ternary, and Giggenbach
      - Thematic Map plots: Bubble, Pie, Radial and Stiff plots at sample locations

- Each of these plots provides a unique interpretation of the many complex interactions between the groundwater and aquifer materials, and identifies important data trends and groupings.

- Minitab 15™
  - Minitab 15™ is a statistical software, of which capabilities include (Minitab, 2008):
    - Data manipulation: merge, subset, sort, transpose, change data type
    - State-of-the-art graphics engine
    - Scatterplots, matrix plots, boxplots, dotplots, histograms, charts, time series plots, line plots
    - Descriptive statistics
    - Multivariate Analysis i.e. principal components analysis, factor analysis, discriminant analysis and cluster analysis

CHAPTER 4 – OVERVIEW OF THE STUDY AREA

4.1. Demography and economic development

The closest towns to the Sandspruit catchment are the towns of Moorreesburg and Riebeek-West (Figure 1.1), and the population in these two towns is about 20 000 (AGSA, 2010). The Sandspruit catchment falls under the Berg Water Management Area (WMA), which also includes the Berg River and the Steenbras River catchments as well as the catchments of the smaller rivers draining into Table Bay and False Bay (DWA, 2007). Water is pumped and purified for domestic consumption at a number of places along the Berg River course. The purification scheme at Wittewaters is a major source of drinking water in the rural Western Cape and is fed by the Misverstand Dam, situated amidst extensive wheat farms, where aerial spraying of pesticides is commonly practiced (DWA, 2007). Misverstand Dam is approximately 10 km north and Voelvlie Dam approximately 10 km south-east of the Sandspruit River catchment. The Berg River basin is of strategic importance to rural and industrial development in the Western Cape Province. Increasing salinity in the river system has been recognised as a serious problem since the 1970s but has hitherto largely been ascribed to irrigation return flow (Flugel, 1995).

Urban development accounted for about 1% of the catchment land-cover. This was mainly residential, commercial and industrial development. Major towns in the Berg River basin included Velddrift and Laaiplek near the coast, Piketberg, Hopefield, Mooreesburg and Darling further inland, and Wellington and Paarl in the upper catchment. Apart from the two cement factories at PPC (Pretoria Portland Cement) Piketberg and Riebeek West, no large mining activity occurs in the Berg WMA. Most major schemes use surface water for their supply. Groundwater is used mainly for the towns of Atlantis, Yzerfontein, Porterville, Hopefield and rural villages, which rely entirely on the groundwater source (DWA, 2007).

There are a number of transfer schemes within the Berg WMA, as well as a number of schemes that transfer water from other WMAs (transfers from the Breede water management area, amounting to 8 million m^3 per year) into the Berg WMA (DWA, 2007). The Wemmershoek and Steenbras Dams supply water to Cape Town. The Riviersonderend/Berg River Government Water Scheme transfers water (172 million m^3 per year) from the Theewaterskloof Dam by means of a tunnel system to the Kleinplaas Dam. From Kleinplaas Dam water is supplied to urban consumers in Cape Town and Stellenbosch, as well as agricultural users (DWA, 2007). The West Coast District Municipality abstracts water from Voëlvlei Dam and supplies Hermon, Moorreesburg, Saldanha, Velddrift, Yzerfontein, Darling, Vredenburg, Malmesbury, Hopefield, Langebaan,

St Helena Bay, Paternoster, Jacobs Bay and some rural areas for their domestic supply. On average 23 million m³ per year of water is transferred from the Palmiet River (G40C) to the Upper Steenbras Dam by means of the hydroelectrical Palmiet Pumped Storage Scheme (DWA, 2007). Irrigation accounts for an estimated 41% of total consumptive water requirements in the Berg WMA (DEA, 2005). DWA (2007) reported that approximately 22 000 ha of farmland rely on the Berg River for irrigation water supply, and exports from these farms generate in the region of R462 million per year.

4.2. Physiography and Drainage

The Sandspruit catchment has a gentle hilly topography, mountains occur towards the east and south of the catchment respectively, with the Table Mountain Group sandstone reaching an altitude of 700 m amsl (Figure 4.1). The rest of the catchment has an altitude of 100-200 m amsl (meters above mean sea level). About 30% of the catchment has a slope gradient greater than 40 degrees (Figure 4.2), in retrospect, the catchment terrain is relatively flat, conducive for groundwater recharge occurring at mountain tops, and discharge on the “flat” regions.

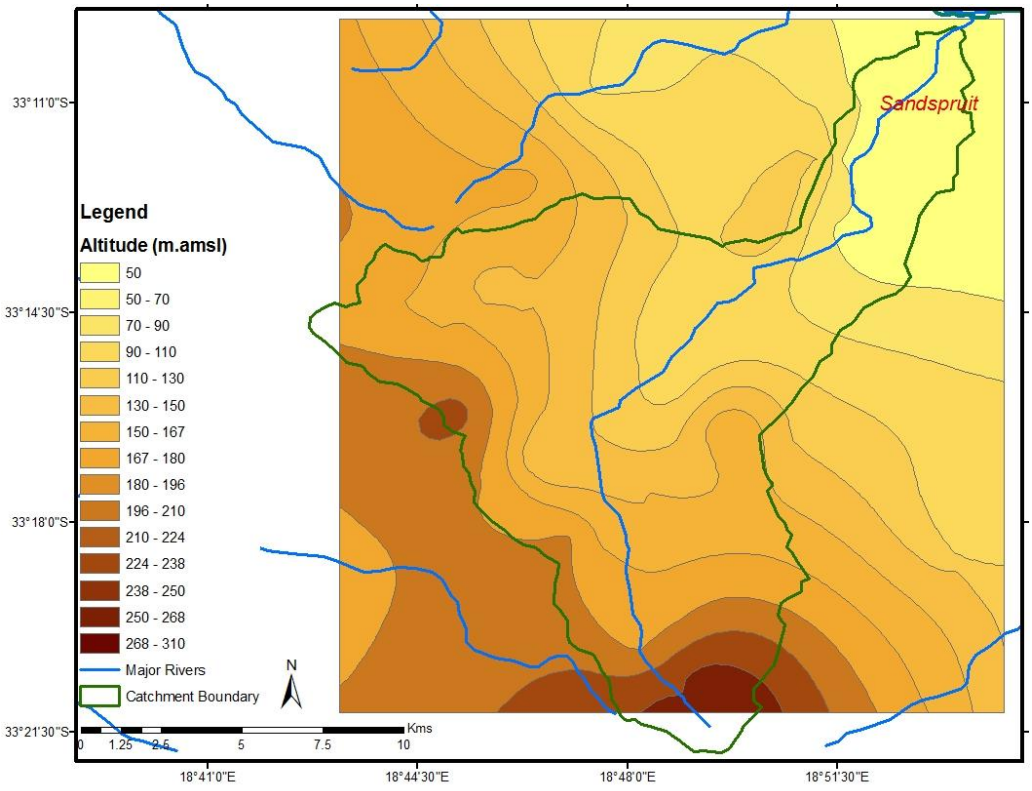


Figure 4.1: Altitude map of the Sandspruit catchment

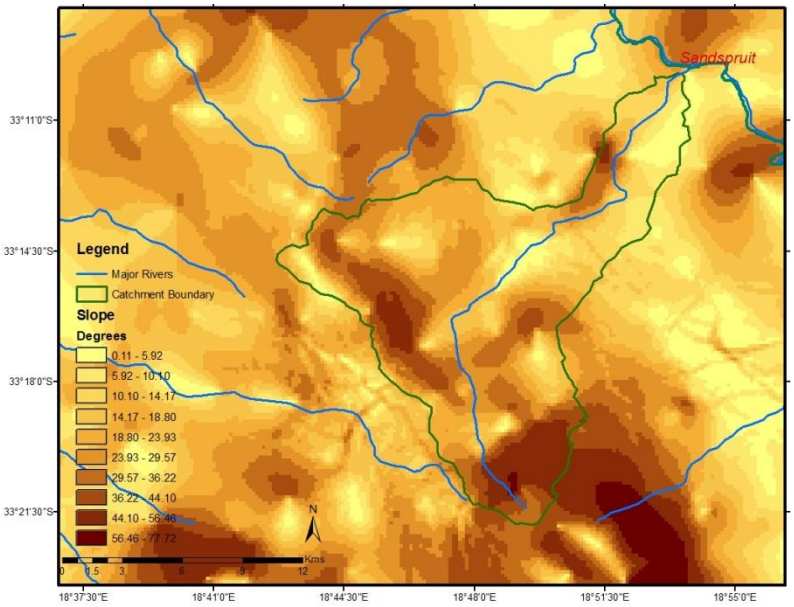


Figure 4.2: Slope variation in degrees within the Sandspruit catchment

Much of the natural vegetation i.e. *Swartland Renosterveld* and *Hawekwas Fynbos* north and south of the catchment respectively (Figure 4.3), has been replaced by agriculture. Roughly 90% of the catchment is used for small grain (wheat etc.), 4% for grapes, and the remainder represents reserves and mountain veld (Figure 4.4). Surface water as well as groundwater is primarily utilized for livestock watering (Figure 4.5).

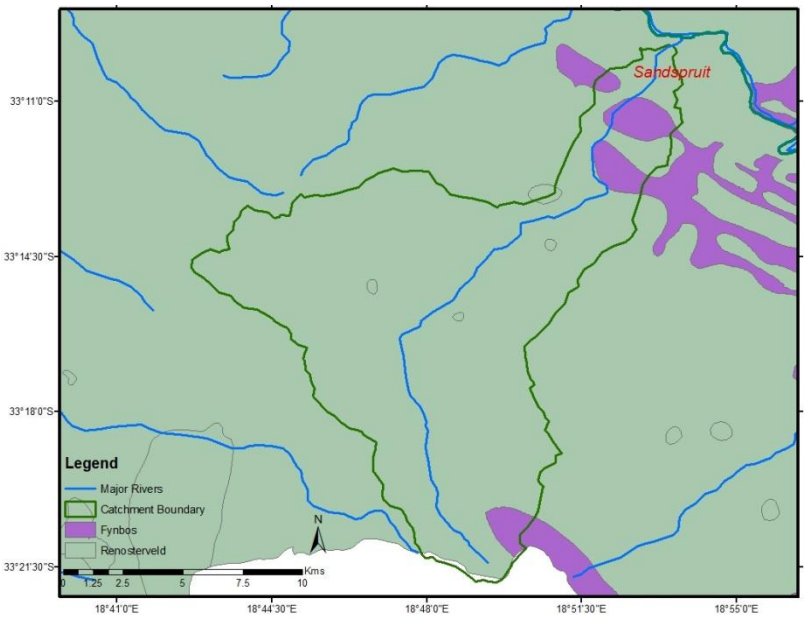


Figure 4.3: Natural vegetation within catchment (DWA, 2009)

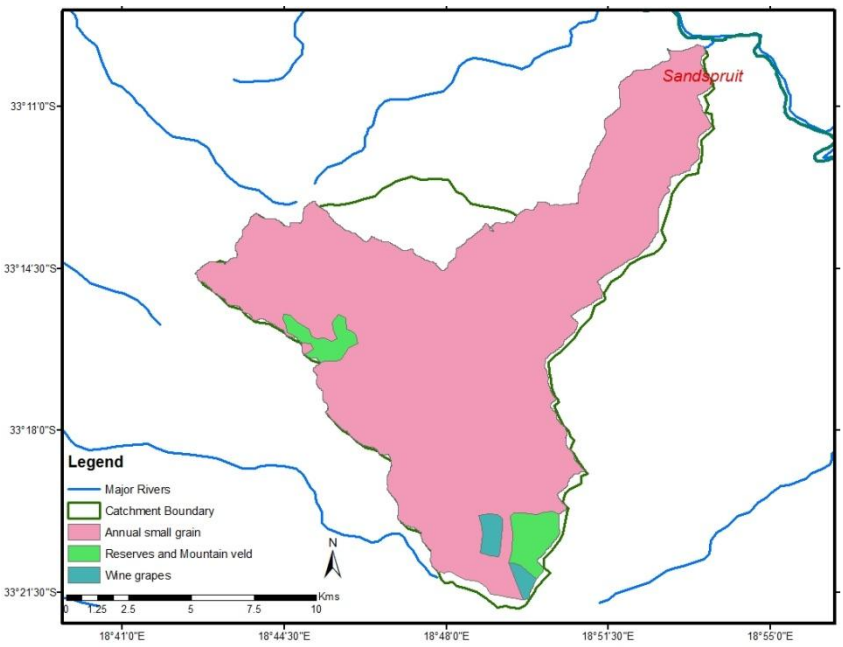


Figure 4.4: Land use within the catchment (DWA, 2009)

Figure 4.5: Windmill pumps used primarily for livestock watering

4.3. Hydrological and hydrometeorological data

The source of the Berg River is south of Franschhoek in the Drakenstein Mountains (DEA, 2001), and flows towards the Atlantic Ocean. The Sandspruit is a tributary of the Berg River lies north-east of the Sandspruit catchment, its tributary is the seasonal Sandspruit River. The Diep River has its source in the central area of the WMA, i.e. in the Riebeeck Kasteel Mountains, and flows in a south-westerly direction through Malmesbury and the wheat and

grape producing areas of the Swartland (DWA, 2007). Drainage is topographically and geologically controlled, i.e. influenced by the folding and subsequent faulting of the underlying lithologies (Figure 4.6).

Climate is amongst the most important factors that drives river salinization. Generally, areas with low rainfall and high evaporation rates are characterised by rivers with high salinity. Such climatic conditions encourage accumulation of salts in the soil and these contribute to river salinization after dissolution from slope run-off (Hughes and Moolman, 1986). A 40 year hydrometeorological data set from the Langewens weather station (Table 4.1) located 4.2 km west of the catchment, revealed that the catchment belongs to the winter rainfall (semi-arid) region, and the mean annual rainfall is about 400 mm, with higher rainfall (about 600 mm) occurring south of the catchment (Figure 4.8). As a result, the Sandspruit represents a non-perennial stream which only flows during the winter season between May and October. Annual daily maximum temperatures range from 24 to 31 ^{o}C and occur from October to April (Table 4.1). The minimum temperatures range from 8 to 11 ^{o}C occurring from May to September. Potential evapotranspiration (Figure 4.7) was calculated (Appendix A) using the Thornthwaite method outlined in section 2.2.1.1, the average potential evaporation is greater in summer, with an annual average of 72.94 mm. The average annual evaporation is approximately 2210 mm, which implies that evaporation by far exceeds precipitation (Figure 4.8).

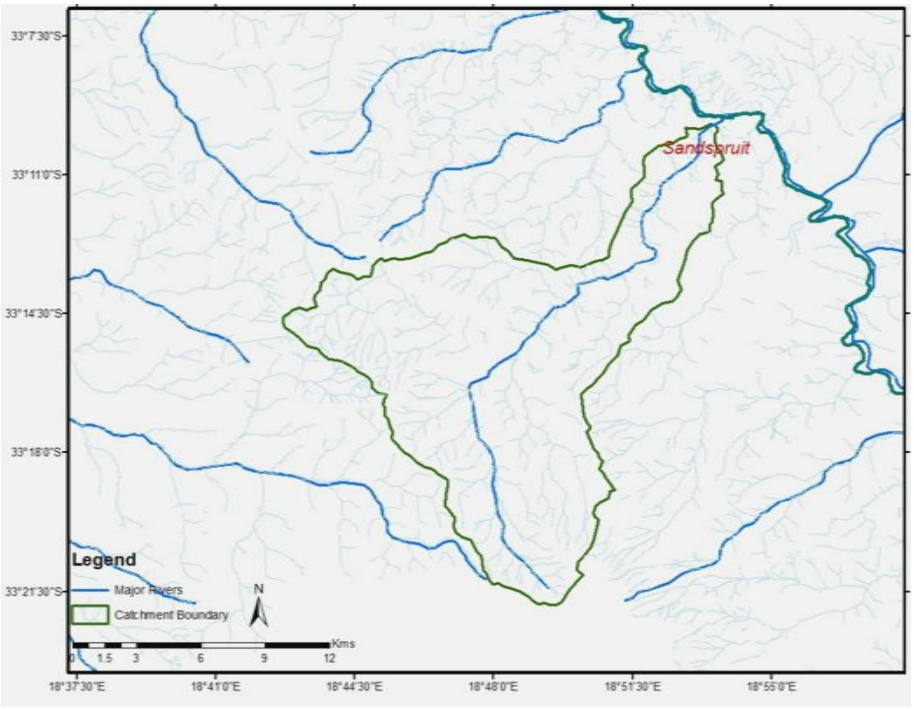


Figure 4.6: Drainage pattern within the Sandspruit catchment

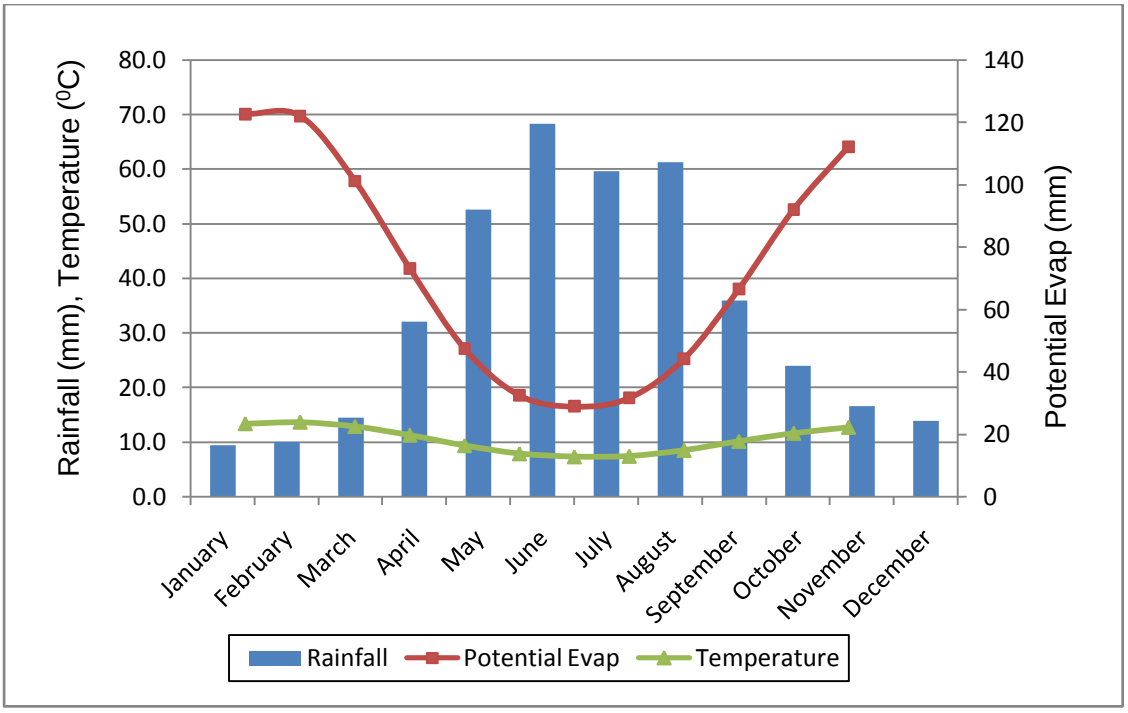


Figure 4.7: 40 year average of meteorological variables from the Langewens weather station

Table 4.1: Meteorological data (1960-2007 average) from Langewens weather station (SAWS, 2009)

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)	9.4	10.0	14.5	32.1	52.6	68.4	59.6	61.3	35.9	24.0	16.6	13.9
Temp (max - °C)	30.3	30.7	29.0	25.4	21.2	18.0	17.3	17.7	20.4	24.1	27.1	29.0
Temp (min - °C)	16.6	17.0	16.0	14.1	11.6	9.5	8.3	8.2	9.3	11.3	13.6	15.5
Humidity (max - %)	79.1	77.9	79.7	82.3	84.	85.9	87.6	89.9	89.4	84.0	81.6	81.3
Humidity (min - %)	29.6	29.0	30.2	35.4	43.3	48.5	50.5	48.9	42.0	32.3	29.4	30.1
Evap (mm)	321.4	284.3	248.1	163.2	102.4	67.9	70.2	81.6	116.3	198.4	259.1	305.4
Wind speed (km/d)	213.5	223.1	214.7	211.0	218.2	226.6	214.1	197	189.8	199.1	212.9	216.5
Sunshine (hrs)	11.3	10.9	9.5	7.8	6.4	5.8	6.2	6.7	7.3	8.8	10.3	10.8

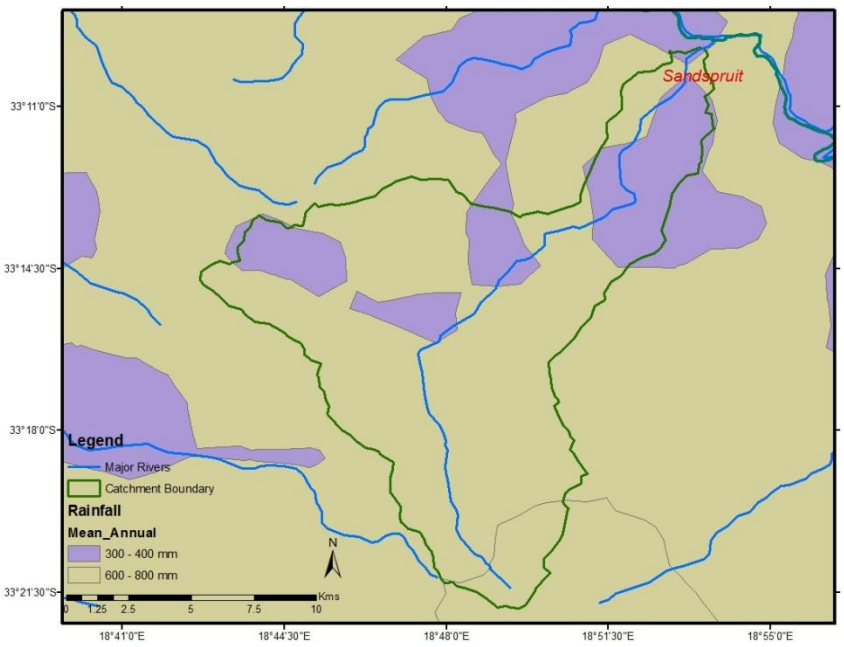


Figure 4.8: Rainfall map of the study catchment (DWA, 2009)

4.4. Regional Geology

The Saldania Belt is a low-grade orogenic belt along the southern and south-western margins of the Kalahari Craton. The main exposure north and north-east of Cape Town is known as the Malmesbury Group. The Malmesbury Group covers approximately 4100 km^2 in the western region of Southern Africa. According to Hartnady, (Hartnady *et al*., 1974) the Saldania belt is subdivided into three tectonic "domains" (north-eastern/Boland, central/Swartland and north-western/Tygerberg), separated by prominent north-west-trending fault and shear zones, of which the central/Swartland is located within the research area (Figure 4.9). Isoclinal folding and thrusting of strata has been identified in what are believed to be the lower parts of the Malmesbury Group in the central Swartland region (e.g. Hartnady *et al*., 1974; Belcher, 2003).The deeply weathered precambrian Malmesbury was flooded by the sea till the late Tertiary period(Verwoerd, 1974).

The central domain is stratigraphically and structurally more complex than the south-western domain and is composed of the Berg River, Klipplaat and Moorreesburg Formations, which together constitute the Swartland Subgroup (Belcher and Kisters, 2003). The Berg River Formation is composed of chlorite schist, greywacke with impure limestone lenses and quartz schist towards the top. As such, the schists of the Berg River Formation represent the presumably deepest stratigraphic levels exposed in the Saldania Belt. The contact with the overlying Klipplaat Formation is placed just above a strongly deformed, ferruginous, cherty quartzite or the uppermost limestone layer (Gresse *et al*., 2006). The Klipplaat Formation is

essentially quartz schist, consisting of quartz, sericite and chlorite. Lenses of phyllite, chlorite schist and limestone may occur. The Moorreesburg Formation covers most of the central domain. It consists of inter-layered greywacke and phyllite (Gresse *et al*., 2006). The schists of the Moorreesburg Formation are composed of two main varieties that represent end-member compositions of whole range of feldspathic schists (Belcher and Kisters, 2003). These include brown-green muscovite schist that contains minor amounts of chlorite, and yellow-brown feldspathic schist. The muscovite schist contains voluminous quartz veining occurring parallel to the S0/S1 (foliation) (Figure 4.10a) sub-horizontal fabric within the feldspathic schist. The schistosity is poorly developed in feldspathic units, but becomes strong in the muscovite-rich lithologies (Belcher and Kisters, 2003). The lower, most deformed part of the formation contains arenitic layers near the contact with the Klipplaat quartz schists. The metavolcanic Bridgetown Formation follows the boundary between the central and north-eastern domains and comprises a complex of “greenstone” bodies, dolomite, chert and graphitic schists, intruded by numerous altered dykes (Gresse *et al*., 2006).

The Cape granite suite intruded into the rocks of Neoproterozoic age, mainly the Malmesbury Group. On the base of petrological and geochemical characteristics, three types of granites are identified (S, I and A), each with several subtypes (Villaros, 2006). Each type is also found only in specific parts of the Saldanian belt. I-type granites are generally post-tectonic (Villaros, 2006). They are found only in the Swartland and Boland terrains, north of the Colenso fault.

The lowermost unit of the TMG, the Piekenierskloof Formation, is composed of conglomerate, quartz arenite and minor mudrock that are confined to the west coast (Rust, 1967). It unconformably overlies phyllites and quartzites of the Malmesbury Group. The Graafwater Formation is characterised by purple, thin-bedded, ripple-marked and mudcracked sandstone, siltstone and shale beds. The Penninsula Formation comprises a succession of coarse-grained, white quartz arenite with scattered small pebbles and discrete thin beds of small-pebble, matrix supported conglomerate (der Beer, 2002). The depositional environments range from shallow marine to fluvial, with glacial interlude towards the middle (Rust, 1967).

The Springfontyn Formation consists of reddish to grey, unconsolidated quartzitic aeolian sands, which are muddy and peaty in places (Rogers, 1980). The sediments were deposited under marine,fluvial and / or aeolian conditions (SRK, 2007). Theron *et al*., (1992) expanded the concept of the formation to include all surficial leached quartz sands in Cape Town.

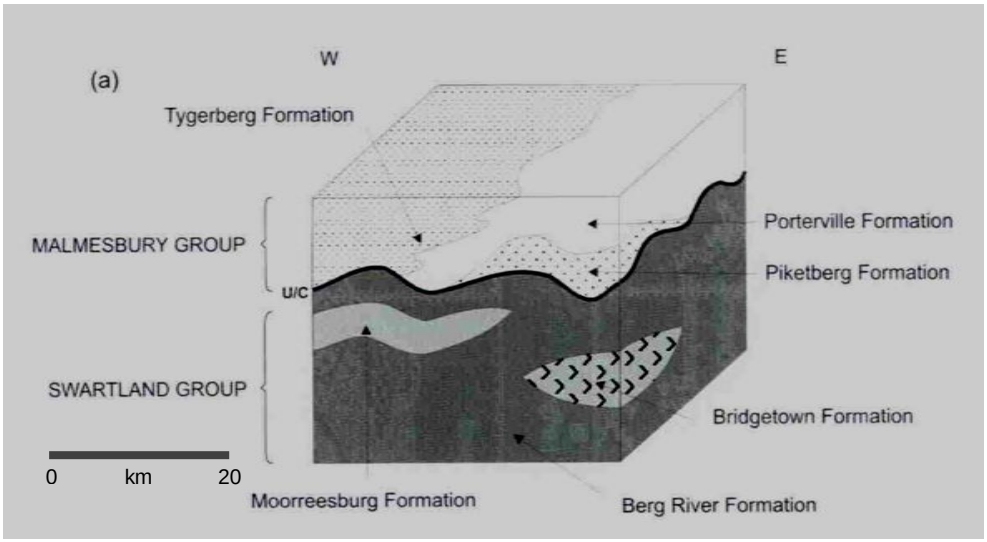


Figure 4.9: Spatial relationship between the Swartland and Malmesbury Groups which are separated by an unconformity (after Belcher and Kisters, 2003).

4.5. Regional tectonic setting

Globally the deformation of the Swartland Group is characterised by intrafolial, isoclinal folding, thrusting and imbrications, and upright open to tight folding (Belcher and Kisters, 2003). Four distinctive foliation (cleavage) planes have been described in the Malmesbury Group of rocks, and are associated with the compressive Saldanian orogeny, with the two minor cleavages regarded as fracture cleavages associated with the later Cape orogeny (Domoney, 2009). The deformational events of the Saldanian orogeny can be described as successive deformation phases in one orogenic cycle, where the total deformation is built up of a series of separate pulsatory, compressive deformations (Domoney, 2009). The foliations in the Malmesbury Group of rocks can be classed as composite foliations form under progressive deformation, with structures having formed as a relatively continuous sequence of events (Domoney, 2009). This implies that the total deformation is derived from a series of separate pulsatory, compressive deformations. The structures formed in the Malmesbury rocks have similar morphologies, and formed under similar metamorphic conditions.

4.6. Local geology

Metasediments of the Malmesbury Group (Table 4.2) covers approximately 90% of the catchment area (Figure 4.11). Belcher and Kisters (2003) reported that the characteristic feature of the Swartland Group is a pervasive bedding-parallel schistosity (Sl) that is defined by the preferred alignment of chlorite and muscovite as well as the formation of parallel-bedding quartz-feldspar and phyllosilicate domains. The subhorizontal to shallowly-dipping Sl foliation is axial planar to isoclinal, intrafolial folds that refold the bedding, S0, and is, as such, a transposition foliation, S0/S1 (Figures 4.10a and 4.b, Plates 5.3 and 5.5). The Cape

Granite Suite which primarily consists of grandiorite covers approximately 1% of the catchment area. The TMG (Figure 4.11) covers approximately 3.5% of the catchment area. The Peninsula, Graafwater and Pieknierskloof Formation are found in the southern region of the study area, whilst the Nardouw Subgroup, as well as the Cedarberg and Pakhuis Formations are absent within the catchment. The Cenozoic deposits (Figure 4.11) of the Springfontyn Formation cover approximately 5.5% of the catchment area. The Sandspriut catchment is bound by the Colenso and Piketberg-Wellington fault systems (Belcher and Kisters, 2003). In cross section A-B (Figure 4.12), located to wards the east are the intermediate to steeply dipping (40^{o}-90^{o}) anticlinal lithologies of the Swartberg feldspathic sericite-schist and the Swartberg sericite schist. The Lower Goudmyn sericite-schists have synclinal dips of 40^{o}-70^{o}, whilst the rest of the lithologies have steep dips of 70^{o}-90^{o} (Verwoerd, 1974).

Table 4.2: Major geological units present within the study catchment

Era		Group	Formation	Lithology
Cenozoic				Silicrete/Ferricrete
				Loam and sandy loam soil
		Sandveld (23-0 Ma)	Springfontyn	Reddish-grey, unconsolidated quartzitic aeolian sands
Palaeozoic	Cape Supergroup	Table Mountain (448-443 Ma)	Peninsula	Coarse-grained quartz arenite, with thin siltstone, shale and polymitic conglomerate beds
			Graafwater	Purple, thin-bedded, ripple-marked and mudcracked sandstone, siltstone and shale beds.
			Piekenierskloof	Conglomerate, quartz arenite and minor mudrock
	Cape Granite Suite (560-510 Ma)			Hybrid grandiorite
Namibian		Malmesbury (1200-500 Ma)	Bridgetown	“Greenstone” bodies, dolomite, chert and graphitic schists
			Moorreesburg	Interlayered greywacke and phyllite
			Klipplaat	Quartz schist, consisting of quartz, sericite and chlorite
			Berg River	Chlorite schist, greywacke with impure limestone lenses and quartz schist

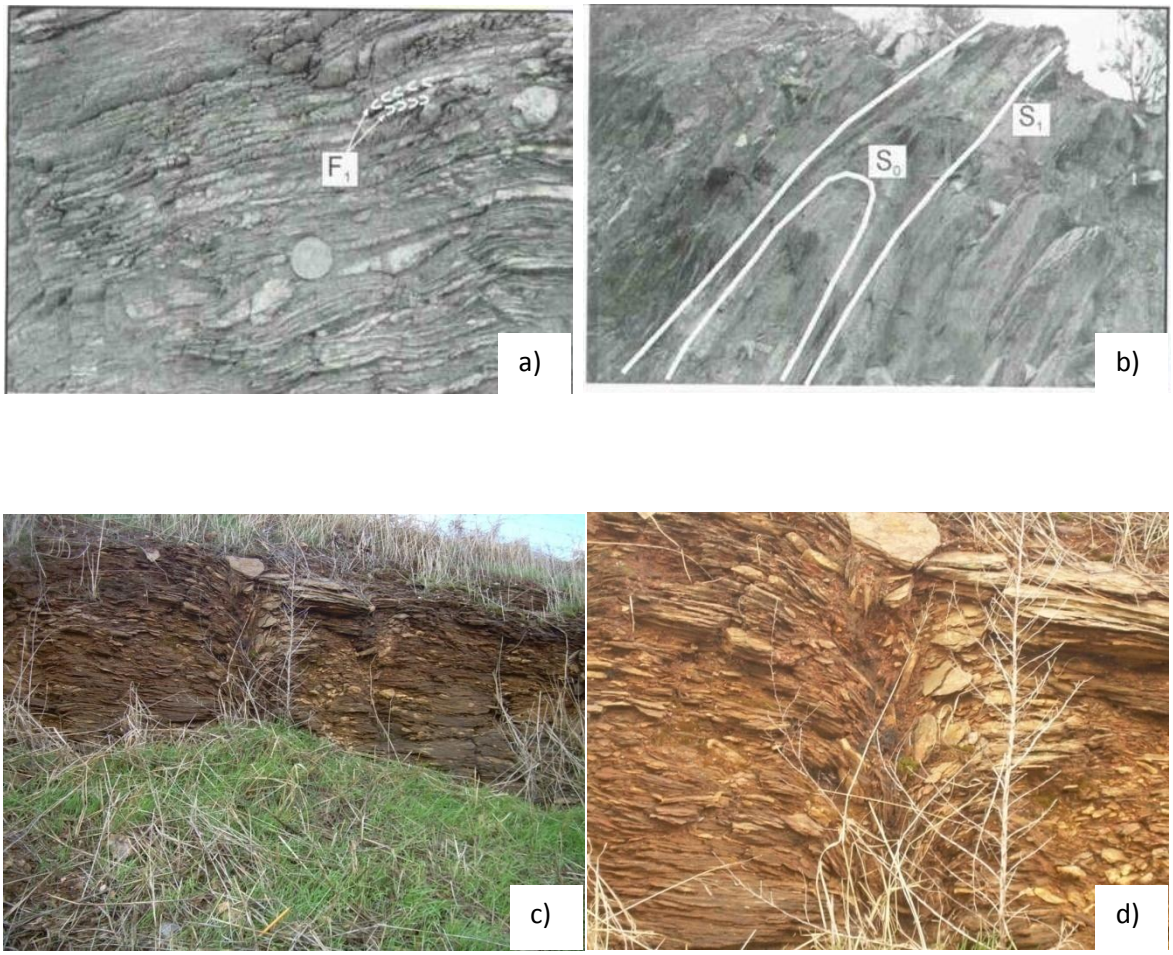


Figure 4.10: Examples of thrusting and westerly verging folds related to the deformation event from across the Swartland Group (Belcher and Kisters, 2003).

(a) Small-scale intrafolial isoclinal folding within quartz-muscovite schists of the Berg River Formation. This transposition fabric (S0/S1) shows the severe deformation the rocks of the Swartland Group have undergone (Belcher and Kisters, 2003).

(b) Large-scale intrafolial isoclinals fold within chlorite-muscovite phyllites of the Berg River Formation. The identification of the transposition fabric indicates that the rock units now form a tectonostratigraphy and the use of only lithostratigraphic principles for the classification of the rocks is misleading (Belcher and Kisters, 2003).

(c) And (d) Folding and fracturing associated with the Moorreesburg Formation phyllites (photo taken during this study).

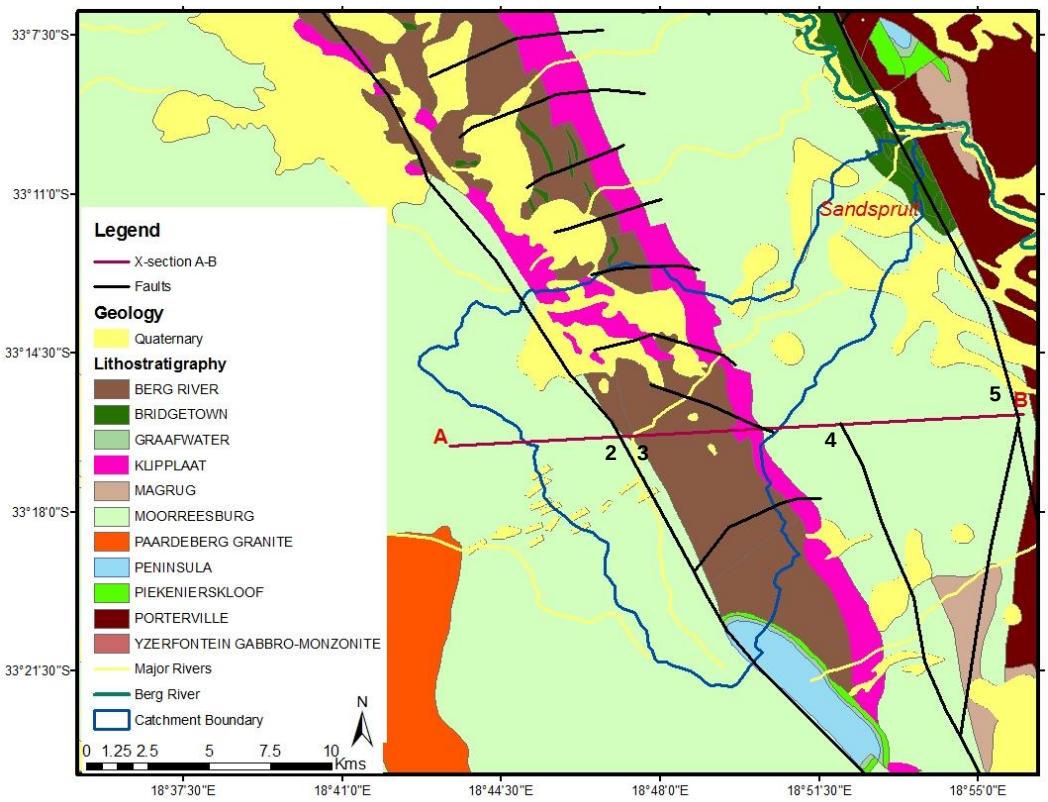


Figure 4.11: Simplified geological map of the study catchment (modified from DWA, 2009). A-B shows the cross section taken in Figure 4.12, whereby 2: Moorreesburg Fault, 3: Sandspruit River, 4: Swartland Fault, and 5: Berg River Fault

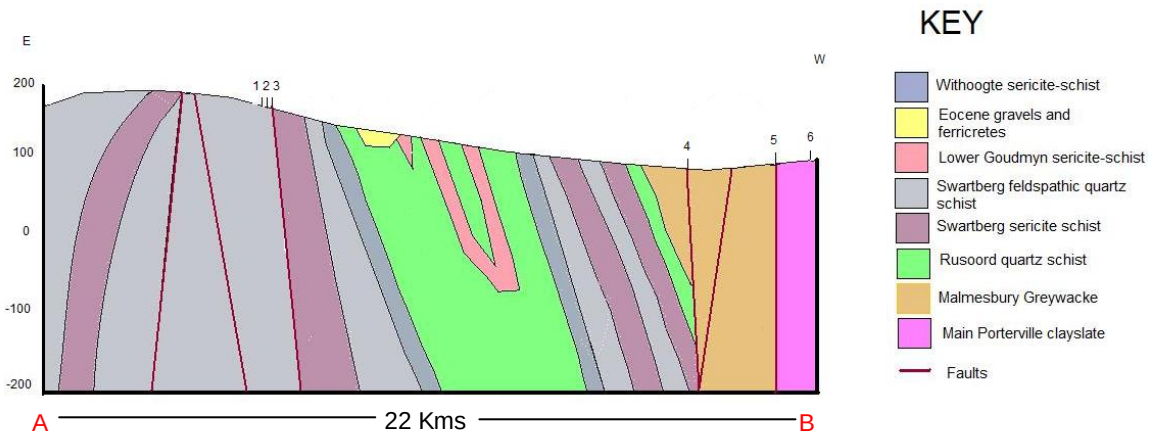


Figure 4.12: Cross-section A-B, with 1: Main Road (311), 2: Moorreesburg Fault, 3: Sandspruit River, 4: Swartland Fault, 5: Berg River Fault, and 6: Main Road (7484)

CHAPTER 5 – RESULTS AND DISCUSSION

5.1. Rock specimen analysis

Rock samples L1, L2, and L3 were sampled within the Moorreesburg Formation, whereas samples L4 and L5 were situated within the Berg River Formation (Figure 4.6). Results of the XRD are presented in Appendix B. Mineral associations found in sample L2: quartz, orthoclase and mica; L3: quartz, orthoclase, chlorite, anorthite, illite and mica. Mineral assemblages are never random, estimation of volumetric proportion through thin section analysis (Plates 5.3; 5.4; 5.5; and 5.6) indicated quartz abundance of 65% and 50% respectively. According to Nesse (2000), these mineral assemblages belong to the pelitic (metamorphosed shale; includes slate, phyllite, mica schist) rock type. Samples L2 and L3 are therefore sericite schists.

The main purpose of gathering whole-rock data is to classify the rocks geochemically and establish geochemical trends systematically. Results of the XRF are provided in Appendix C. The results illustrate the variation in chemical concentrations within the same rock type, i.e. samples L2 and L3 are both sericite schists with different concentrations of phyllosilicates indicative of different weathering/degredation stages. Sample L1 contains approximately 95% of quartz (Plate 5.1) and is therefore classified as a quartz schist. Sample L4 which contains approximately 95% of quartz (Plate 5.7), shows minimal quartz deformation, whereas sample L5 (Plate 5.9) contains a higher volume of phyllosilicate weathering products than L4. Both samples L4 and L5 can be classified as being chert.

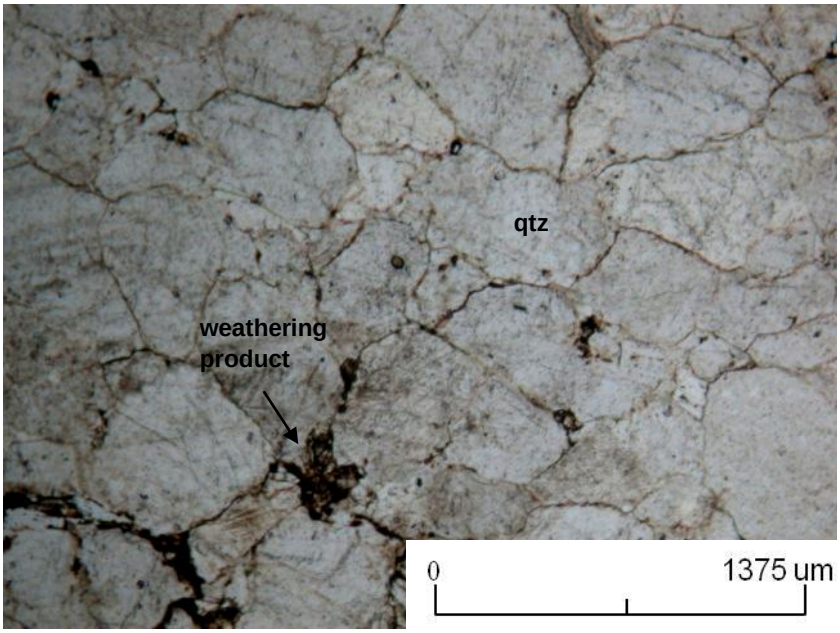


Plate 5.1 Photomicrograph of L1 showing coarse grained, anhedral quartz (qtz), with a volumetric proportion of 95%, along with medium grained phyllosilicate weathering products – volumetric proportion of 5%. Defined by quartz texture (magnification = 10X40; plane-polarised light)

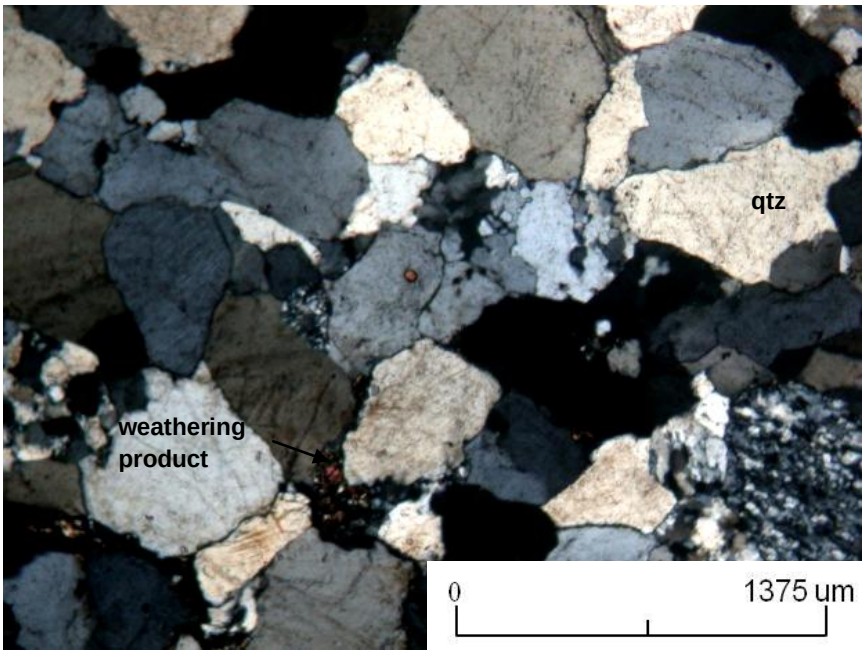


Plate 5.2 Photomicrograph of L1 showing coarse grained anhedral quartz (qtz), with a volumetric proportion of 95%, along with medium grained phyllosilicate weathering products – volumetric proportion of 5% (magnification = 10X40; cross-polarised light)

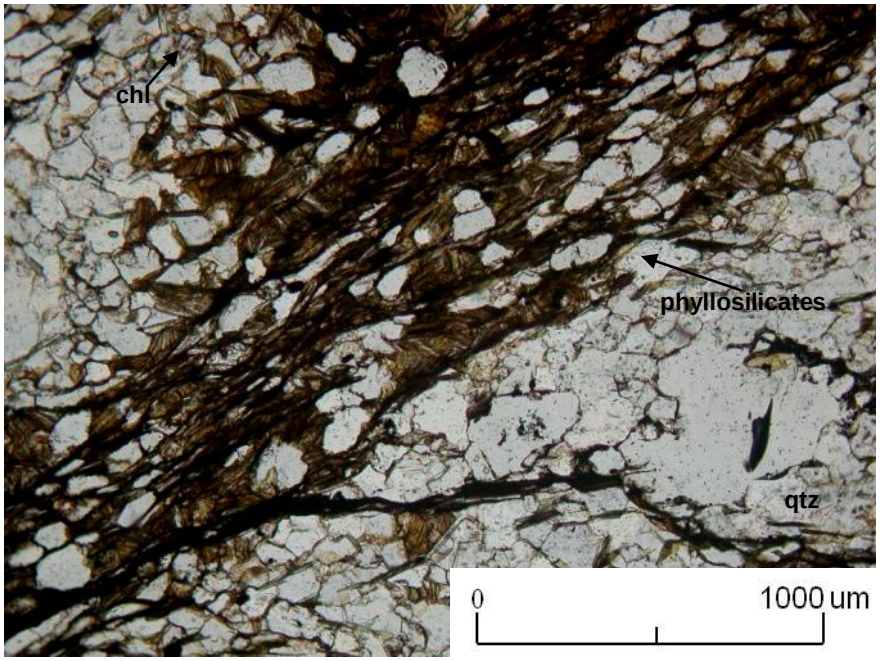


Plate 5.3 Photomicrograph of L2 showing medium grained anhedral quartz (qtz), with a volumetric proportion of 65%, along with fine grained well foliated phyllosilicate, muscovite (mus), chlorite (chl) weathering products – volumetric proportion of 25%. Well developed folding and two sets of foliations. (magnification 10X120= ; plane-polarised light)

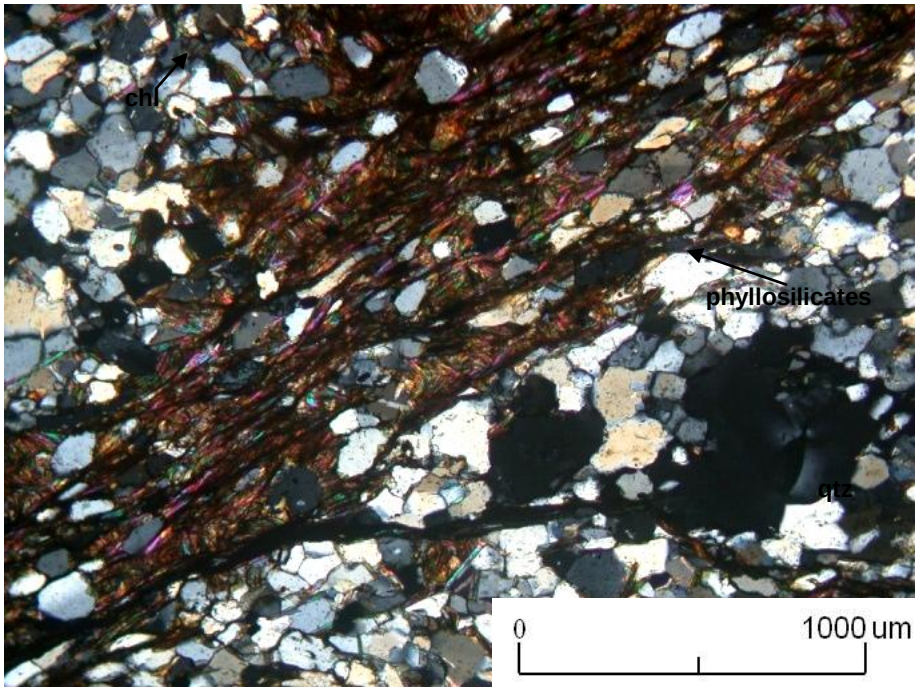


Plate 5.4 Photomicrograph of L2 showing medium grained anhedral quartz (qtz), with a volumetric proportion of 65%, along with fine grained well foliated phyllosilicate, muscovite (mus), chlorite (chl) weathering products – volumetric proportion of 25%. Well developed folding and two sets of foliations. (magnification =10X120 ; cross-polarised light)

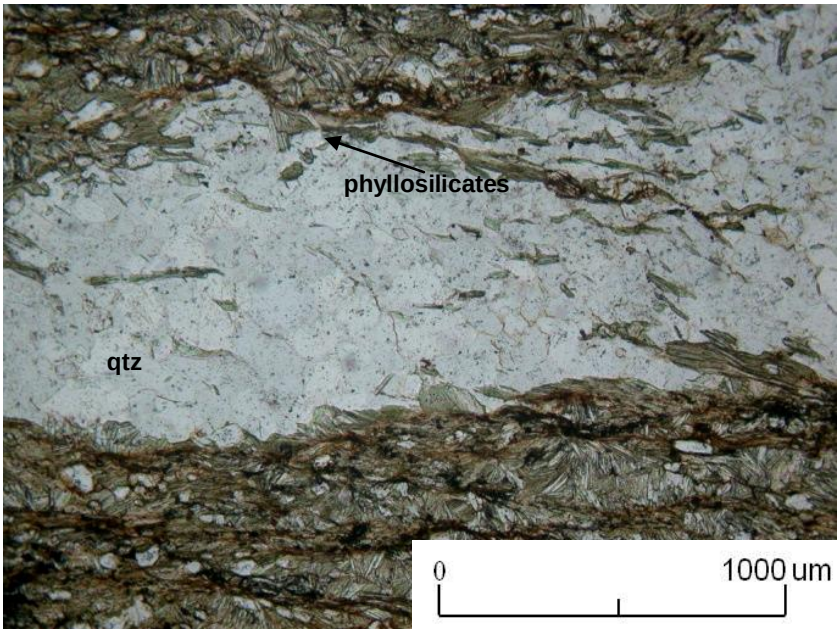


Plate 5.5 Photomicrograph of L3 showing medium grained anhedral quartz (qtz), with a volumetric proportion of 50%, along with fine grained well foliated phyllosilicate, muscovite (mus), chlorite (chl) weathering products – volumetric proportion of 50%. More chlorite present in sample than in L2. One set of foliation (magnification = 10X120; plane-polarised light)

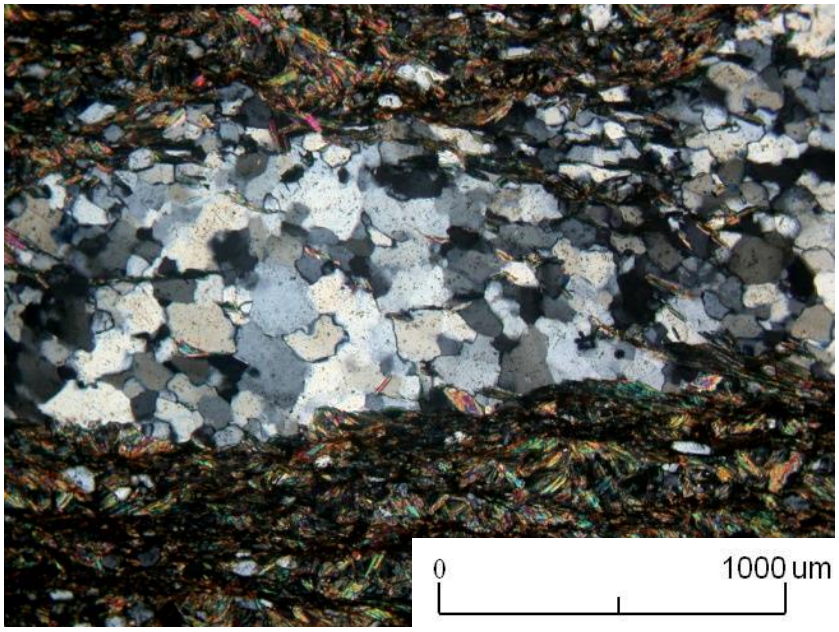


Plate 5.6 Photomicrograph of L3 showing medium grained anhedral quartz (qtz), with a volumetric proportion of 50%, along with fine grained well foliated phyllosilicate, muscovite (mus), chlorite (chl) weathering products – volumetric proportion of 50%. More chlorite present in sample than in L2. One set of foliation (magnification = 10X120; cross-polarised light)

