The characterisation of fractured Karoo Aquifers near Beaufort West

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ABSTRACT

A research project was undertaken to delineate aquifers in Beaufort West. Recent studies in the Karoo Basin utilised geochemistry indicators to differentiate between shallow and deep groundwater. The shale gas exploration studies in particular focused more on regional scale assessments. The opportunity existed to apply these methods on a local well field scale. The current local scale studies have been mainly limited to consultants' reports with resource management limited to basic well field scale monitoring and interpretation. The problem with the current local scale approach is that well fields are operated on a "sustainable yield" level based on available fracture storage. Lateral inflows and outflows are not considered. The field work conducted at Beaufort West municipal well fields presented an opportunity to utilise available data and information to spatially characterise the groundwater, as well as to delineate a) flow directions, and b) potential compartments in the shallow aquifer. A better understanding of the flow dynamics is essential to improve the overall resource management and subsequent decision making.

Geohydrological data was collected through several phases of fieldwork conducted for the Beaufort West Municipality. All existing data and information were collated into a comprehensive database. Maps were produced to spatially identify trends in the respective datasets. A good correlation was observed between borehole yields and transmissivity. High yielding boreholes are present in the municipal well field areas, although there is no clear relation between the borehole yields and the lithology, rather to the occurrence of secondary flow paths in the different formations. The degree of fracturing seems to dictate the successfulness of boreholes rather than the lithology. A good correlation was also observed between recharge and EC. The areas with lower ECs generally have either higher recharge rates or more localised recharge or a combination of the two. The inverse is observed for poorer quality groundwater where the recharge is likely to be less and more delayed within the unsaturated zone. A groundwater level contour grid was compiled over the study area to assist with the delineation of groundwater flow paths and groundwater compartments, originating from dolerite intrusions. Eight groundwater compartments