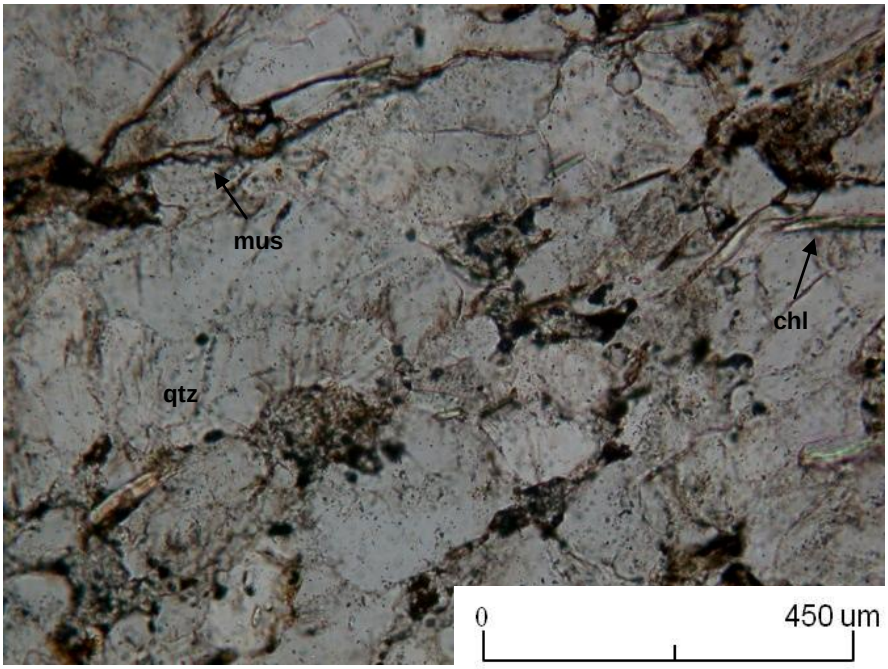


Plate 5.7 Photomicrograph of L4 showing medium grained, anhedral quartz (qtz), with a volumetric proportion of 95%, along with fine grained muscovite (mus) and chlorite (chl) – volumetric proportion of 5%. Note deformation of quartz (recrystallization of quartz) (magnification = 10X120; plane-polarised light)

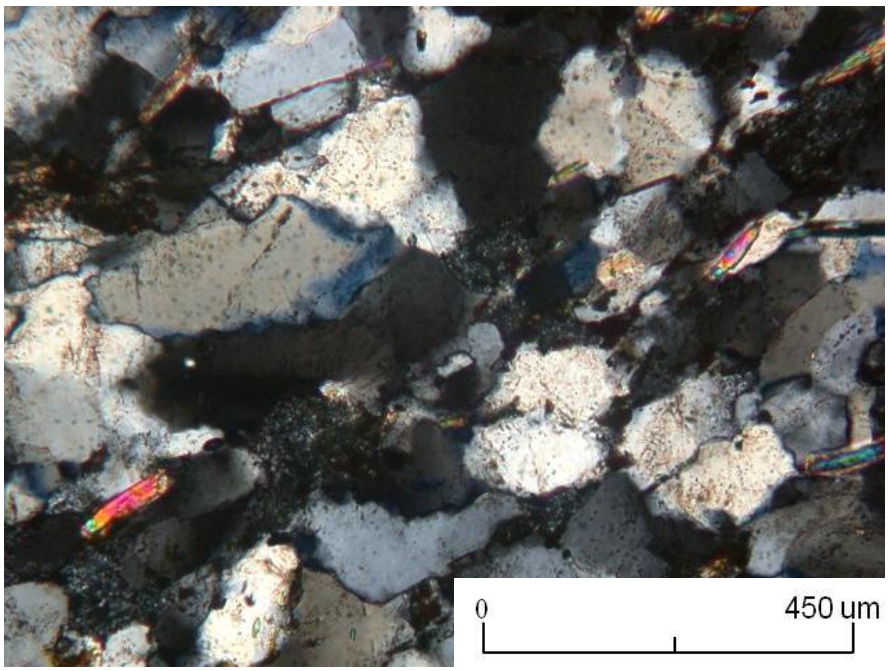


Plate 5.8 Photomicrograph of L4 showing medium grained, anhedral quartz (qtz), with a volumetric proportion of 95%, along with fine grained muscovite (mus) and chlorite (chl) – volumetric proportion of 5%. Note deformation of quartz (recrystallization of quartz) (magnification = 10X120; cross-polarised light)

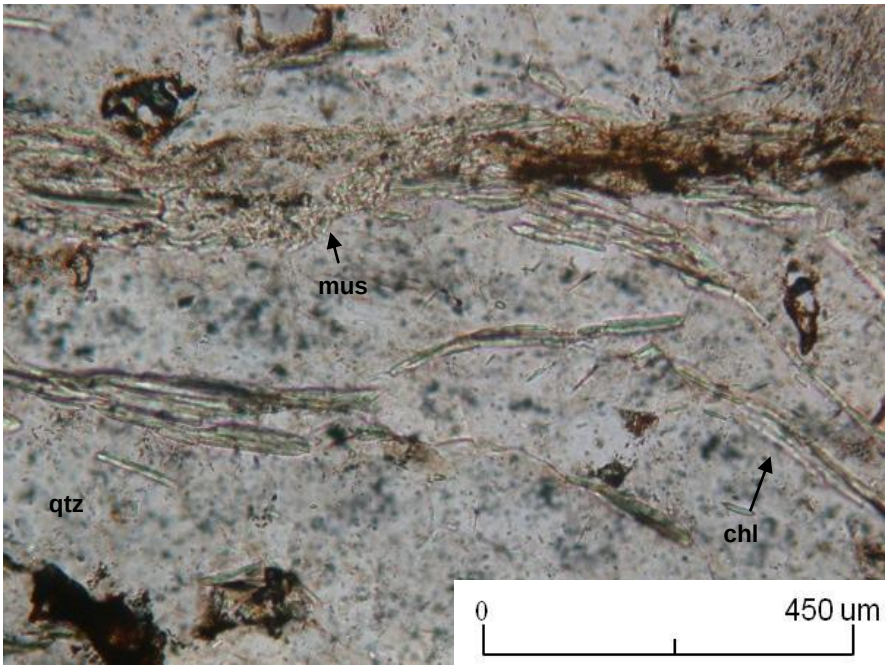


Plate 5.9 Photomicrograph of L5 showing medium grained, anhedral quartz (qtz), with a volumetric proportion of 90%, along with fine grained phyllosilicate weathering products, muscovite (mus) and chlorite (chl) – volumetric proportion of 10% (greater than L4). Note wider bans of quartz (magnification = 10X120; plane-polarised light)

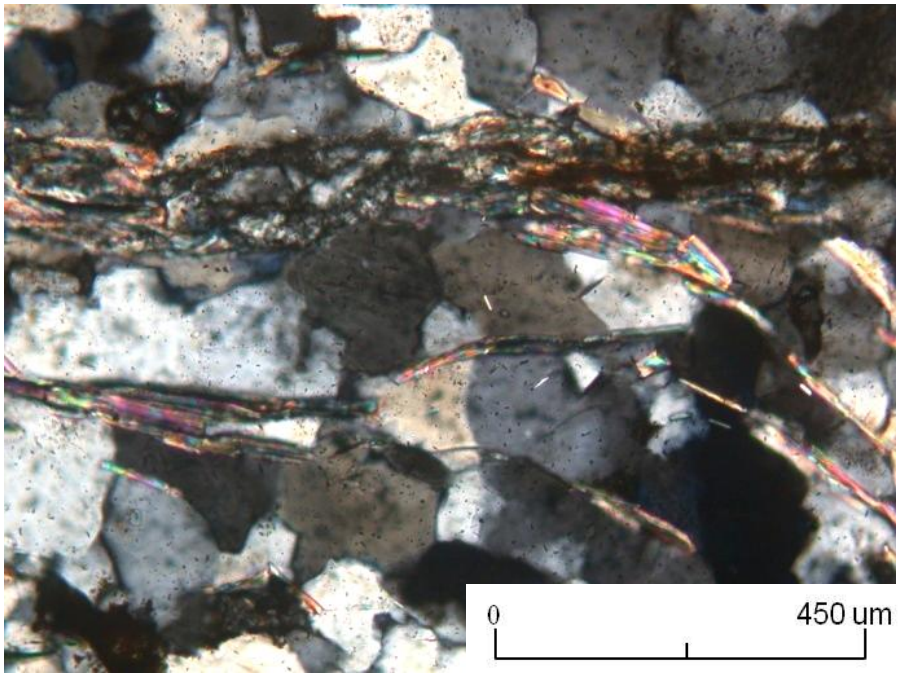


Plate 5.10 Photomicrograph of L5 showing medium grained, anhedral quartz (qtz), with a volumetric proportion of 90%, along with fine grained phyllosilicate weathering products, muscovite (mus) and chlorite (chl) – volumetric proportion of 10% (greater than L4). Note wider bans of quartz (magnification = 10X120; cross-polarised light)

5.2. Hydrogeology

Fractured rocks are the major source of groundwater supplies in South Africa. Over about 90% of the surface area of South Africa, groundwater occurs in secondary openings in so-called hard rocks (Vegter, 1995). Thus groundwater is mainly stored in joints, fractures and faults and to a much lesser degree, in the rock matrix. In some rocks which have primary matrix porosity (such as sandstones), later fracturing (post diagenetic fracturing) renders the rock to act as a dual porosity media where both matrix porosity and fracture porosity play roles in groundwater flow (Meyer, 2001). Consolidated hard rocks cover approximately 93.5% of the catchment area. The study area consists of hard rocks of the Malmesbury and Table Mountain Group, with the remainder being Cenozoic sediments of the Sandveld Group. The Malmesbury phyllites and greywackes produce yields of between 0.9-2 L/s (Parsons, 1995). Groundwater exploitation in the Malmesbury Group is often problematic due to argillaceous and thus structurally complex nature of many of the lithological units. The Malmesbury Group aquifers are classified as minor aquifer systems, as these aquifers have low borehole yields, produce groundwater with variable quality and are of limited significance (Parsons, 1995).

The Table Mountain Group, notably the often fractured arenaceous components, is largely anisotropic. An intricate network of fissures, joints, fractures and even cavities govern the infiltration, storage and transmission of groundwater in the arenaceous units of the TMG. The TMG remains as the most groundwater exploited aquifer, with yields in the sandstones reaching an average of 2.28 l/s (Table 5.1). Increase yields up to 4 l/s are located at major discontinuities (Meyer, 2001).

The only rocks within the catchment area in which groundwater occurs in both weathered rock and in jointed bedrock, and which can thus be termed fractured and intergranular, are the granites. Granites occurring within the study catchment have variable crystal size with varied composition, thus diverse weathering forms occur, with diverse groundwater implications. Weathered medium-crystalline granite with a more balanced composition is likely to be a better aquifer (Meyer, 2001). Borehole yield for the Cape Granite Suite varies between 0.05-2 l/s (Table 5.1).

Intergranular aquifers cover approximately 5.5% of the catchment. This includes the Springfontyn Formation of the Sandveld Group, alluvial sediments and the ferricrete/silcrete deposits. The thickness of the primary aquifer varies from less than a meter to greater than twenty meters. It is estimated (Figure 5.1) that the mud free quartz sands of the Sandveld

Group produce yields of between 0.5-2 l/s, whilst the yields in alluvial deposits vary between 0.1 and 20 l/s.

Table 5.1: Yield in various lithologies that occur in the study area

	Shale (n=11)	**Sandstone (n=12)**	**Granite (n=10)**
Minimum	0.02	0.01	0.01
Maximum	3.38	17.07	1.60
Mean	0.83	2.28	0.38
Standard Deviation	0.95	4.47	0.46

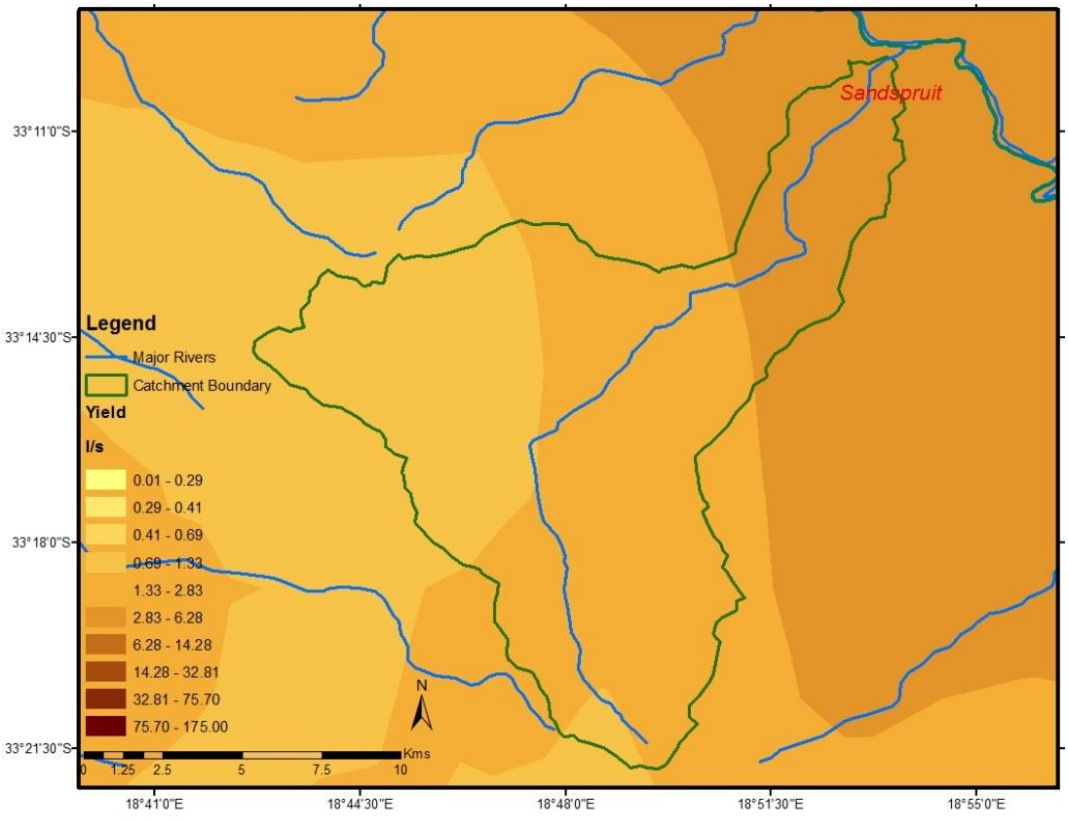


Figure 5.1: Borehole yield within the catchment

5.2.1. Water-level analysis

Depth to water-level (Table 5.2) measurements within the study catchment has revealed which boreholes (Figure 5.2) represent wells in unconfined and confined aquifers. These boreholes are further classed into water quality zones represented by the EC (discussed later in section 5.3.2). The unconfined aquifers are typically recharged directly through precipitation or surface water, and do not follow any distinct pattern related to the EC zonation. The water-table is best defined as "*the surface on which the fluid pressure p in the pore of a porous medium is exactly atmospheric*" (Freeze and Cherry, 1979). A water strike map representing the water-level of the unconfined aquifers is illustrated in Figure 5.4. Permeability and storativity in fractured aquifers vary with depth and it has been found that the water-bearing capacity of most of these aquifers decreases considerably when the water level is lowered by more than 20 to 30 m (Meyer, 2001). Abstraction causes an additional drawdown of the water level in addition to the natural recession (e.g. a decrease in recharge due to precipitation). The degree of the additional drawdown depends on the amount withdrawn and the storativity of the particular aquifer.

A 15 year (1990-2005) water-level map was produced using the data from the National Water Archive (NWA-DWA, 2010b) (Figure 5.3), illustrating that the groundwater level varies with topography. Figure 5.5a, b, and c, reveal that the water-level fluctuations are strongly influenced by amount of seasonal recharge. In comparison to the first field testing campaign in May 2009, the same stations measured in the second campaign in December 2009 generally showed an increased water-level of between 1-47%, preceded by the wet season in May-August. Station SDC11 (Figure 5.2) in contrast had a decrease in water-level when compared to the May 2009 measurement; this could probably be explained by an increase in pumpage or a delayed response by the aquifer. In the third campaign, the stations again, showed a slight decline in the water-level of between 1-12% in response to the November-March dry season. Stations SDC 12, 29, 47, and 56 however, displayed a rise in water-level, SDC 12, 47 and 56 (Figure 5.2) occur in the northern region of the catchment, where artificial recharge through irrigation is predominant. When comparing the groundwater-level in May 2009 to May 2010, station SDC9 located in the western region of the catchment shows a decrease of 4.04m, whilst stations SDC 12, SDC 29, SDC 30 and SDC 32 display an increase in water-level due to increased precipitation in the early months of 2010 as compared to that in 2009.

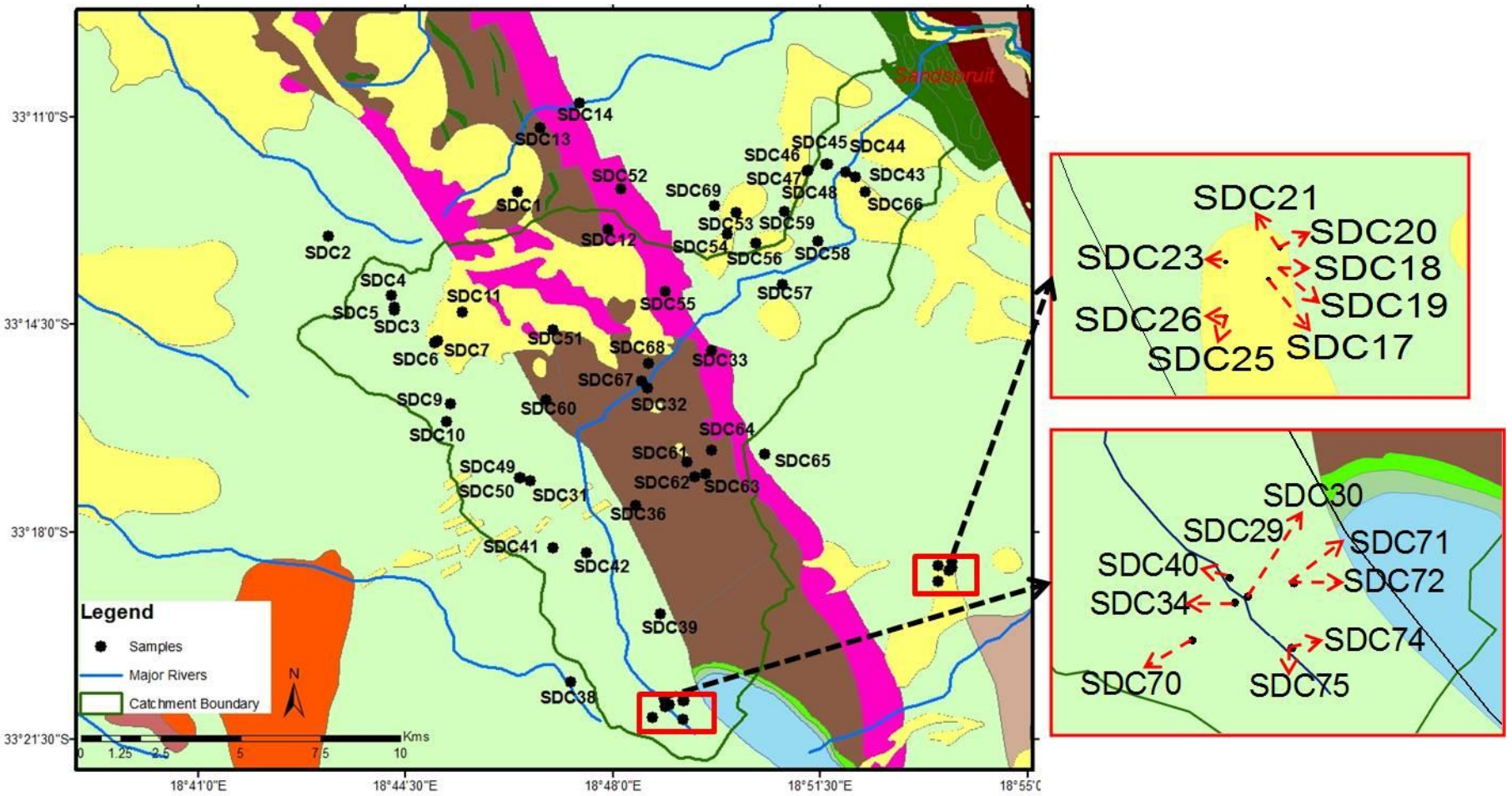


Figure 5.2: Sampling stations in present study

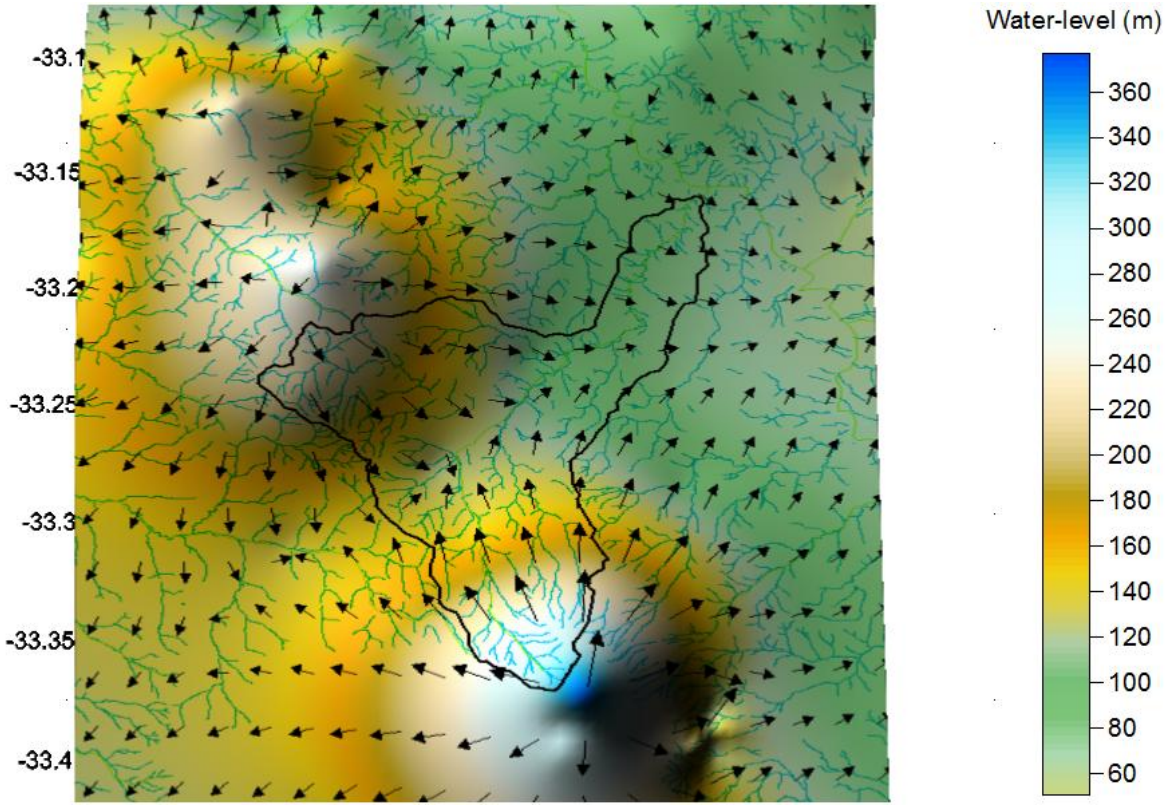


Figure 5.3: 15 year average water-level with flow vectors, produced from NWA data (DWA, 2010b). Flow vectors produced from groundwater-level contour.

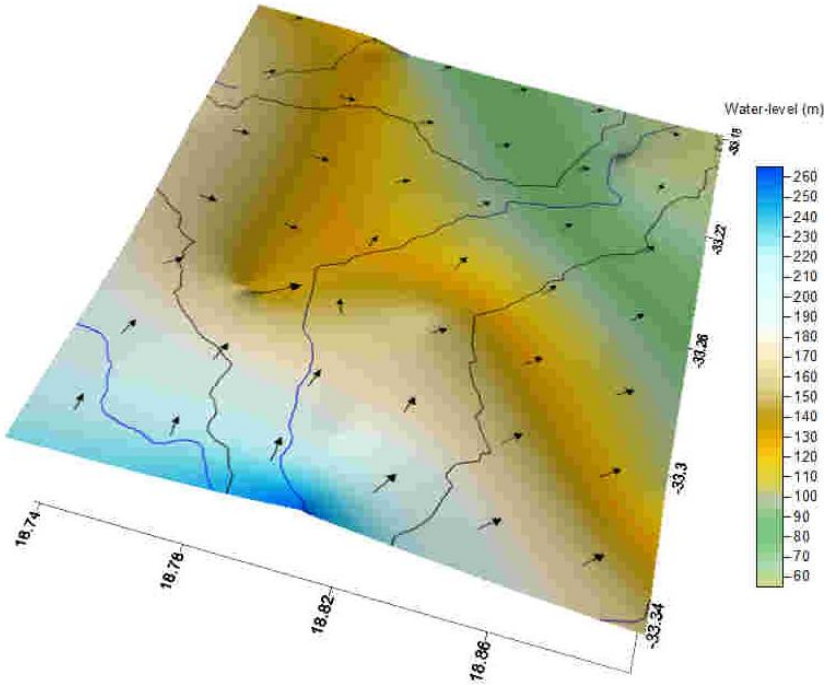


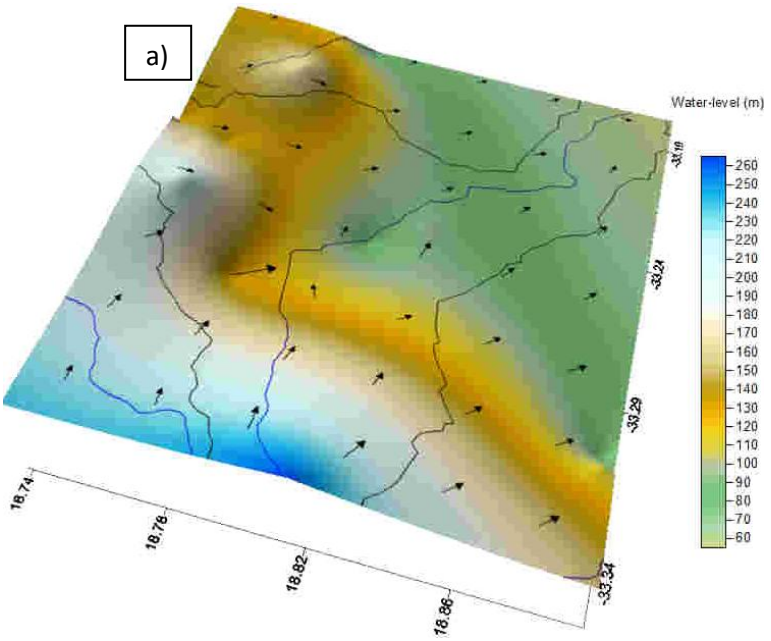
Figure 5.4: Average water strike level from sampling datasets

Table 5.2: Average depth to water-level (m.bgl) of samples located in the different EC zones

Sample	Geological Formation	Type of aquifer	Zone 1	Zone 2	Zone 3	Zone 4
SDC 1	Springfontyn	Confined			7.10	
SDC 3	Moorreesburg	Confined		30.00		
SDC 5	Moorreesburg	Unconfined		1.20		
SDC 6	Springfontyn	Confined		1.56		
SDC 7	Springfontyn	Confined		5.19		
SDC 9	Moorreesburg	Confined		13.26		
SDC 11	Springfontyn	Confined		11.21		
SDC 12	Klipplaat	Confined			7.37	
SDC 13	Berg River	Unconfined			2.05	
SDC 14	Moorreesburg	Unconfined			2.88	
SDC 17	Springfontyn	Confined				27.83
SDC 18	Springfontyn	Confined				14.73
SDC 19	Springfontyn	Confined				14.83
SDC 20	Springfontyn	Unconfined				3.06
SDC 21	Springfontyn	Unconfined				2.90
SDC 23	Springfontyn	Confined				26.27
SDC 25	Springfontyn	Confined				11.70
SDC 26	Springfontyn	Confined				12.04
SDC 29	Moorreesburg	Confined				6.60
SDC 30	Moorreesburg	Confined				7.53
SDC 31	Moorreesburg	Unconfined		1.27		
SDC 32	Berg River	Confined			5.10	
SDC 33	Klipplaat	Unconfined			1.20	
SDC 34	Moorreesburg	Unconfined				2.88
SDC 38	Moorreesburg	Unconfined				1.64
SDC 39	Moorreesburg	Unconfined			0.70	
SDC 40	Moorreesburg	Confined				23.00
SDC 41	Moorreesburg	Confined		20.10		
SDC 42	Moorreesburg	Confined		14.12		
SDC 44	Springfontyn	Unconfined	1.10			
SDC 45	Moorreesburg	Confined	14.02			
SDC 46	Springfontyn	Confined	14.72			

Table 5.2: Continued...

Sample	Geological Formation	Type of aquifer	Zone 1	Zone 2	Zone 3	Zone 4
SDC 47	Springfontyn	Confined	43.99			
SDC 48	Moorreesburg	Confined	43.75			
SDC 49	Moorreesburg	Unconfined		0.66		
SDC 51	Springfontyn	Confined		5.43		
SDC 52	Klipplaat	Confined			13.12	
SDC 54	Springfontyn	Confined			37.95	
SDC 56	Springfontyn	Confined			39.45	
SDC 59	Moorreesburg	Confined	20			
SDC 63	Berg River	Unconfined				2.4
SDC 64	Berg River	Confined				13.65
SDC 67	Berg River	Confined		11.08		
SDC 68	Berg River	Confined			17.98	
SDC 72	Moorreesburg	Confined				11.54
SDC 74	Moorreesburg	Confined				11.82
SDC 75	Moorreesburg	Confined				5.8



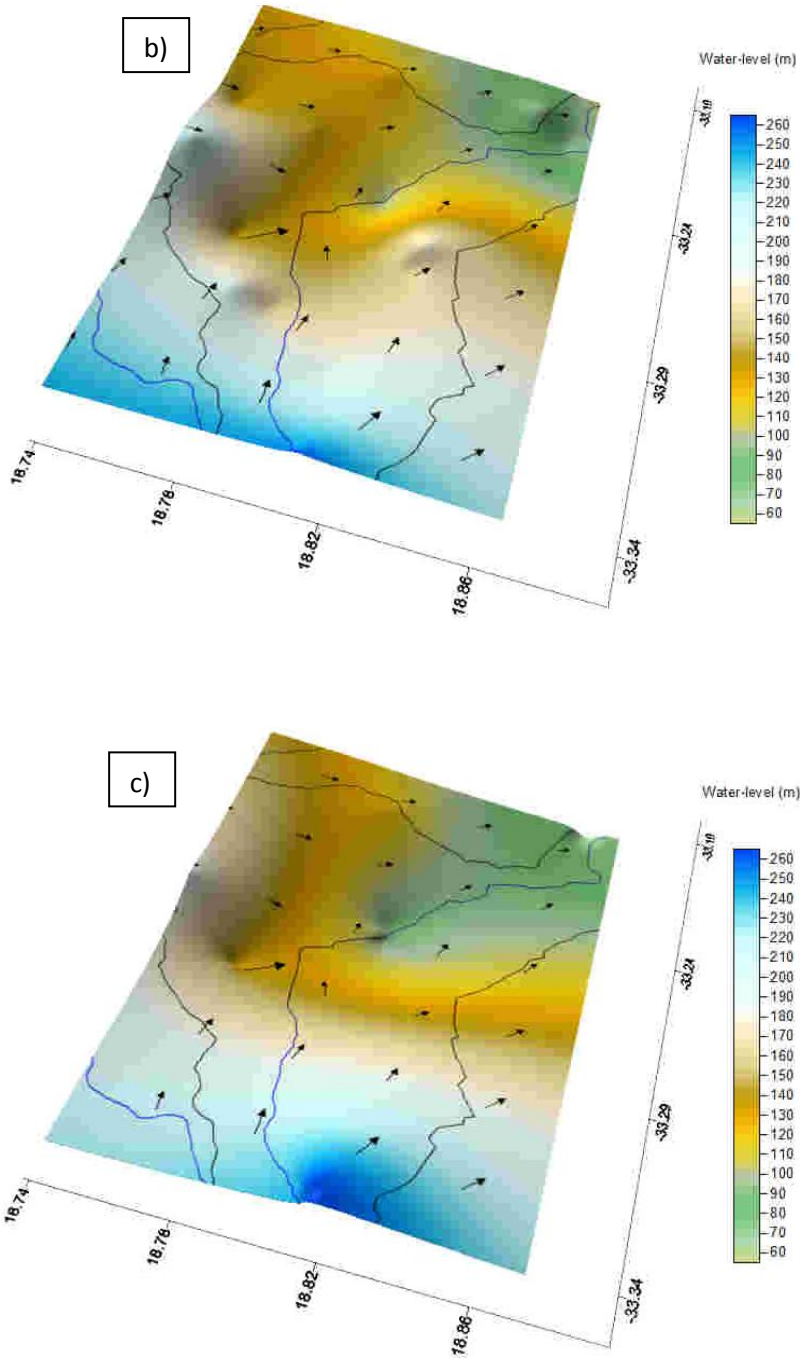


Figure 5.5: Groundwater-level contours within catchment

(a) Water-level contoured from first field testing campaign data (May 2009)
(b) Water-level contoured from second field testing campaign data (December 2009)
(c) Water-level contoured from third field testing campaign data (May 2010)

5.2.2. Local flow direction

The local groundwater-flow direction is predominantly controlled by the topographic head (Figure 5.3 and 5.4). Groundwater generally flows south to north-east in the catchment, similar to surface-water flow i.e. the Sandspruit River. The groundwater flow follows the folded shape of the bedding planes (Appendix D). Borehole logs with the water-strike are presented by the CSIR and WRC (Jovanovic, 2010) for the current project, these include boreholes ZB001→ZB007, OK001→OK003, and UV001→UV005. The rest of the borehole logs are provided from the DWA geodatabase (DWA, 2010b). Flow diagrams were produced to establish the flow behaviour of the groundwater i.e. ability of groundwater to flow along the folded bedding planes, and to identify the major aquifer systems. The flow diagrams illustrate that water-strikes are present in various soil formations and lithologies, with the Swartland schists representing the dominant confined aquifer system. An intricate network of fissures, joints, and fractures govern the infiltration, storage and transmission of groundwater within the Swartland schists.

5.3. Recharge estimation

Recharge is influenced by meteorological and hydrogeological factors, which change spatially and temporally. Understanding the factors and processes that control groundwater recharge are important to determine the variability in the quantity of groundwater recharge. An analysis of the relationship between meteorological, hydrogeological and geomorphologic conditions provides the infrastructure towards recharge estimation. The impact of topography on local and regional groundwater flow paths was demonstrated by Tóth (1963). As the slope gradient increases, the kinetic energy of rainfall remains constant, but transport accelerates towards the foot as the kinetic energy of the runoff increases and outweighs the kinetic energy of the rainfall. This occurs when the slope exceeds 15% (Roose, 1996). Water runs off steeper slopes faster, with less infiltration into the ground, thus producing less recharge than flatter areas where water has more time to soak into the ground (Sophocleous and Buchanan, 2003). Recharge decreases as the soil texture becomes heavier (Kennett-Smith et al., 1994). Recharge processes are more complex in the folded and faulted rock area where more effective recharge may occur in the area with high density of fractures and percolate to local or other catchment via fracture networks. Groundwater recharge estimation using the catchment water-balance, chloride mass balance, and qualified guesses methods will be estimated in the following sections 5.3.1, 5.3.2 and 5.3.3 in the present study.

5.3.1. Catchment water-balance

Following Equation (2.1), and taking the soil moisture storage to be zero, the monthly recharge rate is thus estimated by subtracting the monthly ETc, and runoff from monthly precipitation i.e.

Recharge = Precipitation - ETc – Runoff (5.1)

Units are mm/month. The rate of evapotranspiration increases as the vegetative cover increases. Impact of vegetation on recharge can be observed in many ways, such as interception and transpiration. Reference evapotranspiration (ETo), and crop evapotranspiration (ETc) were calculated using the Penman-Montieth approach (Equation 2.5 and 2.6, Appendix E), mid-seasonal crop coefficient values (Kc) were used for the three "crop types" i.e. annual small grain (wheat), wine grapes and pristine shrub (*Fynbos* and *Renosterveld*) (Appendix E). In Figures 5.7c, 5.8c, and 5.9c, annual small grain is represented in blue, pristine crop in olive, and wine grapes in red. Runoff was calculated using Equation 2.9. The runoff coefficients (C) (Appendix F) were based upon soil, land use, and slope criteria as reported in Table 5.3. The catchment area was then classified according to the criteria presented by Singh *et al*., (1981) (Figure 5.6). "Barren" land use in Figure 5.6b represents the PPC limestone quarry, and contains a C value of 0.8-0.9 (Keller and Sherar, 2011).

Table 5.3: Value of "C" for estimation of peak rate of runoff with rational formula (modified after Singh *et al*., 1981)

Soil Texture	**Slope**	**Land Use**		
		Cultivated	**Pasture**	**Forest**
Sandy loam	0-5%	0.30	0.10	0.10
	5-10%	0.40	0.16	0.25
	10-30%	0.52	0.22	0.30
Clay and silt loam	0-5%	0.50	0.30	0.30
	5-10%	0.60	0.36	0.35
	10-30%	0.72	0.42	0.50
Stiff clay	0-5%	0.60	0.40	0.46
	5-10%	0.70	0.55	0.50
	10-30%	0.82	0.60	0.60

Since the Sandspruit catchment is characterised by a Mediterranean type climate whereby precipitation occurs predominantly in May, June, July and August, the recharge rate is greater during the winter period. The amount of rainfall within these four months accounts for more than 60% of the amount of annual rainfall.

The calculated water balance (Appendix G) revealed that recharge only occurred in June, July, and August, whereas evaporation and transpiration were the dominant processes controlling recharge within the remaining months (September-May). The runoff, ETc, and recharge contour map is shown in Figures 5.7, 5.8, and 5.9. The June runoff (Figure 5.7a) varies between 0.02-0.16 mm, a runoff of 0.057 mm covers 46.60% of the catchment area, whilst a runoff of 0.095 mm covers 42.35% of the catchment. The June ETc (Figure 5.7b) ranges from 30.03-49.33 mm for wine grapes and wheat respectively, an ETc of 49.33 mm covers 91.02% of the catchment area. The June recharge (Figure 5.7c) varies between 18.89-38.30 mm, with a higher recharge associated with the Table Mountain Sandstone south of the catchment. Recharge of 18.96 and 18.99 mm dominates 35.69% and 44.43% of the catchment area respectively.

The July runoff (Figure 5.8a) ranges from 0.02-0.14 mm, with a runoff of 0.05 mm covering 46.60% of the catchment area, and a runoff of 0.08 covering 42.35%. ETc (Figure 5.8b) varies ranges between 32.92-54.10 mm, with an ETc of 54.10 mm covering 91.02% of the catchment area. Recharge in July (Figure 5.8c) varies between 5.40-26.66 mm, with a recharge of 5.46 mm and 5.49 mm covering 35.69% and 44.43% of the catchment area respectively.

Runoff in August (Figure 5.9a) varies between 0.02-0.14 mm, with a runoff of 0.05 mm covering 46.60% of the catchment area, and a runoff of 0.09 mm covering 42.35% of the catchment. August ETc (Figure 5.9b) ranges from 36.42-59.83 mm, with an ETc of 59.83 mm covering 91.02% of the catchment area. August recharge (Figure 5.9c), ranges from 1.37-24.88 mm, with recharge of 1.43 mm, and 1.47 mm covering 35.69% and 44.43% of the catchment area respectively. The annual calculated recharge is shown in Figure 5.10, recharge ranges from 25.66-89.83 mm/yr, with recharge of 25.85 mm and 25.95 mm covering 35.69% and 44.43% of the catchment area respectively.

5.3.1.1. Accuracy of the water-balance model

One of the major uncertainties is preferential recharge during high intensity rainfall events propagating through major and minor fractures. Uncertainties and inaccuracies arise from several sources: spatial and temporal variability in processes and parameter values, measurement errors, and the validity of assumptions upon which different methods are

based (Healy and Cook, 2002). One of the major factors influencing recharge is the calculation of the ETc, which relies on various meteorological and crop growth period data. Parameters such as ETc and runoff are subjective to methods of calculation. However, due to the strong correlation of annual recharge amounts calculated using qualified guesses outlined in section 5.2.3, the accuracy of the water-balance model is quite high.

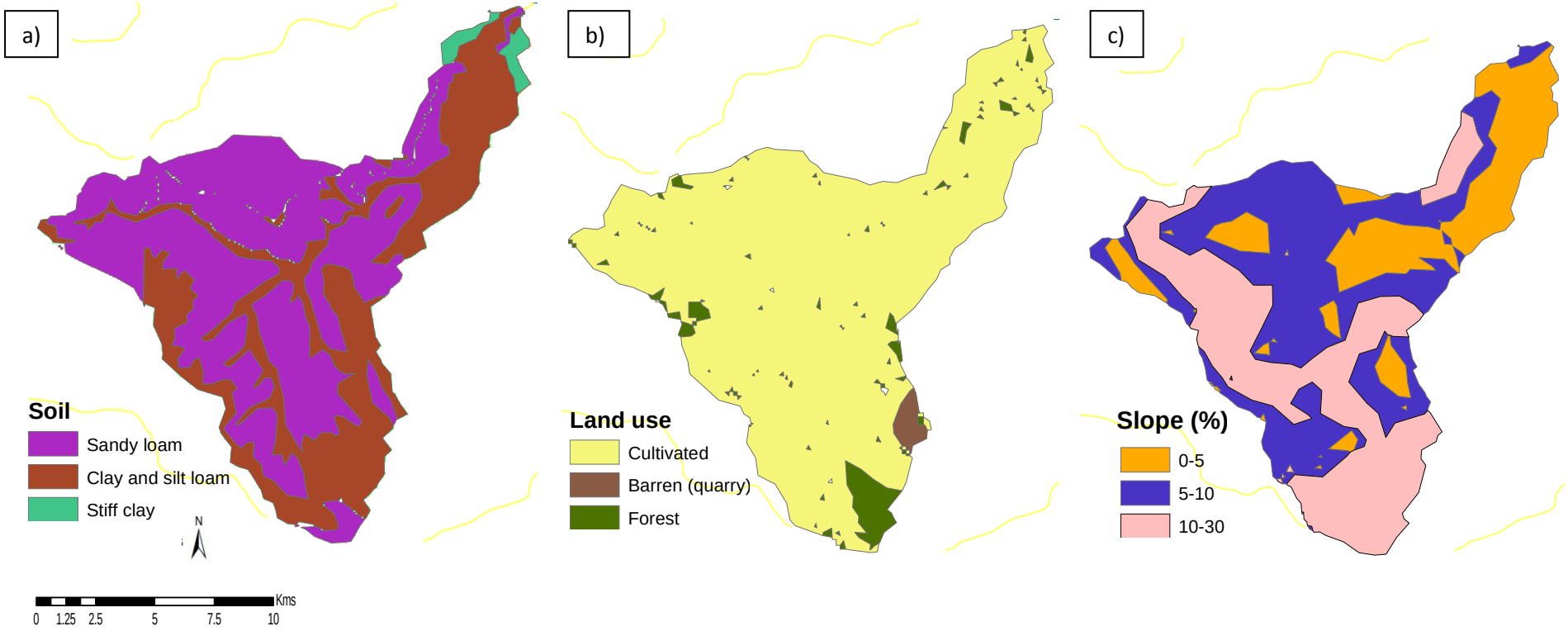


Figure 5.6: a) Soil map, b) Land use map, and c) Slope map of the catchment. Note: a), b), and c) have been reclassified according to Table 5.3, based on Singh et al (1981) runoff coefficient “C” estimation

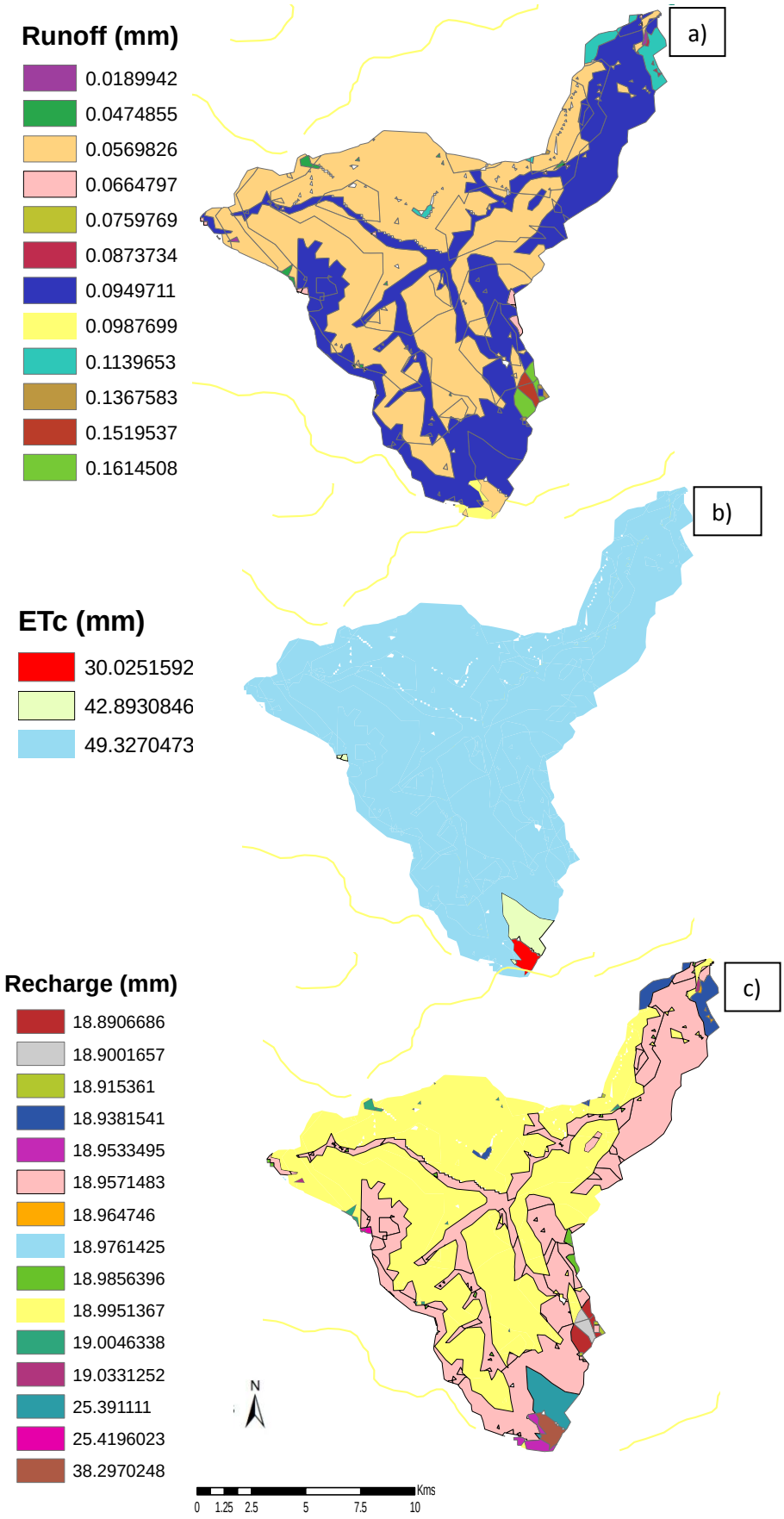


Figure 5.7: a) Runoff map, b) ETc map and c) Recharge map for June

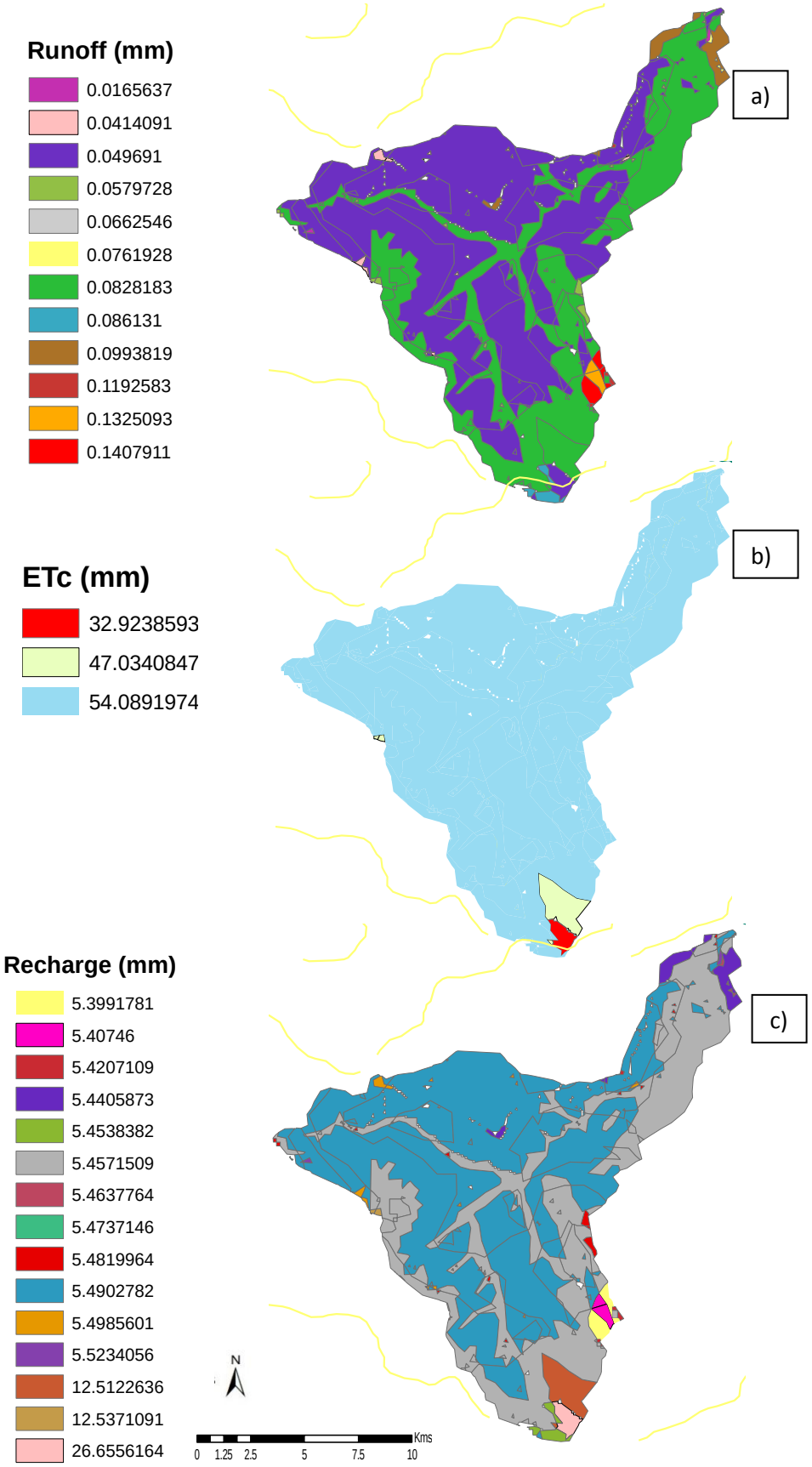


Figure 5.8: a) Runoff map, b) ETc map and c) Recharge map for July

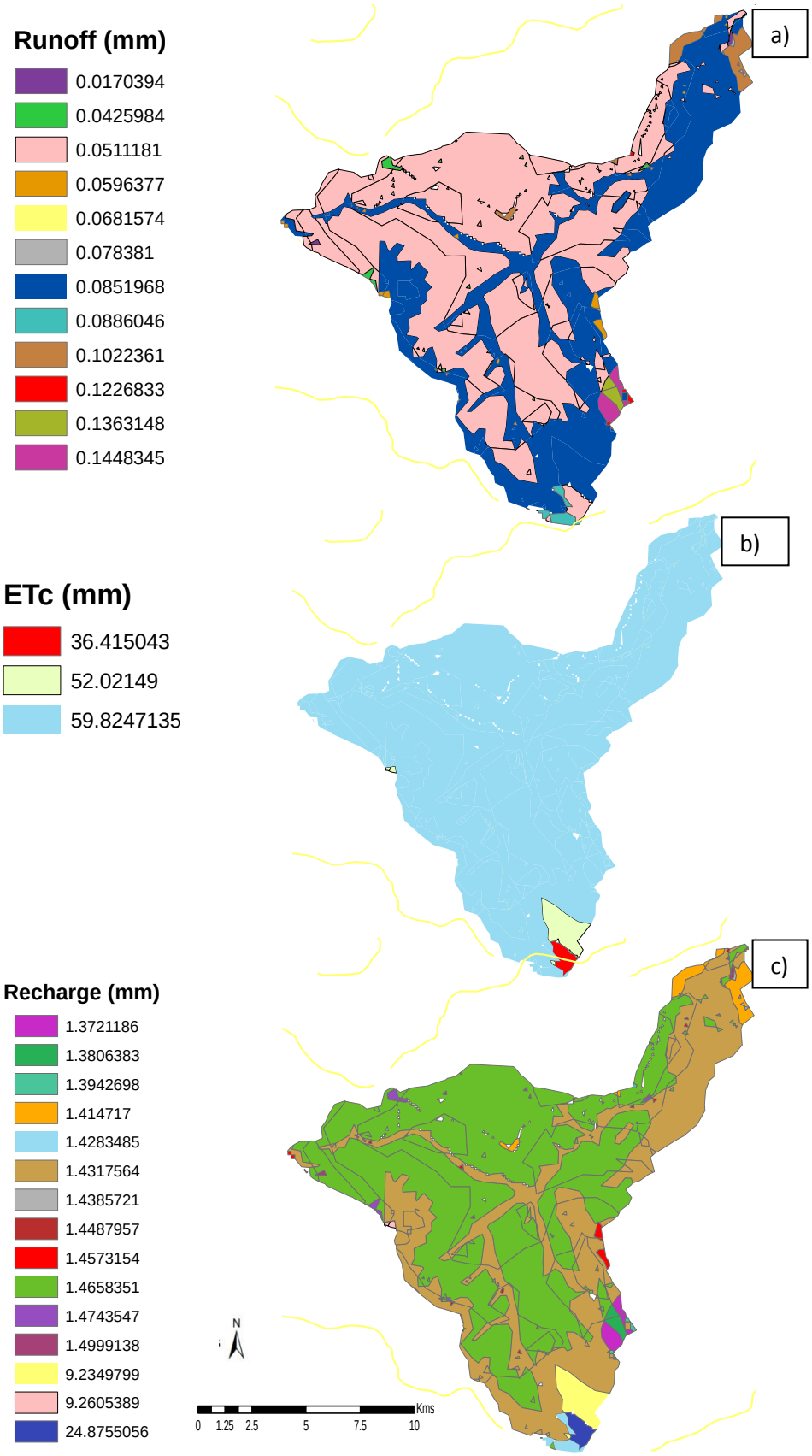


Figure 5.9: a) Runoff map, b) ETc map and c) Recharge map for August

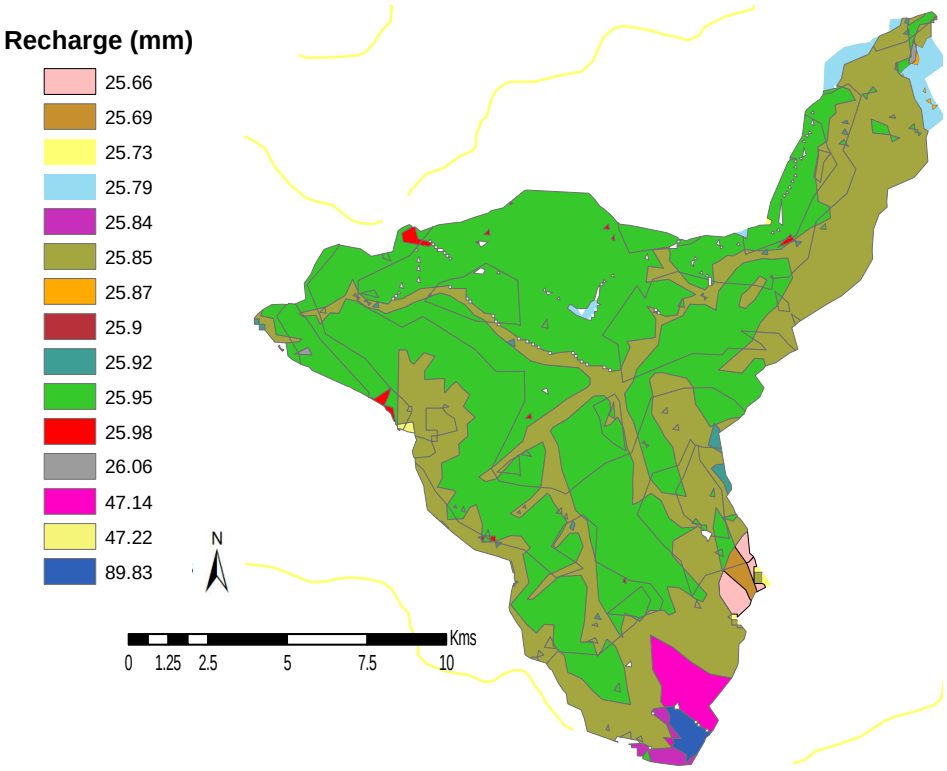


Figure 5.10: Annual recharges map of Sandspruit catchment calculated from water-balance

5.3.2. The chloride mass balance (CMB) method

From a water-balance point of view, groundwater abstraction from an aquifer can be considered a mixture of recent recharge and water stored in the aquifer. For the present study, rainfall chloride and dry deposition data were provided by DWA (2010a), based on meteorological stations in the Cape Town region. Mean rainfall chloride concentrations are 2.55 mg/l and 3.65 mg/l for the winter (May) and summer (December) sampling regimes respectively. Mean dry deposition values ranged from 6 mg/l for winter and 12mg/l for summer. The minimum recharge rate found is 0.70 mm/yr, and a percentage recharge of 0.17 associated with sample SDC 43(iii), the maximum recharge rate of 113.51 mm/yr and a corresponding percentage recharge of 28.5% is associated with sample SDC 30(iii). The average recharge rate is 10.20 mm/yr corresponding to a percentage recharge of 2.56% (Appendix H). The CMB method is unreliable in this calculation as the sole source of chloride is not from precipitation alone. Other natural sources of chloride include rock weathering, sea-water encroachment and salt dissolution, and anthropogenic sources such as irrigation and pollution are suspected to introduce uncertainty to the measured value.

5.3.3. Qualified guesses

The maps of Vegter (1995), ACRU, and Harvest Potential together with the soil, vegetation, slope and lithology, were used to produce qualified guesses of the catchment annual recharge rate (Appendix I). The qualified guesses for recharge from the soil/vegetation and geology are from expert opinions and general equations proposed by Bredenkamp *et al*., (1995) and Kirchner et al., (1991). Based on the criteria and equations provided from the Bredenkamp *et al*., (1995) and Kirchner *et al*., (1991) (Appendix I), recharge through qualified guesses show the results in Table 5.4. The ACRU method yields a much higher recharge rate of 70 mm/yr than the other methods. The average recharge from the methods in Table 5.4 is 25.5 mm/yr corresponding to a recharge percentage of 6.1%.

Table 5.4: Recharge estimation using qualified guesses, after Bredenkamp *et al*., (1995) and Kirchner *et al*., (1991)

Method	Recharge (mm/a)	Recharge as % of precipitation
Soil information	7.9	1.9
Geology	14.5	3.5
Vegter	20.0	4.8
ACRU	70.0	16.7
Harvest Potential	15.0	3.6

5.4. Hydrochemical and environmental isotope results

Result tables of onsite measurements and laboratory chemical analysis of water samples collected within and in the vicinity of the study catchment are presented in Appendix J.

5.4.1 Electrical conductivity (EC)

Electrical conductance, or conductivity, is the ability of a substance to conduct an electric current (Hem, 1985). Since, EC has a relationship with the ionic concentration in water, it was measured onsite, along with the other variables presented in Appendix J. The electrical conductivity values of the groundwater samples from the May 2009 sampling campaign range from 236.6 -812.5 mS/m, December 2009 EC falls within 54.6-2140 mS/m, and the May 2010 field data falls within 42.4-2105 mS/m range. Based on the EC, the study area can be divided into four zones, a north-eastern brackish – salty water region (Zone 1 - Figure

5.11), a north-western brackish water region (Zone 2 - Figure 5.11), a central fresh – brackish water region (Zone 3 - Figure 5.11), and a southern fresh water region (Zone 4 - Figure 5.11). Surface water EC measurements are indicated in Figure 5.13a&b, SDC 27 represents the Berg River samples, which has a higher EC (by 13.2 mS/m) in December, than in May. Sample SDC 35(ii), contains a more dilute groundwater than SDC 37(ii) upstream of the Sandspruit River (Figure 5.13b), this illustrates that discharge of groundwater into the Sandpruit River occurs at the base of the Table Mountain Group sandstone south of the catchment.

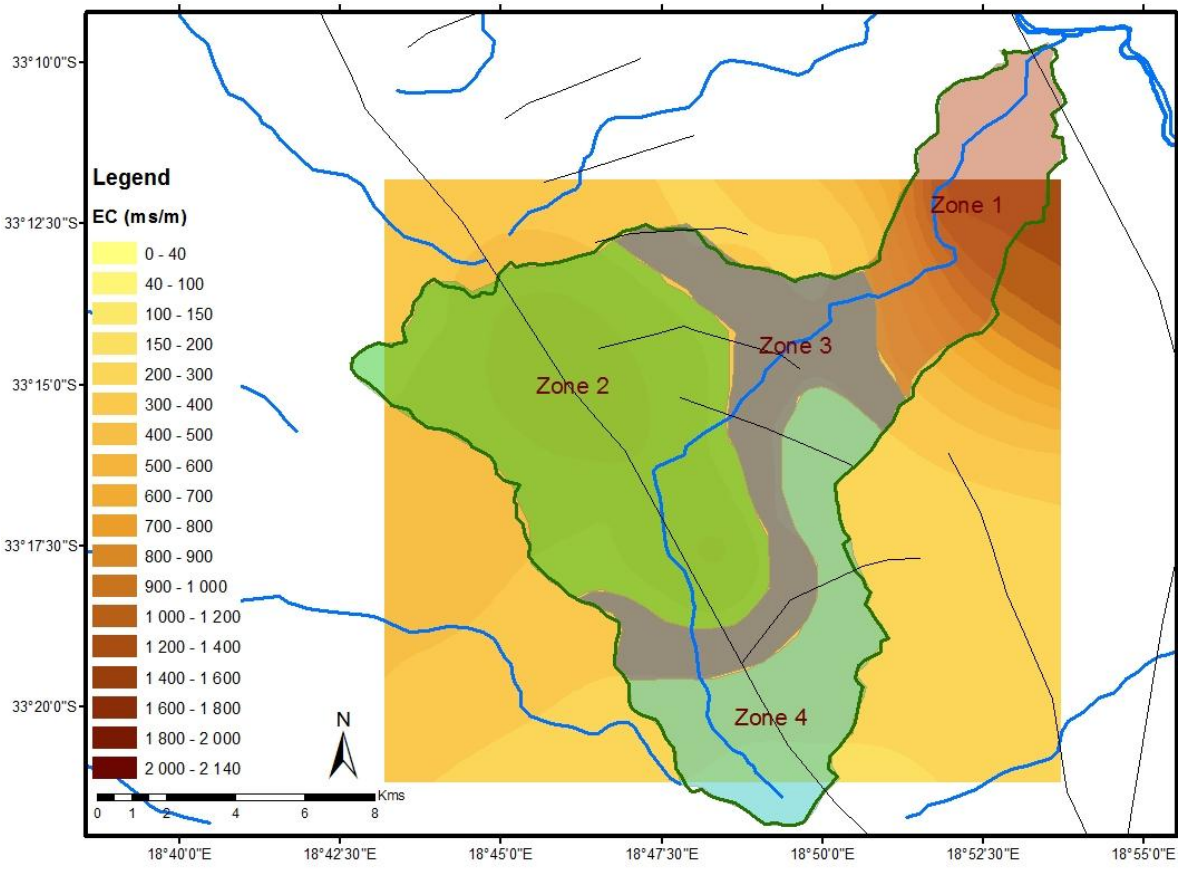


Figure 5.11: EC regions based on average EC measurements during the three sampling campaigns

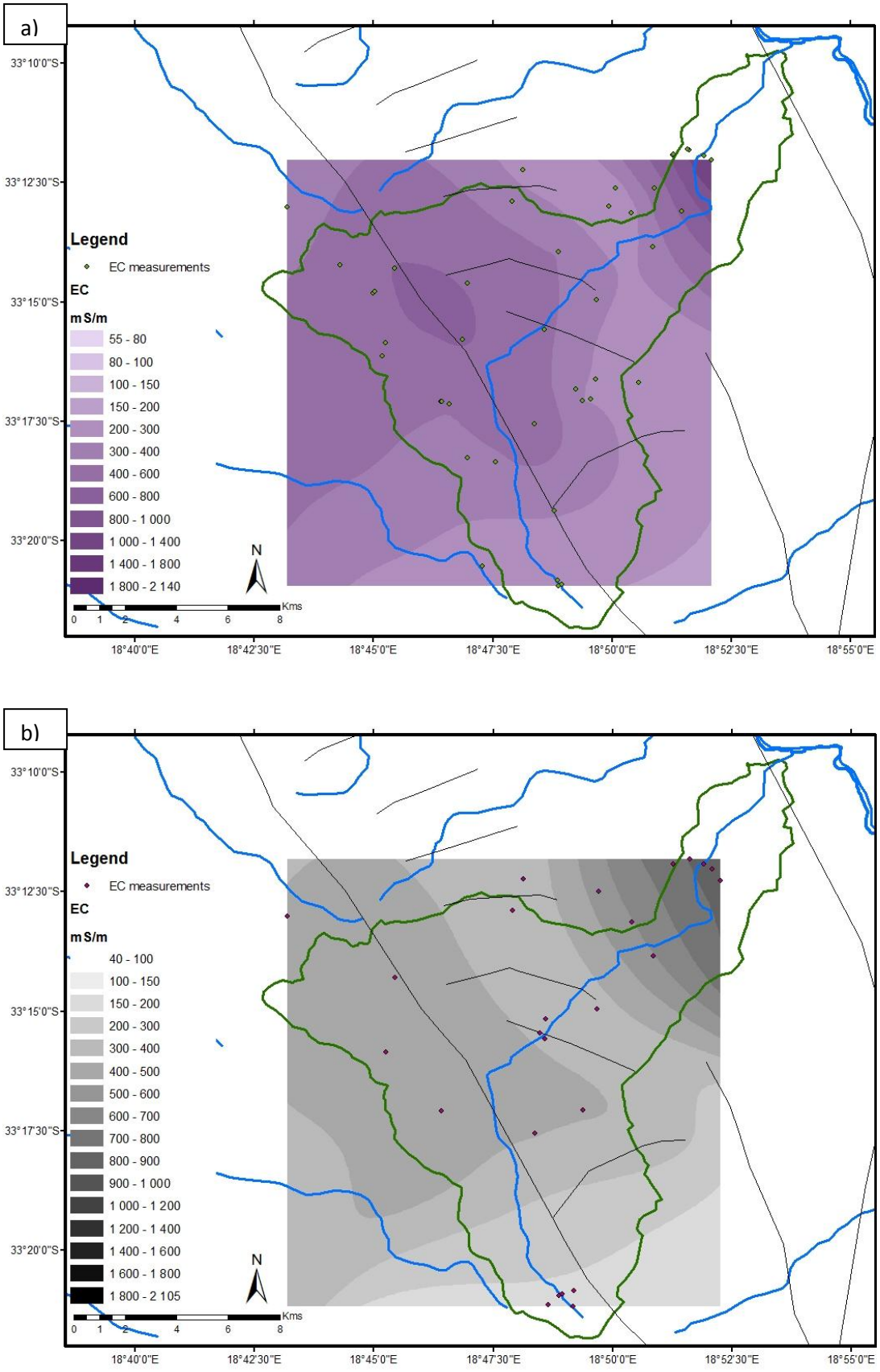


Figure 5.12: a) EC groundwater contour of December 2009 samples and b) EC groundwater contour of May 2010 samples

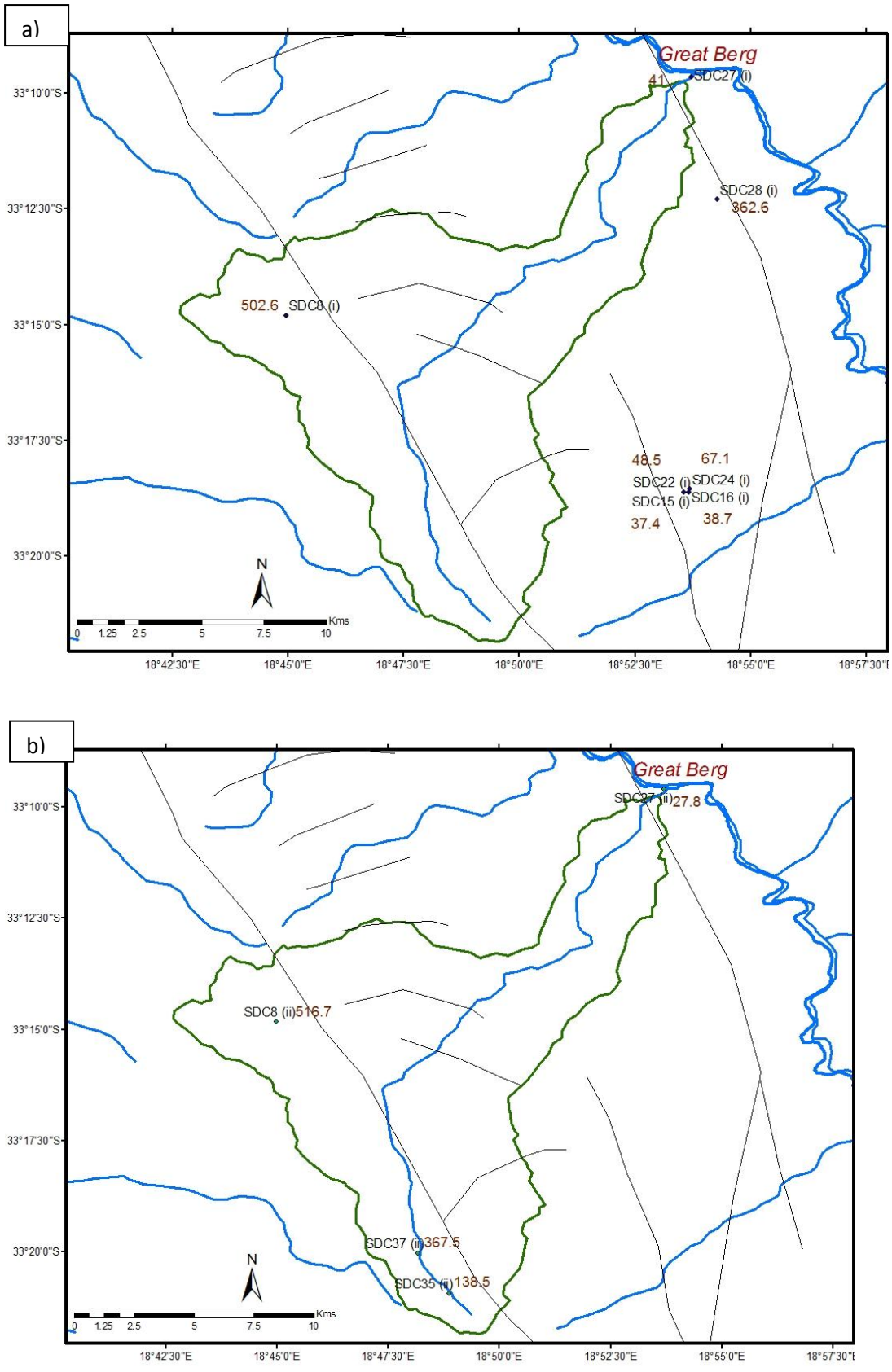


Figure 5.13: a) Surface water EC (mS/m) measurements in May 2009 and b) Surface water measurements in December 2009

The topography of the various zones in relation to EC, illustrates that Zone 1 occurs within a relatively “flat” region with an elevation of 60±5 m above mean sea level (m amsl) (Figure 4.1), Zone 2 occurs within a “hilly” topology with an elevation of 90-230 m amsl (Figure 4.1) of which EC values are expected to be lower than the “valley” region of Zone 3, however due to the flow regime affected by the intense folding, and occurrence of the NW-SE trending Moorreesburg fault, the groundwater EC values are much higher (Figure 5.12a&b). Zone 4 represents a “mountain block – recharge” region with an elevation of 170-310 m amsl (Figure 4.1) and including the outcrop of Table Mountain Sandstone.

The May 2010 EC contour (Figure 5.12b) when compared to December 2009 EC contour (Figure 5.12a) still follows the same EC zonation, however illustrates a relatively more dilute (lower overall EC contour) groundwater than the December 2009 EC, due to recent groundwater recharge. In Figure 5.14, time series analysis of the EC data showed that samples SDC3, SDC10, SDC 12 and SDC 33 had an increase in EC in December 2009, as compared to May 2009, whilst samples SDC 2, SDC 11 and SDC 31 showed a decrease in EC. Samples SDC 9, SDC 12, SDC 31, SDC 33, SDC 36, SDC 43, SDC 49, SDC 50, SDC 52, SDC 56, SDC 57 and SDC 62 showed a decrease in EC in May 2010, when compared to December 2009, whilst samples SDC 2, and SDC 34 showed an increase in EC. The EC for samples SDC 2, SDC 12 and SDC 33 was recorded in all three sampling campaigns, and illustrated a decrease in EC in May 2010 when compared to the previous year i.e. May 2009.

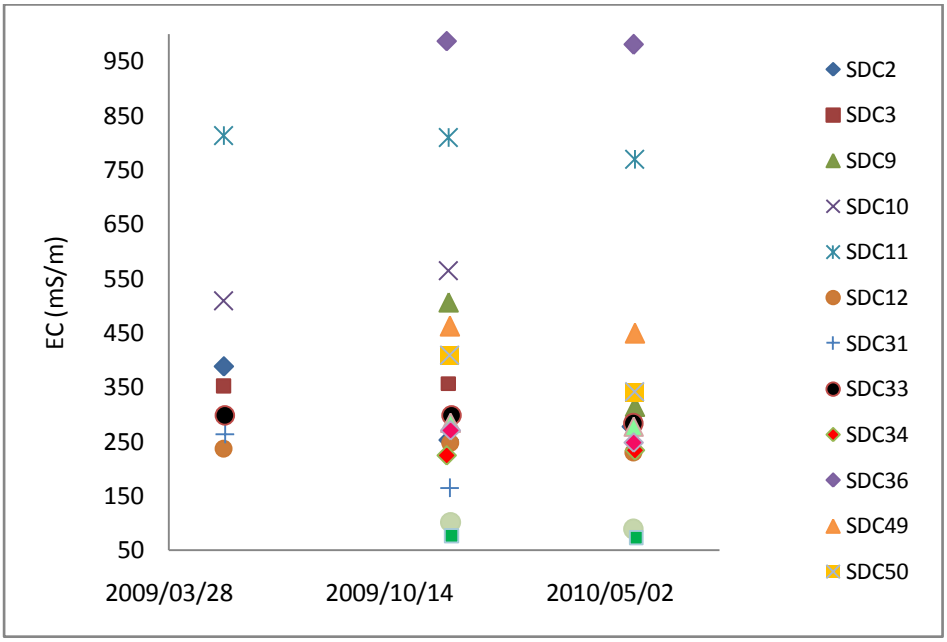
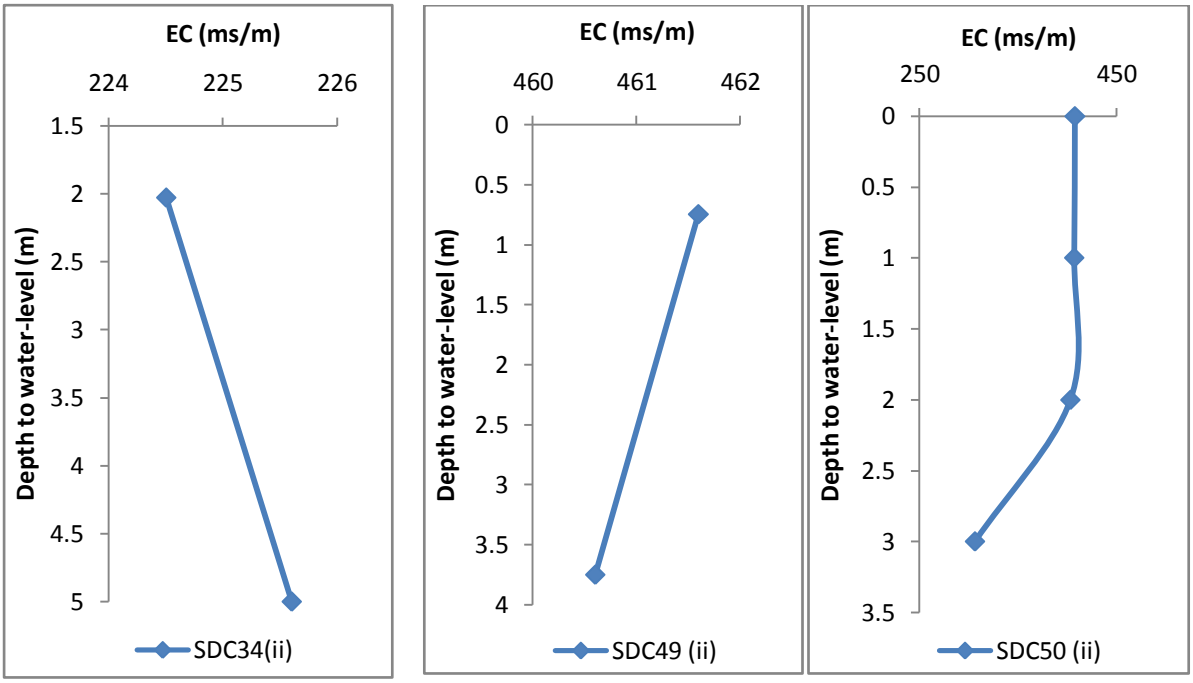
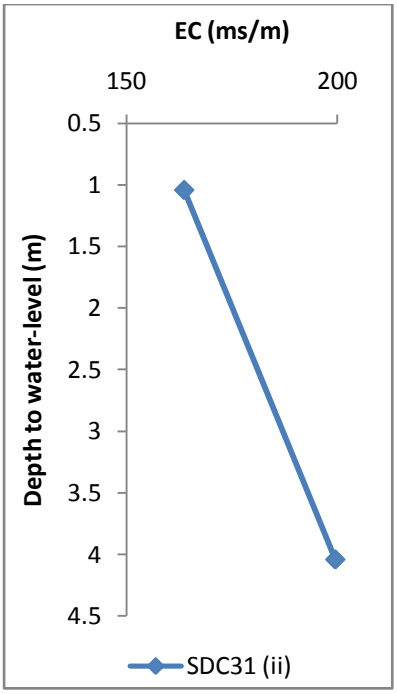
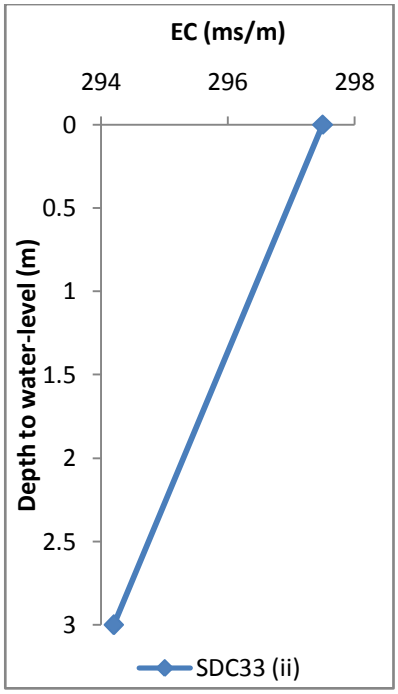


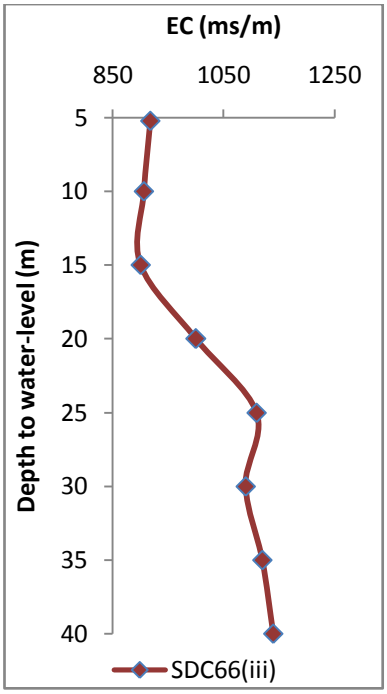
Figure 5.14: Comparison of groundwater EC measurements during the three sampling campaigns

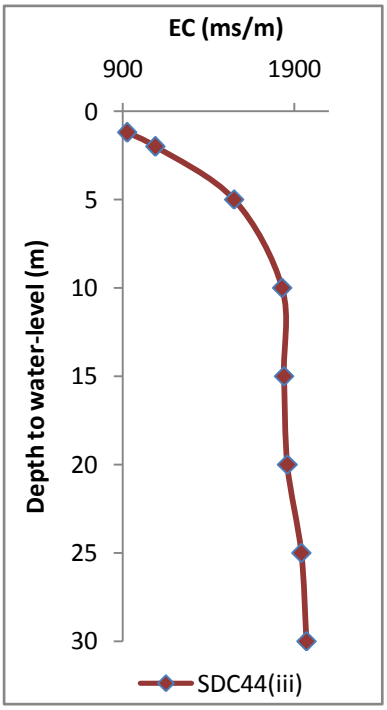
Depth profiles of EC were measured with a multiparameter electrode meter in December 2009, whilst a dip meter was used in May 2010. Depth profiles of EC (Figure 5.15) from groundwater in Zone 1 show a vertical sequence of increasing salinity from different depths. Depth profiles from Zone 2 for samples SDC 10 and SDC 49 illustrate a decrease in salinity with depth. SDC 33 in Zone 3 also shows a decrease in salinity with depth. Whilst samples in Zone 4 showed an overall increase in salinity with depth, sample SDC 74 showed a decrease in salinity with depth. The increase of salinity with depth is indicative of recharge diluting the groundwater near the surface, whereas a decrease in salinity with depth indicates evaporation of groundwater near the surface as well as the presence of different flow and vertical aquifer systems.

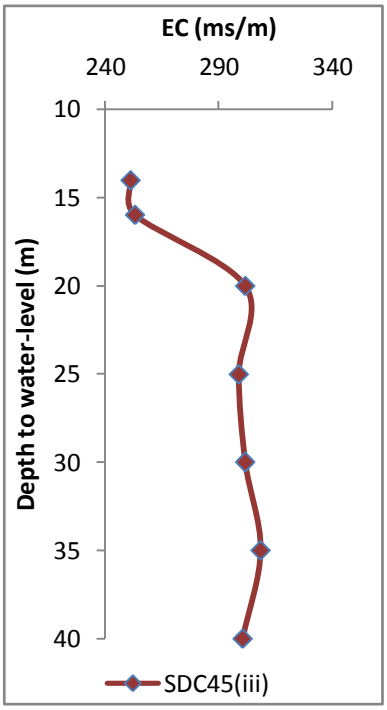


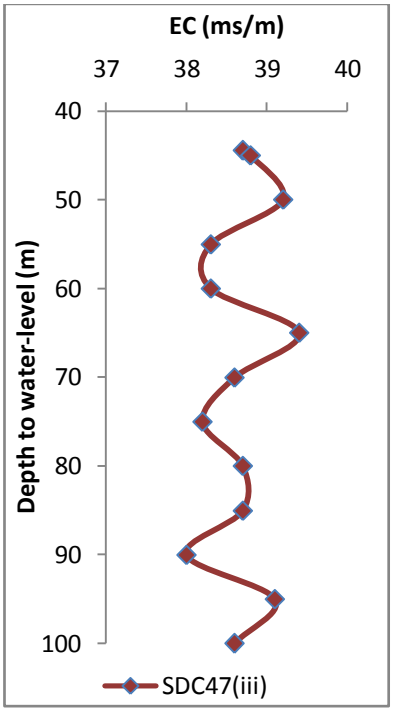

EC (ms/m)
150
200
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Depth to water-level (m)
SDC31 (ii)

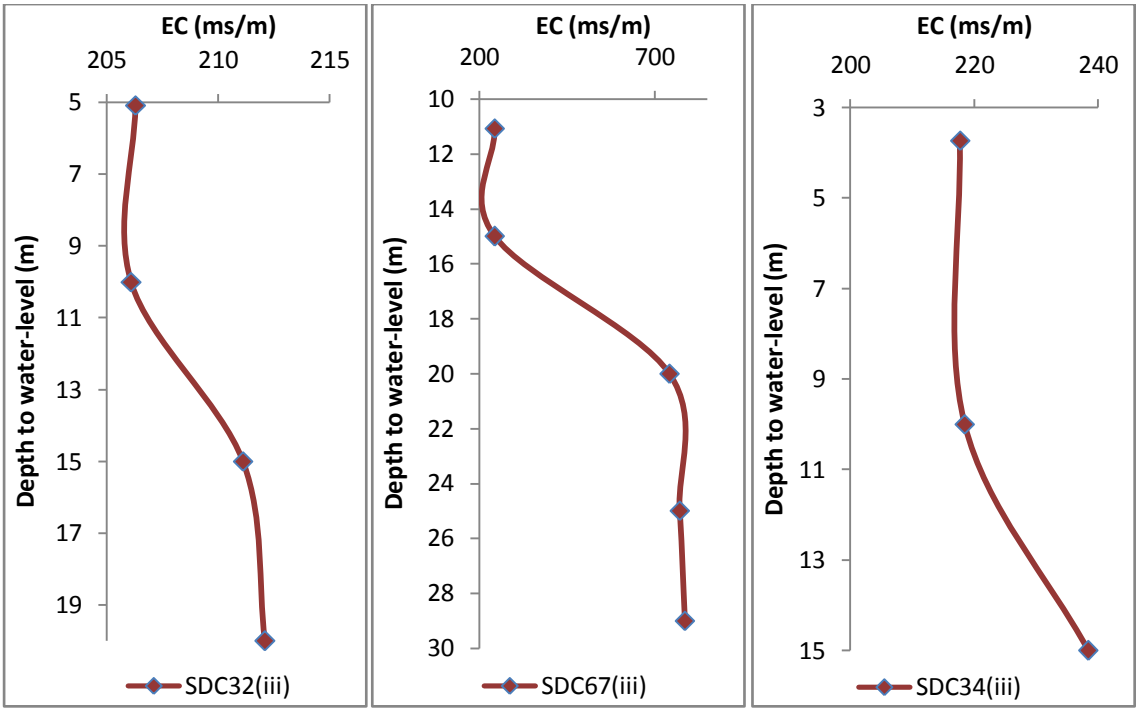

EC (ms/m)
294
296
298
0
0.5
1
1.5
2
2.5
3
Depth to water-level (m)
SDC33 (ii)

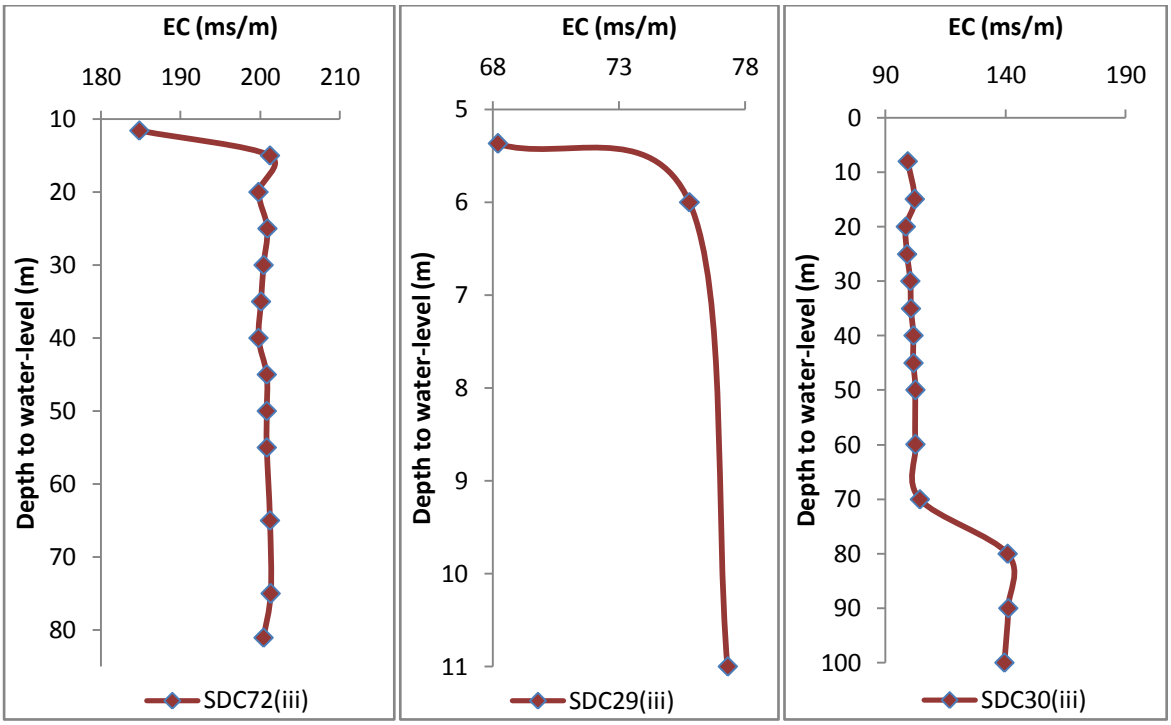

EC (ms/m)
850
1050
1250
5
10
15
20
25
30
35
40
Depth to water-level (m)
SDC66(iii)


EC (ms/m)
900
1900
0
5
10
15
20
25
30
Depth to water-level (m)
SDC44(iii)


EC (ms/m)
240
290
340
10
15
20
25
30
35
40
Depth to water-level (m)
SDC45(iii)


EC (ms/m)
37
38
39
40
40
50
60
70
80
90
100
Depth to water-level (m)
SDC47(iii)


EC (ms/m)
205
210
215
Depth to water-level (m)
5
7
9
11
13
15
17
19
SDC32(iii)
EC (ms/m)
200
700
Depth to water-level (m)
10
12
14
16
18
20
22
24
26
28
30
SDC67(iii)
EC (ms/m)
200
220
240
Depth to water-level (m)
3
5
7
9
11
13
15
SDC34(iii)


EC (ms/m)
180
190
200
210
Depth to water-level (m)
10
20
30
40
50
60
70
80
SDC72(iii)
EC (ms/m)
68
73
78
Depth to water-level (m)
5
6
7
8
9
10
11
SDC29(iii)
EC (ms/m)
90
140
190
Depth to water-level (m)
0
10
20
30
40
50
60
70
80
90
100
SDC30(iii)

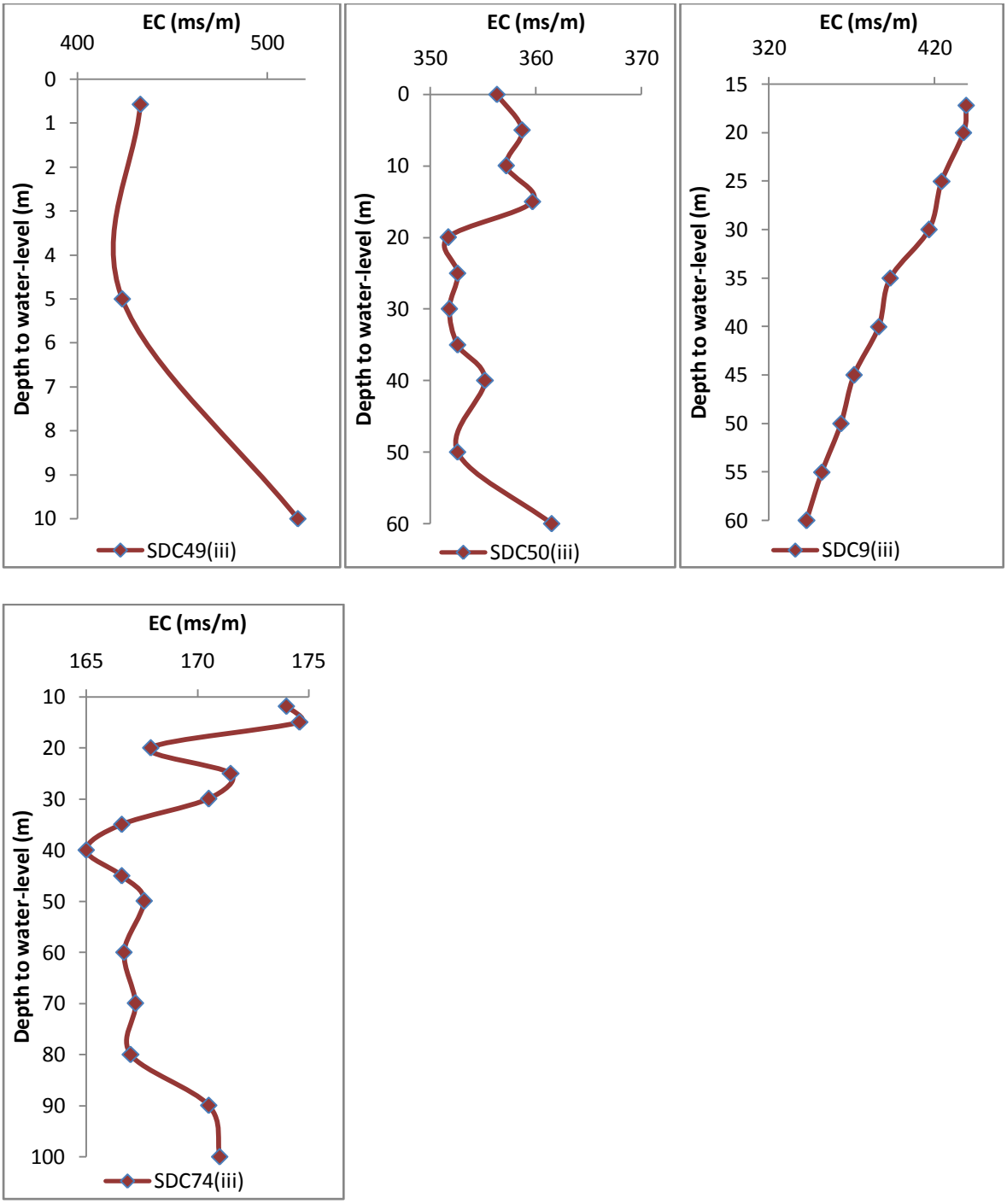


Figure 5.15: EC depth profiles of various samples measured in December 2009 (blue), and May 2010 (red)

5.4.2. Univariate statistics

Analytical data analyses using the EC zonation, provides insight into the dominant ions occurring in each EC zone, this aids in developing water-rock interaction and groundwater recharge relationships. A univariate statistical overview of the groundwater dataset is presented in Table 5.5. The concentrations of Na^+ (Table 5.6) in groundwater samples in

Zone 1, Zone 2, Zone 3 and Zone 4 are of the order of 49-4219, 600-850, 500-750 and 200-650 mg/l respectively. The highest concentration (4219 mg/l) is observed in sample SDC 43 (ii), an artesian borehole in Zone 1 and lowest (49 mg/l) in sample SDC 47 (iii), also in Zone 1. The concentrations of Cl^- are 1100-4888, 975-1500, 790-1170 and 300-1035 mg/l in Zone 1, Zone 2, Zone 3 and Zone 4 respectively. The highest concentration (4888 mg/l) is observed in sample SDC 43(iii) within Zone 1 and lowest (30 mg/l) in sample SDC 30(iii) within Zone 4. A very interesting hydrochemical observation is that Mg is dominant over Ca, indicating a typical geological control as the saturation indices of all the samples with respect to calcite and other common mineral phases except dolomite are negative.

Table 5.5: Univariate statistical overview of the groundwater data set. All values in mg/l unless otherwise indicated

Variable	N	Mean	Standard Deviation	Minimum	Median	Maximum
pH	62	6.9802	0.6017	5.33	6.805	9.31
EC (mS/m)	62	432.2	445.9	42.4	283.4	2140
Temp (^oC)	62	22.159	2.65	14.77	22.275	30.11
Eh (mV)	60	-5.86	34.5	-134.5	-4.7	86.7
Depth to Water-level (m.bgl)	70	11.59	11.48	0.57	8.21	44.45
Water-level (m)	70	148.62	68.22	45.98	131.87	296.46
Alkalinity	48	162.8	105.9	10	147.3	427
TDS	62	2155	2240	212	1418	10870
Ca^{2+}	44	73.7	86	1.3	50.9	508.6
K^+	44	11.6	8.59	1.4	8.88	35
Na^+	44	777	919	49	449	4219
Mg^{2+}	44	130.6	179.9	8.3	67.6	900.9
Cl^-	44	1218	1233	30	751	4888
F^-	37	0.6323	0.4798	0.037	0.479	1.77
NO_3^-+NO_2^- as N	32	5.76	6.31	0.04	4.2	24.4
SO_4^{2-}	44	182.7	180.6	10.3	111	888
HCO_3^-	48	198.6	129.1	12.2	179.6	520.7
$\delta^{18}O$ (‰)	52	-3.7192	0.364	-4.51	-3.735	-2.98
δ^2H (‰)	52	-15.523	2.1	-18.8	-15.66	-10.5
D-excess (‰)	52	14.231	2.39	8.5	13.805	20.68
Tritium (TU)	34	0.3706	0.3656	0.1	0.1	1.3

Table 5.6: Ion concentration in the various EC zones

Ion Concentration (mg/l)	Zone 1	Zone 2	Zone 3	Zone 4
Na^+	800-4218	600-850	500-750	200-650
Mg^{2+}	8-900	72-124	60-115	55-90
Ca^{2+}	1-509	45-92	40-74	40-60
K^+	4-23	2-35	5-17	1-13
Cl^-	1100-4888	975-1500	790-1170	30-1035
HCO_3^-	180-520	160-274	12-230	135-180
SO_4^{2-}	116-888	121-254	108-187	10-166
F^-	0.25-1.19	0.20-1.77	0.04-1.15	0.11-0.62
$NO_2^- + NO_3^-$ as N	0.04-6.00	2.40-24.40	3.18-10.00	1.32-5.77

5.4.3. Correlation between EC and analytical data

In order to study the relationships between the different parameters, a Pearson's correlation matrix of 18 variables were generated (Table 5.7). Pearson correlation "r" assumes that the two variables are measured on at least interval scales, and it determines the extent to which values of the two variables are "proportional" to each other (Statsoft, 2012). Proportional means linearly related; that is, the correlation is high if it can be "summarized" by a straight line (sloped upwards or downwards). The Pearson correlation matrix allows us to distinguish several relevant hydrochemical relationships. The contents of calcium, sodium, chloride, magnesium, sulphate, potassium, and bicarbonate are positively correlated to EC with correlation coefficients of 0.797, 0.982, 0.969, 0.944, 0.692, 0.613, and 0.681 respectively. It was found that a strong correlation exists between $Ca^{2+,}$ Na^+, Cl^- and Mg^{2+} and it can also be deduced that for most of the groundwater samples these parameters originate from a common source. These relationships clearly identify the main elements contributing to the groundwater salinity and their tendency to follow a similar trend (e.g. due to concentration by evaporation). The salinization of the groundwater would be expected to result from the ionic concentrations increasing due to both evaporation of recharge water and to the effects of interactions between the groundwater and the geological formations.

Table 5.7: Pearson's correlation matrices for groundwater data. All values in mg/l unless otherwise indicated DWL=Depth to water-level

	pH	*EC*	*Temp*	*DWL*	*TDS*	*Ca^{2+}*	*K^{+}*	*Na^{+}*	*Mg^{2+}*	*Cl^{-}*	*F^{-}*	*$NO_3^-+NO_2^-$ as N*	*SO_4^{2-}*	*HCO_3^-*	*$\delta^{18}O$*	*$\delta^{2}H$*	*D-excess*	*Tritium*
pH	1																	
EC[a]	-0.072	1																
Temp[b]	0.030	-0.013	1															
DWL[c]	-0.351	-0.294	-0.017	1														
TDS	-0.071	1.000	-0.010	-0.295	1													
Ca^{2+}	-0.035	0.797	0.068	-0.353	0.796	1												
K^{+}	-0.045	0.613	-0.116	0.091	0.606	0.269	1											
Na^{+}	-0.033	0.982	0.005	-0.432	0.984	0.696	0.641	1										
Mg^{2+}	-0.095	0.944	0.088	-0.345	0.944	0.923	0.456	0.895	1									
Cl^{-}	-0.046	0.969	-0.052	-0.453	0.969	0.732	0.656	0.961	0.892	1								
F-	0.219	0.190	-0.104	0.116	0.189	-0.105	0.373	0.284	0.032	0.221	1							
$NO_3^-+NO_2^-$ as N	-0.329	-0.037	-0.145	0.206	-0.038	-0.202	0.459	0.024	-0.132	0.093	0.262	1						
SO_4^{2-}	0.011	0.692	-0.076	-0.294	0.689	0.798	0.442	0.640	0.761	0.688	0.267	0.130	1					
HCO_3^-	0.222	0.681	0.139	-0.387	0.685	0.562	0.281	0.681	0.599	0.603	0.242	-0.172	0.524	1				
$\delta^{18}O$[d]	-0.146	0.346	-0.164	-0.197	0.344	0.333	0.046	0.366	0.409	0.430	-0.169	0.072	0.221	0.150	1			
$\delta^{2}H$[d]	-0.036	0.072	-0.406	-0.173	0.072	0.247	-0.159	0.083	0.210	0.117	-0.281	-0.185	0.124	-0.129	0.587	1		
D-excess[d]	0.147	-0.358	-0.157	0.080	-0.356	-0.214	-0.210	-0.412	-0.350	-0.466	-0.028	-0.255	-0.179	-0.290	-0.703	0.163	1	
Tritium[e]	-0.070	-0.213	0.101	0.005	-0.213	-0.049	-0.307	-0.241	-0.140	-0.226	-0.229	0.072	0.076	0.021	0.253	0.162	-0.208	1

a in m*S*/m

b in ^{o}C

c in m

d in ‰

e in TU

5.4.4. Chemical characteristics of groundwater

Groundwater TDS within the catchment ranges from fresh to salty water. Groundwater temperatures vary from 14.77 to 30.11 ^{o}C with higher temperatures associated with the summer i.e. December 2009 water sampling. The fluctuation in pH, which is between 5.33-9.31 with a mean of 6.98 shows that the groundwater's are generally slightly acidic to slightly alkaline, an indication that the dissolved carbonates are predominantly in the HCO_3^- form. The spatial variation of EC and TDS follows a similar pattern of being low at recharge areas and progressively increases down gradient towards the Berg River in the direction of groundwater flow.

The total hardness of the groundwater ranges for May 2009 is 129.22-886.76 mg/l as $CaCO_3$ in Zone 2 and 251.29-373.92 mg/l as $CaCO_3$ in Zone 3. Range of total hardness for December 2009 is 124-29-3313.41 mg/l as $CaCO_3$ in Zone 1, 327.54-1268.47 mg/l as $CaCO_3$ in Zone 2, 73.95-337.95 mg/l as $CaCO_3$ in Zone 3. The total hardness for May 2010 in Zones 1, 2, 3, and 4 were 37.13-4974.63 mg/l as $CaCO_3$, 314.21-1188.38 mg/l as $CaCO_3$, 79.75-290.11 mg/l as $CaCO_3$ and 192.95-535.93 mg/l as $CaCO_3$ respectively. The total hardness measurements can thus be classified into soft to very hard based on the criteria given by Durfer and Becker (1964). Most of the groundwater are classified as "very hard", with sample SDC 47(iii) being "soft", SDC 62(ii), SDC 56 (iii), SDC 57(iii), SDC 62(iii) and 96183 being "moderately hard", and samples SDC 10(i), SDC 56(ii), SDC 57(ii) and 96160 being "hard".

Hydrochemical characteristics of groundwater are evaluated by Durov (Durov, 1948), Piper Trilinear Diagram (Piper, 1944) Schoeller (Schoeller, 1964), Wilcox (Wilcox, 1955) and Facies Mapping Approach (Back, 1961), which shows the chemical distribution of groundwater based on data collected in May 2009, December 2009, May 2010, and from DWA NGA. Hydrochemical facies are distinct zones that have cation and anion concentrations describable within defined composition categories. Piper diagram (Piper, 1944) which allowed classification of the groundwaters, according to Langguth (1966), into the following types:

- First type: alkaline water with bicarbonate as the dominant ion,
- Second type: alkaline water with bicarbonate and chloride as the dominant ions,
- Third type: alkaline water with an increased proportion of alkali earths and chloride ions,
- Fourth type: alkaline water with chloride as the dominant ion.

The first two water types correspond to fresh groundwater, which originates as contemporary recharge and sometimes as fresh water that percolates over short distances within the aquifer, or they represent unpolluted water (Rimawi, 1992). The third and fourth types correspond to fresh-brackish water of non-contemporary or almost old recharge (Salameh & Rimawi, 1984), which ascends from deep aquifers along major faults, or originates through fresh water mixing with saline water that passes through evaporites (Rimawi & Udluft, 1985). It is evident that from the hydrochemical plots (Figures 5.16, 5.17, 5.18, and 5.19) and water-types (Figure 5.21), that Na^+ represents the dominant cation, whilst Cl^- the dominant anion. Water-types from all three sampling regimes and the DWA's data are listed in Appendix K. From Figure 5.17a&b, Na^+ again represents the dominant cation and Cl^- the dominant anion. The water-types do not display any pattern to catchment zonation, however there is an increasing concentration in Na^+ from Zone 1 and Zone 2, with the slightly acidic groundwater in sample SDC 62 (ii) in Zone 3 also has a high Na concentration. From Figure 5.18a&b during the May 2010 sampling, Na^+ remains the dominant cation and Cl^- the dominant anion, however in samples SDC 30 (iii), and SDC 72 (iii), the dominant anion is HCO_3^- and SO_4^{2-} respectively. Groundwater hydrochemical evolution from Na-Mg-HCO_3 and Na-Ca-Mg-SO_4 type groundwater (upstream samples) (Figure 5.21b) to a Na-Cl type groundwater in the middle and lower reaches of the catchment is occurring. Surface water hydrochemical analysis in Figures 5.20a&b reflected Na^+ as the dominant cation, and Cl^- the dominant anion. The surface-water chemical character is that of a dilute groundwater, and the surface water pH is slightly greater than the groundwater.

5.4.5. Groundwater salinity and alkali hazard

The Wilcox diagram (Figure 5.16d, 5.17d, and 5.18d) widely used for evaluating waters for irrigation, the diagram is divided into 16 areas that are used to rate the degree to which a particular water may give rise to salinity problems and undesirable ion-exchange effects in soil (Hem, 1985). Based on the Wilcox diagrams, the salinity hazard for the percentage groundwater samples for May 2009 is classified as very high (100%), with a high (75%) and very high (25%) alkali hazard. The salinity hazard for December 2009 is very high (76.5%) and high (23.5%), with a low (10%), medium (30%), high (40%) and a very high (20%) alkali hazard. According to Khodapanah *et al*., (2009), groundwater that falls in the medium salinity hazard class (C2) can be used in most cases without any special practices for salinity control. However, water samples fall in the high salinity hazard class (C3) may detrimental effects on sensitive crops and adverse effects on many plants. Such areas require careful management practices. Very high salinity water (C4) is not suitable for irrigation under ordinary conditions but may be used for salt tolerant plants on permeable soils with special management practices.

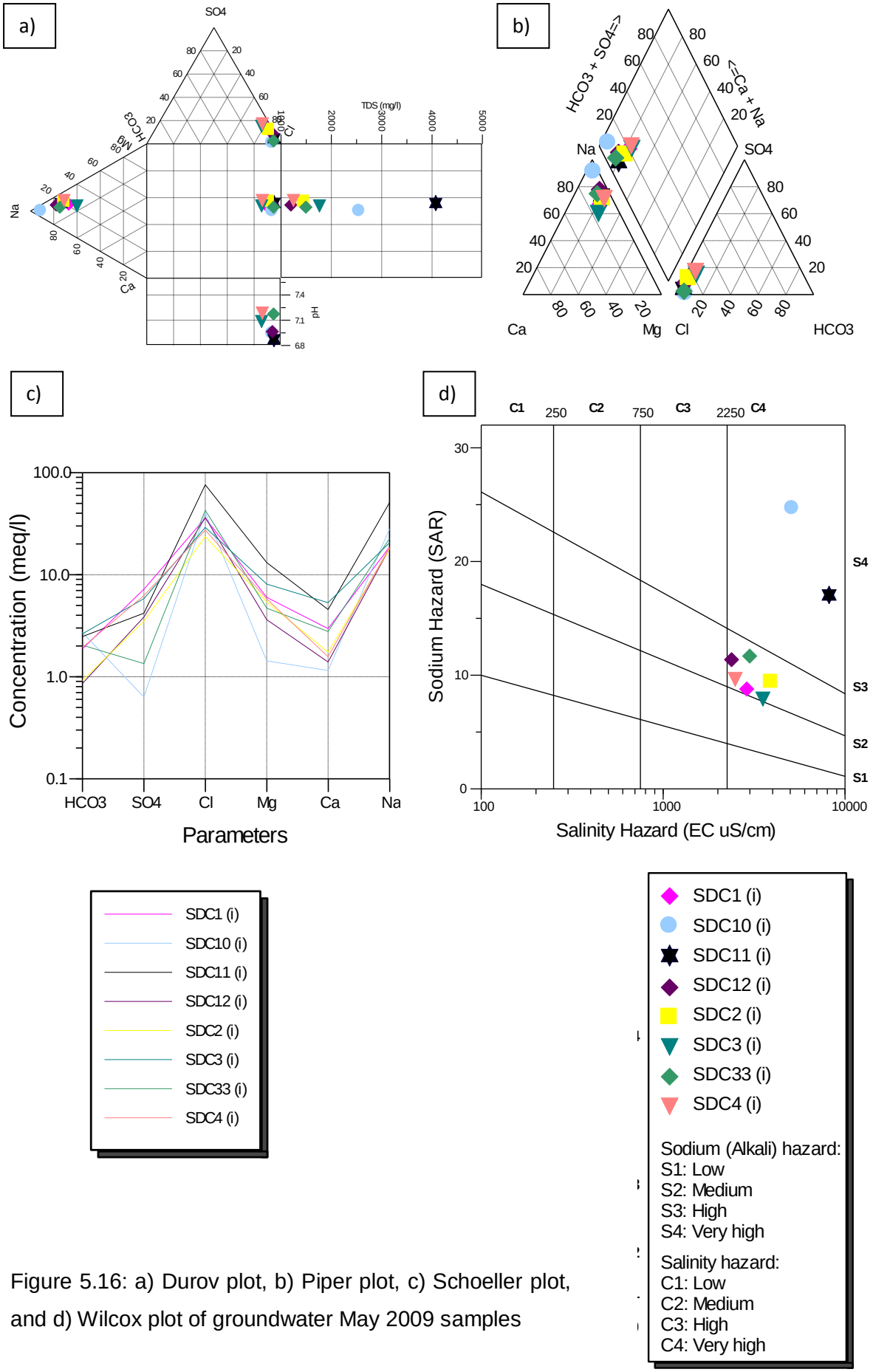


Figure 5.16: a) Durov plot, b) Piper plot, c) Schoeller plot, and d) Wilcox plot of groundwater May 2009 samples

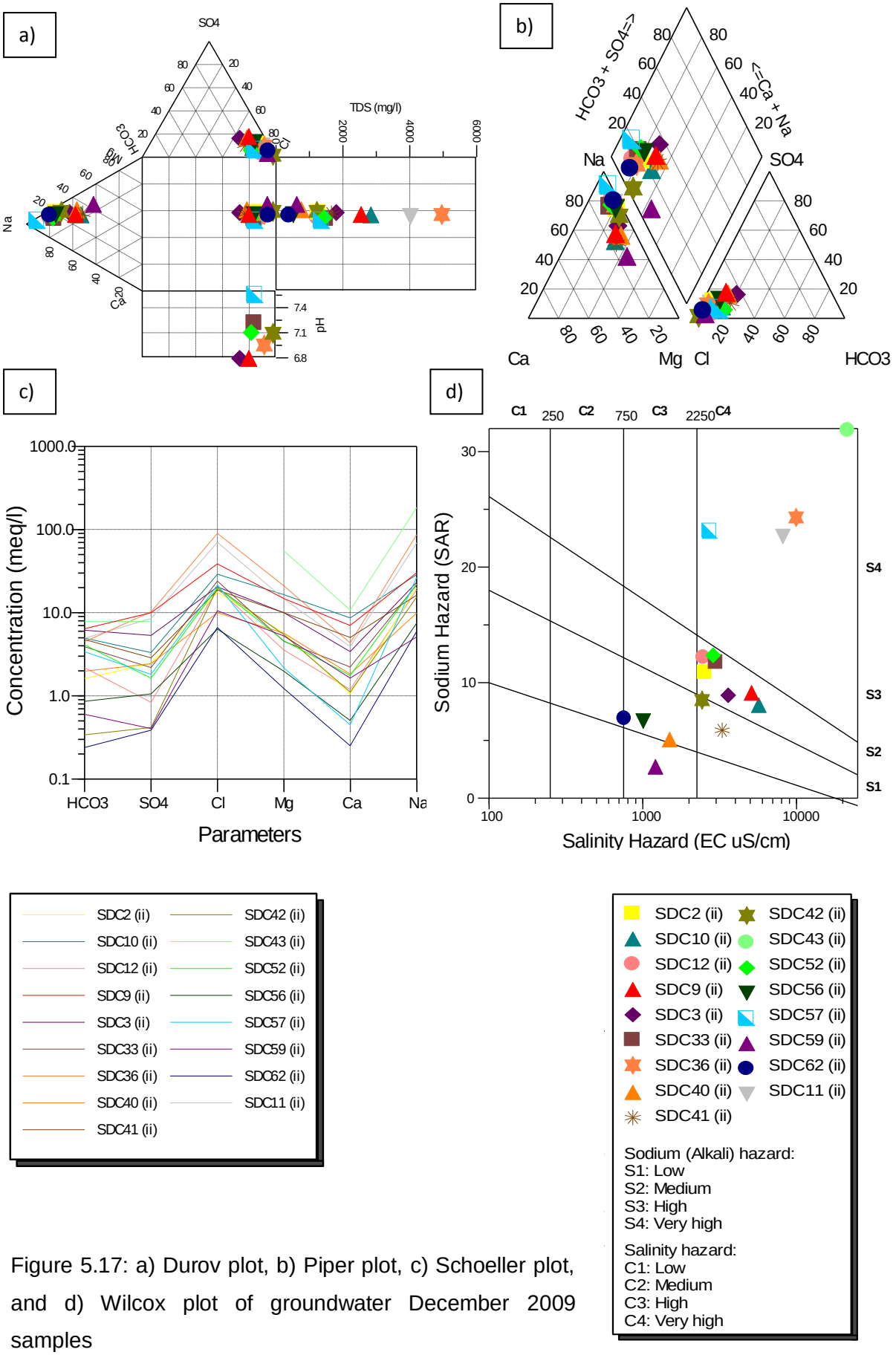


Figure 5.17: a) Durov plot, b) Piper plot, c) Schoeller plot, and d) Wilcox plot of groundwater December 2009 samples

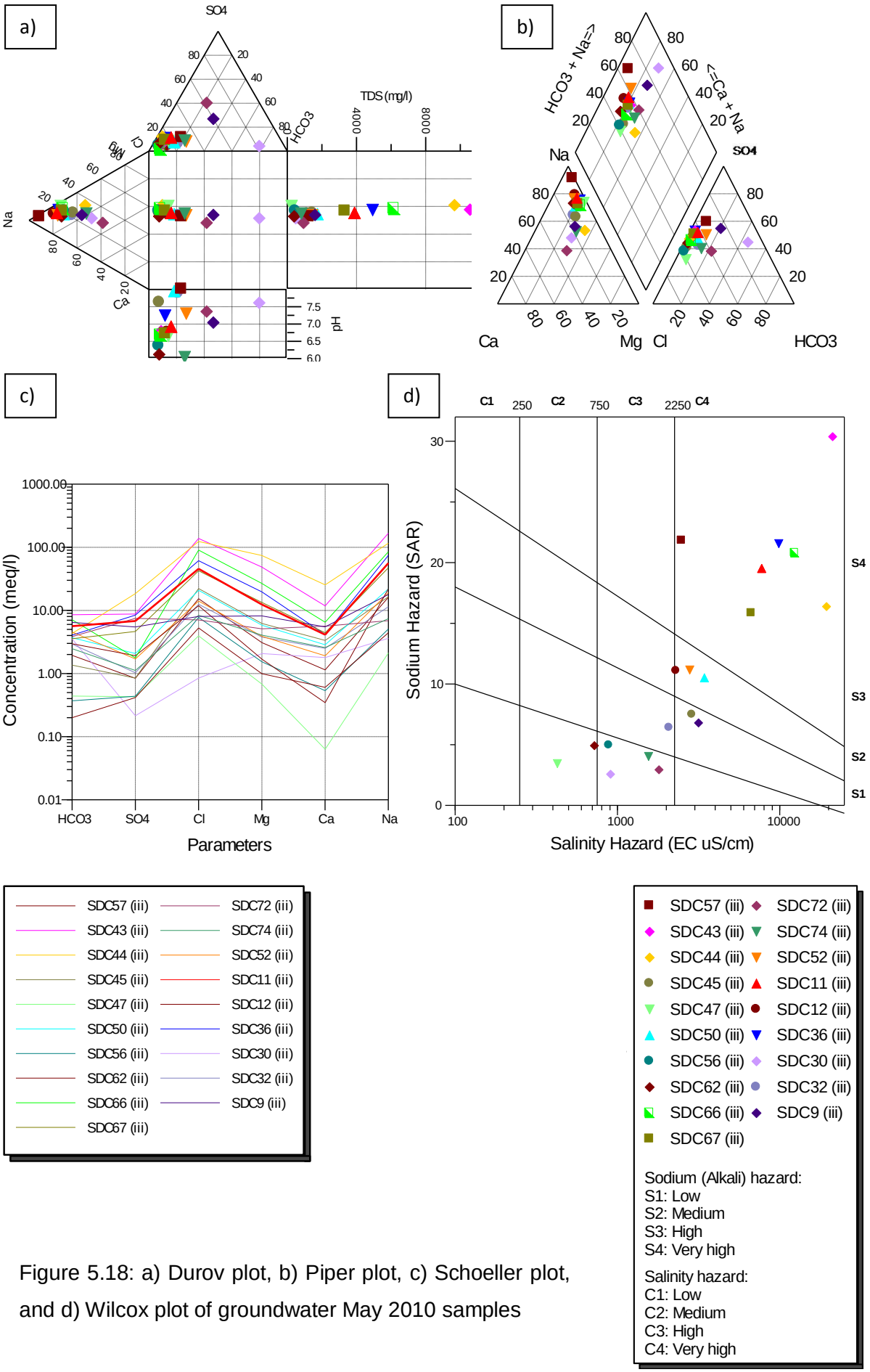


Figure 5.18: a) Durov plot, b) Piper plot, c) Schoeller plot, and d) Wilcox plot of groundwater May 2010 samples

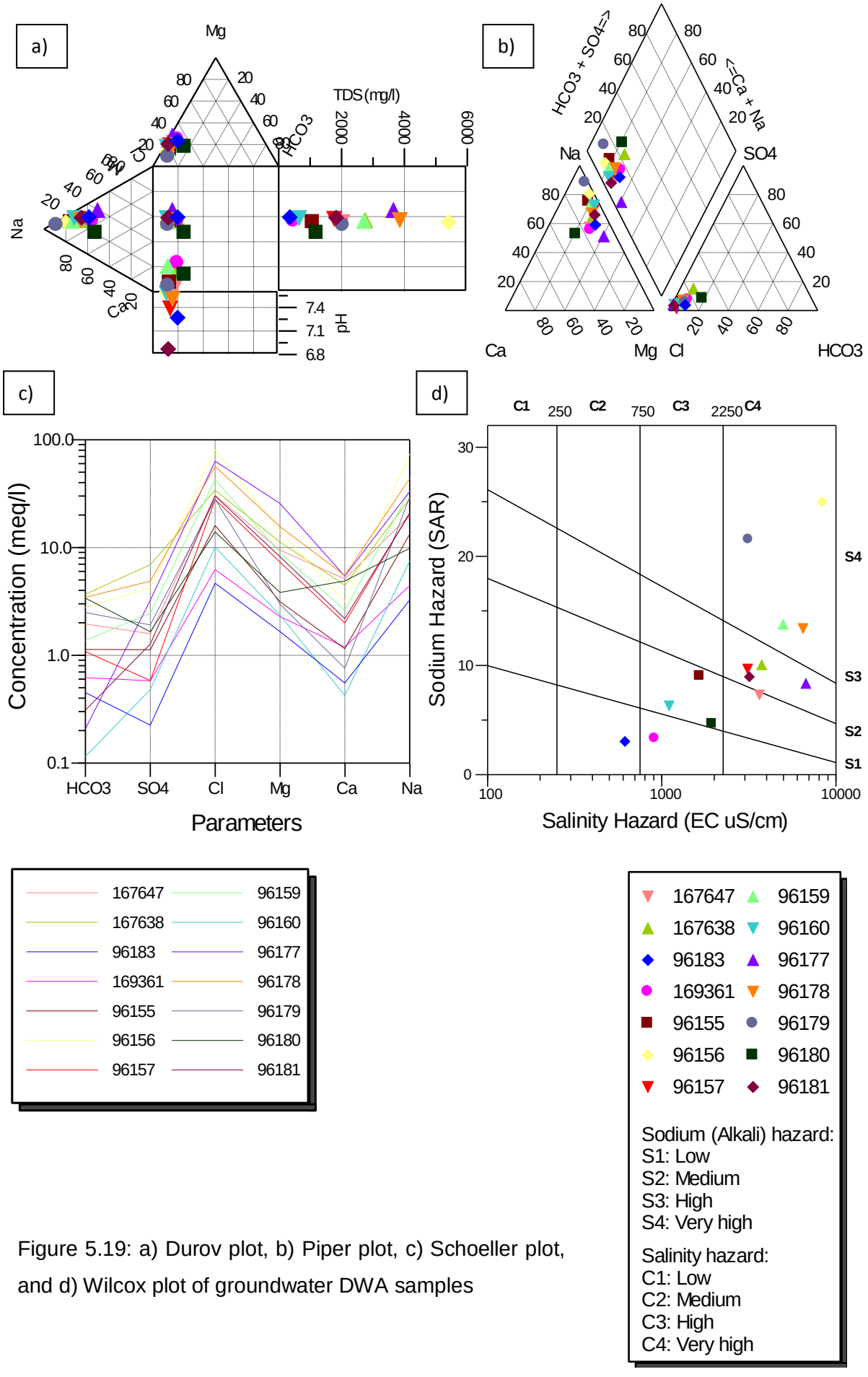


Figure 5.19: a) Durov plot, b) Piper plot, c) Schoeller plot, and d) Wilcox plot of groundwater DWA samples

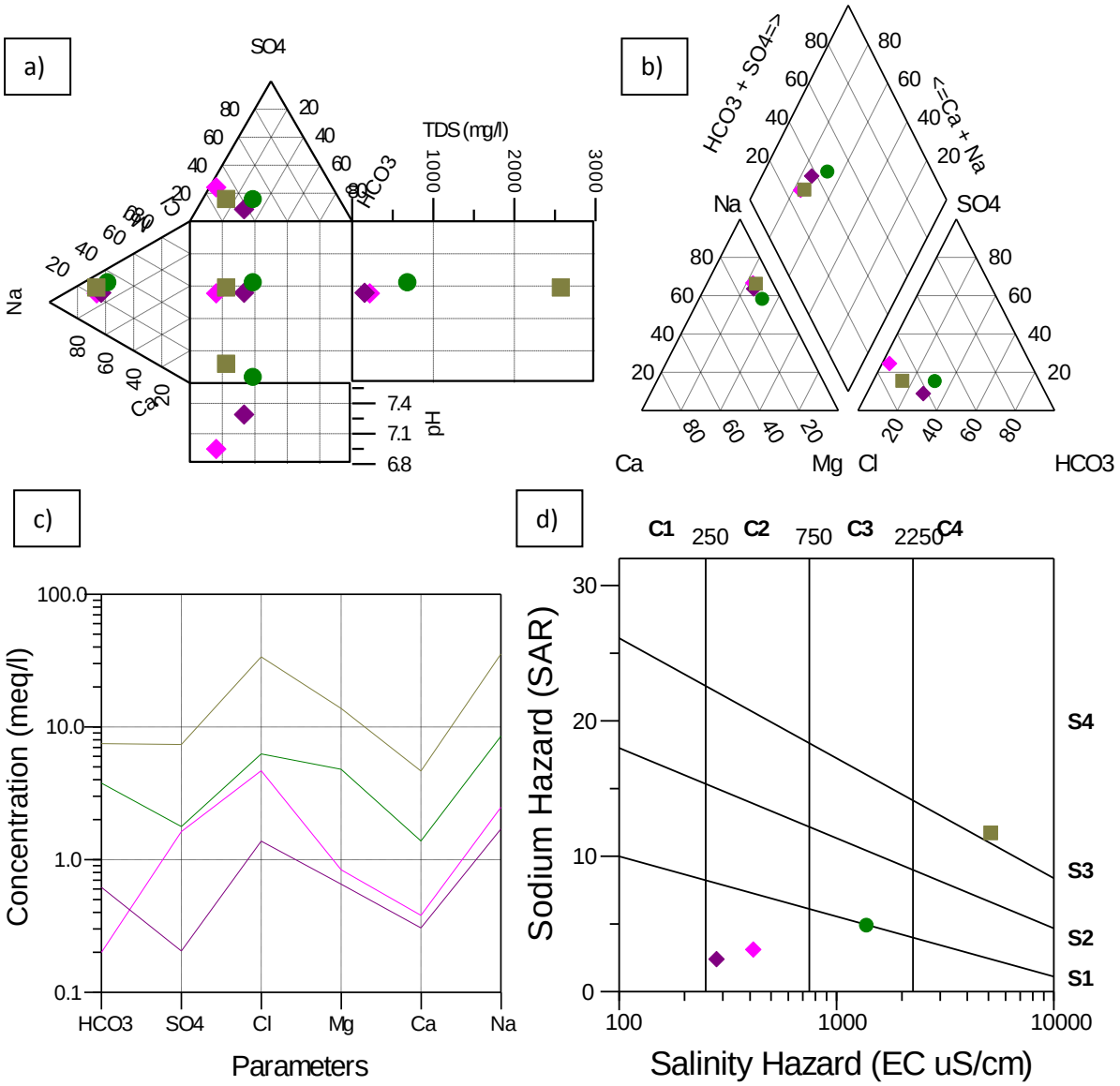


Figure 5.20: a) Durov plot, b) Piper plot, c) Schoeller plot, and d) Wilcox plot of surface water samples

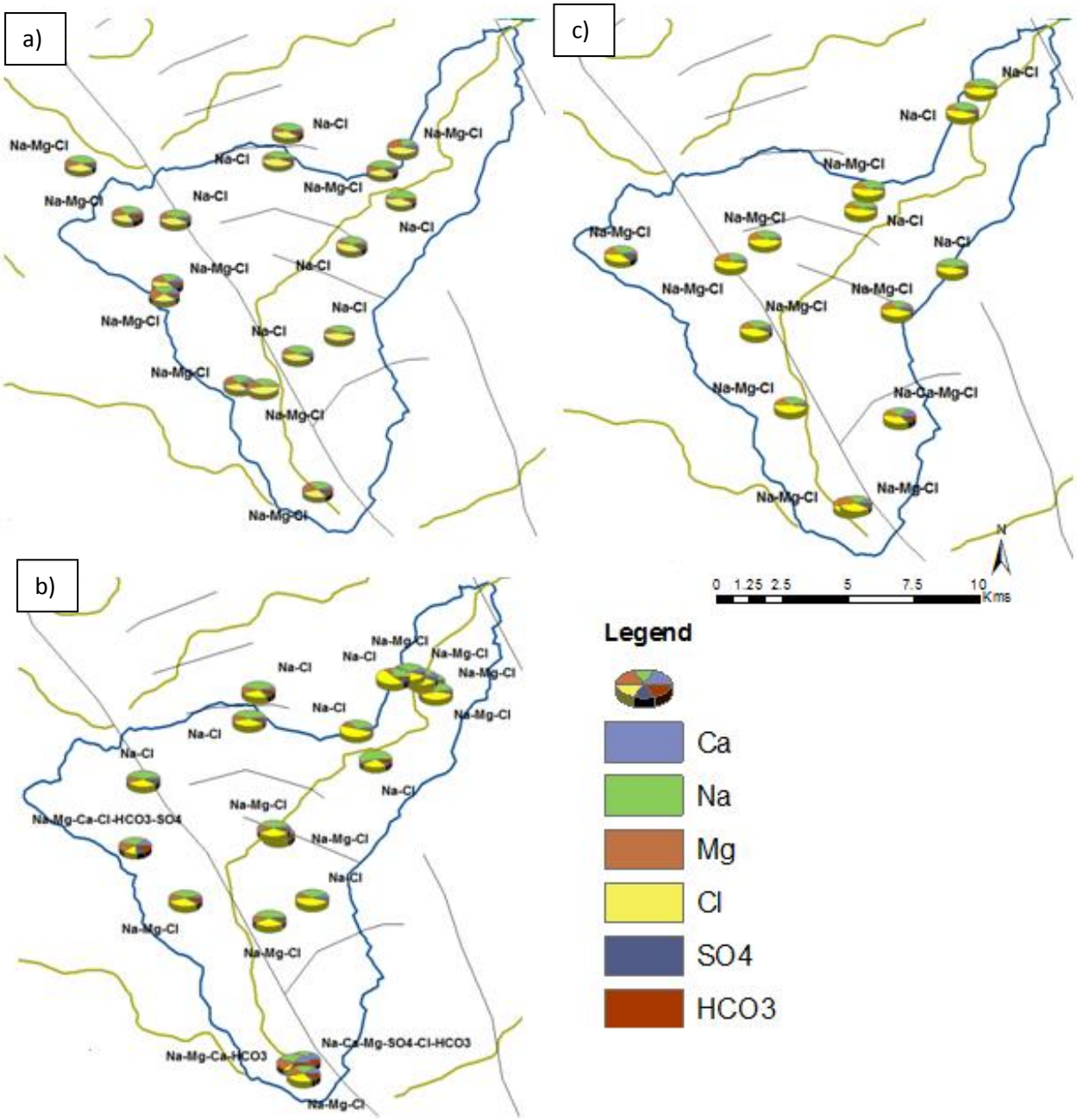


Figure 5.21: a) Water-types for December 2009, b) Water-types for May 2010, and c) Water-types for DWA samples

5.4.6. Quality of chemical data

It is an essential step, before any manipulation of chemical data, to ascertain data quality. The reliability of chemical data can be checked by computation of ionic charge balance error (Mandel and Shiftan, 1981, and Lloyd and Heathcote, 1985). If the reaction error of a chemical data-set is more than 5% it makes the quality of analysis questionable. In the present study, the reaction error criteria were applied to chemical analyses of each data-set. Reaction errors are shown in Appendix K.

5.4.7. Interpretation of host rock from groundwater composition data and water rock interaction

The groundwater chemistry data can be used to gain insight into the possible source of ions in water. Rainfall or diluted seawater, along its flow path is altered by rock weathering, evaporation and aeration (Gibbs, 1970). During rock weathering Ca^{+}, Mg^{2+}, SO_4^{2-}, HCO_3^{-} and SiO_2 are added to the water depending on the rock mineralogy (Hounslow, 1995). Typically, natural salinity in groundwater increases with depth below land surface as chemical reactions with aquifer material, resident time, and mixing of different waters increase. Groundwater in discharge areas typically is of lower quality than groundwater in recharge ares because of water-rock interaction and possible mixing with saline water along the flow path (Richter and Kretler, 1993).

The trend between Ca-rich and Na+K-rich groundwater is generally ascribed to base exchange whereby calcium in solution is exchanged for sodium on clay minerals (Earle and Krogh, 2004). As discussed in section 2.3.3.2 by Hem, (1985), sodium is retained by adsorption on mineral surfaces, especially by minerals having high cation-exchange capacities such as clays. Sodium in groundwater is derived mainly from the decomposition of feldspars and from sodium salts. Sodium is therefore present within the sericite schists in the form of orthoclase in rock specimen L2, and orthoclase and anorthite in rock specimen L3 (Appendix B) within the study area. The silicate minerals that comprise the rocks present in the local geology do not react readily with the groundwaters, SiO_2 cotent in all rock specimens are greater than 50%, with specimens L1, L4, and L5 greater than 90% (Appendix C). Specimens L2, and L3 have a Al_2O_3 greater content than the quart schist and chert samples, this is attributed to the increased amount of hydrolyzate phyllosilicate weathering products displayed in Plates 5.3, 5.4, 5.5, and 5.6.

In many cases the source rock minerals may be deduced from the water composition referred to as source rock deduction. Systematic source rock derivation generally follows

seven sequential steps (Hounslow, 1995). The determination of probable source rock is sequential step procedure and the results of the analyses are given in Appendix M.

The probable source rock analysis and interpretation of groundwater chemical data in the present study help to arrive at the following conclusions:

- The calculated values of the ratio of $(Na^{+}+K^{+}-Cl^{-})/(Na^{+}+K^{+}-Cl^{-}+Ca^{2+})$ is from -17.04-6.94. In most samples, plagioclase weathering is unlikely. Samples SDC 2(ii), SDC 3(ii), SDC 52(ii), SDC 56(ii), SDC 43(iii), SDC 67(iii), SDC 12(iii), SDC 52(iii), SDC 36(iii), SDC 30(iii), SDC 50(iii), SDC 9(iii), and SDC 11(iii) indicate that plagioclase weathering is possible.
- The calculated values of the ratio of $Na^{+}/(Na^{+}+Cl^{-})$ indicate reverse softening (brine sea water), as well as halite solution, and sodium source other than halite - albite, ion exchange.
- The calculated values of the ratio of $Mg^{2+}/(Ca^{2+}+Mg^{2+})$ are all >0.5 indicating dolomite dissolution, calcite precipitation or seawater.
- The calculated TDS values mostly indicate carbonate weathering or brine or seawater as the values are >500 mg/l, samples SDC 47(iii), SDC 62(iii), SDC 62(ii), SDC 56(iii), SDC 30(iii), and SDC 56(ii) indicate silicate weathering as the values are <500 mg/l.
- The values of the ratio of Cl^{-} and sum of anions are 0.18-0.96 indicating rock weathering and seawater or brine or evaporites are a possibility.
- The calculated values of the ratio of HCO_3^{-} and sum of anions are all <0.8, which indicate seawater or brine.

It is clear from the rock source deduction that the groundwater represents a brine type water, with a few instances of rock (plagioclase) weathering. Gibbs (1970) demonstrated that if TDS is plotted against Na/(Na + Ca), this would provide information on the mechanism controlling chemistry of waters. Figure 5.22 displays that groundwater samples were plotted mostly in the evaporation zone, which most likely suggests that evaporation is a dominant factor controlling the shallow groundwater chemistry in the study region.

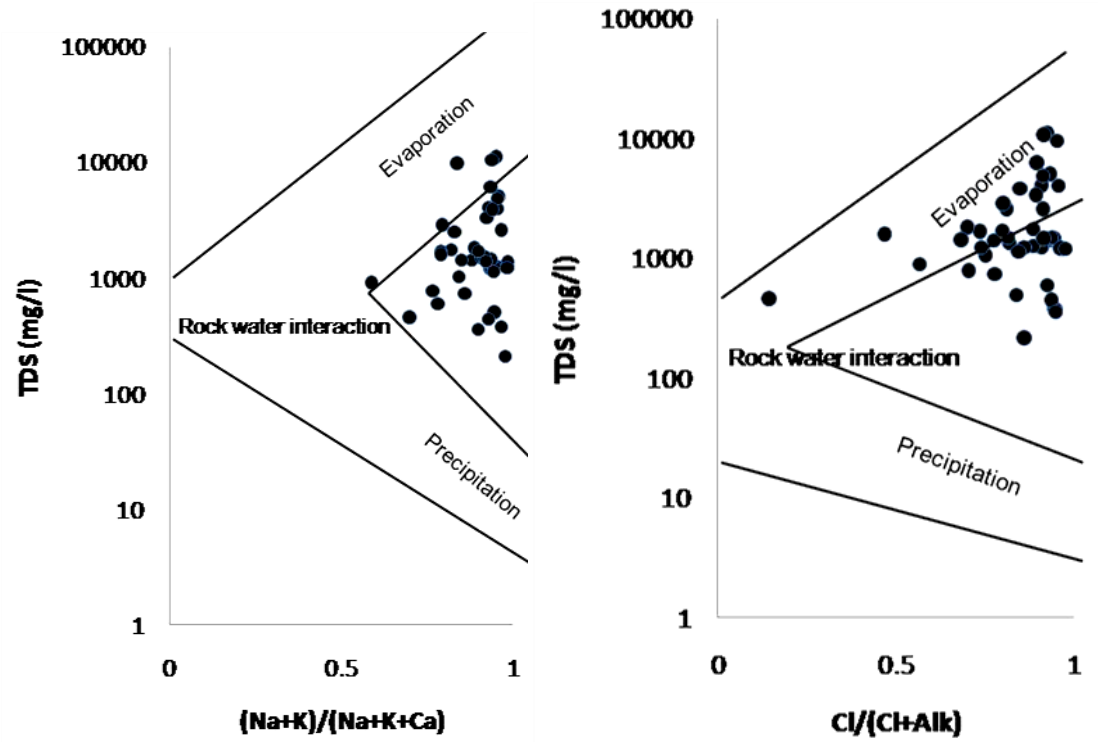


Figure 5.22: Mechanism controlling groundwater chemistry – Gibbs plot

5.4.8. Factor analysis

Factor analysis is a statistical tool which has proven to be useful in the interpretation of geohydrological data by several previous researchers (Schot and Van der Wal, 1992; Usunoff and Guzman-Guzman, 1989; Ashley and Lloyd, 1978; Dawdy and Feth, 1967). The technique involves determining the number of factors through plotting the extracted factors against their eigenvalues in descending order of magnitude to identify distinct breaks in the slope of the plot. This method, called the scree plot (Figure 5.23), was first offered by Cattell (1966) as a way to identify distinct breaks between the steep slope of the larger eigenvalues and the trailing of the smaller ones. To determine where the break occurs, a straight line is drawn through the lower values of the plotted eigenvalues (Figure 5.23). Using the Cattell (1966) criteria for this output, only five factors remain above the line that accounts for the maximum amount of variance in the eighteen items. The environmental isotope data was included in the factor analysis to reveal any underlying relationship with groundwater salinity.

Five factors account for 89.4% of the variance in the data set (Table 5.8). Factor 1 is interpreted as relating mainly to the salinization of the groundwater due to both evaporation and dissolution processes. The main contributors to the groundwater TDS and salinity are Cl, Na, Mg, Ca and SO_4. Though limited in extent, irrigation contributes to salt concentration and accumulation via the evapotranspiration process. Factor 2 indicates the positive correlation of δ^2H and $\delta^{18}O$, and the evaporative signature associated with the stable

isotopes. Factor 3, provides the negative correlation between Eh and pH. Factor 4 a correlation between minor concentrations of F, NO_3 and K, may be from a biochemical pollutant source. Factor 5 is possibly the result of minor water–rock interactions in the subsurface.

Table 5.8: Results of principal component factor analysis with Varimax rotation. All values in mg/l unless otherwise indicated

Variable	Communality	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
pH	0.941	-0.006	-0.017	-0.957	-0.113	0.113
EC (mS/m)	0.982	0.942	0.148	0.087	0.207	0.151
TDS	0.982	0.942	0.148	0.087	0.205	0.152
Eh (mV)	0.858	0.033	0.034	0.917	-0.021	0.12
Ca^{2+}	0.943	0.959	0.011	-0.039	-0.094	-0.115
K^{+}	0.802	0.507	-0.117	0.144	0.684	0.204
Na^{+}	0.974	0.923	0.144	0.106	0.255	0.16
Mg^{2+}	0.971	0.957	0.151	0.126	0.088	0.086
Cl^{-}	0.938	0.886	0.219	0.119	0.286	0.101
F^{-}	0.662	0.298	-0.114	-0.33	0.668	0.071
NO_3^{-}+NO_2^{-} as N	0.874	-0.143	0.025	0.443	0.784	-0.206
SO_4^{2-}	0.923	0.651	-0.24	-0.085	0.39	-0.531
HCO_3^{-}	0.865	0.909	-0.055	-0.177	-0.001	-0.064
$\delta^{18}O$ (‰)	0.989	0.179	0.969	0.082	-0.042	-0.097
$\delta^{2}H$ (‰)	0.788	-0.109	0.79	-0.268	-0.219	-0.181
D-excess (‰)	0.849	-0.353	-0.771	-0.341	-0.119	-0.007
Tritium (TU)	0.873	-0.168	0.304	0.033	-0.062	-0.864
Explained variance		7.8868	2.4771	2.4054	2.0107	1.298
Cumulative % of variance		43.8	57.6	71	82.2	89.4

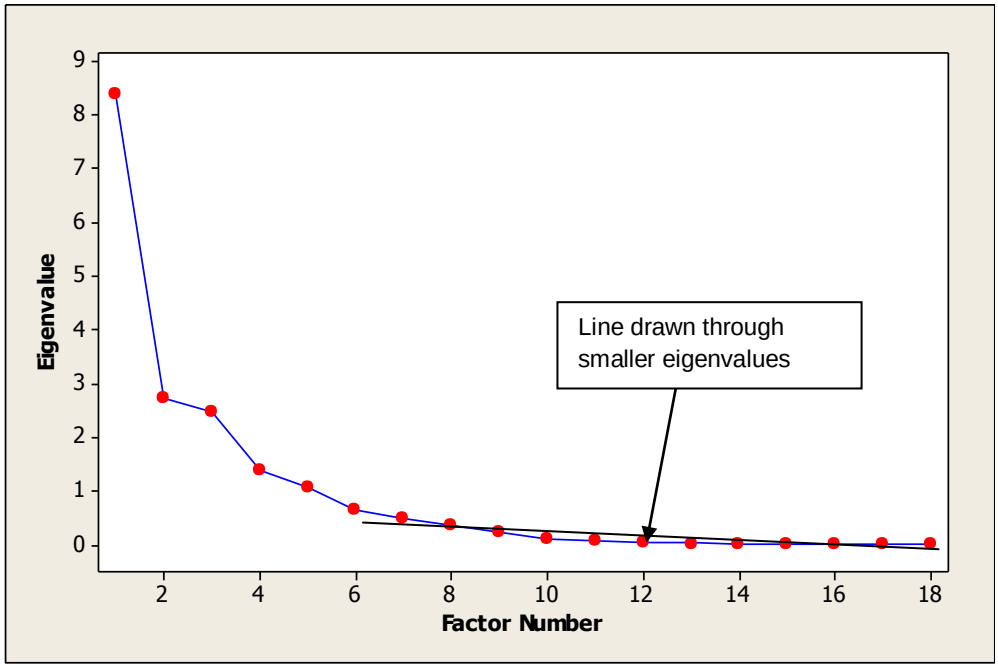


Figure 5.23: Scree plot of factor analysis variables

The score plot (Figure 5.24) graph was done to display the second factor scores versus the first factor scores. The plot of the factors provides checks on the assumption of normality and reveals outliers (Cattell, 1966). If the data are normal and no outliers are present, the score plot shows the points randomly distributed around zero. When the first two factors account for 57.6% of the variance, factor scores at the bottom right of Figure 5.24 fall within Zone 2, the rest of the factor scores are grouped according to similar attributes, as it was indicated by the EC.

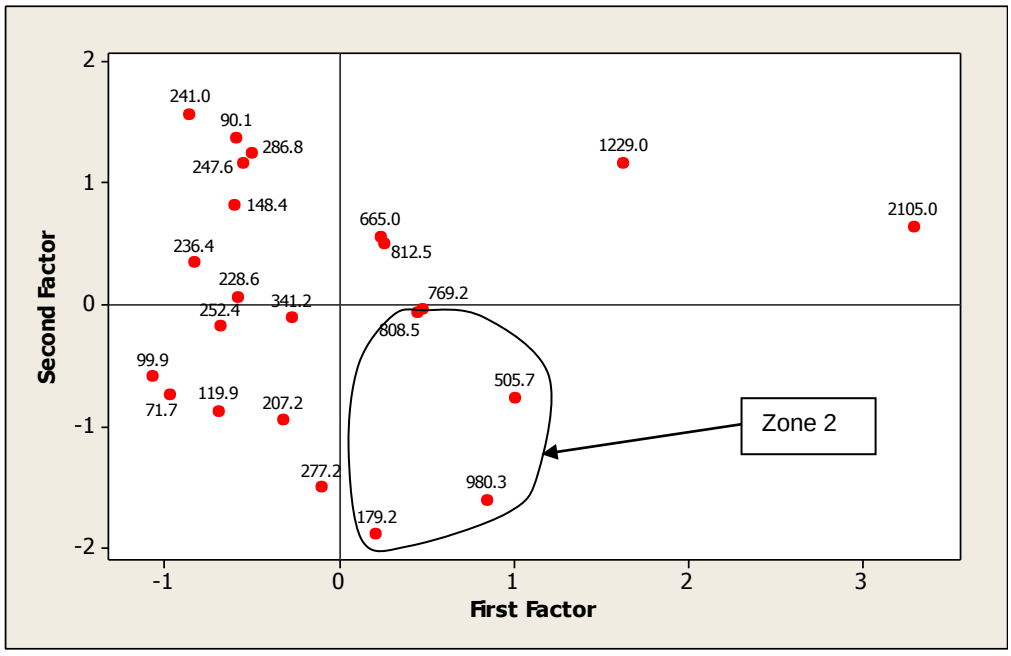


Figure 5.24: Score plot of factor analysis variables displaying EC values

5.4.9. Environmental isotope

5.4.9.1. Stable isotope composition of groundwaters

In temperate climates, the isotopic composition of δ^2H and $\delta^{18}O$ in shallow groundwaters is generally close to the mean-weighted annual isotopic composition of local precipitation (Clark and Fritz, 1997; Gat, 1996). Gunyakti *et al*., (1993) indicated that when only a portion of the annual rainfall recharges groundwater, the isotopic composition of groundwater may not be similar to the mean isotopic composition of precipitation. For ancient waters recharged in the late Quaternary, the isotopic composition of δ^2H and $\delta^{18}O$ in groundwaters may be conserved in deep aquifers (Gat, 1996). In semi-arid environments, the isotopic composition of δ^2H and $\delta^{18}O$ in shallow groundwaters can be significantly modified more from that of local precipitation, as a result of evaporative isotopic enrichment during infiltration (Clark and Fritz, 1997). Figure 5.25 represents GNIP (Global Networks in Precipitation) stations in Southern Africa, and their relationship with each other along the GMWL (Global Meteoric Water-Line). Annual δ^2H and $\delta^{18}O$ trends in precipitation are presented in Appendix N.

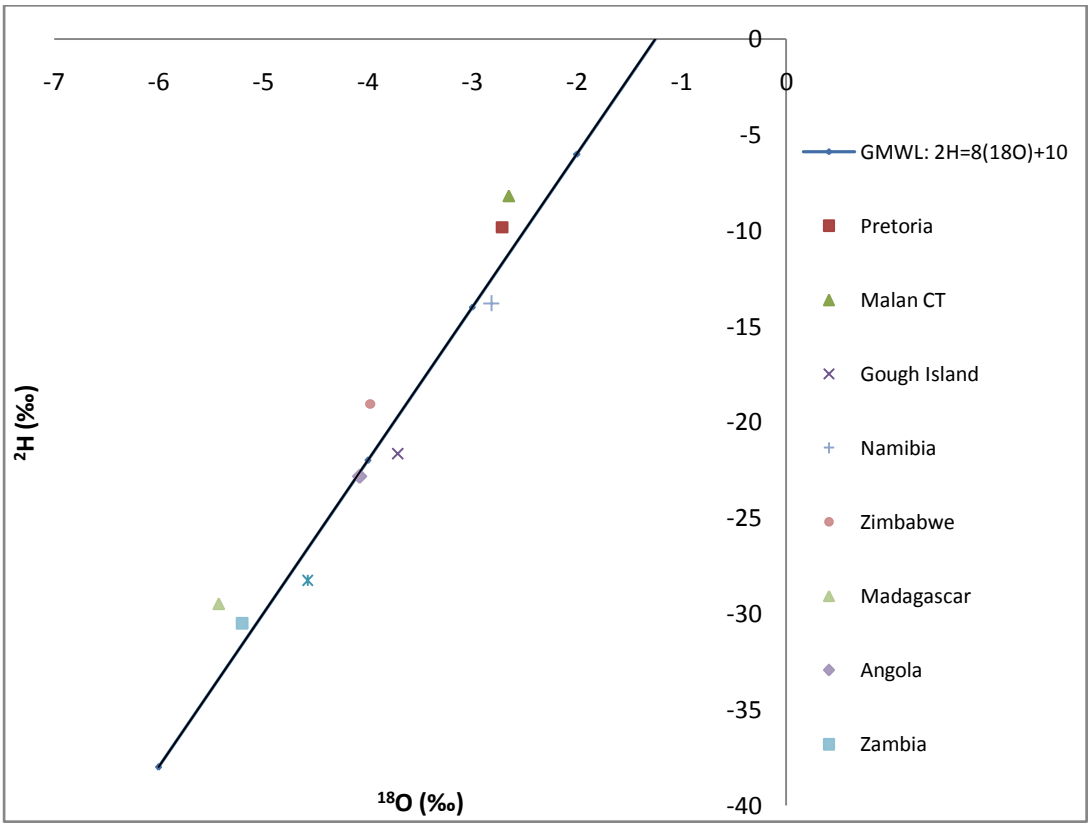


Figure 5.25: GNIP (Global Network for Isotope in Precipitation) stations for Southern Africa along with GMWL (Global Meteoric Water-line) (IAEA, 2011)

The $\delta^{2}H$ and $\delta^{18}O$ signals in groundwater samples collected in the Sandspruit catchment between May 2009 and May 2010 are presented in Appendix O. Basic statistics revealing the seasonal variation of the various isotopes are presented in Table 5.9. The data exhibited a clear seasonality (temperature) effect, with more depleted values occurring in the winter (May-July) (Figure 5.26b) and more enriched values occurring in the summer/early fall (November-March) (Figure 5.26a).

Table 5.9: Basic environmental isotope statistics

		May 2009	**December 2009**	**May 2010**
$\delta^{18}O$‰	Maximum	-3.17	-3.1	-2.98
	Minimum	-3.82	-4.13	-4.35
	Mean	-3.59	-3.74	-3.72
$\delta^{2}H$‰	Maximum	-12.5	-13.2	-11.47
	Minimum	-16.09	-18.8	-18.49
	Mean	-14.91	-17.04	-14.70
D-Excess	Maximum	15.47	14.36	18.21
	Minimum	12.86	10.84	8.50
	Mean	13.83	12.89	15.09
Tritium (TU)	Maximum	1.10	1.30	0.50
	Minimum	0.00	0.00	0.00
	Mean	0.32	0.46	0.17

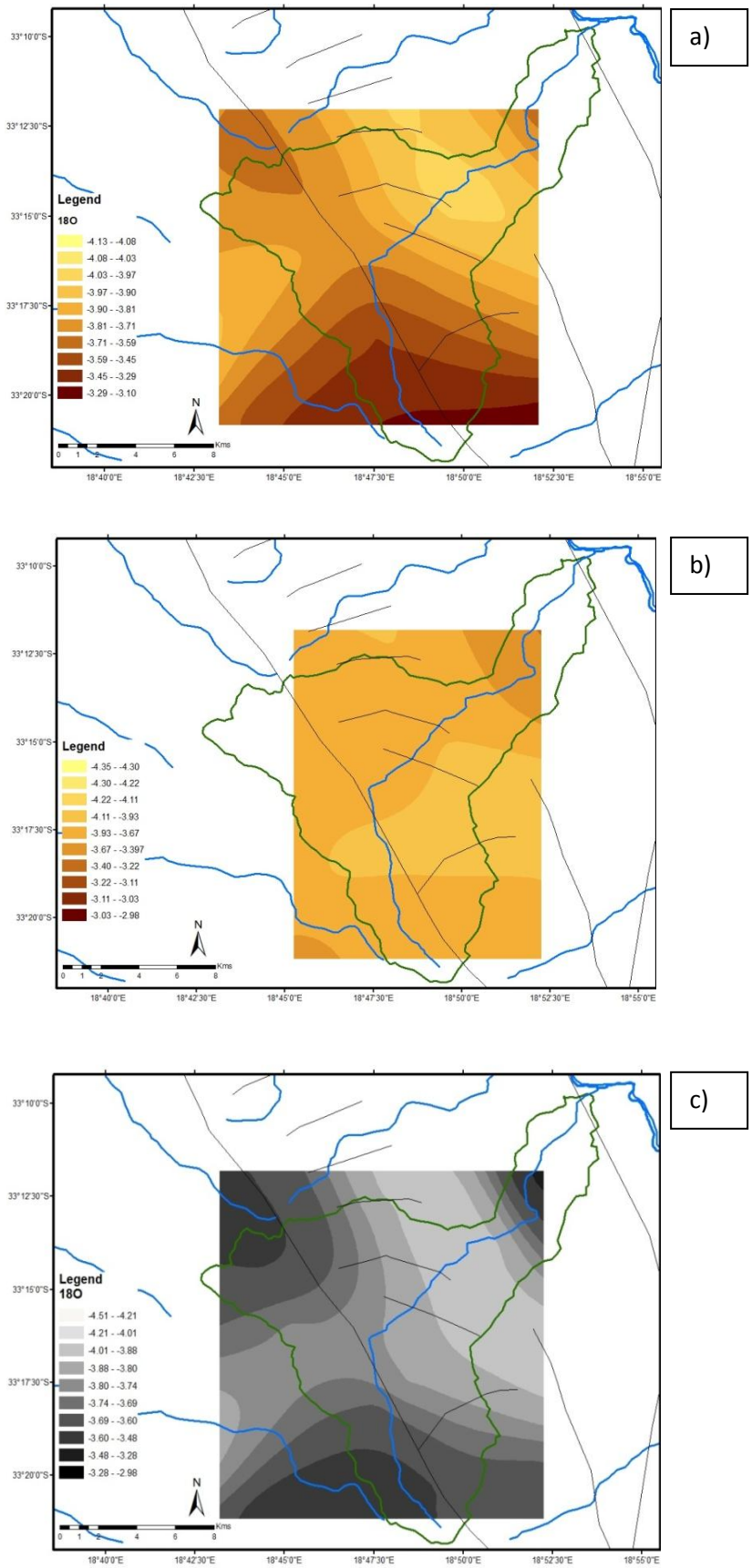


Figure 5.26: a) December 2009 $\delta^{18}O$ contour, b) May 2010 $\delta^{18}O$ contour, and c) Contour of average $\delta^{18}O$ values

5.4.9.2. Trend in the stable isotope composition of groundwater

From Figures 5.27&5.28 , the isotopes measured in May 2009, follow an evaporative trend close to the LWML of Malan and Cape Town, with a slope of 4.81 (R^2=0.82), less than the slopes of both the LMWL's. The December 2009 isotopes also follow an evaporative trend, with a slope of 5.20 (R^2=0.79), the isotope here is slightly more depleted than the May 2009 sampling. Departure of the points is not much from the LMWL, which does not show extensive evaporation. Such slopes may be obtained due to mixing of evaporated soil-water with the infiltrating rain (Clark et al, 1987). Moreover, the variation in the range of isotopic values reflects the seasonal variation in the input. The isotope signature recorded in May 2010 is scattered around the LMWL and the GMWL, the evaporation line has a slope of 2.63 (R^2=0.34). None of the samples plot close to the rain index of Malan (Cape Town), and Cape Town. Sample SDC 74 (ii) plots close to the Berg River index, thus illustrating that the groundwater has been recharged by surface water that has undergone evaporation. The spatial trend of $\delta^{18}O$ values (Figure 5.26a), of groundwater samples are similar to the EC zonation, enriched values of $\delta^{18}O$ occur north-east (Zone 1), north-west (Zone 2), and south (Zone 4) of the catchment. Zone 3, along the "valley" section of the catchment flanked by faults, the groundwater here is more depleted indicating recently recharged water, or the groundwater here is prone to direct recharge with minimal evaporation, or there is virtually no mixing with older groundwater. The most $\delta^{18}O$ and $\delta^{2}H$ enriched samples which have undergone evaporation are SDC 44(iii), SDC 43(iii), and SDC 66 (iii) occur in Zone 1, the most depleted sample is SDC 36(iii), which is found in Zone 3. The deuterium-excess values are listed in Table 5.9, a deuterium-excess greater than 10‰ is characteristic of meteoric water (Vandenschrick et al, 2002).

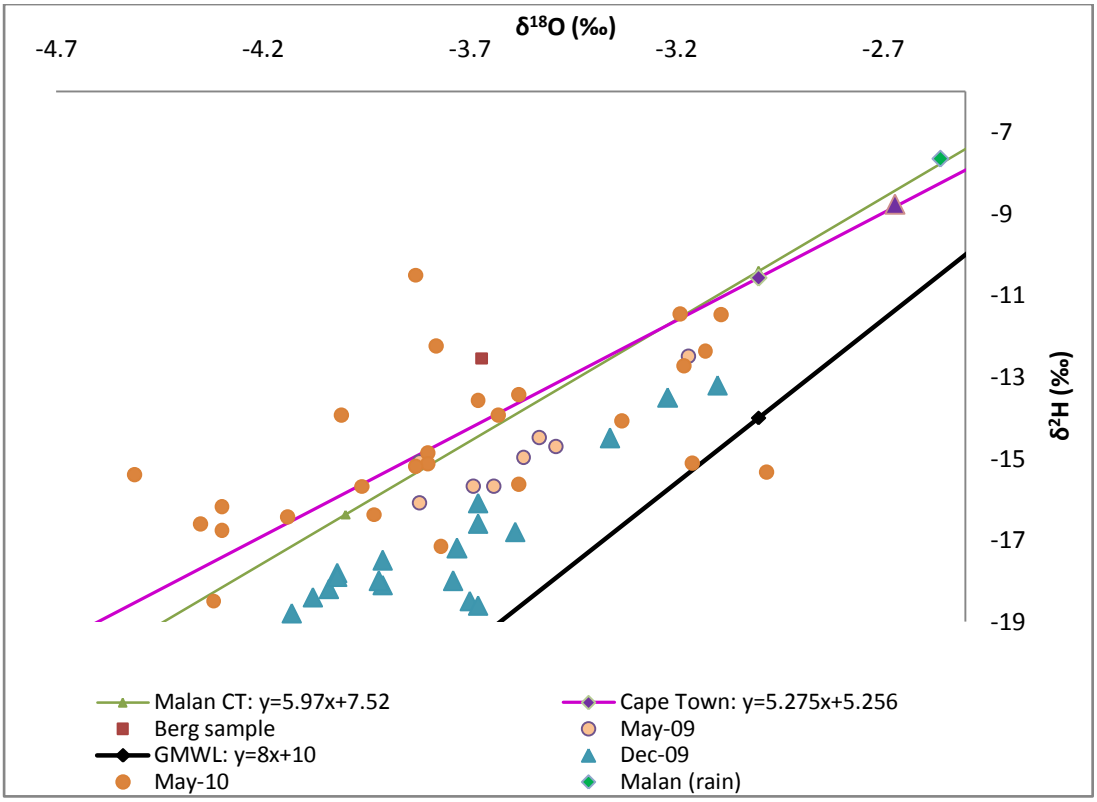


Figure 5.27: Environmental isotope samples plotted together with GMWL and LMWL (Local Meteoric Water-line)

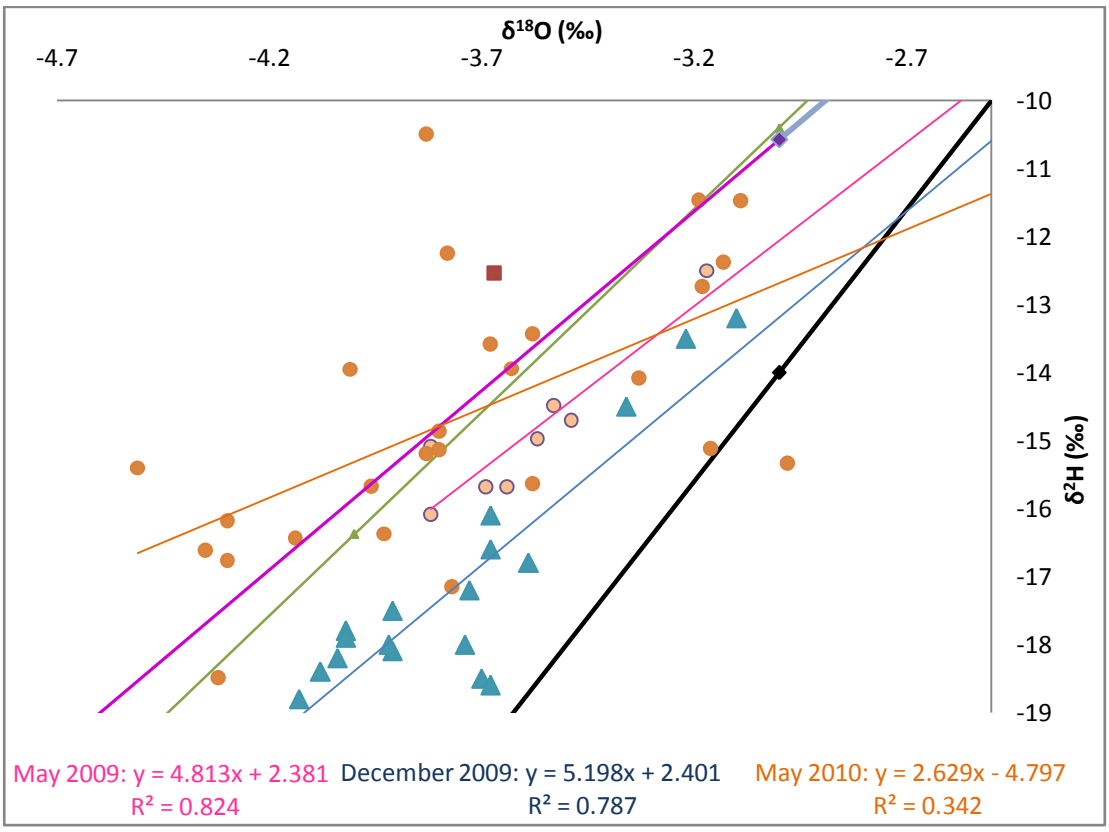


Figure 5.28: Linear trend of δ^2H-$\delta^{18}O$ during the three sampling campaigns

5.4.9.3. Tritium

A plot of tritium versus time recorded at the Malan (Cape Town) GNIP station (Figure 5.29), revealed the exponential decrease of atmospheric tritium with time.

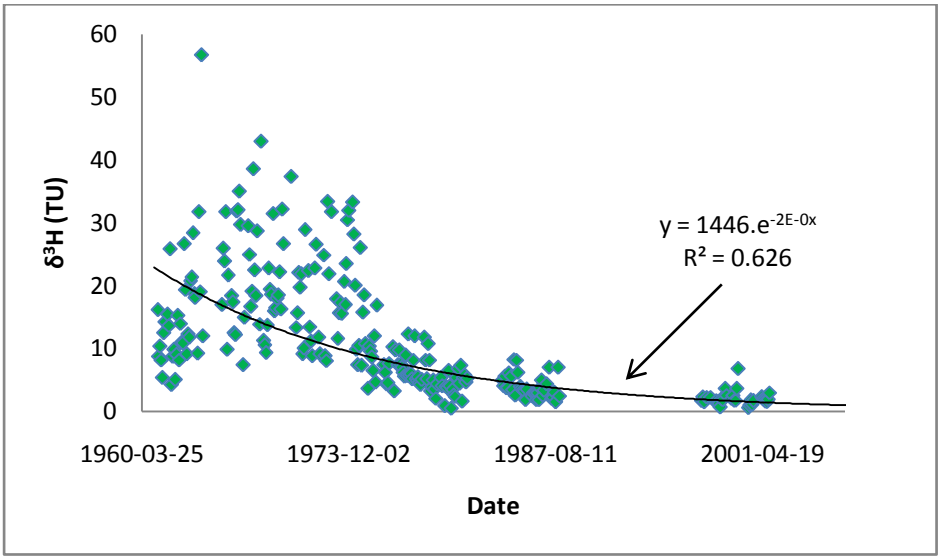


Figure 5.29: Depreciation of measured tritium (Malan-Cape Town) with time

The absence of tritium or low tritium values in the groundwater samples (Figure 5.30) confirms the samples do not contain recently recharged groundwater. Tritium concentration decreases from south-west to north-east of the catchment i.e. towards the Berg River (Figure 5.30), lowest tritium values are also associated with highly saline samples mostly occurring in Zone 1, this is indicative of mixing with ancient (pre 1952) brackish water, and groundwater chemical evolution from south to north-east within the study catchment.

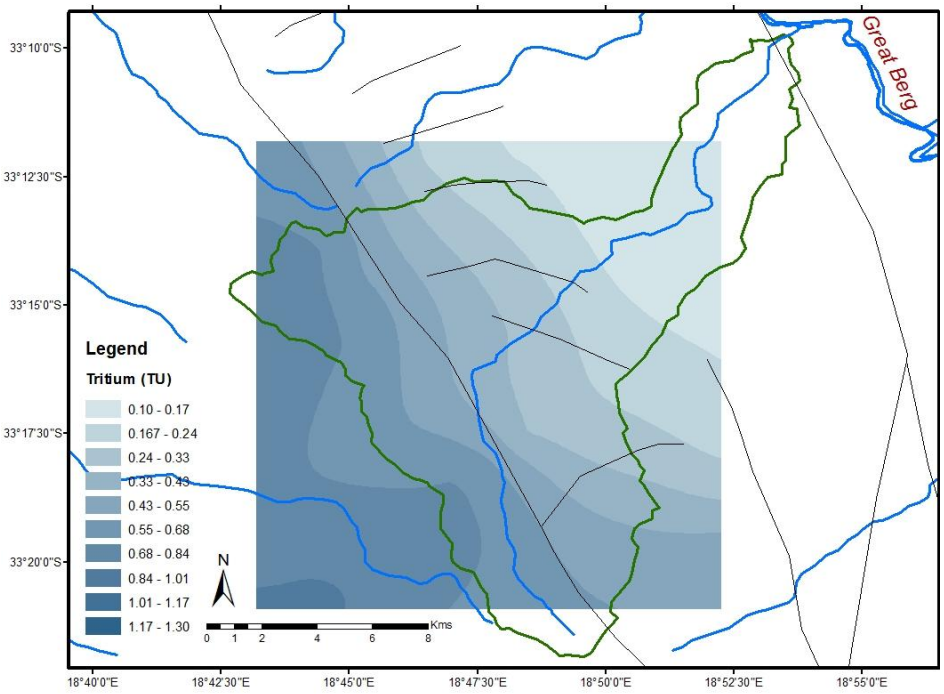


Figure 5.30: Contour of average tritium within study catchment

5.5. Water quality and salinity

5.5.1. Quality of groundwater for utilization

The sole purpose of the guidelines for drinking-water quality is the protection of public health. The guidelines provide the recommendations of the World Health Organization (WHO, 2011) for managing the risk from hazards that may compromise the safety of drinking-water. Limits for South African water quality guidelines (SAWQ, 1996) represent the target range, and does not necessary mean there would be health risks, if the values are exceeded. The WHO (2011) guideline however represents the maximum limit of the element, at which an amount above will result in adverse health effects. According to the drinking water standards recommended by World Health Organization (WHO, 2011) and the Department of Water Affairs (SAWQ, 1996) (Table 5.10), the following samples are suitable for human consumption: SDC 1(i); SDC 2(i); SDC 4(i); SDC 10(i); SDC 12(i); SDC 33(i); SDC40(ii); SDC 42(ii): SDC 2(ii); SDC 12(ii); SDC 52(ii); SDC 56(ii); SDC 59(ii); SDC 62(ii); SDC 47(iii); SDC 32(iii); SDC 12(iii); SDC 12(iii); SDC 52(iii); SDC 56(iii); SDC 57(iii); SDC 74(iii) and SDC 62(iii). Based on the TDS classification by Davies and DeWiest (1996) (Figure 5.11), 77.42% of the sampled groundwater is suitable for drinking, whilst just 9.68% is useful for irrigation.

Table 5.10: South African Water Quality Standards for domestic, industry and agricultural use (SAWQ, 1996) and WHO (drinking water) Guidelines (WHO, 2011), concentrations in mg/l

	Domestic	**Industry**	**Agriculture (irrigation)**	**WHO**
Alkalinity* (as $CaCO_3$)		0-1200		
Aluminium	0 - 0.15		0 - 5	0.9
Arsenic	0 - 0.01		0 - 0.1	0.01
Cadmium	0 - 5		0 - 10	0.003
Calcium	0 - 32			
Chloride	0 - 100	0 - 500	0 - 100	
Chromium(VI)	0 - 0.05		0 - 0.1	0.05
Cobalt			0 - 0.05	
Copper	0 - 1		0 - 0.2	2
Fluoride	0 - 1		0 - 2	1.5
Iron	0 - 0.1	0 - 10.0	0 - 5	
Lead	0 - 0.01		0 - 0.2	0.01
Magnesium	0 - 30			
Manganese	0 - 0.05	0 - 10.0	0 -10	
Mercury	0 - 0.001			0.006
Molybdenum			0 - 0.01	
Nickel			0 - 0.20	0.07
Nitrate+Nitrite	0 - 6		0 - 5	53
Potassium	0 - 50			
Silica			0 - 150	
Sodium	0 - 100		~70	
Sulphate	0 - 200	0 - 500		
Zinc	0 - 3		0 - 1	
pH	6 – 9,	5 – 10	6.5 - 8.4	
TDS	0 - 450	0 - 1 600	~40	
Barium				0.7
Selenium				0.04

Table 5.11: Classification of groundwater based on TDS (after Davies and DeWiest, 1966)

TDS (ppm)	Water type	Percentage
Up to 500	Desirable for drinking	17.74
500-1000	Permissible for drinking	59.68
<3000	Useful for irrigation	9.68
>3000	Unfit for drinking and irrigation	12.90

The sodium concentration of irrigation water is of prime importance and plays a significant part in determining the permeability of soil Na absorbed on clay surfaces, as a substitute for Ca and Mg may damage the soil structure making it compact and impervious. Based on %Na values (Appendix K), it is concluded that none of the groundwater are suitable for irrigation (%Na>35). Sodium content is usually expressed in terms of percentage sodium calculated by :

$$\%Na = \frac{(\mathrm{Na}^{+} + \mathrm{K}^{+})}{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^{+} + \mathrm{K}^{+})} \times 100 \qquad 5.2$$

Where all ionic concentrations are expressed in meq/l

Another groundwater salinity assessment method is sodium absorption ratio (SAR), the SAR recommended by the salinity laboratory of the US Department of Agriculture (1955), directly reflects the degree of adsorption of sodium by soil and is defined by the following formula:

$$SAR = \frac{[\mathrm{Na}^{+}]}{\sqrt{\frac{1}{2}([\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}])}} \qquad 5.3$$

Where the ionic concentrations are expressed in meq/l.

The SAR (Appendix K) for May 2009 ranges from 7.94-24.74 in Zone 2, and 11.41-11.73 in Zone 3. The range for the December 2009 SAR is 2.76-31.88 in Zone 1, 5.92-24.35 in Zone 2, 6.92-12.41 in Zone 3, and one measurement of 5.12 in Zone 4. SAR measurements in May 2010 are 3.48-30.42, 6.44-21.60, 4.95-11.19, and 2.60-4.07 in Zones 1, 2, 3, and 4 respectively. SAR ranges for the DWA data is 9.09-25.05 in Zone 1, 8.41-13.45 in Zone 2, 6.36-21.60 in Zone 3, and 3.10-7.36 in Zone 4. Values lower than 0.3 indicate that the water is suitable for irrigation, whereas values which are greater than 2 indicate that the

groundwater is unsuitable for irrigation purposes. Analyses of the groundwater SAR with a mean of 11.74, renders none of the samples suitable for irrigational purposes. Sample SDC 30 (ii) contains the minimum SAR of 2.60, whilst sample SDC 43 (ii) contains the maximum SAR of 31.88. Groundwater with low alkali (sodium ion) and moderate salinity hazard can be used for irrigation on almost all soil (Lloyd and Heathcote, 1985), but that of with higher water salinity requires regular leaching and special management for salinity control.

5.5.2. The origin of groundwater salinity in the Sandspruit catchment

Evaporation of surface water and moisture in the unsaturated zone has been found as the most influential process in the development of the chemical composition of shallow groundwater (e.g., Boyd and Kreitler, 1986; Richter and Kreitler, 1993). This source of groundwater salinity is amplified in arid lands, such as the study catchment, due to the high evaporation rate and low rainfall, which encourages the development of saline groundwater. In the Sandspruit (G1H043) River, the Load (TDS) greatly exceeds flow TDS=9 tons, and runoff = 7.5 million m^3 (DWA, 1993).

The processes and mechanisms that determine the composition of a water body can be identified from plots of ionic ratios such as Gibbs plot (Richter and Kreitler, 1993). A Gibbs plot of data from the study site (Figure 5.22) and the stable isotope plot (Figure 5.27 and Figure 5.28) indicate that evaporation is the predominant factor controlling shallow groundwater chemistry in the study area. Some groundwater samples have Na/ Cl ratios (Figure 5.31) that are lower than those that would result from either halite dissolution or evaporation of rainfall. This is most likely due to the absorption of Na by clays, which is a common process in salinized areas (e.g., Ghassemi et al., 1995). Gonfiantini and Aragus, (1988) produced a $\delta^{18}O$ versus TDS groundwater plot (Figure 5.32), illustrating the different salinization processes affecting the isotopic composition of groundwater. Figure 5.33, containing the study catchment groundwater samples, follow an evaporative trend based on the (Gonfiantini and Aragus, 1988) diagram. Evaporation of groundwater may not be the only salinization process occurring. The salinity of the groundwater in the study area may also be attributed to minor salt dissolution, and the upcoming or lateral movement of old saline groundwater, indicated by the low tritium values in Appendix O.

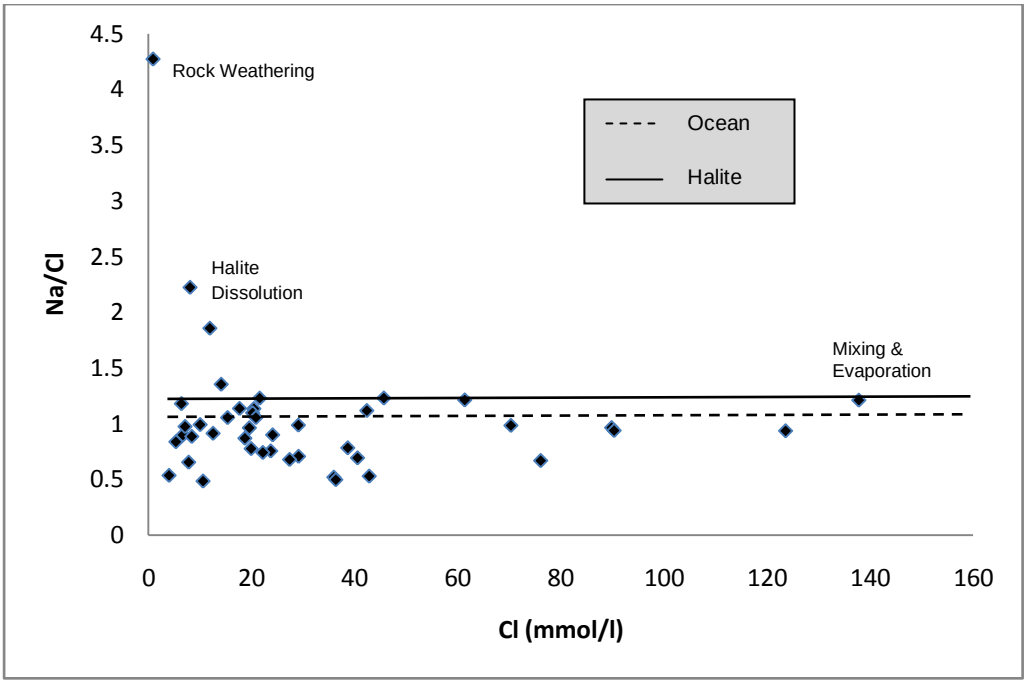


Figure 5.31: Na/Cl plot illustrating groundwater salinization processes

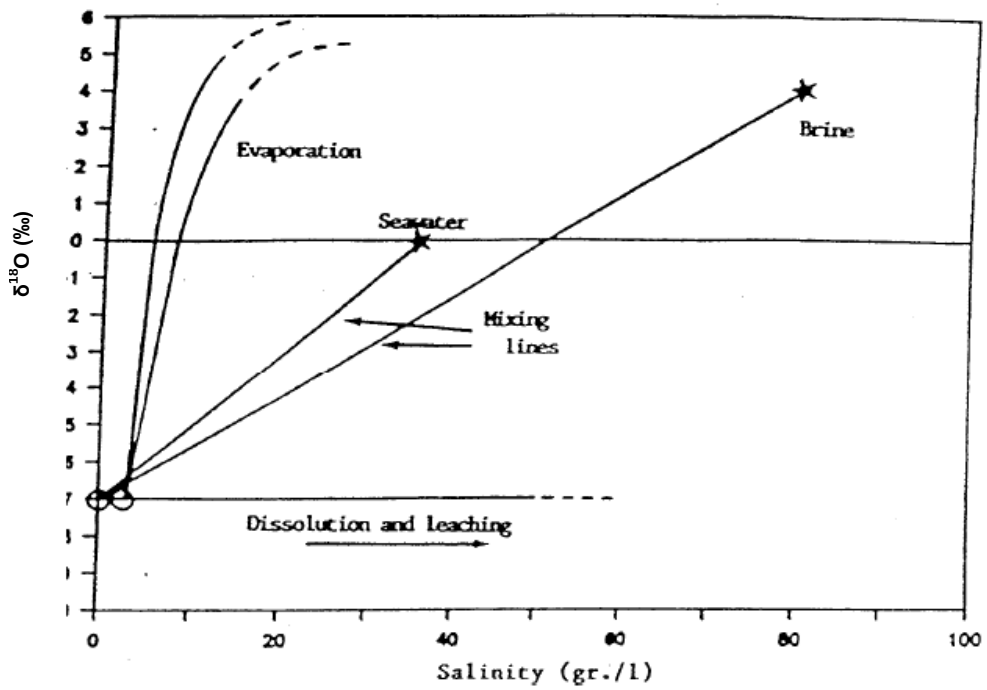


Figure 5.32: Change in isotopic composition of water, associated with different salinization processes. $\delta^{18}O$ versus salinity (Gonfiantini and Aragus, 1988)

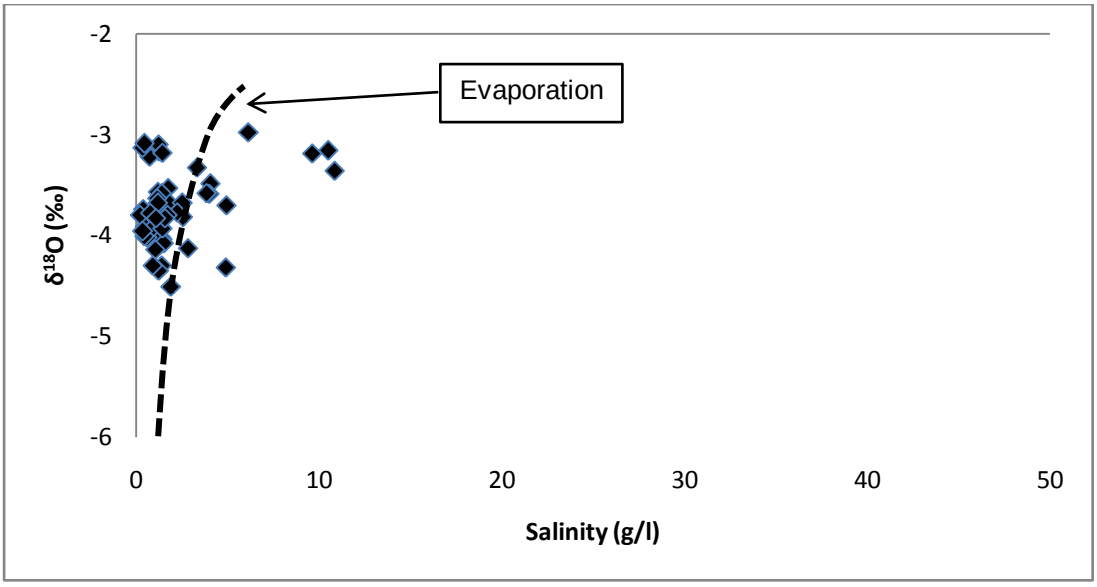


Figure 5.33: $\delta^{18}O$ versus Salinity, in representation of evaporation as the predominant salinization process based on Figure 5.32

CHAPTER 6 – SUMMARY OF MAIN FINDINGS, CONCEPTUAL HYDROGEOLOGICAL FRAMEWORK AND RECOMMENDATIONS

6.1. Summary of main results

The calculated water balance for the Sandspruit catchment revealed that recharge only occurred in June, July, and August, whereas evaporation and transpiration (evapotranspiration) were the dominant processes controlling the water-balance within the remaining months (September-May). The average recharge varies between 19-38mm in June, 5-26mm in July, and 1-25mm in August. The average annual recharge ranges from 26-90mm/yr. The maps of Vegter, ACRU, and Harvest Potential together with the soil, vegetation, slope and lithology, were used to produce qualified guesses of the catchment annual recharge rate. The average recharge from the methods is 25mm/yr corresponding to about 6% of mean annual precipitation. The ACRU method yields a much higher recharge rate of 70mm/yr compared to the other methods.

Descriptive statistics, correlation matrices and factor analysis, together with stable isotope data indicate that the main process influencing the groundwater chemistry is salinization i.e. high concentration of Na^+ and Cl^- due to evaporation and salt dissolution. Groundwater TDS within the catchment ranges from fresh to salty water. Groundwater temperatures vary from 15 to 30 ^oC, with a pH range of 5-9. The spatial variation of EC and TDS follows a similar pattern of being low at recharge areas and progressively increases down gradient towards the Berg River in the direction of groundwater flow.

The electrical conductivity (EC) values of the groundwater samples from the May 2009 sampling range from 237 -813 mS/m, December 2009 falls within 55-2140 mS/m, and lastly May 2010 within 42-2105 mS/m. Based on the EC, and topography, the study area can be divided into four zones, a north-eastern brackish – salty water region (Zone 1), a north-western brackish water region (Zone 2), a central fresh – brackish water region (Zone 3), and a southern fresh water region (Zone 4).

EC measurements in May 2010, illustrates a relatively more dilute groundwater than the December 2009 EC measurements, due to recent groundwater recharge. EC depth profiles indicate an overall increase of salinity with depth. The range of groundwater total hardness for May 2009 is 129-887 mg/l as $CaCO_3$, 124-3313 mg/l as $CaCO_3$ for December 2009, and 37-4974 mg/l as $CaCO_3$ for May 2010.

Total concentrations of calcium, sodium, chloride, magnesium, sulphate, potassium, and bicarconate are positively correlated to EC. These relationships clearly identify the main

elements contributing to the groundwater salinity and their tendency to follow a similar trend (e.g. due to concentration by evaporation). The salinization of the groundwater would be expected to result from the ionic concentrations increasing due to both evaporation of recharge water and to the effects of interactions between the groundwater and the aquifers.

From the Piper and Durov plots, Na^+ represents the dominant cation, whilst Cl^- the dominant anion, groundwater hydrochemical evolution from Na-Mg-HCO_3 and Na-Ca-Mg-SO_4 type groundwaters (upstream samples) to a Na-Cl type groundwater in the middle and lower reaches of the catchment is occurring. This evolution is supported by the existence of measureable amounts of tritium in the upstream borehole samples, while the middle and downstream areas have practically zero tritium signals.

According to the Wilcox diagrams, the majority of samples can be classified in having a very high sodium (alkali) hazard and a very high salinity hazard. The surface-water chemical character is that of a dilute groundwater, with a pH slightly greater than the groundwater. It is clear from the rock source deduction that the groundwater represents brine type water, with a few instances of rock (plagioclase) weathering.

Stable isotope data exhibit a clear seasonality (temperature) effect, with more depleted (mean of -3.65 for $\delta^{18}O$ and -14.81 for $\delta^{2}H$) values occurring in the winter (May-July) and more enriched (mean of -3.74 for $\delta^{18}O$ and -17.04 for $\delta^{2}H$) values occurring in the summer/early fall (November-March). $\delta^{2}H$ and $\delta^{18}O$ measurements in May 2009, and December 2009 follow an evaporative trend close to the LWML of Malan and Cape Town. The isotope signature recorded in May 2010 is scattered around the LMWL, and the GMWL. The spatial trend of $\delta^{18}O$ values of groundwater samples are similar to the EC zonation (Figure 4.3.1.1), enriched values of $\delta^{18}O$ occur north-east (Zone 1), north-west (Zone 2), and south (Zone 4) of the catchment.

Tritium concentration decreases from south-west to north-east of the catchment i.e. towards the Berg River, lowest tritium values are also associated with highly saline samples mostly occurring in Zone 1, this is indicative of mixing with ancient (pre 1952) brackish water and long resistance times. The tritium and stable isotope data suggests that shallow groundwater is significantly mixed with older groundwaters. These preliminary results verify that the mobilisation of salts and their concentrations are not static in nature.

Table 6.1 illustrates the water quality associated with the various geological units. Based on %Na values, it is concluded that none of the groundwater are suitable for irrigation (%Na>35). The SAR ranges from 7.94-24.74 for May 2009, 2.76-31.88 for December 2009, and 2.60-30.42 for May 2010. SAR ranges for the DWA data is 3.10-25.05.

Evaporation of surface water and moisture in the unsaturated zone has been found as the most influential process in the development of the chemical composition of shallow groundwater. This source of groundwater salinity is amplified in arid lands, such as the study catchment, due to the high evaporation rate and low rainfall which encourage the above-mentioned processes and also lower flushing of saline water. A key factor controlling the amount of evaporation is the depth of the water table below the surface. Evaporation of groundwater may not be the only salinization process occurring. The salinity of the groundwater in the study area may also be attributed to minor salt dissolution, and the upcoming or lateral movement of old saline groundwater, indicated by the low tritium signals.

Table 6.1: Yield, EC, and recharge rate found within various geology

	Geological Formation	**Yield (l/s)**	**EC (m*S*/m)**	**Recharge Rate (mm/yr)**
Cape Granite Suite		0.69-1.33	367.53-500.77	25.85-25.95
	Springfontyn	0.69-2.83	297.24-753.37	25.85-25.95
	Peninsula	1.33-2.83	133.24-203.53	47.14-89.83
	Graafwater	1.33-2.83	133.24-203.53	47.14-89.83
	Piekenierskloof	1.33-2.83	133.24-203.53	47.14-89.83
	Bridgetown	2.83-6.28	367.53-753.37	25.79-26.06
	Moorreesburg	0.69-6.28	133.24-1232.22	25.84-89.83
	Klipplaat	0.69-2.83	240.61-753.37	25.85-25.95
	Berg River	0.69-2.83	203.53-753.37	25.85-25.95

6.2. Conceptual hydrological model

Conceptual models are static and best describes the present condition of a system. A conceptual hydrological model through cross section C-D is presented in Figure 6.2. The Table Mountain Sandstone located south of the catchment with an approximate elevation of 300m represents the main recharge area, whereas groundwater discharge occurs predominantly towards the Berg River. The groundwater level is much lower at high elevations as compared with levels a few meters below ground level particularly on slopes. Region “A” represents the local flow system, and “B”, the regional flow system. Higher electrical conductivities (300-400 m*S*/m) are encountered at valley bottom, and relatively “flat” areas, with lower electrical conductivities (50-300 m*S*/m) occurring at “hilly” regions. These “flat” areas are subjected to local ponding and evaporation of groundwater even in the

unsaturated zone, thus leading to increased salinity. Groundwater salinity also increases from the recharge area towards the discharge area.

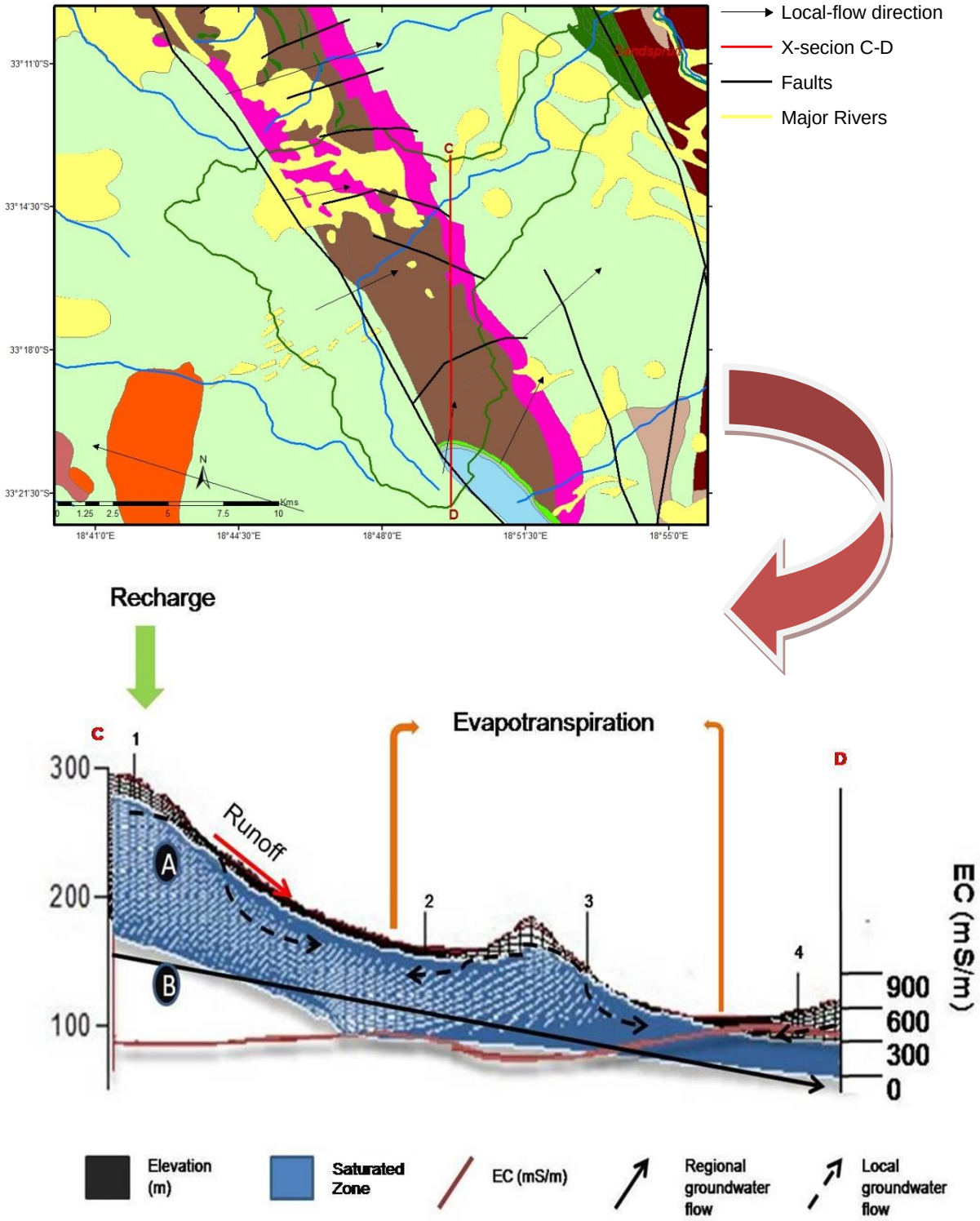


Figure 6.2: Conceptual hydrological model through section C-D, 1=Moorreesburg fault, 2=Fault, 3=Swartland fault, and 4=Sandspruit River

6.3. Proposed optimized groundwater monitoring for the Sandspruit catchment

DWA monitoring stations within the catchment are included in Appendix L, this includes station 96157 and 96181, renamed in the present study as SDC 51 and SDC 42 respectively. The DWA hydrochemical data for these monitoring stations however, only covers a 2 two span (i.e. from 1990 to 1992 – Appendix L), therefore any long-term trend analysis for the hydrochemical data unfortunately cannot be done. Different regions within the catchment were distinguished based on EC. Factor analysis revealed hat the first two factorial relationships controlling groundwater chemistry were major ion concentrations (groundwater salinity) and the relationship between $\delta^{2}H$, and $\delta^{18}O$, these two factors explained 57.6% of sample variance. A qualitative approach for adding boreholes to a monitoring network, based on EC zonation, factor analysis, isotope signature, and water quality data deduced that the following stations should be monitored: SDC 11; SDC 36; SDC 66; SDC 44; SDC 30; and SDC 50 (Figure 6.3). SDC 11 is found in Zone 2, contains a high TDS, and high Se, SDC 36 also found in Zone 2, contains a high TDS, high Se, and represents the most isotopically depleted sample, SDC 66 and SDC 44 is found in Zone 1 and contains a high TDS, high Hg and has an enriched isotopic signature, SDC 30 is found in Zone 4 and contains a low TDS, with high levels of Fe and Hg, and SDC 50 is found in Zone 2 and contains a low TDS, with high levels of F and Hg. The selected stations do not exhibit much temporal variation, water-levels vary by a few meters, and the groundwater chemistry is similar. Recharge is a critical factor in diluting the groundwater TDS, and since recharge predominantly occurs within the winter period, it is therefore feasible to sample from the above stations twice a year i.e. during winter and summer.

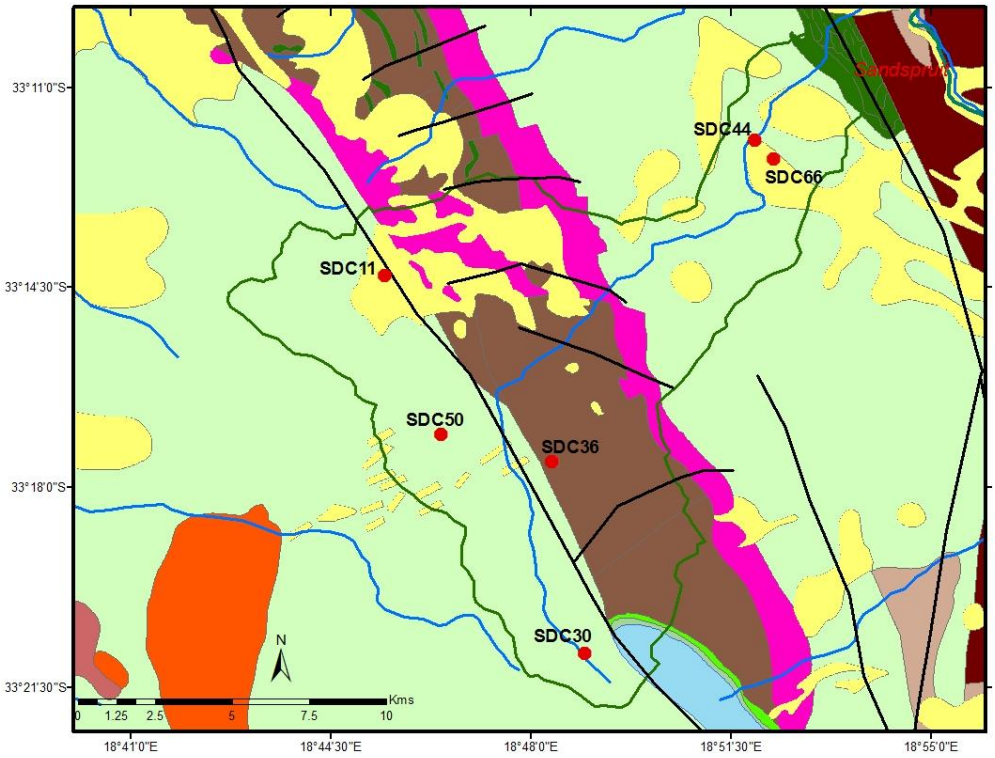


Figure 6.3: Proposed monitoring sites within the study area

6.4. Recommendations for future research

This research has revealed the following data and future research needs:

- Validation of the recharge model needs to be performed using other recharge estimation techniques, such as the Cumulative Rainfall Departure (CRD) method proposed by Bredenkamp et al. (1995). This approach is based on the premise that the CRD conforms to the concept that equilibrium conditions develop in an aquifer over time.
- In a continuous conceptual model, where the properties of an aquifer are known at every point, numerical modelling is proposed to further substantiate the hydrodynamics within the catchment. Numerical groundwater modelling based on a more detailed conceptual hydrogeological model.
- Research on the amount of maritime aerosol deposition and long term monitoring of local environmental isotopes of precipitation and groundwater, groundwater levels are recommended.
- Finally, it is highly recommended that development of salt balance and water-balance within the unsaturated zone can be incorporated in future researchers to estimate the net quantity of salt that enters the aquifers through percolation of precipitation and irrigation water.

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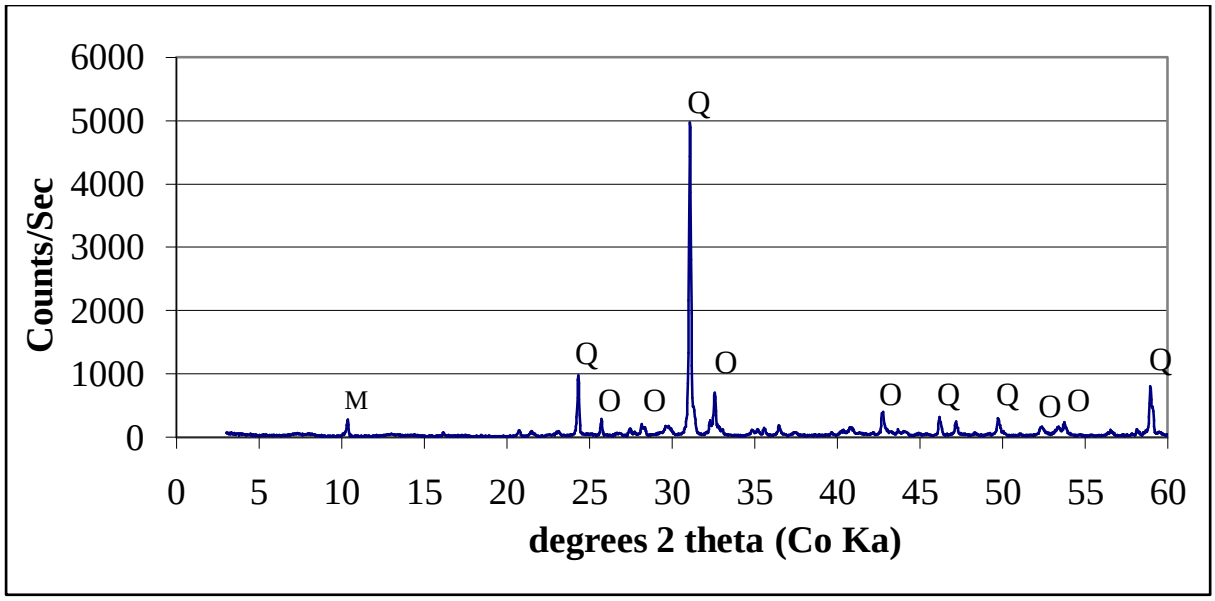
Appendix A - Thornthwaite Calculation

Month	ppt (mm)	Temp (^{o}C)	(Tm/5)1.51	c coeff	I	a	PeT (mm)	Avail moisture (mm)
January	9.39	23.4	10.28	1.16	87.20	1.91	122.79	-113.40
February	10.02	23.9	10.60	1.11	87.20	1.91	122.12	-112.10
March	14.46	22.5	9.70	1.03	87.20	1.91	101.26	-86.80
April	32.05	19.7	7.94	0.96	87.20	1.91	73.18	-41.12
May	52.63	16.4	5.99	0.89	87.20	1.91	47.50	5.13
June	68.38	13.8	4.61	0.85	87.20	1.91	32.54	35.84
July	59.63	12.8	4.13	0.87	87.20	1.91	28.96	30.67
August	61.34	13.0	4.21	0.93	87.20	1.91	31.73	29.61
September	35.91	14.8	5.17	1.00	87.20	1.91	44.26	-8.35
October	24.01	17.7	6.76	1.07	87.20	1.91	66.58	-42.58
November	16.59	20.3	8.31	1.14	87.20	1.91	92.13	-75.54
December	13.86	22.2	9.51	1.17	87.20	1.91	112.21	-98.34
Total	398.28	I equals	87.20					
		a equals	1.91					

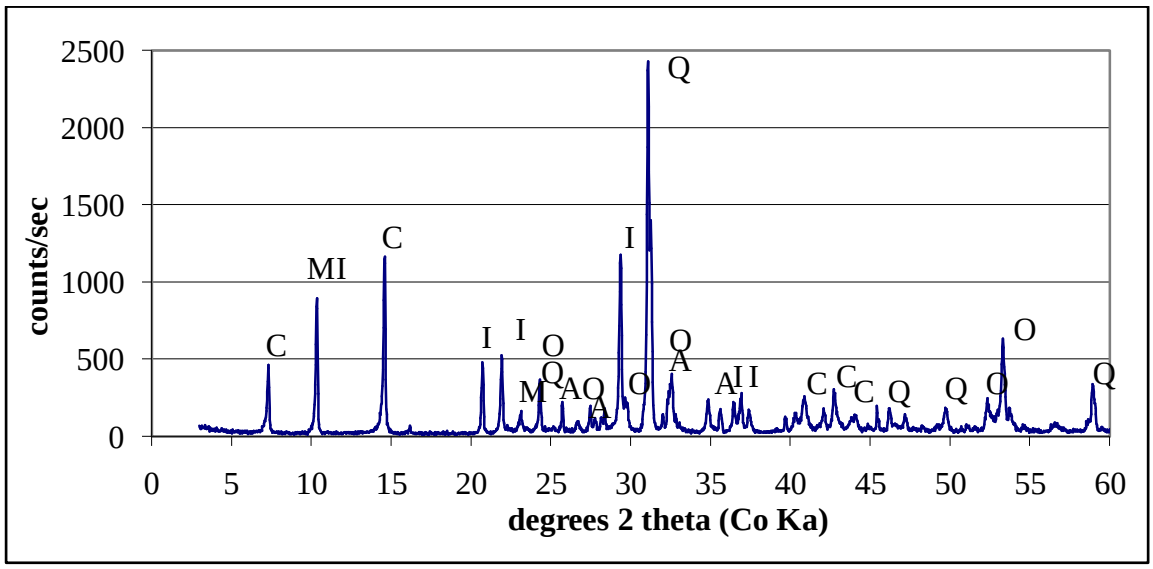
Appendix B – XRD Results

L2



Markers				
		Pos	d	Ip
Mica	M	8.8	10.000	600
Quartz	Q	22.7	4.260	1350
	Q	29.5	3.343	5300
	Q	44.7	2.282	700
	Q	48.2	2.128	700
	Q	57.5	1.817	1250
Orthoclase	O	24.1	4.030	600
		26.9	3.650	600
		31.2	3.180	1200
		41.1	2.460	700
		50.8	2.030	500
		52.5	1.970	600

L3



Markers				
		Pos	d	Ip
Mica	M	8.26	10.200	1100
		21.54	4.479	300
Quartz	Q	22.94	4.260	425
	Q	30.84	3.343	2400
	Q	44.65	2.282	300
	Q	48.21	2.128	320
	Q	57.48	1.817	420
Orthoclase	O	22.97	4.220	600
		25.50	3.831	320
		28.38	3.470	350
		30.96	3.200	630
		50.79	2.030	350
		52.51	1.970	700
Chlorite	C	5.72	14.200	600
		12.97	7.100	1300
		39.57	2.550	350
		41.42	2.445	400
		42.51	2.387	300
Anorthite	A	24.08	4.041	320
		25.90	3.777	200
		30.93	3.203	500
		33.80	2.950	350
Illite	I	10.12	9.944	1100
		19.23	4.972	650
		21.37	4.512	700
		34.98	2.858	400
		35.94	2.787	400
		28.19	3.491	1300

Appendix C – XRF Results

MAJOR ELEMENT COMPOSITIONS - WEIGHT PERCENTAGE

Rock Sample	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	Cr_2O_3	NiO	TOTAL	L.O.I
L-1	98.78	0.41	0.26	0.01	0.00	0.00	0.26	0.07	0.04	0.22	0.02	0.00	100.07	0.35
L-2	74.36	11.85	6.10	0.11	2.01	0.10	2.88	1.85	0.68	0.19	0.04	0.01	100.17	3.14
L-3	59.66	20.23	9.36	0.12	3.95	0.03	2.25	3.34	0.93	0.07	0.05	0.01	100.02	5.26
L-4	96.61	2.29	0.51	0.01	0.11	0.00	0.14	0.47	0.13	0.01	0.03	0.00	100.31	0.72
L-5	97.57	1.21	0.55	0.01	0.04	0.03	0.29	0.34	0.10	0.17	0.03	0.01	100.35	0.65

Appendix D – Groundwater flow diagrams within lithologies

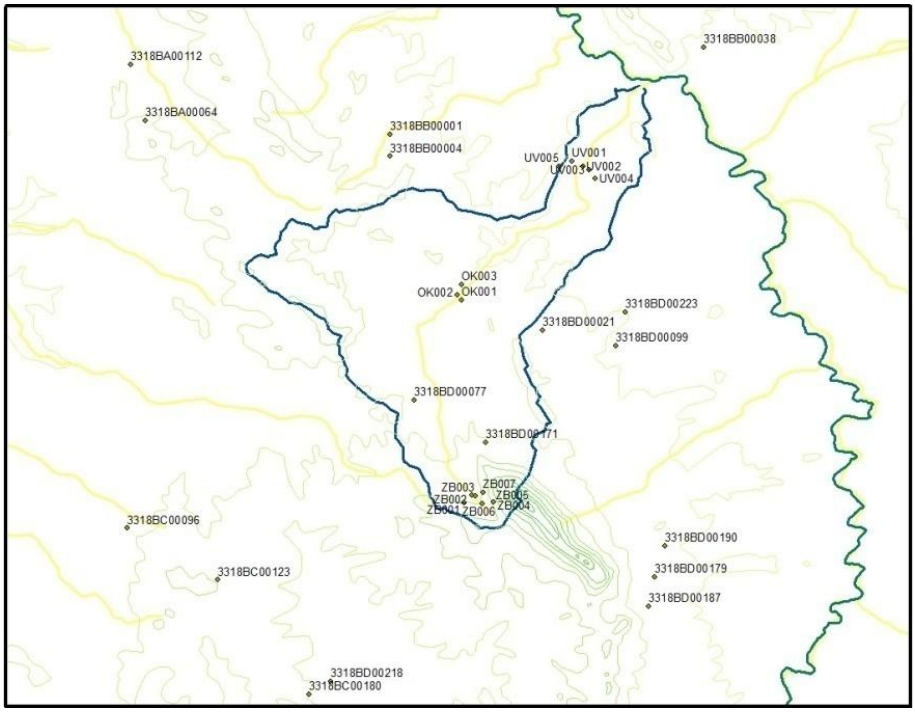


Figure: Location of boreholes where borehole logs were provided

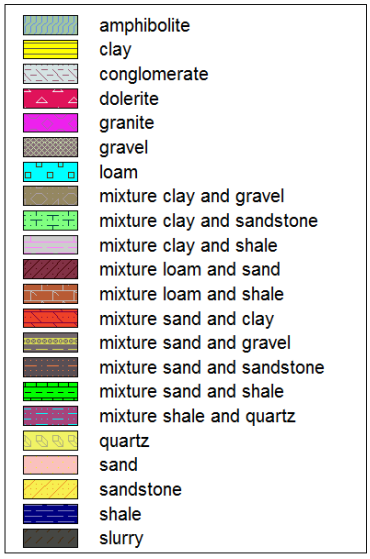
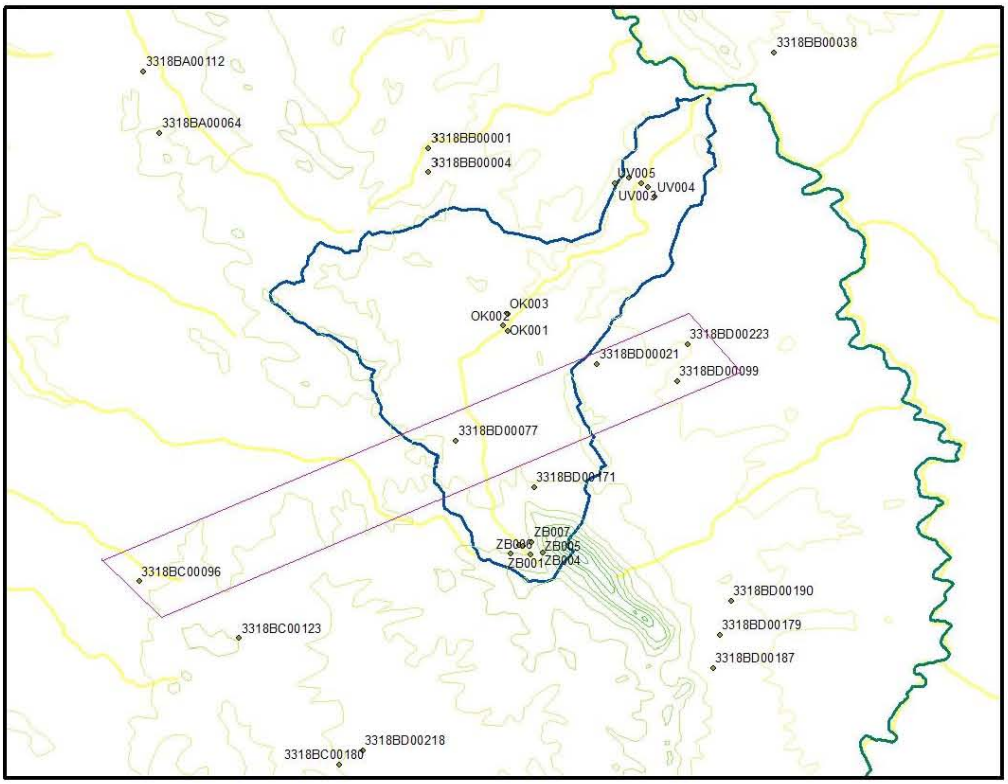


Figure: Key to various lithologies and soil mixtures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ZB007
ZB006
ZB005
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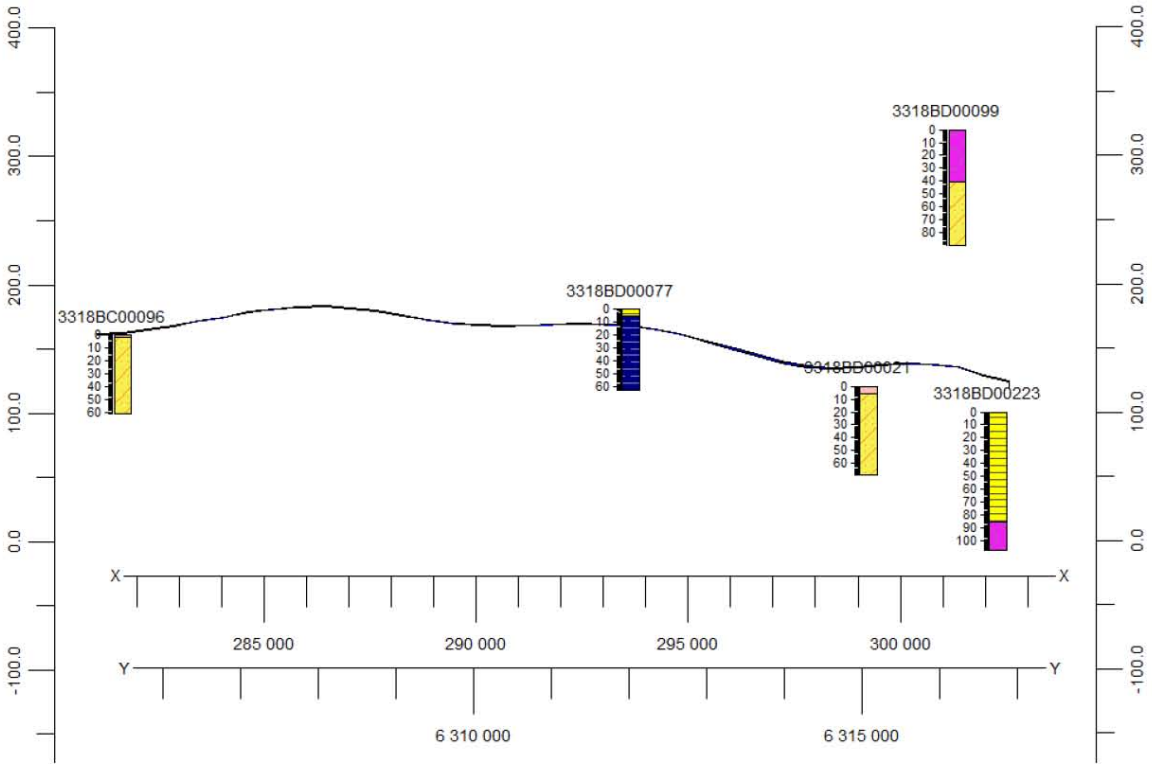
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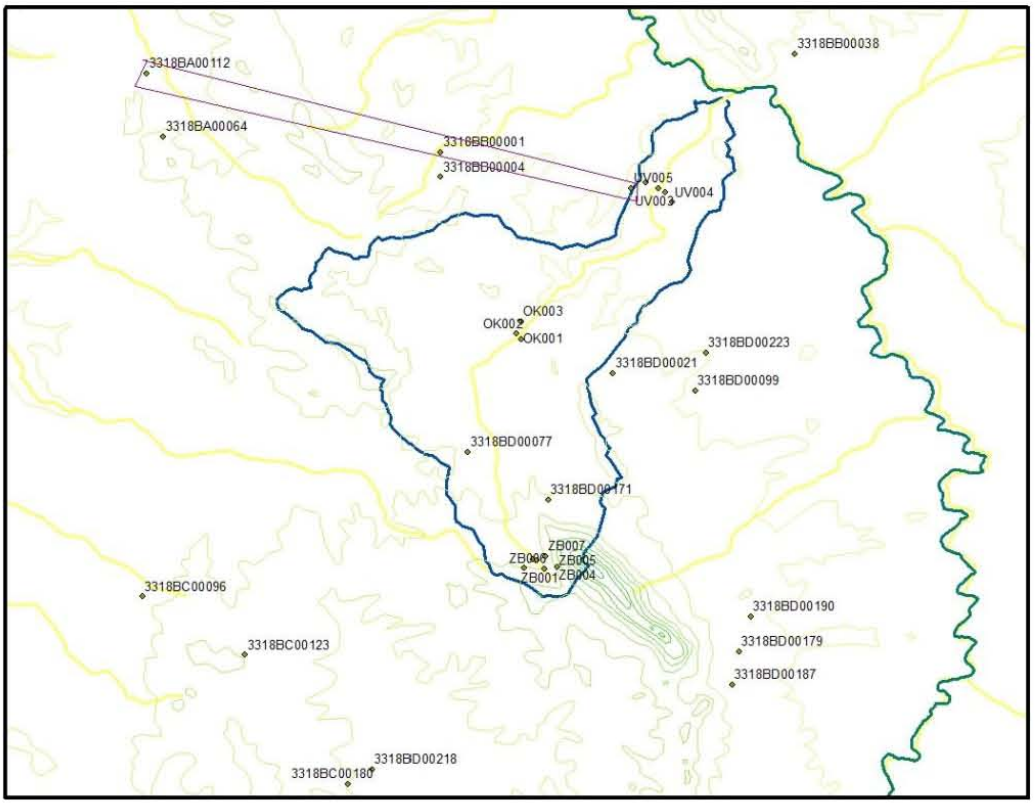
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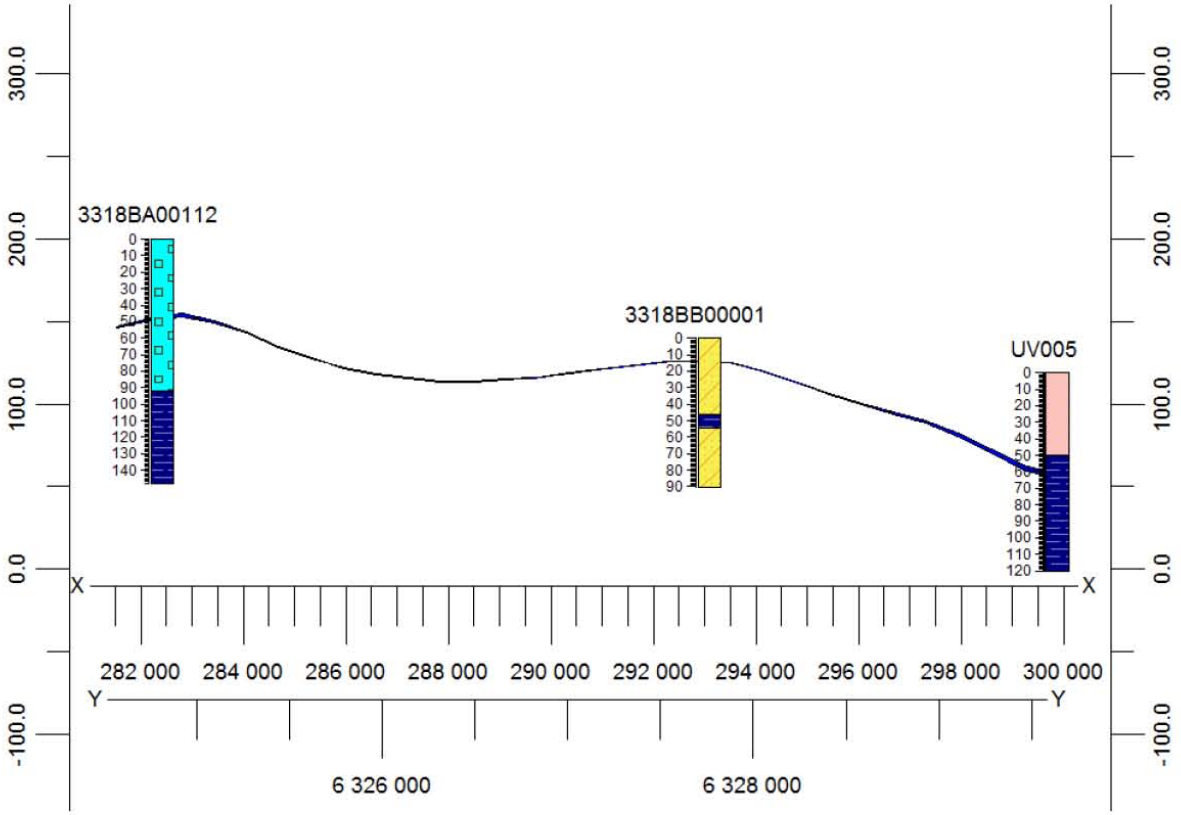
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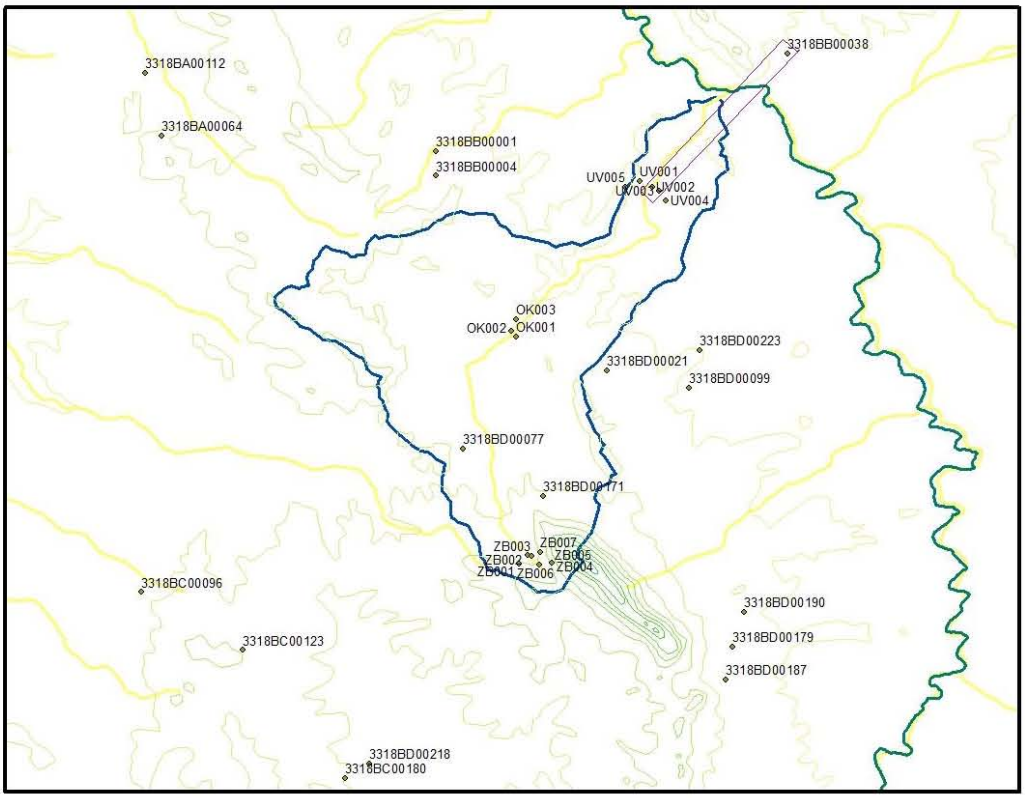
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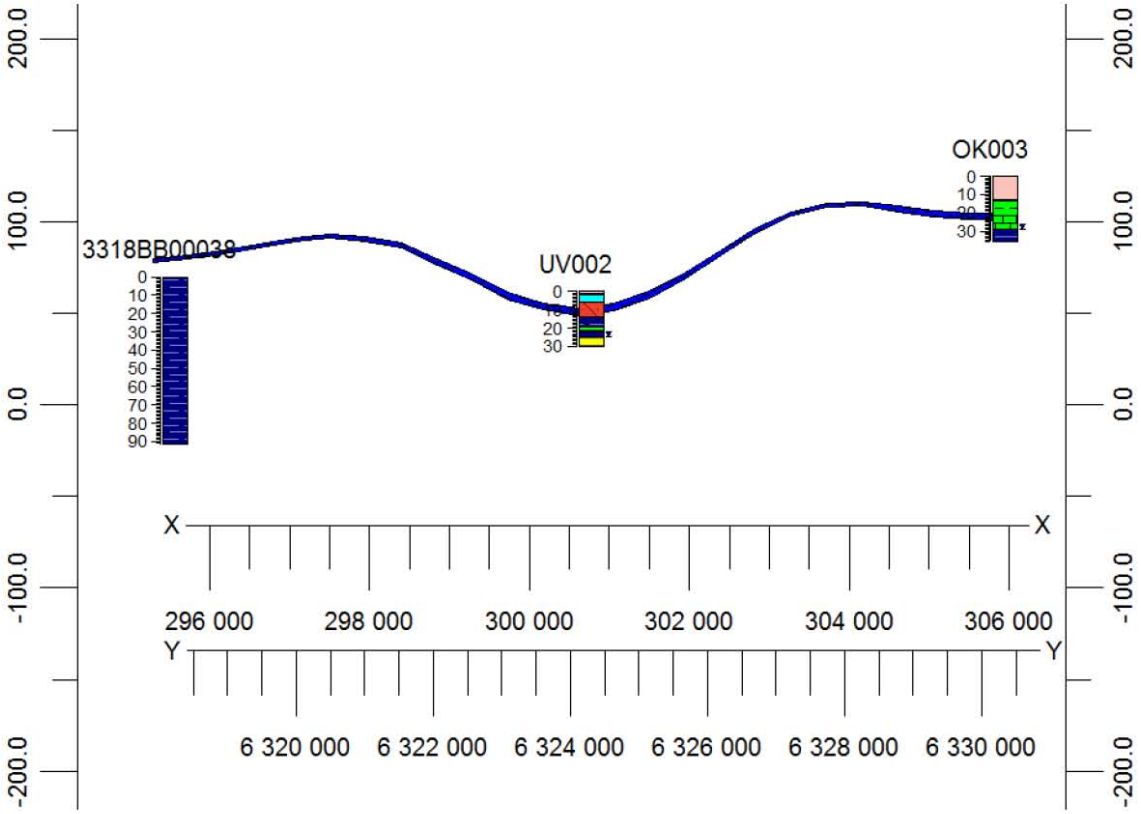
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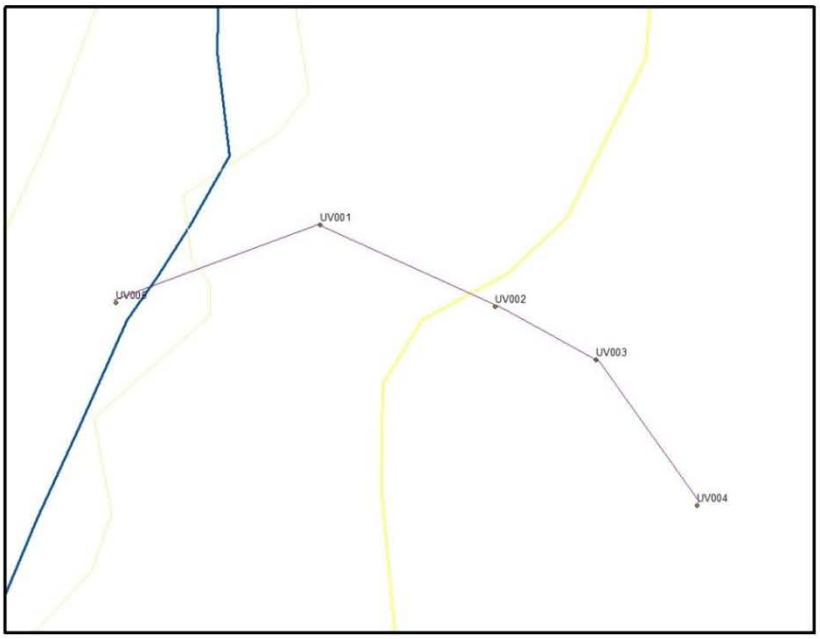
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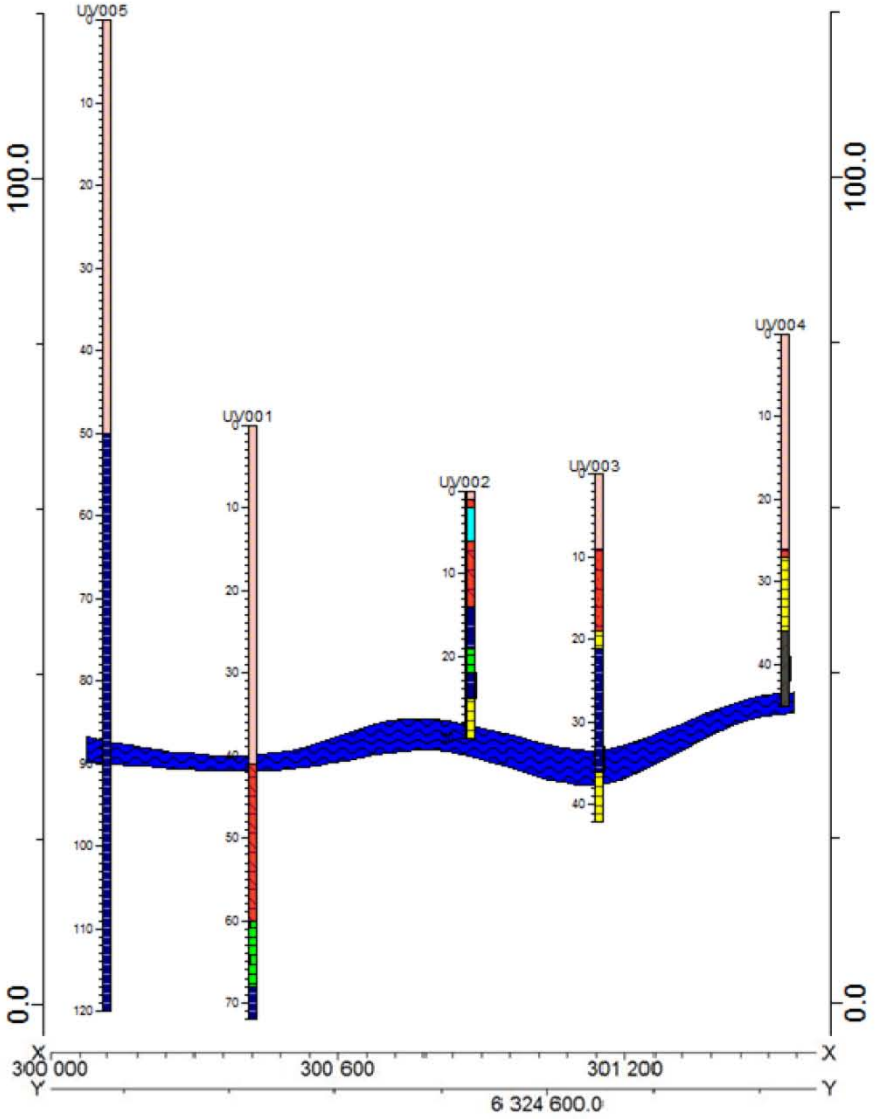
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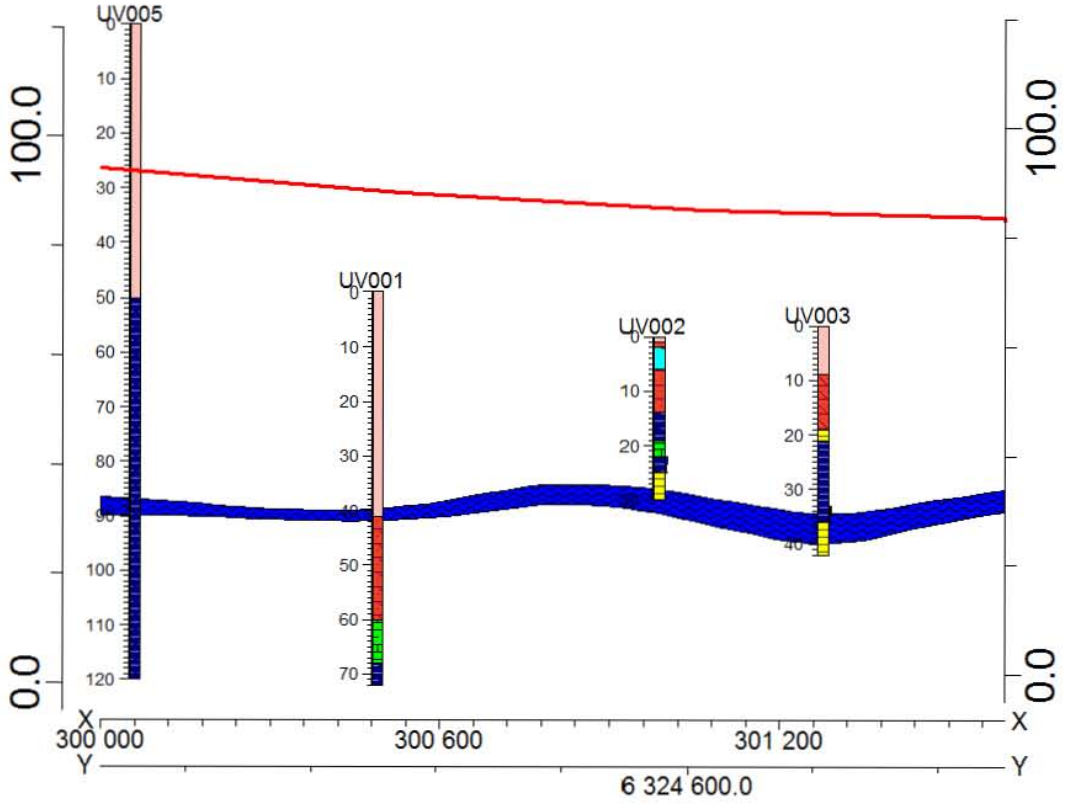
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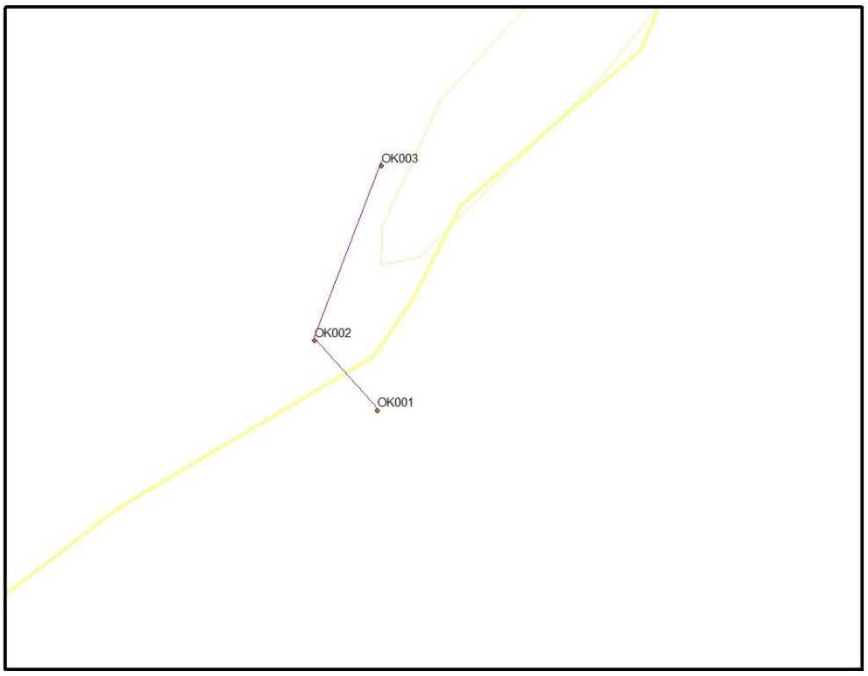
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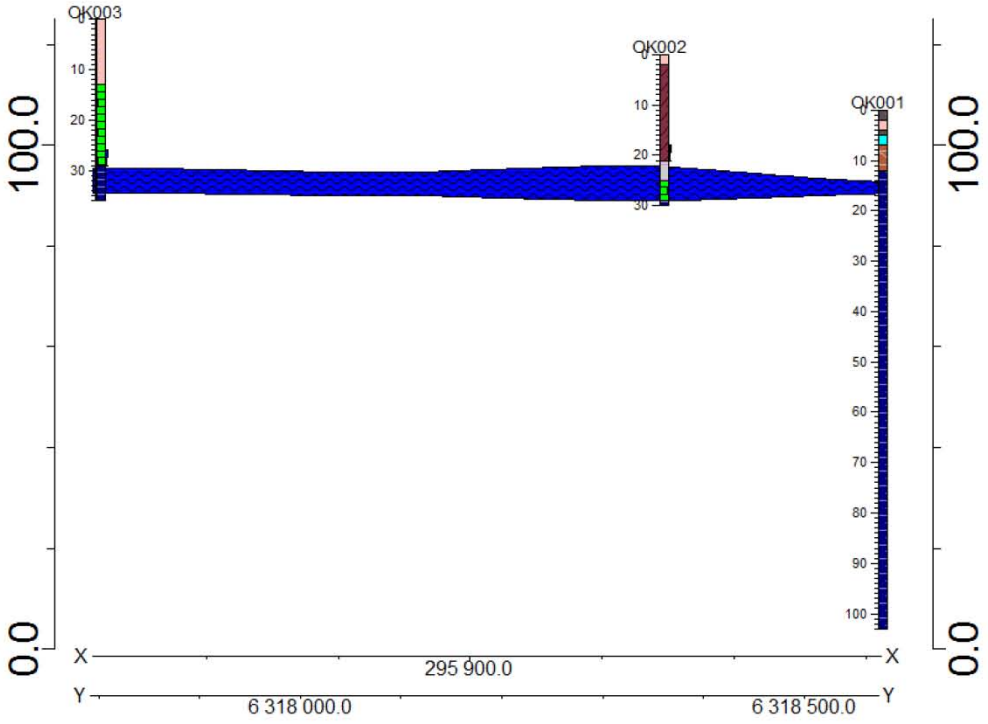
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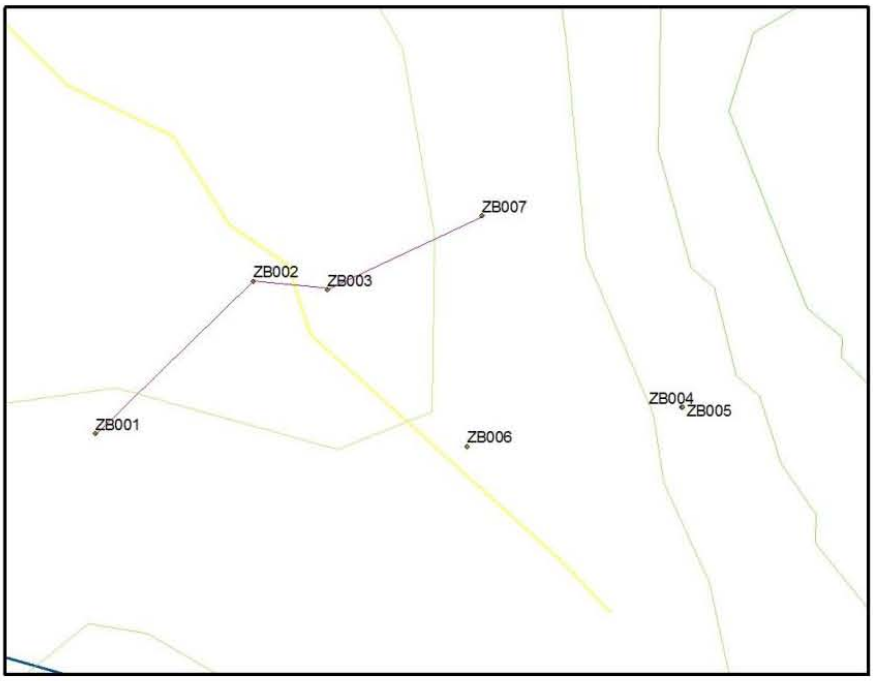
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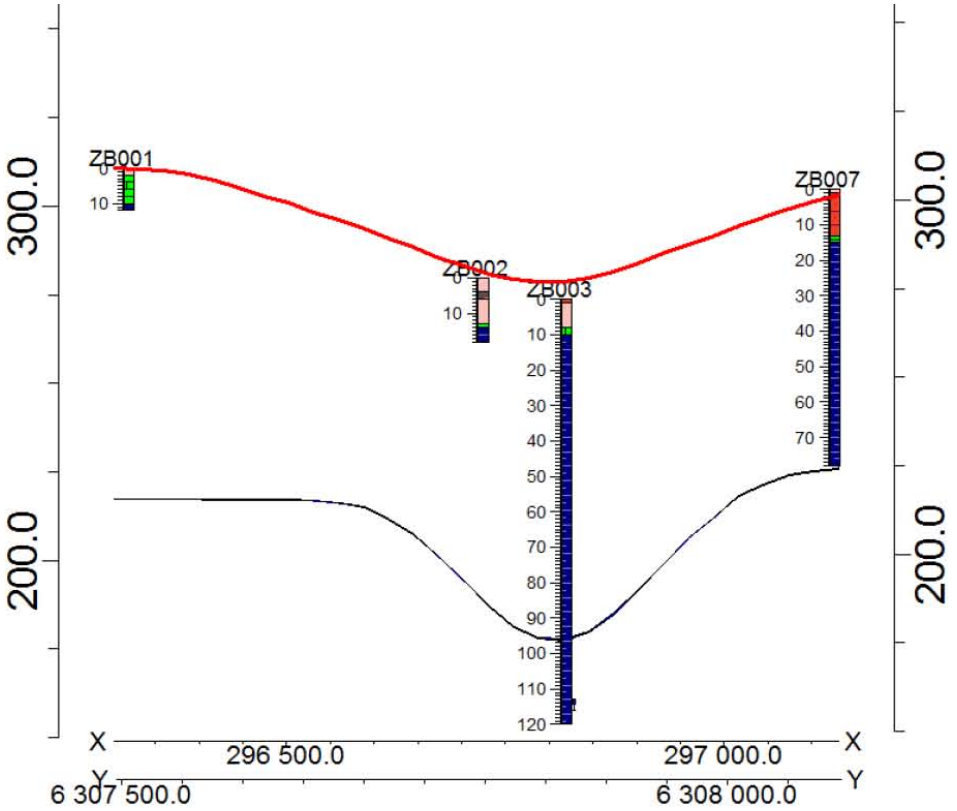
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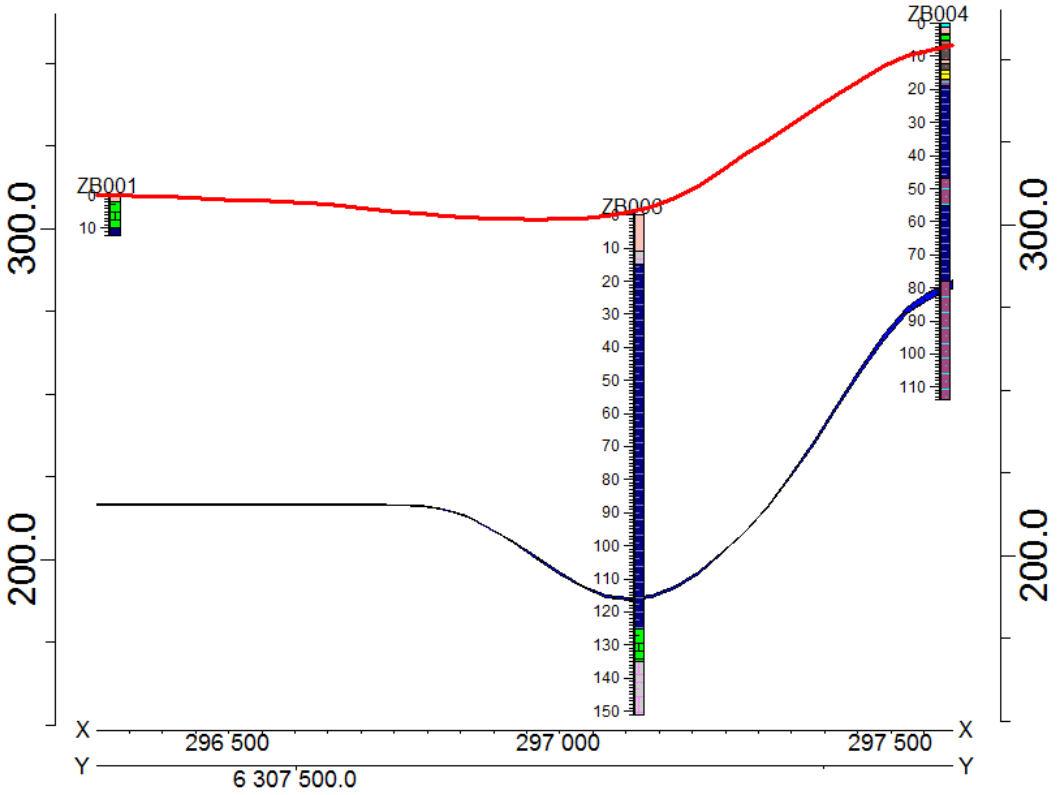
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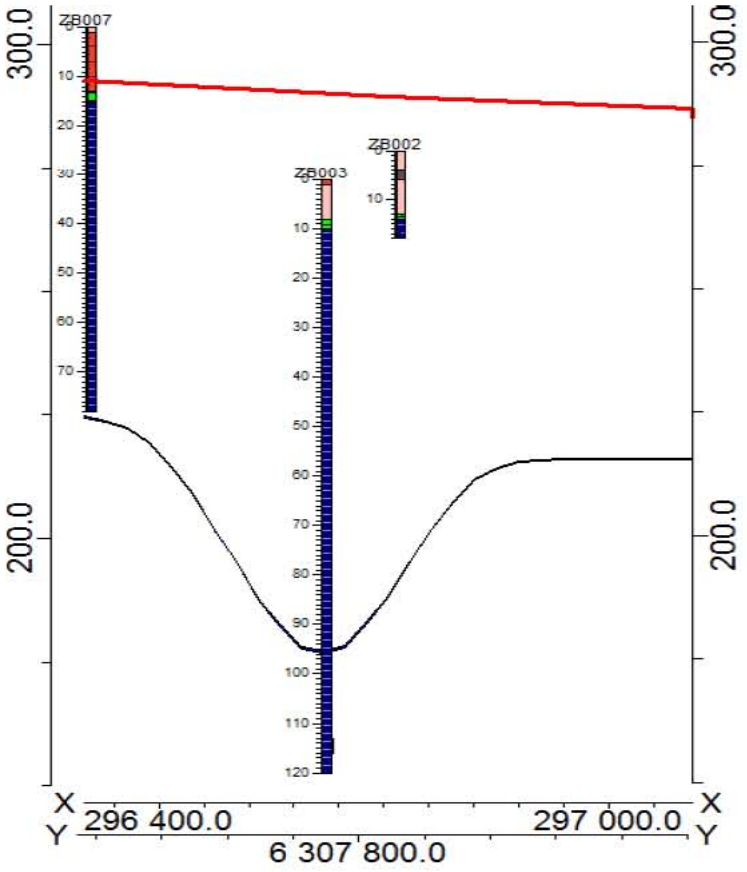
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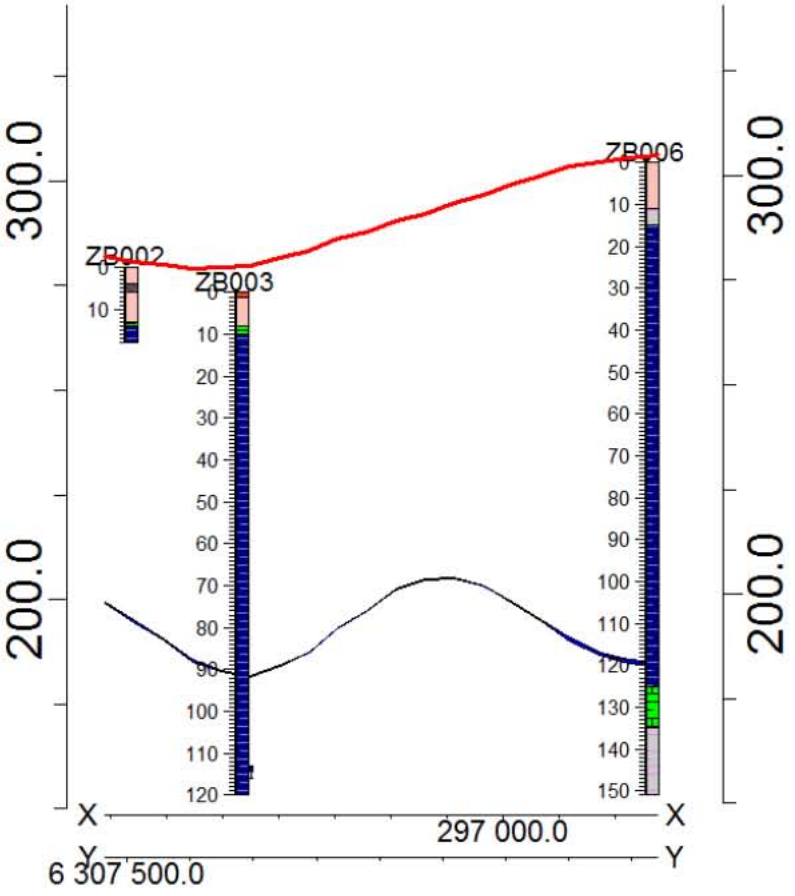
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Appendix E - ETc calculation using Penman-Montieth Method

Month	Tmin	Tmax	Tmean	Rhmin	Rhmax	Rhmean(%)	U tot	U2	N	P@177m	γ
	°C	°C	°C	%	%			m/s	hrs		kPa °C^{-1}
January	18.56	31.24	24.90	11.16	58.13	34.65	237.10	2.74	7.88	99.23	0.07
February	18.21	32.48	25.35	10.32	65.68	38.00	204.70	2.37	7.72	99.23	0.07
March	17.12	30.15	23.64	10.77	59.45	35.11	207.36	2.40	7.64	99.23	0.07
April	14.43	25.35	19.89	18.97	71.83	45.40	194.03	2.25	7.69	99.23	0.07
May	11.75	19.88	15.82	31.45	85.68	58.57	245.25	2.84	7.84	99.23	0.07
June	9.62	16.94	13.28	36.07	84.93	60.50	190.85	2.21	7.95	99.23	0.07
July	9.96	20.09	15.03	25.35	72.71	49.03	188.87	2.19	7.89	99.23	0.07
August	7.33	15.97	11.65	33.52	91.77	62.65	176.39	2.04	7.73	99.23	0.07
September	9.00	20.72	14.86	22.80	89.80	56.30	149.66	1.73	7.64	99.23	0.07
October	10.68	24.15	17.42	10.42	75.94	43.18	168.62	1.95	7.69	99.23	0.07
November	14.34	27.48	20.91	7.07	62.53	34.80	212.92	2.46	7.84	99.23	0.07
December	16.58	30.49	23.54	10.76	69.73	40.25	194.32	2.25	7.95	99.23	0.07
	σ	e^o (Tmean)	e^o (Tmin)	e^o (Tmax)	Δ	e_s	e_a	J	rad	dr	δ
	MJ K^{-4} m^{-2} day^{-1}	kPa	kPa	kPa	kPa°C^{-1}	kPa	kPa				rad
January	4.903E-09	3.15	2.14	2.09	0.19	2.11	0.74	16	-0.58	1.03	-0.37
February	4.903E-09	3.23	2.09	1.95	0.19	2.02	0.79	47	-0.58	1.02	-0.22
March	4.903E-09	2.92	1.95	1.64	0.18	1.80	0.67	75	-0.58	1.01	-0.04
April	4.903E-09	2.32	1.64	1.38	0.14	1.51	0.72	106	-0.58	0.99	0.17
May	4.903E-09	1.80	1.38	1.20	0.11	1.29	0.78	136	-0.58	0.98	0.33
June	4.903E-09	1.53	1.20	1.22	0.10	1.21	0.73	167	-0.58	0.97	0.41
July	4.903E-09	1.71	1.22	1.02	0.11	1.12	0.58	197	-0.58	0.97	0.37
August	4.903E-09	1.37	1.02	1.15	0.09	1.09	0.66	228	-0.58	0.98	0.23
September	4.903E-09	1.69	1.15	1.29	0.11	1.22	0.66	259	-0.58	0.99	0.03
October	4.903E-09	1.99	1.29	1.63	0.13	1.46	0.57	289	-0.58	1.01	-0.18
November	4.903E-09	2.47	1.63	1.89	0.15	1.76	0.58	320	-0.58	1.02	-0.34
December	4.903E-09	2.90	1.89	0.61	0.17	1.25	0.69	350	-0.58	1.03	-0.41

	ωs	sin(Φ)sin(δ)	cos(Φ)cos(δ)	Ra	total N	days	n	Rs	Rso	Rns	Tkmin
	rad				hrs			MJ m^{-2} day^{-1}	MJ m^{-2} day^{-1}	MJ m^{-2} day^{-1}	
January	1.03	0.20	0.78	33.88	348.8	31	11.25	32.64	25.44	25.14	291.72
February	1.01	0.12	0.82	31.34	311.7	28	11.13	30.43	23.53	23.43	291.37
March	1.00	0.02	0.84	27.58	292.3	31	9.43	23.91	20.71	18.41	290.28
April	1.01	-0.09	0.83	22.52	232.2	30	7.74	16.97	16.91	13.06	287.59
May	1.03	-0.18	0.79	18.18	162.1	31	5.23	10.61	13.65	8.17	284.91
June	1.04	-0.22	0.77	16.00	167.7	30	5.59	9.63	12.01	7.41	282.78
July	1.03	-0.20	0.78	16.98	212.5	31	6.85	11.62	12.75	8.95	283.12
August	1.01	-0.13	0.82	20.72	175.1	31	5.65	12.75	15.56	9.82	280.49
September	1.00	-0.02	0.84	25.69	242.9	30	8.10	20.03	19.29	15.43	282.16
October	1.01	0.10	0.83	30.08	280.4	31	9.05	25.21	22.58	19.41	283.84
November	1.03	0.18	0.79	33.19	301.6	30	10.05	29.57	24.92	22.77	287.50
December	1.04	0.22	0.77	34.48	367.1	31	11.84	34.30	25.89	26.41	289.74
											Wheat
	Tkmax	**Tkmean**	**σTkmin**	**σTkmax**	**air hum**	**Rs/Rso**	**Rnl**	**Rn**	**G**	**ETo**	**Kc ini**
					%	MJ m^{-2} day^{-1}	MJ m^{-2} day^{-1}	MJ m^{-2} day^{-1}	MJ m^{-2} day^{-1}	mm/d	
January	304.40	298.06	35.51	42.10	0.22	1.28	11.79	13.35	0.16	5.59	0.7
February	305.64	298.51	35.34	42.79	0.22	1.29	11.76	11.67	-0.09	4.83	0.7
March	303.31	296.80	34.81	41.50	0.23	1.15	10.40	8.01	-0.38	3.87	0.7
April	298.51	293.05	33.54	38.93	0.22	1.00	8.05	5.02	-0.55	2.64	0.7
May	293.04	288.98	32.31	36.16	0.22	0.78	5.18	2.99	-0.46	1.88	0.7
June	290.10	286.44	31.35	34.73	0.22	0.80	5.33	2.08	-0.06	1.43	0.7
July	293.25	288.19	31.50	36.26	0.23	0.91	6.98	1.97	-0.11	1.52	0.7
August	289.13	284.81	30.35	34.26	0.23	0.82	5.52	4.29	-0.01	1.68	0.7
September	293.88	288.02	31.08	36.57	0.23	1.04	8.05	7.38	0.40	2.38	0.7
October	297.31	290.58	31.82	38.31	0.23	1.12	9.49	9.92	0.42	3.57	0.7
November	300.64	294.07	33.50	40.05	0.23	1.19	10.75	12.01	0.43	4.78	0.7
December	303.65	296.70	34.55	41.68	0.22	1.32	12.27	14.14	0.27	4.26	0.7

	Wheat			Grape				Pristine			
	Kc mid	Kc end	ETc	Kc ini	Kc mid	Kc end	ETc	Kc ini	Kc mid	Kc end	ETc
			mm/mnth				mm/mnth				mm/mnth
January	1.15	0.25	199.34	0.3	0.7	0.45	121.33	1	1	1	173.34
February	1.15	0.25	155.56	0.3	0.7	0.45	94.69	1	1	1	135.27
March	1.15	0.25	138.05	0.3	0.7	0.45	84.03	1	1	1	120.04
April	1.15	0.25	91.00	0.3	0.7	0.45	55.39	1	1	1	79.13
May	1.15	0.25	66.91	0.3	0.7	0.45	40.73	1	1	1	58.18
June	1.15	0.25	49.33	0.3	0.7	0.45	30.03	1	1	1	42.89
July	1.15	0.25	54.09	0.3	0.7	0.45	32.92	1	1	1	47.03
August	1.15	0.25	59.82	0.3	0.7	0.45	36.42	1	1	1	52.02
September	1.15	0.25	82.01	0.3	0.7	0.45	49.92	1	1	1	71.31
October	1.15	0.25	127.28	0.3	0.7	0.45	77.47	1	1	1	110.67
November	1.15	0.25	165.05	0.3	0.7	0.45	100.46	1	1	1	143.52
December	1.15	0.25	148.26	0.3	0.7	0.45	92.48	1	1	1	132.11

Appendix F - Runoff estimation (in mm for various months)

Month	ppt	Area	C	Run	Run	Run	Run	Run	Run	Run	Run	Run	Run	Run	Run
	mm	ha		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
January	9.39	0.20	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
February	10.02	0.40	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
March	14.46	0.11	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
April	32.05	0.49	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
May	52.63	0.29	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
June	68.38	2.96	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
July	59.63	18.70	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
August	61.34	0.42	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
September	35.91	7.29	0.10	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.00	0.00
October	24.01	0.66	0.10	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.00	0.00
November	16.59	19.53	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
December	13.86	12.23	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
		11.15	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
		73.97	0.70	0.02	0.02	0.03	0.06	0.10	0.13	0.12	0.12	0.07	0.05	0.03	0.03
		3.57	0.46	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.08	0.05	0.03	0.02	0.02
		0.39	0.46	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.08	0.05	0.03	0.02	0.02
		0.77	0.46	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.08	0.05	0.03	0.02	0.02
		1.31	0.46	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.08	0.05	0.03	0.02	0.02
		1.33	0.46	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.08	0.05	0.03	0.02	0.02
		130.38	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
		2.45	0.72	0.02	0.02	0.03	0.06	0.11	0.14	0.12	0.12	0.07	0.05	0.03	0.03
		2.87	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
		1.67	0.72	0.02	0.02	0.03	0.06	0.11	0.14	0.12	0.12	0.07	0.05	0.03	0.03
		0.66	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
		1.83	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
		1.01	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
		4.13	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
		0.12	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
		6.96	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
		297.92	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
		29.35	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
		262.67	0.52	0.01	0.01	0.02	0.05	0.08	0.10	0.09	0.09	0.05	0.03	0.02	0.02
		21.34	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
		6.47	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
		17.46	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
		1.98	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01

Area	C	Run	Run	Run	Run	Run	Run	Run	Run	Run	Run	Run	Run
ha		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
2.26	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
26.87	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
3.04	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
0.23	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
0.29	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
0.18	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
0.39	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.39	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.13	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.39	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
2.95	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
433.86	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
394.32	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
6.70	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
42.70	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
197.19	0.52	0.01	0.01	0.02	0.05	0.08	0.10	0.09	0.09	0.05	0.03	0.02	0.02
0.00	0.10	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.00	0.00
0.01	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
18.10	0.80	0.02	0.02	0.03	0.07	0.12	0.15	0.13	0.14	0.08	0.05	0.04	0.03
38.85	0.83	0.02	0.02	0.03	0.07	0.12	0.16	0.14	0.14	0.08	0.06	0.04	0.03
21.63	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
1.81	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
26.34	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
0.01	0.52	0.01	0.01	0.02	0.05	0.08	0.10	0.09	0.09	0.05	0.03	0.02	0.02
0.76	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
0.01	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
51.69	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
253.19	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
107.61	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
51.28	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02

Area (ha)	C	Run_J	Run_F	Run_M	Run_A	Run_M	Run_J	Run_J	Run_A	Run_S	Run_O	Run_N	Run_D
141.11	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
581.19	0.52	0.01	0.01	0.02	0.05	0.08	0.10	0.09	0.09	0.05	0.03	0.02	0.02
0.37	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
1.33	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
1.33	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
0.77	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
0.36	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
3.85	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
16.63	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
2.98	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.01	0.10	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.00	0.00
0.02	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
0.00	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
0.42	0.10	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.00	0.00
0.04	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
0.32	0.10	0.00	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.00	0.00
4.49	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
9.79	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
0.01	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.08	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
1.33	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
4.71	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
0.09	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
0.39	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.58	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
1.33	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.88	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
0.00	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.35	0.25	0.01	0.01	0.01	0.02	0.04	0.05	0.04	0.04	0.02	0.02	0.01	0.01
1.89	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
2.15	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
79.71	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
4.47	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
228.48	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
2.15	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
38.99	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
223.40	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
175.42	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01

Area (ha)	C	Run_J	Run_F	Run_M	Run_A	Run_M	Run_J	Run_J	Run_A	Run_S	Run_O	Run_N	Run_D
176.32	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
1.96	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
13.98	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
2353.97	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
0.77	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
0.33	0.40	0.01	0.01	0.02	0.04	0.06	0.08	0.07	0.07	0.04	0.03	0.02	0.02
0.49	0.52	0.01	0.01	0.02	0.05	0.08	0.10	0.09	0.09	0.05	0.03	0.02	0.02
367.24	0.52	0.01	0.01	0.02	0.05	0.08	0.10	0.09	0.09	0.05	0.03	0.02	0.02
1722.84	0.52	0.01	0.01	0.02	0.05	0.08	0.10	0.09	0.09	0.05	0.03	0.02	0.02
0.00	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.10	0.52	0.01	0.01	0.02	0.05	0.08	0.10	0.09	0.09	0.05	0.03	0.02	0.02
1.36	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
0.91	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
0.24	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.51	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.00	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
2.01	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
1.33	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.76	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.76	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
1.33	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.57	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
1.34	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
13.69	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.39	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
2.13	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.38	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
1.53	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
16.01	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
1.33	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.29	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
1.33	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
1.21	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
0.39	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.29	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.08	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
0.39	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.23	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01

Area (ha)	C	Run_J	Run_F	Run_M	Run_A	Run_M	Run_J	Run_J	Run_A	Run_S	Run_O	Run_N	Run_D
0.16	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.39	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.36	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
0.39	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
1.32	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
1.73	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
1.33	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.26	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
2.21	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
0.77	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
1.33	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
3.52	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
1.33	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
2.92	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
6.51	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
46.50	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
2.26	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
1.53	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
14.29	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
26.26	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
17.29	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
1.60	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.39	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.39	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.74	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.77	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.13	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
3.56	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
1.82	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.20	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
2.04	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
2.09	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
0.17	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
0.44	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
0.00	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
0.02	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02

Area (ha)	C	Run_J	Run_F	Run_M	Run_A	Run_M	Run_J	Run_J	Run_A	Run_S	Run_O	Run_N	Run_D
1.04	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
0.29	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
2.73	0.72	0.02	0.02	0.03	0.06	0.11	0.14	0.12	0.12	0.07	0.05	0.03	0.03
0.36	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
6.78	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.37	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
4.78	0.72	0.02	0.02	0.03	0.06	0.11	0.14	0.12	0.12	0.07	0.05	0.03	0.03
1.82	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
1.34	0.35	0.01	0.01	0.01	0.03	0.05	0.07	0.06	0.06	0.03	0.02	0.02	0.01
0.79	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
2.10	0.72	0.02	0.02	0.03	0.06	0.11	0.14	0.12	0.12	0.07	0.05	0.03	0.03
2.25	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.66	0.72	0.02	0.02	0.03	0.06	0.11	0.14	0.12	0.12	0.07	0.05	0.03	0.03
20.63	0.85	0.02	0.02	0.03	0.08	0.12	0.16	0.14	0.14	0.08	0.06	0.04	0.03
73.49	0.87	0.02	0.02	0.03	0.08	0.13	0.17	0.14	0.15	0.09	0.06	0.04	0.03
0.97	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.77	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
1.31	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
3.12	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
269.70	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
43.77	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
27.75	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
8.49	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
40.58	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
2.84	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
1378.11	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.52	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
1.49	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
26.86	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
18.49	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.05	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
3.88	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
902.79	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.04	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.02	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02
0.74	0.50	0.01	0.01	0.02	0.04	0.07	0.09	0.08	0.09	0.05	0.03	0.02	0.02

Area (ha)	C	Run_J	Run_F	Run_M	Run_A	Run_M	Run_J	Run_J	Run_A	Run_S	Run_O	Run_N	Run_D
157.12	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
0.44	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
1.25	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
279.81	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
0.43	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
0.76	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
1.96	0.60	0.02	0.02	0.02	0.05	0.09	0.11	0.10	0.10	0.06	0.04	0.03	0.02
4.61	0.72	0.02	0.02	0.03	0.06	0.11	0.14	0.12	0.12	0.07	0.05	0.03	0.03
1.52	0.72	0.02	0.02	0.03	0.06	0.11	0.14	0.12	0.12	0.07	0.05	0.03	0.03
1.27	0.72	0.02	0.02	0.03	0.06	0.11	0.14	0.12	0.12	0.07	0.05	0.03	0.03
448.45	0.72	0.02	0.02	0.03	0.06	0.11	0.14	0.12	0.12	0.07	0.05	0.03	0.03
1653.20	0.72	0.02	0.02	0.03	0.06	0.11	0.14	0.12	0.12	0.07	0.05	0.03	0.03
0.10	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
3.93	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
88.08	0.30	0.01	0.01	0.01	0.03	0.04	0.06	0.05	0.05	0.03	0.02	0.01	0.01
70.45	0.52	0.01	0.01	0.02	0.05	0.08	0.10	0.09	0.09	0.05	0.03	0.02	0.02

Appendix G - Water-balance calculation

Appendix H - Chloride Mass Balance Calculation

StationID	Cl gw	Clrain	Precipitation	Dry deposition	Recharge	% Recharge
	mg/l	mg/l	mm/yr	mg/l	mm/yr	
SDC1 (i)	1274.19	2.55	398.275	6	2.67	0.67
SDC10 (i)	1437.21	2.55	398.275	6	2.37	0.59
SDC10 (ii)	1030.00	3.65	398.275	12	6.05	1.52
SDC11 (i)	2697.78	2.55	398.275	6	1.26	0.32
SDC11 (ii)	2493.00	3.65	398.275	12	2.50	0.63
SDC11 (iii)	1618.39	2.55	398.275	6	2.10	0.53
SDC12 (i)	1287.77	2.55	398.275	6	2.64	0.66
SDC12 (ii)	693.00	3.65	398.275	12	8.99	2.26
SDC12 (iii)	543.00	2.55	398.275	6	6.27	1.57
SDC2 (i)	839.75	2.55	398.275	6	4.06	1.02
SDC2 (ii)	625.00	3.65	398.275	12	9.97	2.50
SDC3 (i)	1031.39	2.55	398.275	6	3.30	0.83
SDC3 (ii)	724.00	3.65	398.275	12	8.61	2.16
SDC30 (iii)	30.00	2.55	398.275	6	113.51	28.50
SDC32 (iii)	442.95	2.55	398.275	6	7.69	1.93
SDC33 (i)	1517.88	2.55	398.275	6	2.24	0.56
SDC33 (ii)	853.00	3.65	398.275	12	7.31	1.83
SDC36 (ii)	3186.00	3.65	398.275	12	1.96	0.49
SDC36 (iii)	2174.99	2.55	398.275	6	1.57	0.39
SDC4 (i)	969.88	2.55	398.275	6	3.51	0.88
SDC40 (ii)	354.00	3.65	398.275	12	17.61	4.42
SDC41 (ii)	662.00	3.65	398.275	12	9.42	2.36
SDC42 (ii)	705.00	3.65	398.275	12	8.84	2.22
SDC43 (ii)	4882.95	3.65	398.275	12	1.28	0.32
SDC43 (iii)	4887.51	2.55	398.275	6	0.70	0.17
SDC44 (iii)	4383.48	2.55	398.275	6	0.78	0.20
SDC45 (iii)	785.40	2.55	398.275	6	4.34	1.09
SDC47 (iii)	140.00	2.55	398.275	6	24.32	6.11
SDC50 (iii)	737.77	2.55	398.275	6	4.62	1.16
SDC52 (ii)	715.00	3.65	398.275	12	8.72	2.19
SDC52 (iii)	498.79	2.55	398.275	6	6.83	1.71
SDC56 (ii)	225.00	3.65	398.275	12	27.70	6.96
SDC56 (iii)	275.00	2.55	398.275	6	12.38	3.11
SDC57 (ii)	764.00	3.65	398.275	12	8.16	2.05
SDC57 (iii)	420.95	2.55	398.275	6	8.09	2.03
SDC59 (ii)	374.00	3.65	398.275	12	16.67	4.18
SDC62 (ii)	235.00	3.65	398.275	12	26.52	6.66
SDC62 (iii)	187.08	2.55	398.275	6	18.20	4.57
SDC66 (iii)	3203.18	2.55	398.275	6	1.06	0.27
SDC67 (iii)	1501.02	2.55	398.275	6	2.27	0.57
SDC72 (iii)	250.00	2.55	398.275	6	13.62	3.42
SDC74 (iii)	296.26	2.55	398.275	6	11.49	2.89
SDC9 (ii)	1370.00	3.65	398.275	12	4.55	1.14
SDC9 (iii)	284.64	2.55	398.275	6	11.96	3.00

Appendix I - Qualified Guess of Recharge

Performed by using existing data, expert opinions and interpolation of known values

Recharge from Soil/Vegetation | Recharge from Geology | Vegter | N | ACRU | Harvest Potential | Expert's Guesses

Summary

Method	Recharge (mm/a)	%
Soil information	7.9	1.9
Geology	14.5	3.5
Vegter	20.0	4.8
Acru	70.0	16.7
Harvest Potential	15.0	3.6
From experts guesses	25.5	6.1

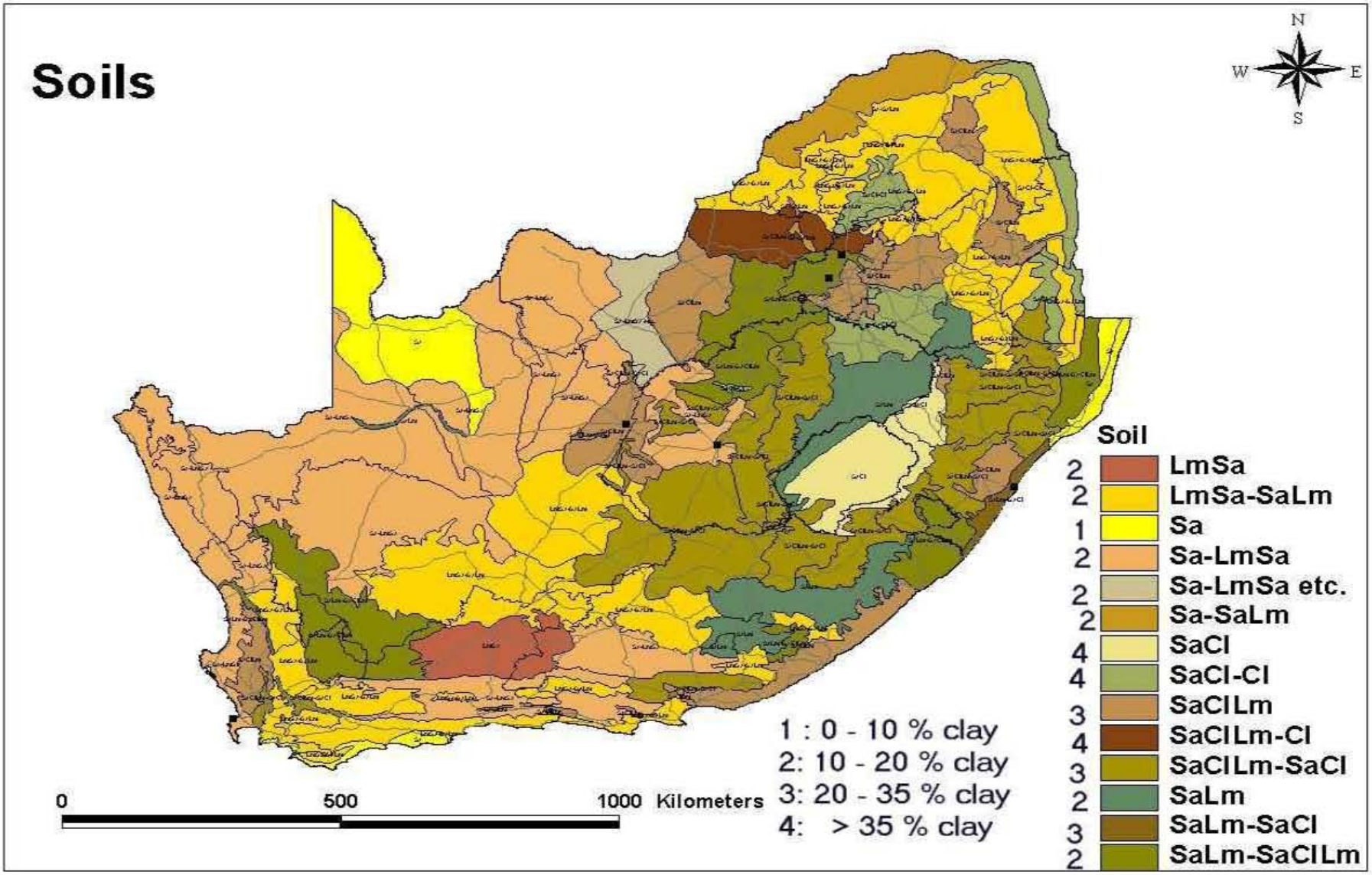
MAIN

Top

Soil/Vegetation Info

See Soil Map (next page 157)

Soil Type	% of area	%	Vegetation	
0 - 10 % clay	0	93.9	Wood/Trees/Crops	
10 - 20 % clay	59.28	4.88	Grass land	
20 - 35% clay	39	1.22	Bare	
> 35 % clay	1.72		0-10% CL	Sa (sand)
			10-20% Cl	LmSa; LmSa-SaLm; Sa-LmSa; Sa-SaLm
			20-35% Cl	SaClLm; SaClLm-SaCl
Total =	100	100	>35% Cl	SaCl; SaClLm-Cl; SaClLm-SaCl
Recharge (mm/a) =	**7.9**		**% Rech =**	**1.9**


Soils
N
W
E
S
Soil
2 LmSa
2 LmSa-SaLm
1 Sa
2 Sa-LmSa
2 Sa-LmSa etc.
2 Sa-SaLm
4 SaCl
4 SaCl-Cl
3 SaClLm
4 SaClLm-Cl
3 SaClLm-SaCl
2 SaLm
3 SaLm-SaCl
2 SaLm-SaClLm
1 : 0 - 10 % clay
2: 10 - 20 % clay
3: 20 - 35 % clay
4: > 35 % clay
0
500
1000 Kilometers

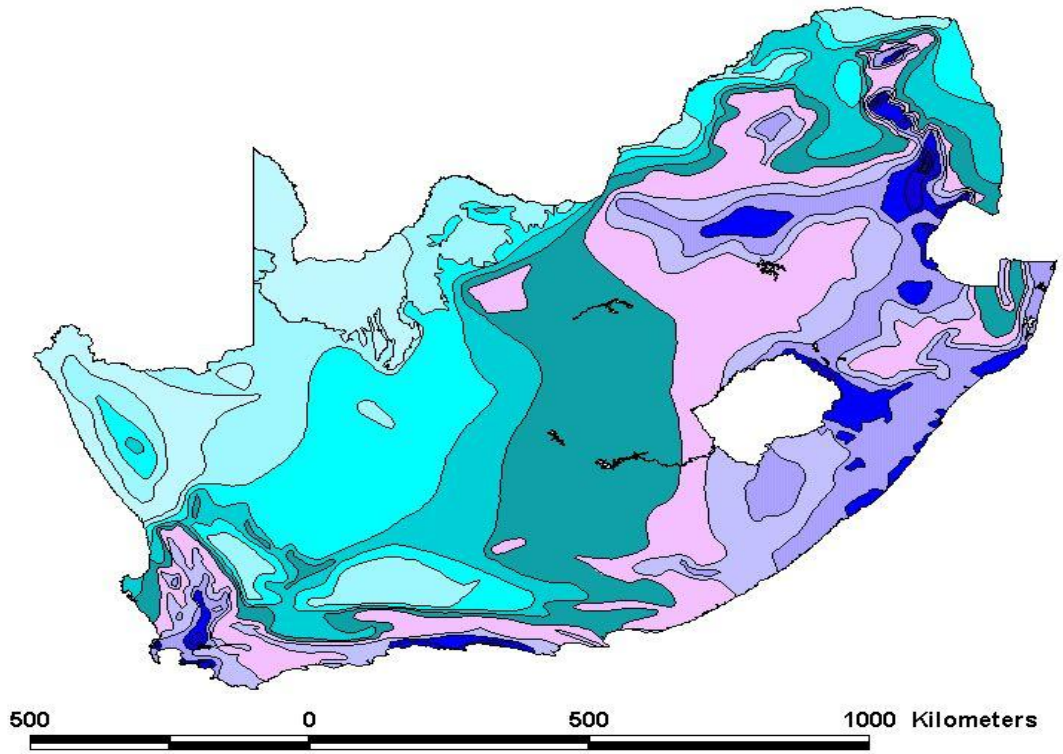
Geology	% of area	Top	Rain(mm/a) =	398.3	Slope (%)
Sandstone, mudstone, siltstone	84.43		%Soil cover < .5 m	71.96	15
Hard rock (Granite, gneiss, etc.)			%Soil cover > .5 m	28.04	50
Dolomite	0.76		Total =	100	
Calcrete					
Alluvial sand					
Alluvium	14.81				
Coastal sand					
Total =	100				
Recharge (%) =	**3.64**				
Recharge (mm/a) =	**14.51**				

Vegters Map

Top

Recharge from map =	20
Recharge (mm/a) =	20
Recharge (%) =	4.76

Groundwater Recharge (Vegter 1995)



Recharge (mm/yr)

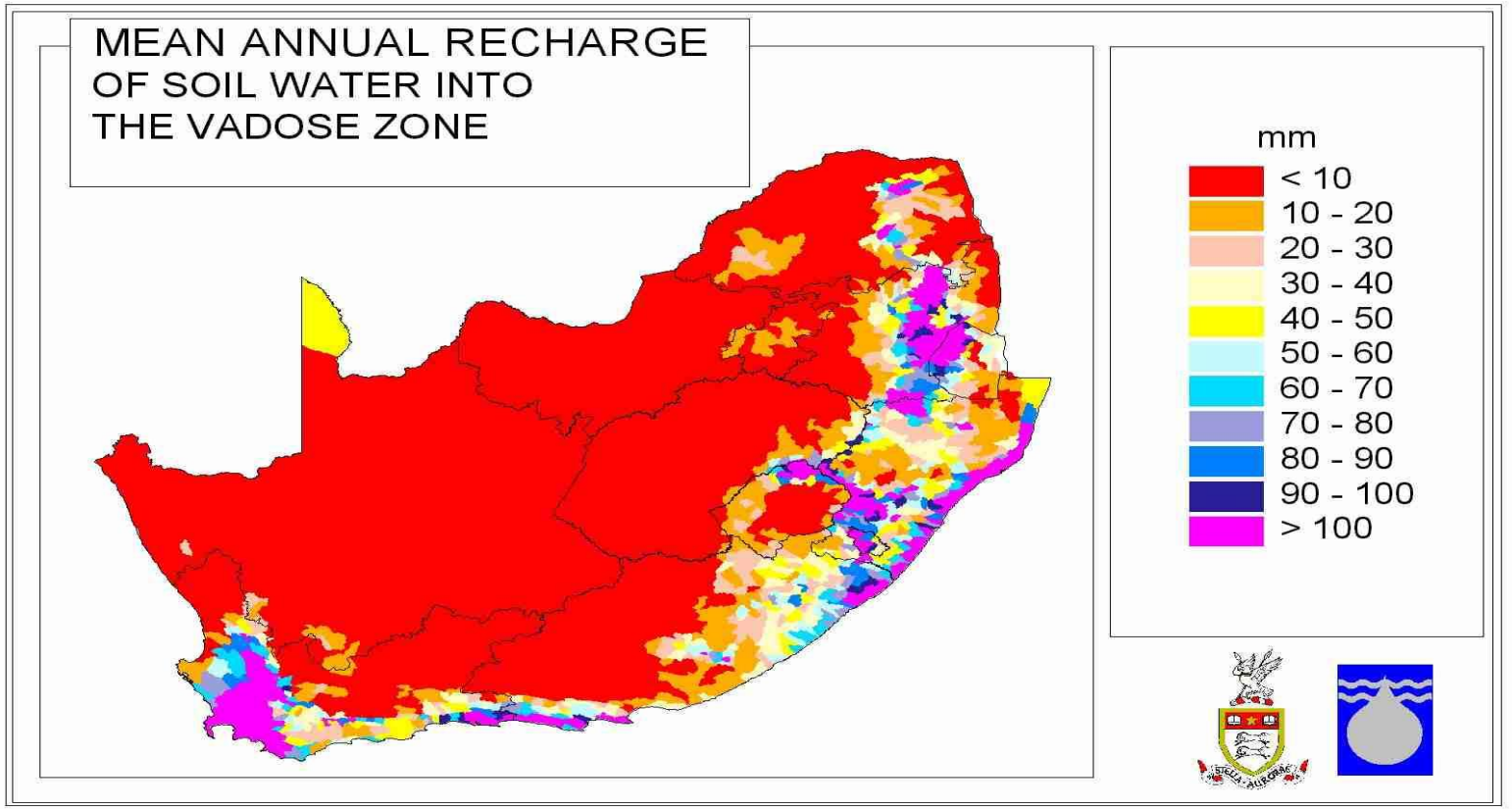
- 0.1
- 3
- 8
- 12
- 20
- 32
- 45
- 65
- 95
- 135
- 180
- 220

N
W
E
S

ACRU recharge by Roland Schulze

Top

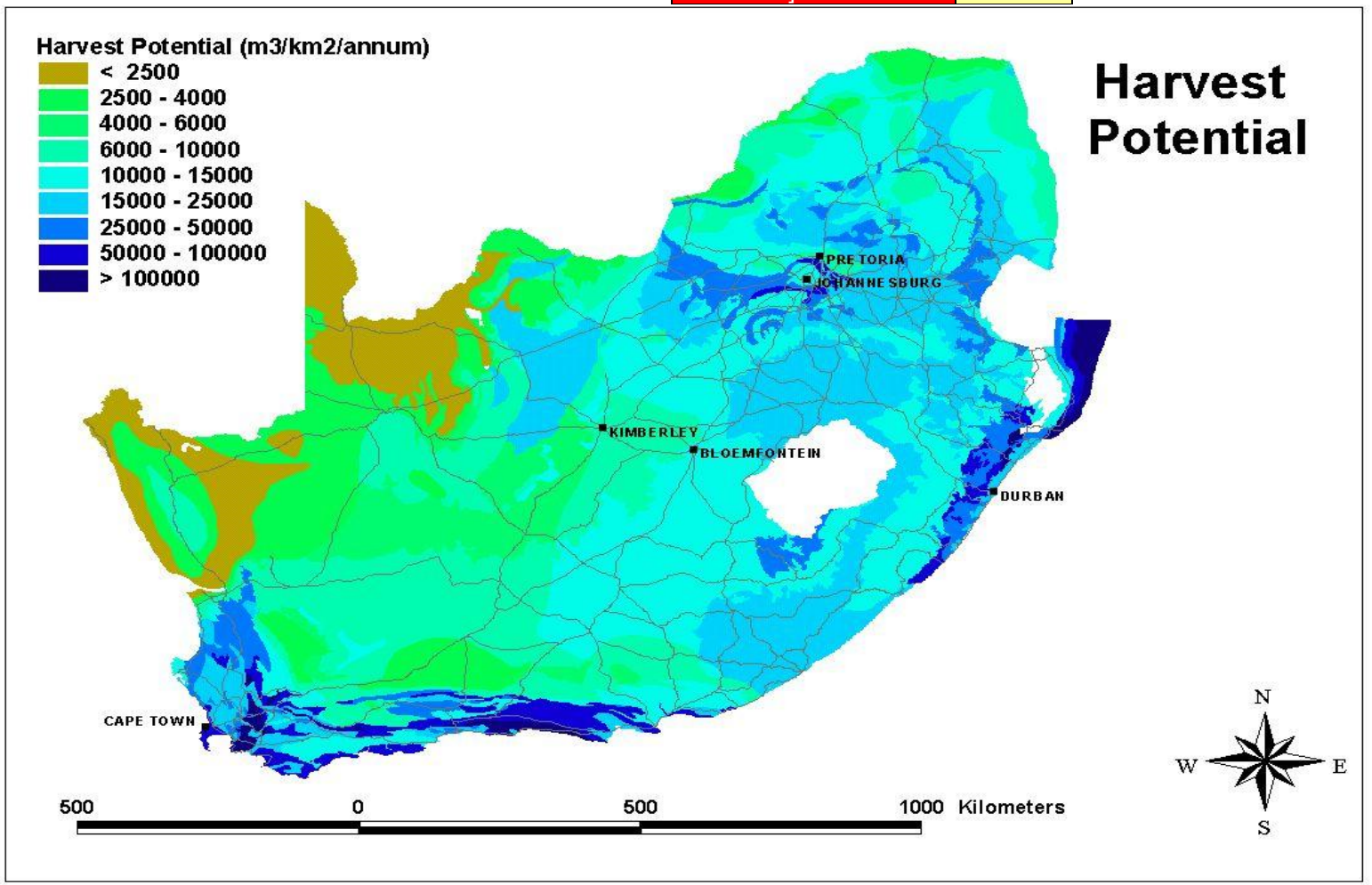
From map: **ACRU recharge**	70
Recharge (%) =	**16.67**



Harvest Potential Map

Top

Recharge (mm/a)	15.00
% Recharge	3.57
HP from Map[m3/km2/a]=	15000



Appendix J - Groundwater and surface water physical parameters measured onsite within the study catchment

Station ID	Sampling Date	Sample Location		Drainage Region	Water Source	Altitude m.amsl	DTW m.bgl	EC mS/m	TDS ppm	Temp °C	pH	DO ppm	Eh mV	Salinity	TAL mg/l
		Latitude	Longitude												
SDC1 (i)	2009/05/16	-33.20443	18.77295	G10J	GW	180	7.1	286.3	1427	20.12	6.52	2.86			94
SDC2 (i)	2009/05/17	-33.21691	18.71984	G10J	GW	204		388.5	1443	19.74	6.74	4.4		1.51	46
SDC3 (i)	2009/05/17	-33.23699	18.73843	G10J	GW	174	30	351.3	1756	14.77	7.09	4.27	-65.7	1.86	132
SDC4 (i)	2009/05/17	-33.23347	18.73771	G10J	GW	185		247.6	1238	18.47	7.19	3.56	-20.1	1.28	97
SDC5 (i)	2009/05/17	-33.23762	18.73832	G10J	GW	173	1.2								
SDC6 (i)	2009/05/17	-33.24695	18.74983	G10J	GW	174	1.58								
SDC7 (i)	2009/05/17	-33.24635	18.75061	G10J	GW	180	5.22								
SDC8 (i)	2009/05/17	-33.24667	18.74965	G10J	SW	173		502.6	2516	17.97	8.16	4.31	-75	2.72	
SDC9 (i)	2009/05/17	-33.26409	18.75432	G10J	GW	224	13.11								
SDC10 (i)	2009/05/17	-33.26888	18.75312	G10J	GW	246		508.6	2542	15.35	6.95	4.15	-16	2.75	136
SDC11 (i)	2009/05/17	-33.23829	18.75748	G10J	GW	153	9.96	812.5	4065	17.01	6.88	4.12	-12.1	4.54	124
SDC12 (i)	2009/05/17	-33.21487	18.79870	G10J	GW	137	11	236.4	1187	20.03	6.97	3.95	-23.7	1.23	43
SDC13 (i)	2009/05/17	-33.18646	18.77938	G10J	GW	132	2.05								
SDC14 (i)	2009/05/17	-33.17961	18.79060	G10J	GW	97	2.88								
SDC15 (i)	2009/05/17	-33.31025	18.89456	G10F	SW	123		37.4	186	13.86	7.04			0.18	
SDC16 (i)	2009/05/17	-33.31028	18.89447	G10F	SW	123		38.7	193	13.47	6.74			0.19	
SDC17 (i)	2009/05/17	-33.31085	18.89442	G10F	GW	127	27.83								
SDC18 (i)	2009/05/17	-33.31002	18.89522	G10F	GW	116	14.73								
SDC19 (i)	2009/05/17	-33.31001	18.89528	G10F	GW	116	14.83								
SDC20 (i)	2009/05/17	-33.30842	18.89522	G10F	GW	107	3.06	251.3	1258	22.42	7.12	3.26	-13.7	1.3	
SDC21 (i)	2009/05/17	-33.30831	18.89522	G10J	GW	106	2.9	346.8	1735	22.64	7.91	3.78	-57.2	1.82	
SDC22 (i)	2009/05/17	-33.31013	18.89279	G10F	SW	119		48.5	243	13.64	7.21			0.24	
SDC23 (i)	2009/05/17	-33.30948	18.89153	G10F	GW	121	26.27								
SDC24 (i)	2009/05/17	-33.30919	18.89474	G10F	SW	106		67.1	336	15.95	7.26	3.81	-21.1	0.33	
SDC25 (i)	2009/05/18	-33.31383	18.89153	G10F	GW	135	11.7								
SDC26 (i)	2009/05/18	-33.31385	18.89152	G10F	GW	135	12.04								

Station ID	Sampling Date	Sample Location		Drainage Region	Water Source	Altitude m.amsl	DTW m.bgl	EC mS/m	TDS ppm	Temp °C	pH	DO ppm	Eh mV	Salinity	TAL mg/l
		Latitude	Longitude												
SDC27 (i)	2009/05/18	-33.16078	18.89550	G10J	SW	51		41	205	15.06	6.96	3.96	-4.6	0.2	10
SDC28 (i)	2009/05/18	-33.20488	18.90481	G10J	SW	57		362.6	1815	16.92	7.52	3.86	-35.7	1.92	
SDC29 (i)	2009/05/18	-33.34851	18.81584	G10J	GW	271	8.41								
SDC30 (i)	2009/05/18	-33.34855	18.81582	G10J	GW	271	9.13								
SDC31 (i)	2009/05/18	-33.28572	18.77667	G10J	GW	139	1.5	263.4	1317	21.8	9.31	1.93	-134.5	1.36	
SDC32 (i)	2009/05/18	-33.25963	18.80971	G10J	GW	103	5.36	0							
SDC33 (i)	2009/05/18	-33.24908	18.82781	G10J	GW	109	1.2	297.3	1486	22.57	7.18	2.24	-17	1.55	102
SDC34 (ii)	2009/12/05	-33.34902	18.81471	G10J	GW	261	2.03	224.5	1121	22.44	6.64		13.5	1.15	
SDC35 (ii)	2009/12/05	-33.34877	18.81463	G10J	SW	265		138.5	693	20.16	7.65		-43.1	0.7	189
SDC29 (ii)	2009/12/05	-33.34852	18.81585	G10J	GW	264	6.03								
SDC30 (ii)	2009/12/05	-33.34847	18.81578	G10J	GW	264	5.46								
SDC36 (ii)	2009/12/05	-33.29258	18.80627	G10J	GW	150		986.4	4941	24.29	6.96	1.1	-4.4	5.79	224
SDC37 (ii)	2009/12/06	-33.33382	18.80282	G10J	SW	194		367.5	1845	22.4	7.83	0.14	-53.6	1.94	
SDC38 (ii)	2009/12/06	-33.34218	18.78813	G10L	GW	236	1.64								
SDC39 (ii)	2009/12/06	-33.32293	18.81326	G10J	GW	188	0.7								
SDC40 (ii)	2009/12/07	-33.34697	18.81425	G10J	GW	265	23	148.4	738	23.84	6.29	0.18	19.5	0.75	99
SDC41 (ii)	2009/12/07	-33.30441	18.78292	G10J	GW	206	20.1	325.9	1641	23.26	6.62	0.33	14.6	1.72	238
SDC42 (ii)	2009/12/07	-33.30580	18.79258	G10J	GW	173	14.12	241	1206	24.14	7.1	0.38	-12.8	1.24	17
SDC2 (ii)	2009/12/07	-33.21679	18.71979	G10J	GW	206		252.4	1264	20.43	6.48	0.53	21.8	1.31	81
SDC3 (ii)	2009/12/07	-33.23701	18.73845	G10J	GW	174		356.6	1782	23.74	6.8	0.82	2.6	1.88	308
SDC6 (ii)	2009/12/07	-33.24693	18.74986	G10J	GW	178	1.53								
SDC8 (ii)	2009/12/07	-33.24698	18.74973	G10J	SW	176		516.7	2585	24.47	7.78	1.38	-39.8	2.75	375
SDC7 (ii)	2009/12/07	-33.24632	18.75067	G10J	GW	178	5.15								
SDC9 (ii)	2009/12/07	-33.26408	18.75434	G10J	GW	221	9.51	505.7	2529	23.72	6.8	2.08	-21.8	2.73	321
SDC10 (ii)	2009/12/07	-33.26887	18.75312	G10J	GW	240		563.8	2820	29.06	6.6	1.4	12.5	3.01	248
SDC11 (ii)	2009/12/07	-33.23830	18.75749	G10J	GW	146	12.45	808.5	4002	22.76	6.76	2.47	5.7	4.34	246

Station ID	Sampling Date	Sample Location		Drainage Region	Water Source	Altitude m.amsl	DTW m.bgl	EC mS/m	TDS ppm	Temp °C	pH	DO ppm	Eh mV	Salinity	TAL mg/l
		Latitude	Longitude												
SDC27 (ii)	2009/12/08	-33.15982	18.89496	G10J	SW	51		27.8	139	23.78	7.3	5	-23.4	0.13	31
SDC43 (ii)	2009/12/08	-33.20023	18.86812	G10J	GW	60		2140	10870	22.22	6.56	3.86	13.5	12.81	391
SDC44 (ii)	2009/12/08	-33.19880	18.86546	G10J	GW	59	1								
SDC45 (ii)	2009/12/08	-33.19676	18.86043	G10J	GW	76	14.02								
SDC46 (ii)	2009/12/08	-33.19672	18.85973	G10J	GW	76	14.72								
SDC47 (ii)	2009/12/08	-33.19851	18.85443	G10J	GW	117	43.52								
SDC48 (ii)	2009/12/08	-33.19842	18.85486	G10J	GW	119	43.75								
SDC49 (ii)	2009/12/08	-33.28469	18.77376	G10J	GW	136	0.75	461.6	2303	25.37	7.42	2.91	-29	2.45	
SDC50 (ii)	2009/12/08	-33.28471	18.77383	G10J	GW	135		408.1	2039	30.11	7.39	2.6	-29.5	2.14	
SDC31 (ii)	2009/12/08	-33.28568	18.77665	G10J	GW	141	1.04	163.7	818	23.87	8.39	2.93	-85	0.83	
SDC51 (ii)	2009/12/08	-33.24327	18.78302	G10J	GW	147	5.43								
SDC12 (ii)	2009/12/09	-33.21484	18.79851	G10J	GW	136	5.81	246.9	1235	22.1	6.54	6.31	15.2	1.27	109
SDC52 (ii)	2009/12/09	-33.20368	18.80224	G10J	GW	123	13.3	284.4	1422	24.26	7.11	5.1	-31.4	1.48	206
SDC53 (ii)	2009/12/09	-33.21012	18.83463	G10J	GW	127		54.6	272	26.3	6.56	7.46	13.7	0.26	
SDC54 (ii)	2009/12/09	-33.21639	18.83215	G10J	GW	127	37.95								
SDC55 (ii)	2009/12/09	-33.23255	18.81472	G10J	GW	112		594.9	2967	21.85	6.72	8.9	4.8	3.3	
SDC56 (ii)	2009/12/09	-33.21879	18.84017	G10J	GW	125	36.51	99.9	499	22.33	6.48	7.77	21.9	0.49	43
SDC57 (ii)	2009/12/09	-33.23060	18.84752	G10J	GW	95		270.4	1350	25.13	7.56	4.59	-38.6	1.4	170
SDC58 (ii)	2009/12/09	-33.21834	18.85773	G10J	GW	74	4.36								
SDC59 (ii)	2009/12/09	-33.21008	18.84814	G10J	GW	116	20	119.9	603	23.04	6.51	9.64	5.4	0.6	30
SDC60 (ii)	2009/12/09	-33.26292	18.78106	G10J	GW	147		872.1	4377	26.88	6.97	4.29	-6.8	5.01	299
SDC32 (ii)	2009/12/10	-33.25956	18.80983	G10J	GW	105	4.85								
SDC33 (ii)	2009/12/10	-33.24906	18.82784	G10J	GW	108		297.5	1488	23.12	7.22	3.16	-19.2	1.55	195
SDC61 (ii)	2009/12/10	-33.28031	18.82084	G10J	GW	141		189.7	946	23.6	7.49	6.38	-36.2	0.96	
SDC62 (ii)	2009/12/10	-33.28446	18.82296	G10J	GW	145		75.6	379	23.8	5.33	7.27	86.7	0.37	12
SDC63 (ii)	2009/12/10	-33.28368	18.82592	G10J	GW	159	2.4								

Station ID	Sampling Date	Sample Location		Drainage Region	Water Source	Altitude m.amsl	DTW m.bgl	EC mS/m	TDS ppm	Temp °C	pH	DO ppm	Eh mV	Salinity	TAL mg/l
		Latitude	Longitude												
SDC64 (ii)	2009/12/10	-33.27698	18.82772	G10J	GW	190	13.65								
SDC65 (ii)	2009/12/10	-33.27803	18.84255	G10J	GW	137									
SDC2 (iii)	2010/05/22	-33.21682	18.71982	G10J	GW	205		277.5	1387	21.97	6.77	7.72	12.3	1.44	
SDC43 (iii)	2010/05/23	-33.20024	18.86811	G10J	GW	61		2105	10520	21.36	6.81	4.36	15.1	12.65	427
SDC66 (iii)	2010/05/23	-33.20432	18.87094	G10J	GW	73	5.21	1229	6142	22.4	6.69	1.12	24.9	7.04	356
SDC44 (iii)	2010/05/23	-33.19875	18.86531	G10J	GW	69	1.2	1928	9623	22.92	6.74	2.7	13.8	11.52	215.5
SDC45 (iii)	2010/05/23	-33.19681	18.86040	G10J	GW	60	14.02	286.8	1435	22.11	7.64	3.75	-23.2	1.5	68
SDC47 (iii)	2010/05/23	-33.19852	18.85443	G10J	GW	118	44.45	42.4	212	25	6.67	5.15	-5	0.2	22
SDC32 (iii)	2010/05/24	-33.25959	18.80982	G10J	GW	99	5.08	207.2	1035	21.28	7.9	2.09	-41	1.06	146.5
SDC67 (iii)	2010/05/24	-33.25753	18.80807	G10J	GW	116	11.08	665	3316	21.79	6.73	5.01	19.8	3.63	178
SDC68 (iii)	2010/05/24	-33.25260	18.81003	G10J	GW	104	17.98								
SDC33 (iii)	2010/05/24	-33.24908	18.82782	G10J	GW	107		282.5	1413	23.11	7.4	0.11	-14.3	1.47	219
SDC12 (iii)	2010/05/24	-33.21485	18.79846	G10J	GW	135	5.29	228.6	1144	21.17	6.77	6.23	16.9	1.18	97
SDC52 (iii)	2010/05/24	-33.20367	18.80222	G10J	GW	127	12.93	277.2	1393	22.73	7.32	6.86	-14.9	1.43	227
SDC69 (iii)	2010/05/24	-33.20818	18.82843	G10J	GW	99		380.6	1903	21.08	6.78	7.53	-4	2.02	112
SDC56 (iii)	2010/05/24	-33.21879	18.84017	G10J	GW	131	42.38	88.1	440	22.18	6.38	6.41	39.1	0.43	18.5
SDC57 (iii)	2010/05/24	-33.23057	18.84751	G10J	GW	95		247.5	1237	21.9	8.02	6.17	-43.7	1.28	148
SDC36 (iii)	2010/05/24	-33.29257	18.80636	G10J	GW	155		980.3	4900	20.46	7.26	6.35	-27.5	5.53	203
SDC70 (iii)	2010/05/25	-33.35219	18.81102	G10J	GW	284									
SDC34 (iii)	2010/05/25	-33.34907	18.81464	G10J	GW	271	3.73	233.1	1167	20.59	6.8	3.91	15.3	1.2	
SDC35 (iii)	2010/05/25	-33.34877	18.81463	G10J	SW	265		140.2	700	13.91	8.22	6.57	-53.4	0.71	208
SDC71 (iii)	2010/05/25	-33.34740	18.81976	G10J	GW	310									
SDC72 (iii)	2010/05/25	-33.34739	18.81983	G10J	GW	308	11.54	179.2	895	20.67	7.38	5.08	-13.9	0.91	192
SDC29 (iii)	2010/05/25	-33.34847	18.81578	G10J	GW	271	5.37	68.2	341	19.93	6.8	5.3	45.2	0.33	
SDC30 (iii)	2010/05/25	-33.34852	18.81581	G10J	GW	273	8.01	90.1	450	20.79	7.63	3.09	-30.9	0.44	177
SDC49 (iii)	2010/05/25	-33.28473	18.77377	G10J	GW	156	0.57	448.7	2243	22.45	6.67	4.6	20.3	2.4	

Station ID	Sampling Date	Sample Location		Drainage Region	Water Source	Altitude m.amsl	DTW m.bgl	EC mS/m	TDS ppm	Temp °C	pH	DO ppm	Eh mV	Salinity	TAL mg/l
		Latitude	Longitude												
SDC50 (iii)	2010/05/25	-33.28469	18.77378	G10J	GW	141		341.2	1704	22.1	7.97	3.83	-41.8	1.79	185
SDC9 (iii)	2010/05/25	-33.26415	18.75431	G10J	GW	224	17.15	314	1565	19.38	7.06	6.09	-2.1	1.64	323
SDC11 (iii)	2010/05/25	-33.23831	18.75748	G10J	GW	169		769.2	3848	17.79	6.94	5.12	6.9	4.28	281
SDC74 (iii)	2010/05/26	-33.35284	18.81960	G10J	GW	295	11.82	154.6	775	18.92	6.06	5.43	-7.2	0.79	124
SDC75 (iii)	2010/05/26	-33.35284	18.81968	G10J	GW	299	5.8	215.9	1080	20.62	6.28	5.13	45.4	1.11	75
SDC62 (iii)	2010/05/26	-33.28449	18.82290	G10J	GW	145		71.7	359	22.56	6.14	4.9	66	0.35	10

Major ion hydrochemical data of surface water and groundwater within the study area in units of mg/l

Station ID	Sampling Date	Sample Location		EC	TDS	pH	Ca	K	Na	Mg	Cl	F	HCO_3	NO_3+NO_2 as N	SO_4
		Latitude	Longitude	mS/m	ppm										
SDC1 (i)	2009/05/16	-33.20443	18.77295	286.3	1427	6.52	59.40	6.14	429.87	73.05	1274.19	1.47	114.63	12.65	346.31
SDC2 (i)	2009/05/17	-33.21691	18.71984	388.5	1443	6.74	34.86	19.80	411.64	65.88	839.75		56.09		168.58
SDC3 (i)	2009/05/17	-33.23699	18.73843	351.3	1756	7.09	106.70	11.70	473.09	98.58	1031.39		160.96		279.91
SDC4 (i)	2009/05/17	-33.23347	18.73771	247.6	1238	7.19	31.53	1.83	427.08	70.54	969.88	0.86	118.28	7.56	300.31
SDC10 (i)	2009/05/17	-33.26888	18.75312	508.6	2542	6.95	23.09	12.00	646.50	17.41	1437.21		165.84		30.43
SDC11 (i)	2009/05/17	-33.23829	18.75748	812.5	4065	6.88	91.39	25.29	1171.00	160.16	2697.78	0.41	151.21	10.81	201.51
SDC12 (i)	2009/05/17	-33.21487	18.79870	236.4	1187	6.97	27.99	9.08	415.96	44.12	1287.77	0.50	52.44	15.08	184.84
SDC27 (i)	2009/05/18	-33.16078	18.89550	41.0	205	6.96	7.63	5.40	57.00	10.20	165.86		12.19	25.76	78.12
SDC33 (i)	2009/05/18	-33.24908	18.82781	297.3	1486	7.18	55.64	11.45	521.33	57.16	1517.88	0.09	124.38		64.59
SDC35 (ii)	2009/12/05	-33.34877	18.81463	138.5	693	7.65	27.73	1.99	195.73	58.37	222.00	0.61	230.47	<0.05	85.20
SDC36 (ii)	2009/12/05	-33.29258	18.80627	986.4	4941	6.96	86.83	32.70	1993.97	255.73	3186.00	1.43	273.15		492.00
SDC40 (ii)	2009/12/07	-33.34697	18.81425	148.4	738	6.29	36.61	2.83	227.75	68.99	354.00	0.36	120.72	6.75	117.00
SDC41 (ii)	2009/12/07	-33.30441	18.78292	325.9	1641	6.62	100.85	8.02	373.39	121.57	662.00	0.31	290.22		138.00
SDC42 (ii)	2009/12/07	-33.30580	18.79258	241.0	1206	7.10	22.26	7.45	355.07	66.13	705.00	0.17	20.73	4.26	20.00
SDC2 (ii)	2009/12/07	-33.21679	18.71979	252.4	1264	6.48	21.21	8.76	460.93	69.30	625.00	1.34	98.77	10.10	118.00
SDC3 (ii)	2009/12/07	-33.23701	18.73845	356.6	1782	6.80	68.31	5.62	532.89	121.44	724.00	0.72	375.58		256.00
SDC8 (ii)	2009/12/07	-33.24698	18.74973	516.7	2585	7.78	93.25	7.01	814.83	167.79	1196.00	1.73	457.28	8.91	354.00
SDC9 (ii)	2009/12/07	-33.26408	18.75434	505.7	2529	6.80	140.97	5.24	696.31	180.15	1370.00	0.40	391.44	5.94	480.00
SDC10 (ii)	2009/12/07	-33.26887	18.75312	563.8	2820	6.60	173.40	5.74	659.63	200.13	1030.00	0.41	302.42	4.34	159.00
SDC11 (ii)	2009/12/07	-33.23830	18.75749	808.5	4002	6.76	78.21	26.53	1592.16	178.81	2493.00	1.34	299.98	24.40	410.00
SDC27 (ii)	2009/12/08	-33.15982	18.89496	27.8	139	7.30	6.13	3.42	39.15	7.95	48.90	0.16	37.80	0.37	9.85
SDC43 (ii)	2009/12/08	-33.20023	18.86812	2140.0	10870	6.56	216.11	24.06	4218.59	674.50	4882.95		476.79		377.00
SDC12 (ii)	2009/12/09	-33.21484	18.79851	246.9	1235	6.54	23.96	9.51	433.00	43.28	693.00		132.92		40.20
SDC52 (ii)	2009/12/09	-33.20368	18.80224	284.4	1422	7.11	35.29	12.63	509.22	56.00	715.00		251.20		78.30
SDC56 (ii)	2009/12/09	-33.21879	18.84017	99.9	499	6.48	10.14	18.25	172.24	24.07	225.00	0.31	52.44	18.60	50.70
SDC57 (ii)	2009/12/09	-33.23060	18.84752	270.4	1350	7.56	9.01	9.00	609.22	26.34	764.00	1.30	207.30		87.30
SDC59 (ii)	2009/12/09	-33.21008	18.84814	119.9	603	6.51	32.80	2.24	117.72	63.85	374.00	0.20	36.58	2.35	19.40
SDC33 (ii)	2009/12/10	-33.24906	18.82784	297.5	1488	7.22	44.68	11.03	498.01	55.07	853.00	0.55	237.79		105.00
SDC62 (ii)	2009/12/10	-33.28446	18.82296	75.6	379	5.33	5.04	5.77	136.95	14.92	235.00		14.63	4.17	18.60

Station ID	Sampling Date	Sample Location		Water Source	EC mS/m	TDS ppm	pH	Ca	K	Na	Mg	Cl	F	HCO_3	NO_3+NO_2 as N	SO_4
		Latitude	Longitude													
SDC43 (iii)	2010/05/23	-33.20024	18.86811	GW	2105.0	10520	6.81	236.50	22.49	3840.03	589.75	4887.51	0.94	520.69	2.10	420.00
SDC66 (iii)	2010/05/23	-33.20432	18.87094	GW	1229.0	6142	6.69	129.96	13.69	1950.97	324.54	3203.18	0.48	434.12	0.06	85.00
SDC44 (iii)	2010/05/23	-33.19875	18.86531	GW	1928.0	9623	6.74	508.64	17.16	2661.73	900.94	4383.48	0.23	262.79	0.04	888.00
SDC45 (iii)	2010/05/23	-33.19681	18.86040	GW	286.8	1435	7.64	67.12	5.41	377.80	75.47	785.40	0.19	82.92	0.08	40.60
SDC47 (iii)	2010/05/23	-33.19852	18.85443	GW	42.4	212	6.67	1.27	5.88	48.71	8.26	140.00	0.49	26.83	2.42	20.60
SDC32 (iii)	2010/05/24	-33.25959	18.80982	GW	207.2	1035	7.90	50.23	5.27	262.43	45.92	442.95	0.08	178.65	0.07	49.40
SDC67 (iii)	2010/05/24	-33.25753	18.80807	GW	665.0	3316	6.73	88.52	22.02	1088.39	162.35	1501.02	0.23	217.06	13.41	223.00
SDC12 (iii)	2010/05/24	-33.21485	18.79846	GW	228.6	1144	6.77	22.90	8.34	371.51	37.47	543.00	0.26	118.28	1.94	40.30
SDC52 (iii)	2010/05/24	-33.20367	18.80222	GW	277.2	1393	7.32	38.29	10.51	438.05	47.31	498.79	0.77	276.81	0.67	81.80
SDC56 (iii)	2010/05/24	-33.21879	18.84017	GW	88.1	440	6.38	10.72	21.56	116.77	18.68	275.00	0.78	22.56	8.56	21.00
SDC57 (iii)	2010/05/24	-33.23057	18.84751	GW	247.5	1237	8.02	6.92	7.81	506.89	20.54	420.95	1.19	180.47	0.22	92.00
SDC36 (iii)	2010/05/24	-33.29257	18.80636	GW	980.3	4900	7.26	83.13	35.00	1711.40	238.51	2174.99	1.21	247.54	4.23	404.00
SDC72 (iii)	2010/05/25	-33.34739	18.81983	GW	179.2	895	7.38	112.51	2.59	158.07	62.05	250.00	0.28	234.13	0.10	359.00
SDC30 (iii)	2010/05/25	-33.34852	18.81581	GW	90.1	450	7.63	35.88	1.40	83.12	25.15	30.00	0.23	215.84	0.05	10.31
SDC50 (iii)	2010/05/25	-33.28469	18.77378	GW	341.2	1704	7.97	57.06	6.30	505.09	70.84	737.77	1.77	225.59	0.08	99.50
SDC9 (iii)	2010/05/25	-33.26415	18.75431	GW	314.0	1565	7.06	109.87	3.76	410.51	99.54	284.64	0.48	393.87	0.32	262.00
SDC11 (iii)	2010/05/25	-33.23831	18.75748	GW	769.2	3848	6.94	82.63	21.58	1291.53	150.47	1618.39	1.29	342.66	13.45	326.00
SDC74 (iii)	2010/05/26	-33.35284	18.81960	GW	154.6	775	6.06	51.63	2.11	170.20	49.26	296.26	0.29	151.21	0.44	53.60
SDC62 (iii)	2010/05/26	-33.28449	18.82290	GW	71.7	359	6.14	12.10	4.78	101.70	12.05	187.08	0.04	12.19	9.06	20.00

Trace element hydrochemical data of surface water and groundwater within the study area in units of ppb

Station ID	Sampling Date	Sample Location		As	Ba	Cr	Cu	Fe	Hg	Mn	Mo	Ni	Pb	Sr	Zn	Co	Se	Li	Al	Cs	Ag	Cd
		Latitude	Longitude																			
SDC1 (i)	2009/05/16	-33.20443	18.77295	3	19	4	11	143	3	2		3		572	15							
SDC4 (i)	2009/05/17	-33.23347	18.73771	3	29	4	7	281	1	32		2	1	418	299							
SDC11 (i)	2009/05/17	-33.23829	18.75748	10	41	5	16	100	1	3	1	5	1	1491	28							
SDC12 (i)	2009/05/17	-33.21487	18.79870	4	10	3	9	87		46		2	1	396	552							
SDC27 (i)	2009/05/18	-33.16078	18.89550	1	23	2	5	74		2		2		114	10		2					
SDC33 (i)	2009/05/18	-33.24908	18.82781	4	4	4	7	248		146		3		596	107							
SDC8 (ii)	2009/12/07	-33.24698	18.74973	8	71	26	15	376		14	1	4	2	1143	24		38		20			
SDC27 (ii)	2009/12/08	-33.15982	18.89496	1	50	2	3	572	1	83	0	2	1	126	38	0	1	2	26	1		
SDC35 (ii)	2009/12/05	-33.34877	18.81463	3	46	2	4	138	0	171	0	2	1	324	6	1	6	0	4	0		
SDC36 (ii)	2009/12/05	-33.29258	18.80627	13	7	7	27	516		25	2	4		1629	476	0	74	37	5	1		
SDC40 (ii)	2009/12/07	-33.34697	18.81425	4	31	7	8	167		416	1	16		429	27	5	9	10	4	9		
SDC41 (ii)	2009/12/07	-33.30441	18.78292	3	4	2	6	377		147	0	6		1147	37	0	16	18	7	5		
SDC42 (ii)	2009/12/07	-33.30580	18.79258	3	124	0	8	58		53	0	9		399	182	4	13	5	41	0		
SDC2 (ii)	2009/12/07	-33.21679	18.71979	3	11	0	9	169		2	0	1		473	25	0	19	8	3	0		
SDC3 (ii)	2009/12/07	-33.23701	18.73845	3	54	4	9	233		483	1	27		1363	18	9	42	18	5	9		
SDC9 (ii)	2009/12/07	-33.26408	18.75434	8	67	4	13	573	10	1711	23	31		1539	73	24	58	29	3	16		
SDC10 (ii)	2009/12/07	-33.26887	18.75312	6	51	9	11	749	6	551	8	26		1918	108	9	90	34	3	7		
SDC11 (ii)	2009/12/07	-33.23830	18.75749	8	57	8	23	341	4	1	1	4		1272	32	0	59	22	12	0		
SDC43 (ii)	2009/12/08	-33.20023	18.86812	36	116	27	62	3192	2	805	1	9	2	12793	25	1	115	124	18	10		
SDC12 (ii)	2009/12/09	-33.21484	18.79851	2	15	6	14	122	1	12		1		374	72	0	17	13	3	0		
SDC52 (ii)	2009/12/09	-33.20368	18.80224	3	27	7	9	579		185	1	1		524	18	0	12	18	3	1		
SDC56 (ii)	2009/12/09	-33.21879	18.84017	1	81	2	8	190		73		11	1	164	93	0	5	6	15	0		
SDC57 (ii)	2009/12/09	-33.23060	18.84752	15	4	6	12	46		67	4	0	0	384	15	0	15	30	4	2		
SDC59 (ii)	2009/12/09	-33.21008	18.84814	2	30	2	6	140		11		2	0	514	16	0	9	21	8	0		
SDC33 (ii)	2009/12/10	-33.24906	18.82784	3	26	6	8	551		146		1	0	545	10	0	12	14	5	1		

Station ID	Sampling Date	Sample Location		As	Ba	Cr	Cu	Fe	Hg	Mn	Mo	Ni	Pb	Sr	Zn	Co	Se	Li	Al	Cs	Ag	Cd
		Latitude	Longitude																			
SDC62 (ii)	2009/12/10	-33.28446	18.82296	1	65	2	4	693		96		8		105	27	4	4	3	9	0		
SDC43 (iii)	2010/05/23	-33.20024	18.86811	52	117	125	84	3408	366	712	1	22		11302	51		33	117	194	13	6	
SDC66 (iii)	2010/05/23	-33.20432	18.87094	19	143	27	52	2433	205			23		4299		1		20	8	3	5	
SDC44 (iii)	2010/05/23	-33.19875	18.86531	44	92	10	47	6031	133	7822		13		35567		3		228		13	3	
SDC45 (iii)	2010/05/23	-33.19681	18.86040	5	43	4	8	1382	9	120		2		4090			13	52	34			
SDC47 (iii)	2010/05/23	-33.19852	18.85443	0	138	5	14	285	6	9		2	1	71	107		0	0	12			
SDC32 (iii)	2010/05/24	-33.25959	18.80982	2	107	3	5	925	4	365				5513	0		9	46	21			
SDC67 (iii)	2010/05/24	-33.25753	18.80807	12	27	14	13	608	3			3		1596	4		44	25	1			
SDC12 (iii)	2010/05/24	-33.21485	18.79846	2	50	16	10	391	1			3		337	213		6	5	8			
SDC52 (iii)	2010/05/24	-33.20367	18.80222	4	43	14	7	614		157		2		490	7			14		1		
SDC56 (iii)	2010/05/24	-33.21879	18.84017	0	198	14	14	509				4		160	164		8		17			
SDC57 (iii)	2010/05/24	-33.23057	18.84751	15	40	6	9	377		33	4	2		322	4		8	24	35	2		
SDC36 (iii)	2010/05/24	-33.29257	18.80636	12	38	38	43	4041				10		1610	321		106	8	148	1	1	
SDC72 (iii)	2010/05/25	-33.34739	18.81983	4	75	7	7	839	35	694	1	4		832	8		17	18	8	4	1	
SDC30 (iii)	2010/05/25	-33.34852	18.81581	1	57	6	5	19572	19	1338		1		325	1		15	6	7	1	1	
SDC50 (iii)	2010/05/25	-33.28469	18.77378	6	81	10	8	635	13	217				2430			19	87	19	7		
SDC9 (iii)	2010/05/25	-33.26415	18.75431	8	49	11	8	475	8	536	24	13		1078	47	2	49	23	3	10		
SDC11 (iii)	2010/05/25	-33.23831	18.75748	12	80	12	34	1057	6	87	1	4		1204	219		54	19	48			1
SDC74 (iii)	2010/05/26	-33.35284	18.81960	3	54	5	6	322	3	685		6		591	15	1	14	18	9	1		
SDC62 (iii)	2010/05/26	-33.28449	18.82290	0	63	16	6	1290	2	79		7		97	322	4	18		8			

Appendix K - Reaction error, percentage sodium, sodium adsorption ratio, and hardness of surface water and groundwater hydrochemical data within the study catchment, units in meq/l

Station ID	Sampling Date	Sample Location		Ca	K	Na	Mg	Cl	F	NO_3+NO_2 as N	SO_4	HCO_3	SAR	Hardness mg/l $CaCO_3$	Water-types	Na%	Reaction Error (%)
		Latitude	Longitude														
SDC1 (i)	2009/05/16	-33.20443	18.77295	2.964	0.164	18.699	6.009	35.945	0.077	0.204	7.210	1.879	8.828	448.659	Na-Cl	67.765	-23.894
SDC2 (i)	2009/05/17	-33.21691	18.71984	1.740	0.528	17.906	5.419	23.689			3.510	0.919	9.465	357.940	Na-Mg-Cl	72.029	-4.702
SDC3 (i)	2009/05/17	-33.23699	18.73843	5.324	0.312	20.579	8.109	29.096			5.828	2.638	7.941	671.676	Na-Mg-Cl	60.864	-4.502
SDC4 (i)	2009/05/17	-33.23347	18.73771	1.573	0.049	18.578	5.802	27.360	0.045	0.122	6.252	1.939	9.674	368.774	Na-Cl-SO_4	71.635	-15.743
SDC10 (i)	2009/05/17	-33.26888	18.75312	1.152	0.320	28.123	1.432	40.544			0.634	2.718	24.740	129.217	Na-Cl	91.671	-17.175
SDC11 (i)	2009/05/17	-33.23829	18.75748	4.561	0.674	50.939	13.175	76.104	0.022	0.174	4.195	2.478	17.106	886.758	Na-Cl	74.426	-8.946
SDC12 (i)	2009/05/17	-33.21487	18.79870	1.397	0.242	18.094	3.629	36.328	0.026	0.243	3.848	0.859	11.414	251.287	Na-Cl	78.487	-27.747
SDC27 (i)	2009/05/18	-33.16078	18.89550	0.380	0.144	2.480	0.839	4.679		0.416	1.626	0.200	3.175	60.985	Na-Cl-SO_4	68.264	-28.590
SDC33 (i)	2009/05/18	-33.24908	18.82781	2.776	0.305	22.678	4.702	42.819	0.005		1.345	2.039	11.728	373.922	Na-Cl	75.450	-20.538
SDC8 (ii)	2009/12/07	-33.24698	18.74973	4.653	0.187	35.445	13.803	33.739	0.091	0.144	7.370	7.495	11.668	922.805	Na-Mg-Cl	65.878	5.097
SDC27 (ii)	2009/12/08	-33.15982	18.89496	0.306	0.091	1.703	0.654	1.379	0.009	0.006	0.205	0.620	2.458	48.003	Na-Mg-Cl-HCO_3	65.143	10.697
SDC35 (ii)	2009/12/05	-33.34877	18.81463	1.384	0.053	8.514	4.801	6.263	0.032	0.001	1.774	3.777	4.842	309.242	Na-Mg-Cl-HCO_3	58.075	10.906
SDC36 (ii)	2009/12/05	-33.29258	18.80627	4.333	0.872	86.738	21.037	89.877	0.075	0.001	10.243	4.477	24.354	1268.467	Na-Cl	77.545	3.814
SDC40 (ii)	2009/12/07	-33.34697	18.81425	1.827	0.075	9.907	5.675	9.986	0.019	0.109	2.436	1.979	5.115	375.089	Na-Mg-Cl	57.094	9.215
SDC41 (ii)	2009/12/07	-33.30441	18.78292	5.032	0.214	16.243	10.001	18.675	0.017	0.001	2.873	4.757	5.924	751.653	Na-Mg-Cl	52.260	8.932
SDC42 (ii)	2009/12/07	-33.30580	18.79258	1.111	0.199	15.446	5.440	19.888	0.009	0.069	0.416	0.340	8.534	327.542	Na-Mg-Cl	70.485	3.426
SDC2 (ii)	2009/12/07	-33.21679	18.71979	1.058	0.234	20.050	5.701	17.631	0.070	0.163	2.457	1.619	10.907	337.952	Na-Mg-Cl	75.006	10.394
SDC3 (ii)	2009/12/07	-33.23701	18.73845	3.409	0.150	23.181	9.990	20.424	0.038	0.001	5.330	6.156	8.956	669.933	Na-Mg-Cl	63.520	6.954
SDC9 (ii)	2009/12/07	-33.26408	18.75434	7.034	0.140	30.289	14.819	38.648	0.021	0.096	9.994	6.416	9.163	1092.658	Na-Mg-Cl	58.202	-2.693
SDC10 (ii)	2009/12/07	-33.26887	18.75312	8.653	0.153	28.694	16.463	29.056	0.021	0.070	3.310	4.957	8.097	1255.792	Na-Mg-Cl	53.457	18.103
SDC11 (ii)	2009/12/07	-33.23830	18.75749	3.902	0.708	69.259	14.708	70.328	0.070	0.394	8.536	4.917	22.704	930.546	Na-Cl	78.989	2.505
SDC43 (ii)	2009/12/08	-33.20023	18.86812	10.784	0.642	183.509	55.484				7.849	7.815	31.880	3313.407	Na-Mg	73.537	
SDC12 (ii)	2009/12/09	-33.21484	18.79851	1.196	0.254	18.835	3.560	19.550		0.001	0.837	2.179	12.214	237.795	Na-Cl	80.055	2.742
SDC52 (ii)	2009/12/09	-33.20368	18.80224	1.761	0.337	22.151	4.607	20.170		0.001	1.630	4.117	12.414	318.375	Na-Cl	77.933	5.354
SDC56 (ii)	2009/12/09	-33.21879	18.84017	0.506	0.487	7.492	1.980	6.347	0.016	0.300	1.056	0.859	6.720	124.294	Na-Mg-Cl	76.245	9.881
SDC57 (ii)	2009/12/09	-33.23060	18.84752	0.449	0.240	26.501	2.166	21.552	0.069	0.001	1.818	3.398	23.173	130.788	Na-Cl	91.090	4.469

Station ID	Sampling Date	Sample Location		Ca	K	Na	Mg	Cl	F	NO_3+NO_2 as N	SO_4	HCO_3	SAR	Hardness mg/l $CaCO_3$	Water-types	Na%	Reaction Error (%)
		Latitude	Longitude														
SDC59 (ii)	2009/12/09	-33.21008	18.84814	1.636	0.060	5.121	5.252	10.551	0.010	0.038	0.404	0.600	2.759	344.430	Na-Mg-Cl	42.923	1.905
SDC33 (ii)	2009/12/10	-33.24906	18.82784	2.229	0.294	21.663	4.530	24.063	0.029	0.001	2.186	3.897	11.784	337.954	Na-Cl	76.463	-2.486
SDC62 (ii)	2009/12/10	-33.28446	18.82296	0.252	0.154	5.957	1.227	6.629	0.005	0.067	0.387	0.240	6.928	73.950	Na-Cl	80.514	1.733
SDC43 (iii)	2010/05/23	-33.20024	18.86811	11.801	0.600	167.041	48.513	137.877	0.049	0.034	8.744	8.534	30.418	3015.689	Na-Mg-Cl	73.541	18.977
SDC66 (iii)	2010/05/23	-33.20432	18.87094	6.485	0.365	84.867	26.697	90.362	0.025	0.001	1.770	7.115	20.836	1659.087	Na-Mg-Cl	71.978	8.793
SDC44 (iii)	2010/05/23	-33.19875	18.86531	25.381	0.458	115.785	74.112	123.658	0.012	0.001	18.488	4.307	16.416	4974.627	Na-Mg-Cl	53.882	19.125
SDC45 (iii)	2010/05/23	-33.19681	18.86040	3.349	0.144	16.434	6.208	22.156	0.010	0.001	0.845	1.359	7.518	477.878	Na-Mg-Cl	63.432	3.493
SDC47 (iii)	2010/05/23	-33.19852	18.85443	0.063	0.157	2.119	0.679	3.949	0.026	0.039	0.429	0.440	3.477	37.129	Na-Cl	75.396	-23.602
SDC32 (iii)	2010/05/24	-33.25959	18.80982	2.507	0.140	11.416	3.778	12.495	0.004	0.001	1.029	2.928	6.440	314.214	Na-Mg-Cl	64.775	4.033
SDC67 (iii)	2010/05/24	-33.25753	18.80807	4.417	0.587	47.345	13.355	42.344	0.012	0.216	4.643	3.558	15.883	888.595	Na-Mg-Cl	72.952	12.819
SDC12 (iii)	2010/05/24	-33.21485	18.79846	1.143	0.222	16.161	3.082	15.318	0.014	0.031	0.839	1.939	11.119	211.250	Na-Cl	79.498	6.367
SDC52 (iii)	2010/05/24	-33.20367	18.80222	1.911	0.280	19.055	3.891	14.071	0.041	0.011	1.703	4.537	11.187	290.113	Na-Cl	76.918	10.496
SDC56 (iii)	2010/05/24	-33.21879	18.84017	0.535	0.575	5.079	1.536	7.758	0.041	0.138	0.437	0.370	4.992	103.544	Na-Cl	73.194	-6.183
SDC57 (iii)	2010/05/24	-33.23057	18.84751	0.345	0.208	22.050	1.690	11.875	0.063	0.004	1.915	2.958	21.858	101.763	Na-Cl	91.622	18.193
SDC36 (iii)	2010/05/24	-33.29257	18.80636	4.148	0.933	74.446	19.620	61.356	0.064	0.068	8.411	4.057	21.595	1188.383	Na-Mg-Cl	76.028	14.552
SDC72 (iii)	2010/05/25	-33.34739	18.81983	5.614	0.069	6.876	5.104	7.053	0.015	0.002	7.474	3.837	2.970	535.925	Na-Ca-Mg-SO4-Cl-HCO_3	39.318	-1.989
SDC30 (iii)	2010/05/25	-33.34852	18.81581	1.790	0.037	3.616	2.069	0.846	0.012	0.001	0.215	3.538	2.603	192.953	Na-Mg-Ca-HCO_3	48.630	23.929
SDC50 (iii)	2010/05/25	-33.28469	18.77378	2.847	0.168	21.972	5.827	20.812	0.093	0.001	2.072	3.697	10.550	433.714	Na-Mg-Cl	71.849	7.198
SDC9 (iii)	2010/05/25	-33.26415	18.75431	5.483	0.100	17.857	8.188	8.030	0.025	0.005	5.455	6.456	6.830	683.550	Na-Mg-Ca-Cl-HCO_3-SO_4	56.776	22.594
SDC11 (iii)	2010/05/25	-33.23831	18.75748	4.123	0.575	56.182	12.378	45.655	0.068	0.217	6.787	5.616	19.559	825.061	Na-Cl	77.475	11.333
SDC74 (iii)	2010/05/26	-33.35284	18.81960	2.576	0.056	7.404	4.052	8.358	0.015	0.007	1.116	2.478	4.067	331.436	Na-Mg-Cl	52.950	8.114
SDC62 (iii)	2010/05/26	-33.28449	18.82290	0.604	0.127	4.424	0.991	5.278	0.002	0.146	0.416	0.200	4.954	79.753	Na-Cl	74.048	0.856

Appendix L - Major ion hydrochemical data of DWA boreholes within the study area in units of meq/l

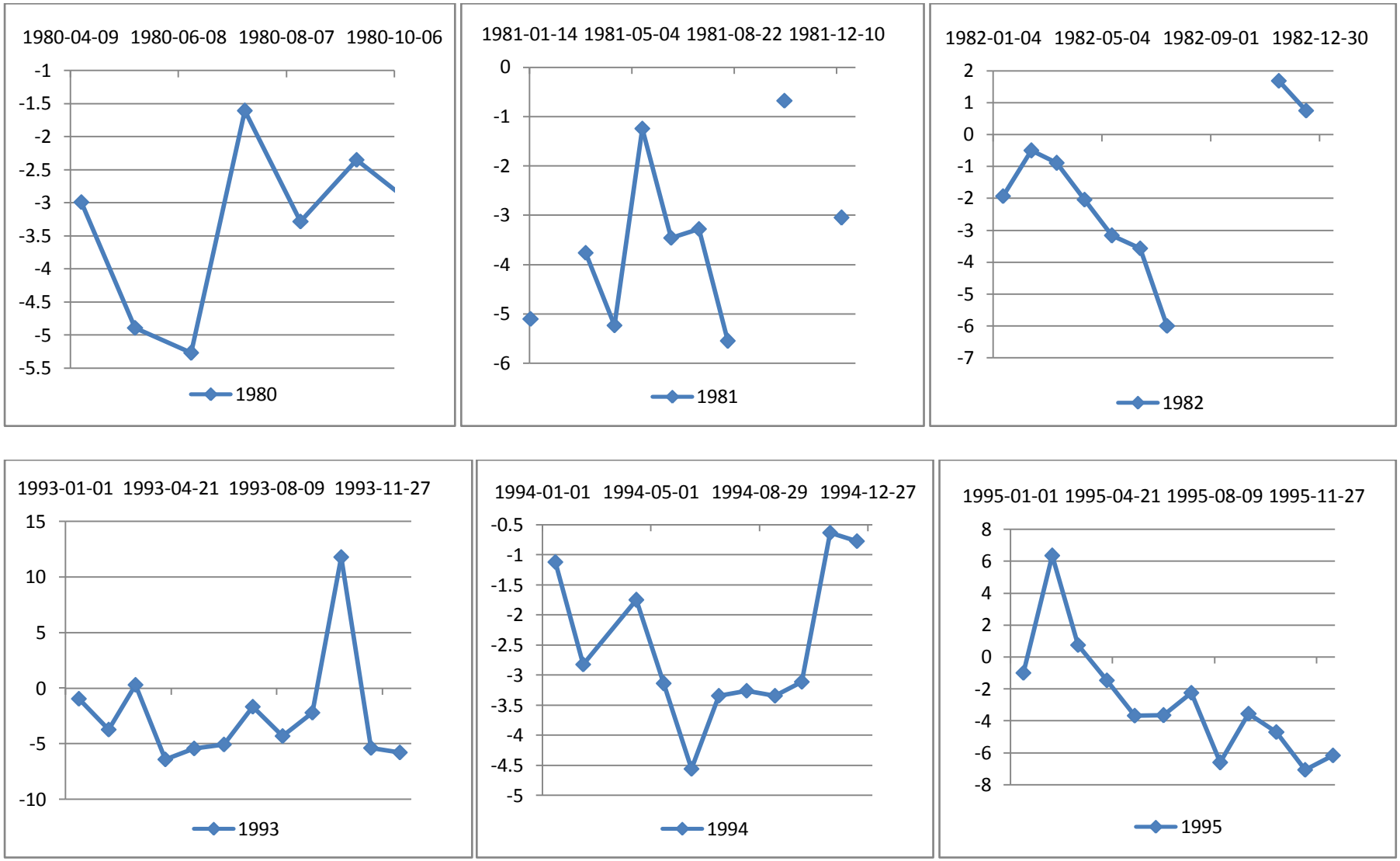
Station ID	Sampling Date	Sample Location		TDS	EC	pH	Ca	K	Na	Mg	Cl	F	NO_3+NO_2 as N	SO_4	HCO_3	Hardness mg/l $CaCO_3$	SAR	Water types	Na%	Reaction Error (%)
		Latitude	Longitude	ppm	mS/m															
96183	1990/10/08	-33.34472	18.81611	327	61	7.28	0.554	0.046	3.263	1.662	4.663	0.012	0.033	0.225	0.451	110.57	3.100	Na-Mg-Cl	59.894	0.013
96180	1990/10/08	-33.31083	18.83528	1201	193	7.82	4.905	0.066	9.835	3.833	13.955	0.033	0.000	1.657	3.396	436.81	4.705	Na-Ca-Mg-Cl	53.119	-0.011
96181	1990/10/08	-33.30667	18.79361	1798	316	6.88	2.191	0.262	20.580	8.218	30.171	0.012	0.061	1.272	0.310	519.34	9.021	Na-Mg-Cl	66.694	-0.009
96178	1990/10/08	-33.27750	18.78056	3825	642	7.52	5.514	0.254	43.757	15.662	56.804	0.051	0.009	4.882	3.453	1056.89	13.447	Na-Mg-Cl	67.515	-0.0001
167647	1990/10/08	-33.27000	18.83417	2003	361	7.65	5.115	0.206	19.853	9.452	30.571	0.019	0.059	1.582	1.957	727.34	7.357	Na-Mg-Cl	57.932	0.006
96179	1990/10/08	-33.25389	18.85528	2029	313	7.68	0.758	0.279	29.554	2.986	28.097	0.098	0.044	1.915	2.498	186.83	21.599	Na-Cl	88.848	0.014
96177	1990/10/08	-33.25194	18.77083	3625	667	3.11	5.424	0.750	33.169	25.690	63.207	0.014	0.000	3.242	0.208	1552.18	8.409	Na-Mg-Cl	52.156	-0.012
167638	1990/10/08	-33.24917	18.72889	2722	372	7.88	4.461	0.129	28.371	11.270	33.987	0.061	0.092	6.927	3.691	785.2	10.116	Na-Mg-Cl	64.435	-0.006
96157	1990/10/09	-33.24333	18.78389	1743	309	7.40	1.996	0.216	21.011	7.321	27.984	0.026	0.081	0.583	1.082	464.9	9.734	Na-Mg-Cl	69.496	0.013
96159	1990/10/09	-33.23167	18.82056	2688	493	7.94	2.625	0.582	33.343	8.999	42.625	0.018	0.019	2.461	1.377	580.04	13.831	Na-Cl	74.480	-0.010
96160	1990/10/09	-33.22417	18.82333	619	109.4	7.59	0.424	0.197	7.499	2.361	10.122	0.011	0.041	0.481	0.115	138.92	6.355	Na-Mg-Cl	73.428	-0.014
96155	1990/10/09	-33.19444	18.85917	1084	164	7.72	1.153	0.157	13.328	3.151	16.032	0.017	0.012	1.126	1.134	214.78	9.086	Na-Cl	75.808	-0.015
96156	1990/10/09	-33.18556	18.86611	5371	827	7.60	3.124	0.462	74.094	14.371	81.634	0.048	0.398	4.226	2.772	872.77	25.052	Na-Cl	80.995	0.016
169361	1992/04/24	-33.34417	18.81861	464	90.3	7.97	1.193	0.059	4.446	2.287	6.249	0.029	0.041	0.581	0.621	173.73	3.371	Na-Mg-Cl	56.419	0.030

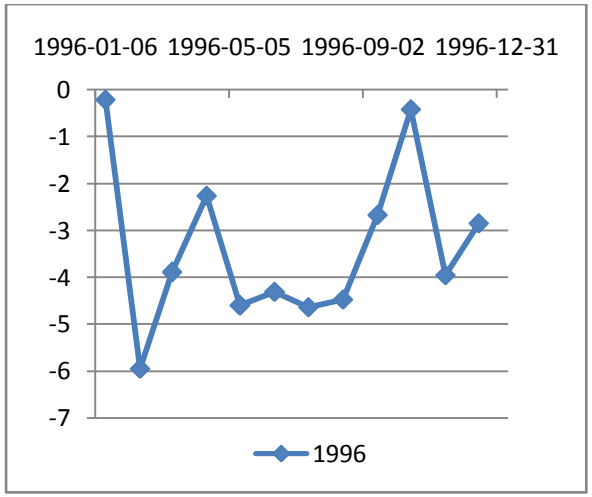
Appendix M - Rock source deduction of groundwater within the study catchment, units in meq/l

Station ID	Sampling Date	Sample Location		EC	TDS					
		Latitude	Longitude	mS/m	ppm	(Na+K-Cl)/(Na+K+Ca-Cl)	Na/(Na+Cl)	Mg/(Ca+Mg)	Cl/Sum Anion	HCO_3/Sum Anion
SDC47 (iii)	2010/05/23	-33.19852	18.85443	42.4	212	1.039	0.349	0.670	0.184	0.767
SDC62 (iii)	2010/05/26	-33.28449	18.82290	71.7	359	5.933	0.456	0.757	0.384	0.209
SDC62 (ii)	2009/12/10	-33.28446	18.82296	75.6	379	1.944	0.473	0.604	0.402	0.323
SDC56 (iii)	2010/05/24	-33.21879	18.84017	88.1	440	1.341	0.396	0.787	0.499	0.035
SDC30 (iii)	2010/05/25	-33.34852	18.81581	90.1	450	0.611	0.810	0.554	0.639	0.193
SDC56 (ii)	2009/12/09	-33.21879	18.84017	99.9	499	0.763	0.541	0.743	0.662	0.035
SDC59 (ii)	2009/12/09	-33.21008	18.84814	119.9	603	1.438	0.327	0.722	0.687	0.136
SDC40 (ii)	2009/12/07	-33.34697	18.81425	148.4	738	-0.002	0.498	0.629	0.691	0.223
SDC74 (iii)	2010/05/26	-33.35284	18.81960	154.6	775	-0.534	0.470	0.829	0.698	0.207
SDC72 (iii)	2010/05/25	-33.34739	18.81983	179.2	895	-0.020	0.494	0.756	0.700	0.116
SDC32 (iii)	2010/05/24	-33.25959	18.80982	207.2	1035	-0.599	0.477	0.665	0.706	0.176
SDC12 (iii)	2010/05/24	-33.21485	18.79846	228.6	1144	0.482	0.513	0.830	0.709	0.181
SDC12 (i)	2009/05/17	-33.21487	18.79870	236.4	1187	1.084	0.332	0.843	0.740	0.100
SDC42 (ii)	2009/12/07	-33.30580	18.79258	241	1206	1.355	0.437	0.746	0.759	0.178
SDC12 (ii)	2009/12/09	-33.21484	18.79851	246.9	1235	-0.626	0.491	0.678	0.775	0.070
SDC57 (iii)	2010/05/24	-33.23057	18.84751	247.5	1237	0.968	0.650	0.655	0.777	0.132
SDC4 (i)	2009/05/17	-33.23347	18.73771	247.6	1238	1.220	0.404	0.790	0.778	0.159
SDC2 (ii)	2009/12/07	-33.21679	18.71979	252.4	1264	0.715	0.532	0.837	0.780	0.139
SDC57 (ii)	2009/12/09	-33.23060	18.84752	270.4	1350	0.920	0.551	0.749	0.783	0.096
SDC52 (iii)	2010/05/24	-33.20367	18.80222	277.2	1393	0.734	0.575	0.723	0.785	0.053
SDC52 (ii)	2009/12/09	-33.20368	18.80224	284.4	1422	0.568	0.523	0.796	0.791	0.026
SDC1 (i)	2009/05/16	-33.20443	18.77295	286.3	1427	1.210	0.342	0.828	0.794	0.019
SDC45 (iii)	2010/05/23	-33.19681	18.86040	286.8	1435	2.503	0.426	0.762	0.797	0.129
SDC2 (i)	2009/05/17	-33.21691	18.71984	388.5	1443	1.495	0.430	0.670	0.800	0.038

Station ID	Sampling Date	Sample Location		EC	TDS					
		Latitude	Longitude	mS/m	ppm	(Na+K-Cl)/(Na+K+Ca-Cl)	Na/(Na+Cl)	Mg/(Ca+Mg)	Cl/Sum Anion	HCO_3/Sum Anion
SDC33 (i)	2009/05/18	-33.24908	18.82781	297.3	1486	1.163	0.346	0.830	0.803	0.127
SDC33 (ii)	2009/12/10	-33.24906	18.82784	297.5	1488	-17.037	0.474	0.804	0.804	0.074
SDC9 (iii)	2010/05/25	-33.26415	18.75431	314	1565	0.644	0.690	0.805	0.809	0.090
SDC41 (ii)	2009/12/07	-33.30441	18.78292	325.9	1641	-0.788	0.465	0.745	0.830	0.055
SDC50 (iii)	2010/05/25	-33.28469	18.77378	341.2	1704	0.318	0.514	0.650	0.834	0.070
SDC3 (i)	2009/05/17	-33.23699	18.73843	351.3	1756	2.849	0.414	0.915	0.835	0.058
SDC3 (ii)	2009/12/07	-33.23701	18.73845	356.6	1782	0.460	0.532	0.601	0.842	0.033
SDC9 (ii)	2009/12/07	-33.26408	18.75434	505.7	2529	6.940	0.439	0.751	0.844	0.029
SDC10 (i)	2009/05/17	-33.26888	18.75312	508.6	2542	1.105	0.410	0.730	0.844	0.107
SDC10 (ii)	2009/12/07	-33.26887	18.75312	563.8	2820	-0.025	0.497	0.671	0.859	0.043
SDC67 (iii)	2010/05/24	-33.25753	18.80807	665	3316	0.559	0.528	0.742	0.866	0.097
SDC11 (iii)	2010/05/25	-33.23831	18.75748	769.2	3848	0.729	0.552	0.830	0.874	0.033
SDC11 (ii)	2009/12/07	-33.23830	18.75749	808.5	4002	-0.102	0.496	0.825	0.887	0.042
SDC11 (i)	2009/05/17	-33.23829	18.75748	812.5	4065	1.229	0.401	0.476	0.888	0.055
SDC36 (iii)	2010/05/24	-33.29257	18.80636	980.3	4900	0.772	0.548	0.536	0.905	0.033
SDC36 (ii)	2009/12/05	-33.29258	18.80627	986.4	4941	-1.098	0.491	0.672	0.909	0.056
SDC66 (iii)	2010/05/23	-33.20432	18.87094	1229	6142	-3.783	0.484	0.599	0.909	0.052
SDC44 (iii)	2010/05/23	-33.19875	18.86531	1928	9623	-0.413	0.484	0.750	0.910	0.072
SDC43 (iii)	2010/05/23	-33.20024	18.86811	2105	10520	0.716	0.548	0.611	0.960	0.016
SDC43 (ii)	2009/12/08	-33.20023	18.86812	2140	10870			0.621		0.499

Appendix N – Annual variation of $\delta^{18}O$ (blue) and $\delta^{2}H$ (red) in precipitation plots

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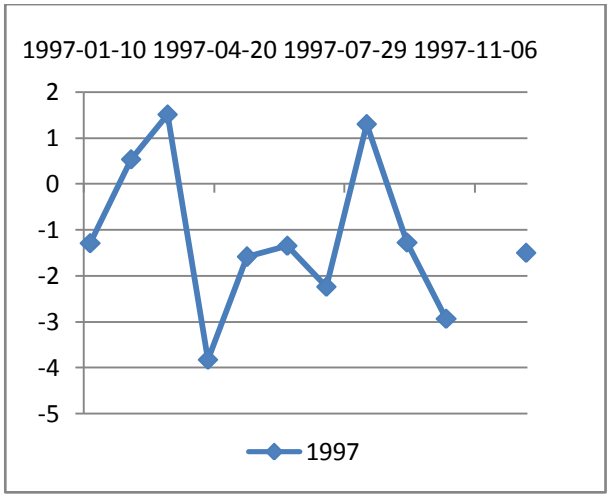
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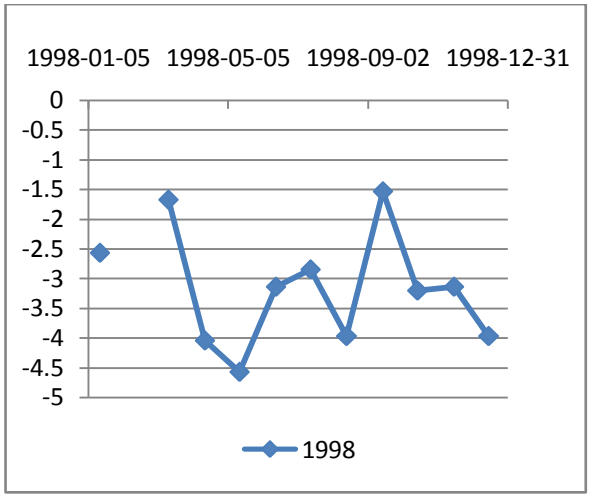
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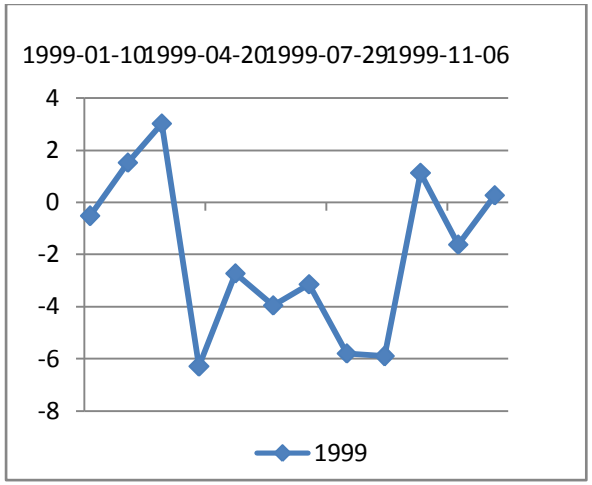
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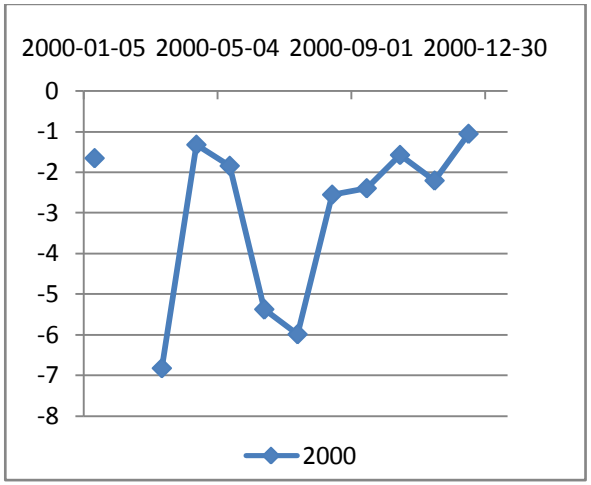
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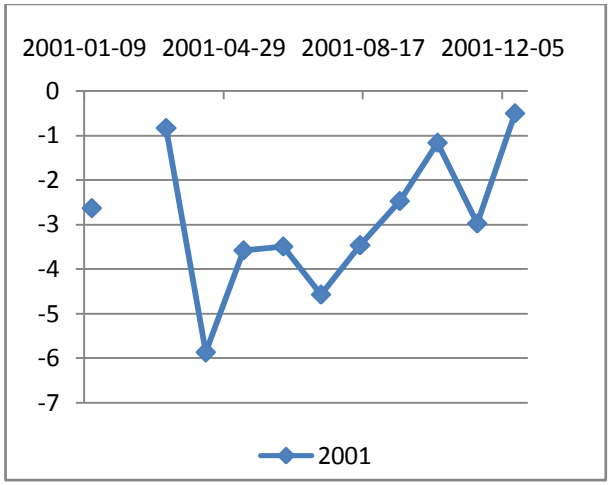
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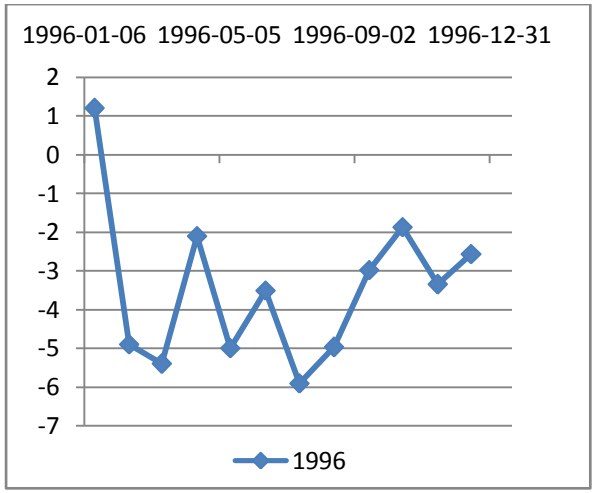
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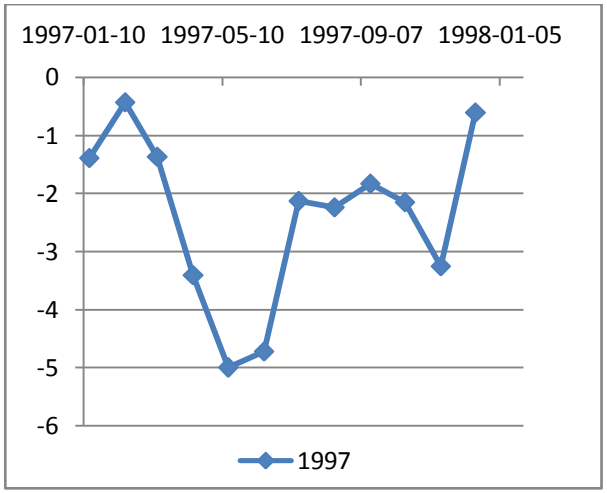
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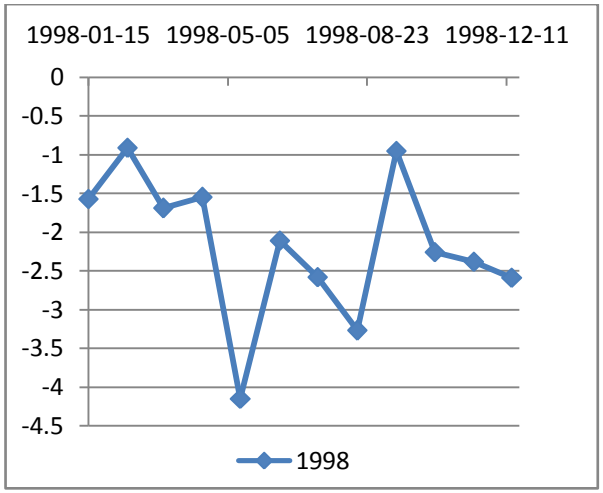
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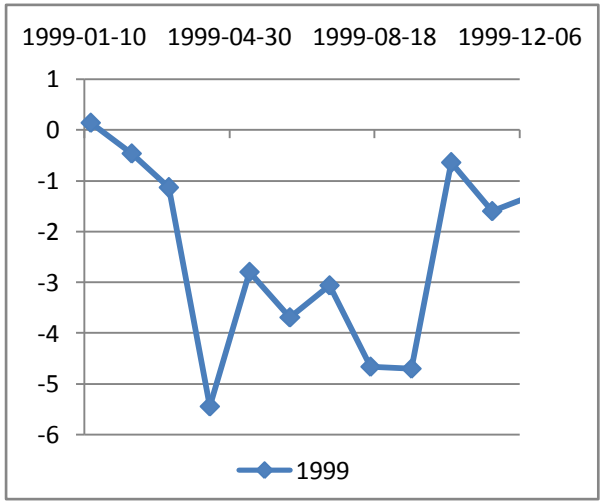
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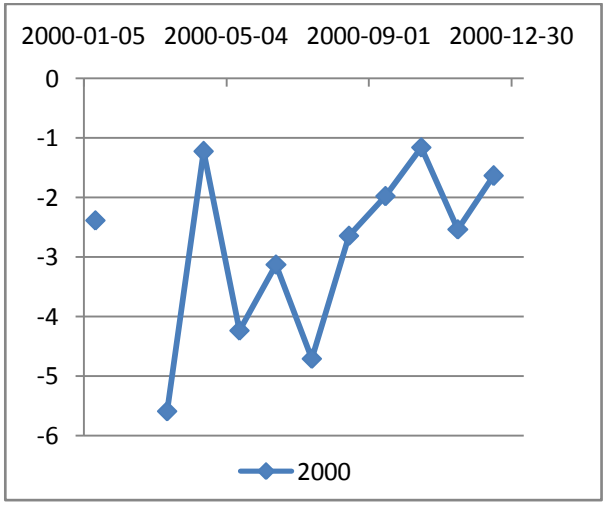
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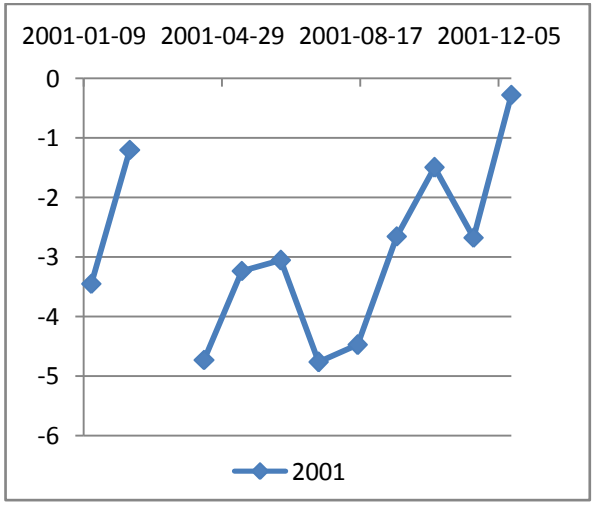
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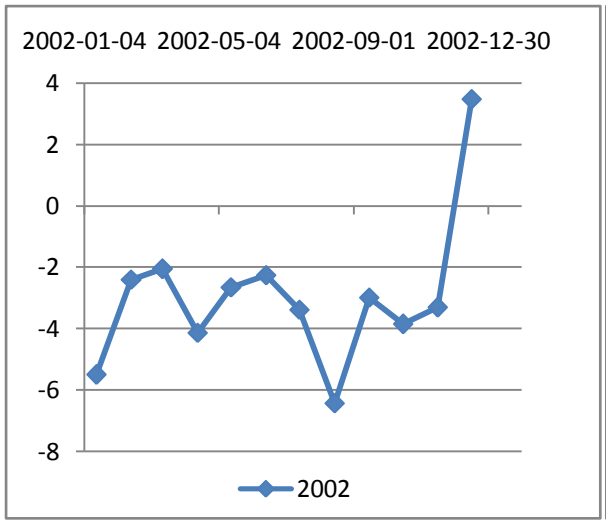
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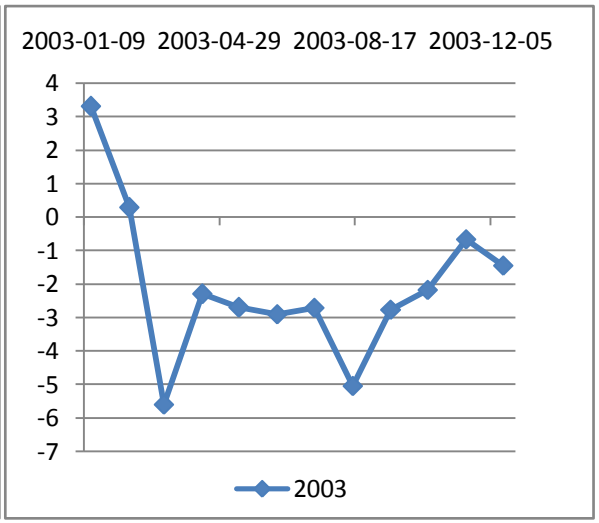
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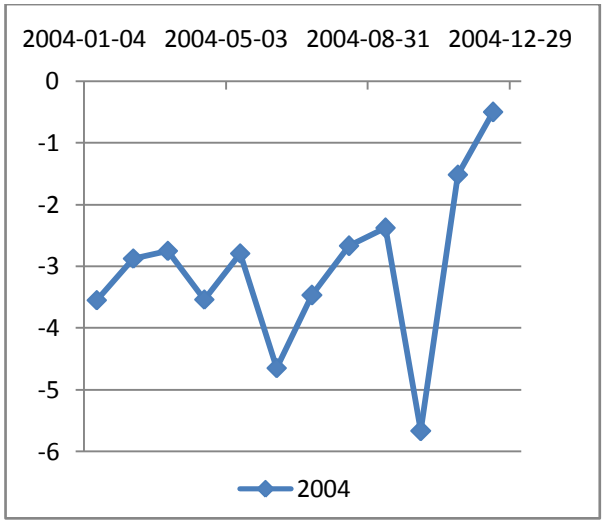
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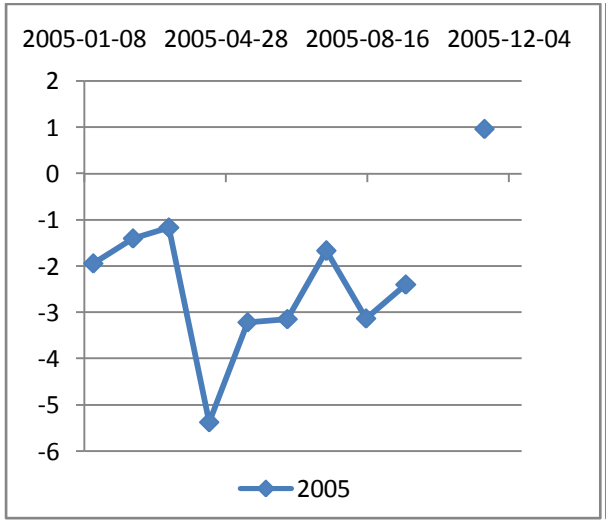
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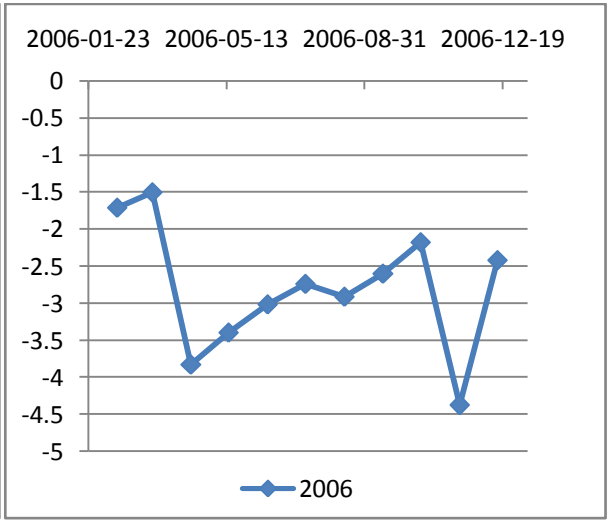
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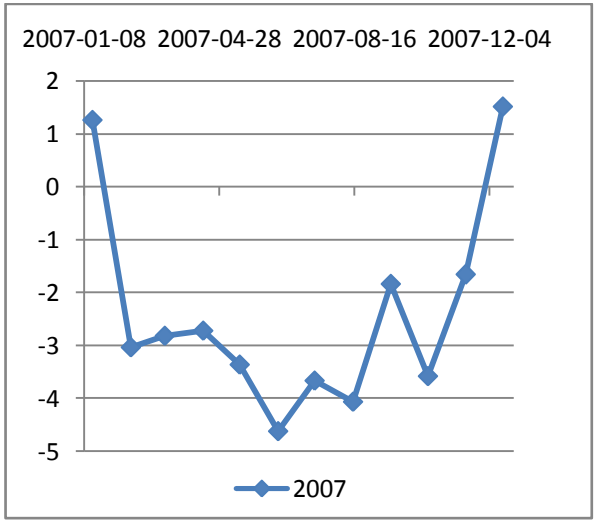
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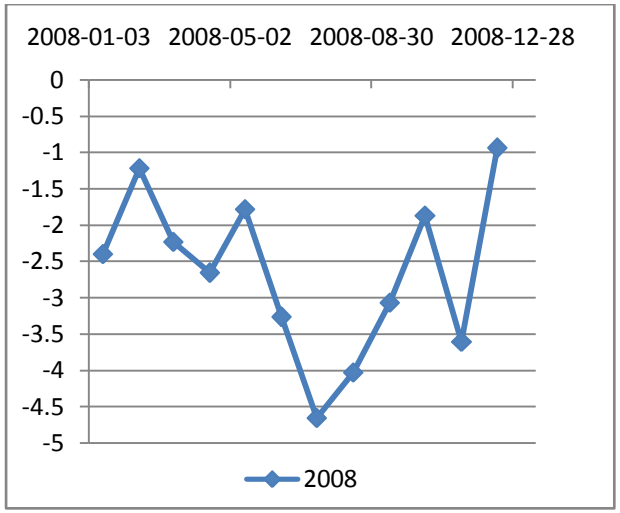
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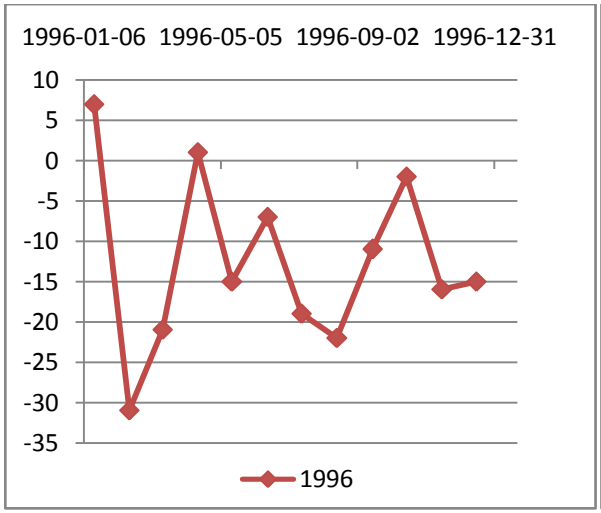
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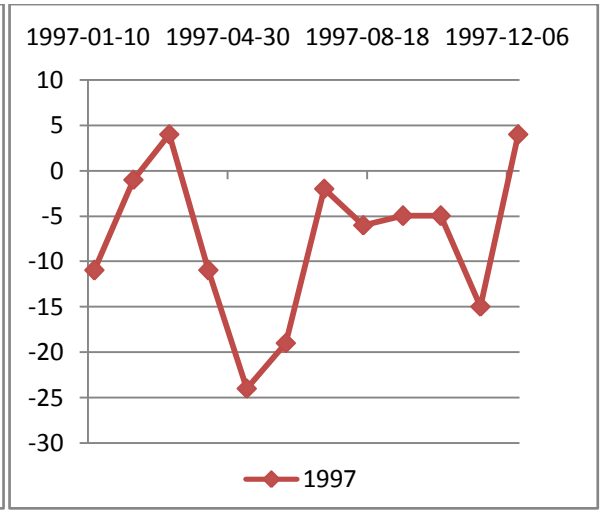
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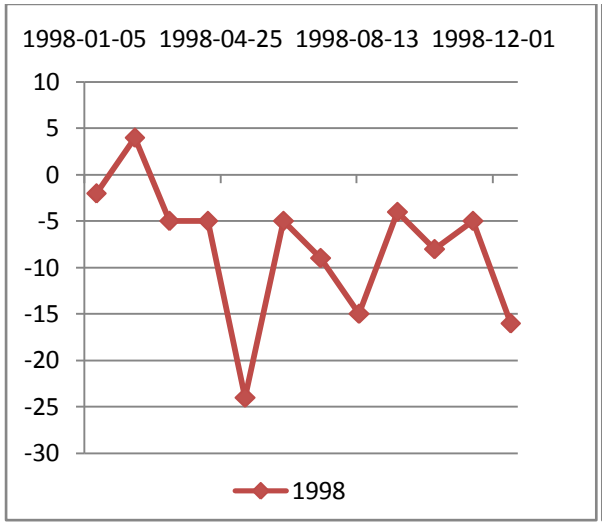
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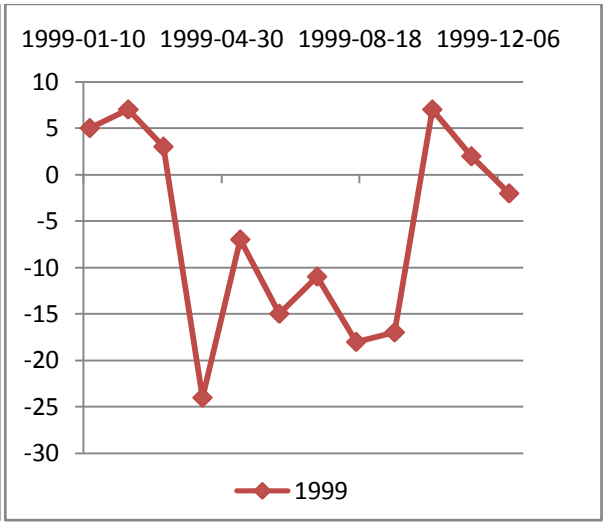
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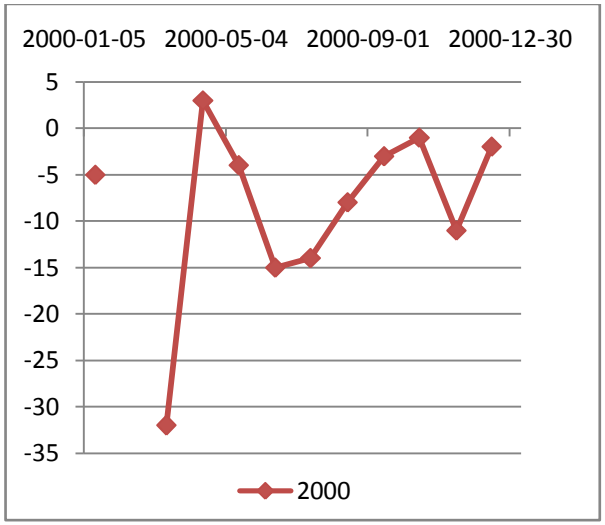
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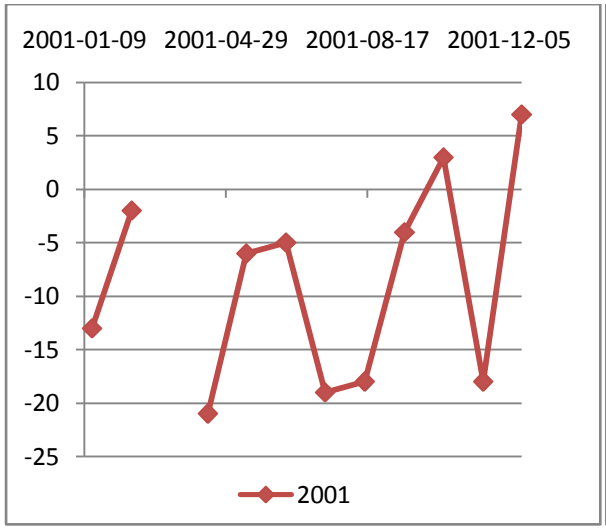
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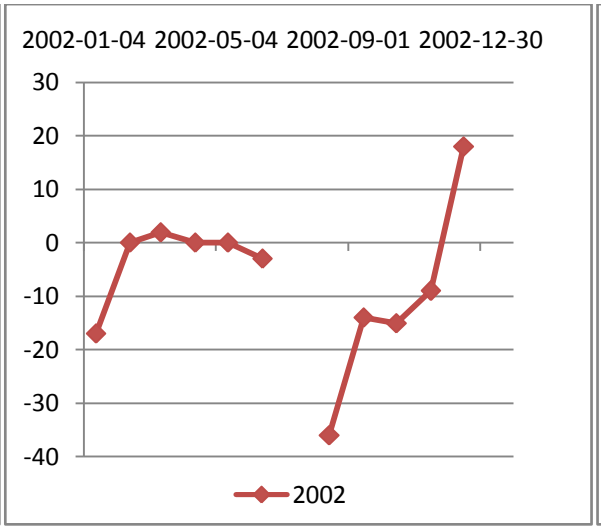
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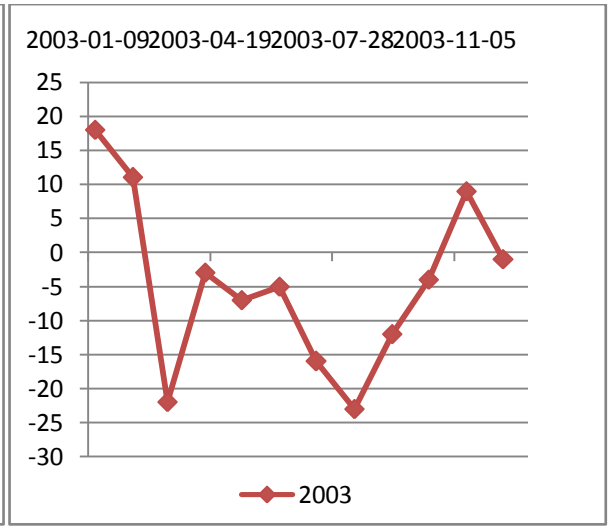
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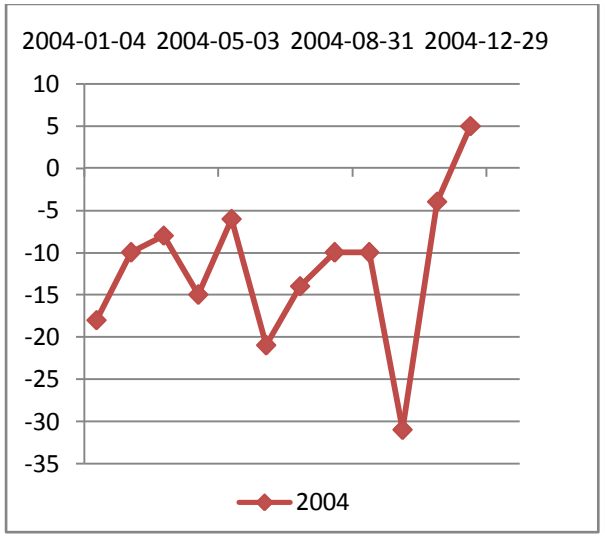
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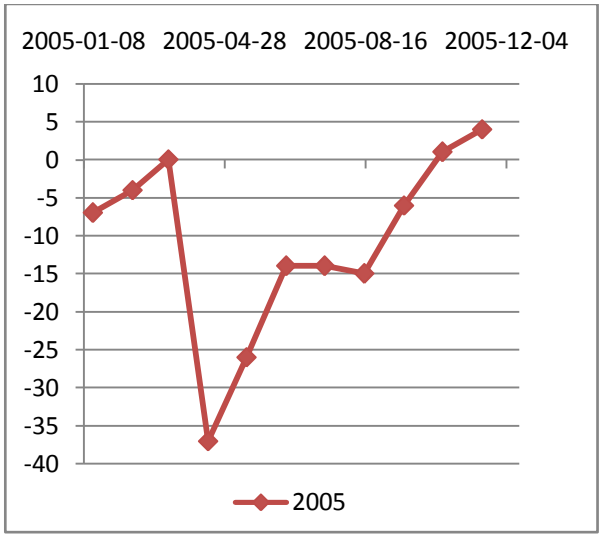
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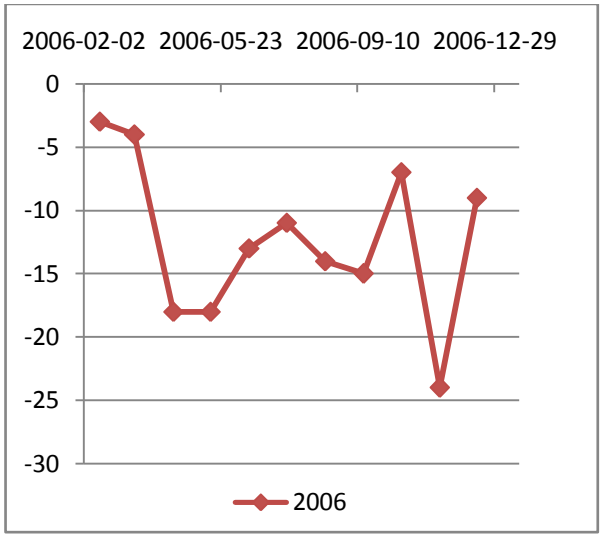
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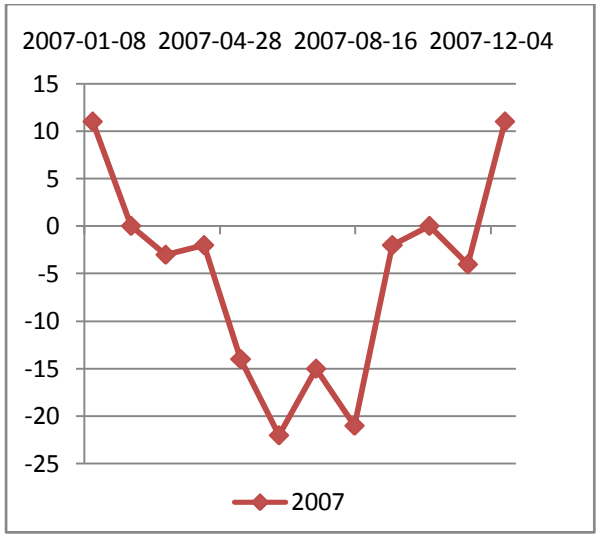
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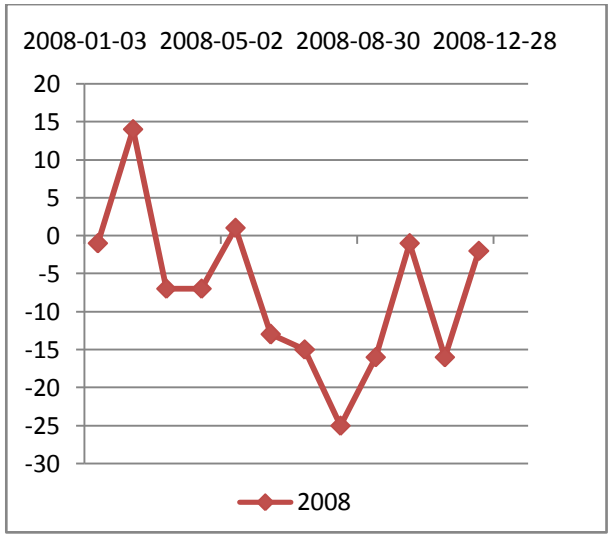
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Appendix O - Environmental isotope results

Station ID	Sampling Date	Sample Location Latitude	Longitude	Drainage Region	Water Source	Altitude (m.amsl)	DTW (m.bgl)	EC (mS/m)	TDS (ppm)	Temp (^{o}C)	pH	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	d-excess ‰	^{3}H TU
SDC1 (i)	2009/05/16	-33.20443	18.77295	G10J	GW	180	7.1	286.3	1427	20.12	6.52	-3.69	-15.69	13.83	0.1±0.2
SDC2 (i)	2009/05/17	-33.21691	18.71984	G10J	GW	204		388.5	1443	19.74	6.74	-3.64	-15.69	13.43	
SDC3 (i)	2009/05/17	-33.23699	18.73843	G10J	GW	174	30	351.3	1756	14.77	7.09	-3.53	-14.49	13.75	0.0±0.2
SDC4 (i)	2009/05/17	-33.23347	18.73771	G10J	GW	185		247.6	1238	18.47	7.19	-3.17	-12.50	12.86	1.1±0.2
SDC10 (i)	2009/05/17	-33.26888	18.75312	G10J	GW	246		508.6	2542	15.35	6.95	-3.82	-16.09	14.47	
SDC11 (i)	2009/05/17	-33.23829	18.75748	G10J	GW	153	9.96	812.5	4065	17.01	6.88	-3.49	-14.71	13.21	0.7±0.2
SDC12 (i)	2009/05/17	-33.21487	18.79870	G10J	GW	137	11	236.4	1187	20.03	6.97	-3.57	-14.98	13.58	0.0±0.2
SDC33 (i)	2009/05/18	-33.24908	18.82781	G10J	GW	109	1.2	297.3	1486	22.57	7.18	-3.82	-15.09	15.47	0.0±0.2
SDC35 (ii)	2009/12/05	-33.34877	18.81463	G10J	SW	265		138.5	693	20.16	7.65	-3.39	-13.80	13.32	
SDC36 (ii)	2009/12/05	-33.29258	18.80627	G10J	GW	150		986.4	4941	24.29	6.96	-3.70	-18.50	11.10	0 ±0.2
SDC40 (ii)	2009/12/07	-33.34697	18.81425	G10J	GW	265	23	148.4	738	23.84	6.29	-3.22	-13.50	12.26	0.7 ±0.2
SDC41 (ii)	2009/12/07	-33.30441	18.78292	G10J	GW	206	20.1	325.9	1641	23.26	6.62	-3.68	-18.60	10.84	1 ±0.3
SDC42 (ii)	2009/12/07	-33.30580	18.79258	G10J	GW	173	14.12	241.0	1206	24.14	7.10	-3.10	-13.20	11.60	1.1 ±0.3
SDC2 (ii)	2009/12/07	-33.21679	18.71979	G10J	GW	206		252.4	1264	20.43	6.48	-3.73	-17.20	12.64	0.6 ±0.2
SDC3 (ii)	2009/12/07	-33.23701	18.73845	G10J	GW	174		356.6	1782	23.74	6.80	-3.68	-16.60	12.84	1.3 ±0.3
SDC8 (ii)	2009/12/07	-33.24698	18.74973	G10J	SW	176		516.7	2585	24.47	7.78	-2.94	-13.60	9.92	
SDC9 (ii)	2009/12/07	-33.26408	18.75434	G10J	GW	221	9.51	505.7	2529	23.72	6.80	-3.68	-16.10	13.34	1 ±0.3
SDC10 (ii)	2009/12/07	-33.26887	18.75312	G10J	GW	240		563.8	2820	29.06	6.60	-4.13	-18.80	14.24	
SDC11 (ii)	2009/12/07	-33.23830	18.75749	G10J	GW	146	12.45	808.5	4002	22.76	6.76	-3.59	-16.80	11.92	0.4 ±0.2
SDC27 (ii)	2009/12/08	-33.15982	18.89496	G10J	SW	51		27.8	139	23.78	7.30	-3.33	-14.70	11.94	
SDC43 (ii)	2009/12/08	-33.20023	18.86812	G10J	GW	60		2140.0	10870	22.22	6.56	-3.36	-14.50	12.38	0 ±0.2
SDC12 (ii)	2009/12/09	-33.21484	18.79851	G10J	GW	136	5.81	246.9	1235	22.10	6.54	-3.91	-17.50	13.78	0.5 ±0.2
SDC52 (ii)	2009/12/09	-33.20368	18.80224	G10J	GW	123	13.3	284.4	1422	24.26	7.11	-4.04	-18.20	14.12	
SDC56 (ii)	2009/12/09	-33.21879	18.84017	G10J	GW	125	36.51	99.9	499	22.33	6.48	-3.91	-18.10	13.18	0.1 ±0.2

Station ID	Sampling Date	Sample Location		Drainage Region	Water Source	Altitude (m.amsl)	DTW (m.bgl)	EC (mS/m)	TDS (ppm)	Temp (^{o}C)	pH	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	d-excess ‰	^{3}H TU
		Latitude	Longitude												
SDC57 (ii)	2009/12/09	-33.23060	18.84752	G10J	GW	95		270.4	1350	25.13	7.56	-4.02	-17.80	14.36	0 ±0.2
SDC59 (ii)	2009/12/09	-33.21008	18.84814	G10J	GW	116	20	119.9	603	23.04	6.51	-4.02	-17.90	14.26	0 ±0.2
SDC33 (ii)	2009/12/10	-33.24906	18.82784	G10J	GW	108		297.5	1488	23.12	7.22	-4.08	-18.40	14.24	0.2±0.2
SDC61 (ii)	2009/12/10	-33.28031	18.82084	G10J	GW	141		189.7	946	23.60	7.49	-3.92	-18.00	13.36	
SDC62 (ii)	2009/12/10	-33.28446	18.82296	G10J	GW	145		75.6	379	23.80	5.33	-3.74	-18.00	11.92	0 ±0.2
SDC2 (iii)	2010/05/22	-33.21682	18.71982	G10J	GW	205		277.5	1387	21.97	6.77	-3.58	-15.64	13.00	
SDC43 (iii)	2010/05/23	-33.20024	18.86811	G10J	GW	61		2105.0	10520	21.36	6.81	-3.16	-15.12	10.16	0.0 ±0.2
SDC66 (iii)	2010/05/23	-33.20432	18.87094	G10J	GW	73	5.21	1229.0	6142	22.40	6.69	-2.98	-15.34	8.50	0.0 ±0.2
SDC44 (iii)	2010/05/23	-33.19875	18.86531	G10J	GW	69	1.2	1928.0	9623	22.92	6.74	-3.19	-11.47	14.05	
SDC45 (iii)	2010/05/23	-33.19681	18.86040	G10J	GW	60	14.02	286.8	1435	22.11	7.64	-3.18	-12.74	12.70	0.0 ±0.2
SDC47 (iii)	2010/05/23	-33.19852	18.85443	G10J	GW	118	44.45	42.4	212	25.00	6.67	-3.80	-14.87	15.53	
SDC32 (iii)	2010/05/24	-33.25959	18.80982	G10J	GW	99	5.08	207.2	1035	21.28	7.90	-4.14	-16.44	16.68	0.3 ±0.2
SDC67 (iii)	2010/05/24	-33.25753	18.80807	G10J	GW	116	11.08	665.0	3316	21.79	6.73	-3.33	-14.09	12.55	0.5 ±0.2
SDC33 (iii)	2010/05/24	-33.24908	18.82782	G10J	GW	107		282.5	1413	23.11	7.40	-3.93	-16.37	15.07	
SDC12 (iii)	2010/05/24	-33.21485	18.79846	G10J	GW	135	5.29	228.6	1144	21.17	6.77	-3.63	-13.94	15.10	0.0 ±0.2
SDC52 (iii)	2010/05/24	-33.20367	18.80222	G10J	GW	127	12.93	277.2	1393	22.73	7.32	-4.30	-16.77	17.63	0.0 ±0.2
SDC69 (iii)	2010/05/24	-33.20818	18.82843	G10J	GW	99		380.6	1903	21.08	6.78	-4.51	-15.40	20.68	
SDC56 (iii)	2010/05/24	-33.21879	18.84017	G10J	GW	131	42.38	88.1	440	22.18	6.38	-4.01	-13.95	18.13	0.2 ±0.2
SDC57 (iii)	2010/05/24	-33.23057	18.84751	G10J	GW	95		247.5	1237	21.90	8.02	-4.35	-16.62	18.18	
SDC36 (iii)	2010/05/24	-33.29257	18.80636	G10J	GW	155		980.3	4900	20.46	7.26	-4.32	-18.49	16.07	0.0 ±0.2
SDC34 (iii)	2010/05/25	-33.34907	18.81464	G10J	GW	271	3.73	233.1	1167	20.59	6.80	-3.68	-13.59	15.85	
SDC35 (iii)	2010/05/25	-33.34877	18.81463	G10J	SW	265		140.2	700	13.91	8.22	-3.18	-8.76	16.68	
SDC72 (iii)	2010/05/25	-33.34739	18.81983	G10J	GW	308	11.54	179.2	895	20.67	7.38	-4.30	-16.19	18.21	0.5 ±0.2
SDC29 (iii)	2010/05/25	-33.34847	18.81578	G10J	GW	271	5.37	68.2	341	19.93	6.80	-3.13	-12.38	12.66	
SDC30 (iii)	2010/05/25	-33.34852	18.81581	G10J	GW	273	8.01	90.1	450	20.79	7.63	-3.09	-11.48	13.24	0.5 ±0.2
SDC49 (iii)	2010/05/25	-33.28473	18.77377	G10J	GW	156	0.57	448.7	2243	22.45	6.67	-3.77	-17.16	13.00	

Station ID	Sampling Date	Sample Location		Drainage Region	Water Source	Altitude (m.amsl)	DTW (m.bgl)	EC (mS/m)	TDS (ppm)	Temp (^{o}C)	pH	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	d-excess ‰	^{3}H TU
		Latitude	Longitude												
SDC50 (iii)	2010/05/25	-33.28469	18.77378	G10J	GW	141		341.2	1704	22.10	7.97	-3.80	-15.14	15.26	0.0 ±0.2
SDC9 (iii)	2010/05/25	-33.26415	18.75431	G10J	GW	224	17.15	314.0	1565	19.38	7.06	-3.83	-15.20	15.44	
SDC11 (iii)	2010/05/25	-33.23831	18.75748	G10J	GW	169		769.2	3848	17.79	6.94	-3.58	-13.44	15.20	0.0 ±0.2
SDC74 (iii)	2010/05/26	-33.35284	18.81960	G10J	GW	295	11.82	154.6	775	18.92	6.06	-3.78	-12.25	17.99	
SDC75 (iii)	2010/05/26	-33.35284	18.81968	G10J	GW	299	5.8	215.9	1080	20.62	6.28	-3.83	-10.50	20.14	
SDC62 (iii)	2010/05/26	-33.28449	18.82290	G10J	GW	145		71.7	359	22.56	6.14	-3.96	-15.68	16.00	0.4 ±0.2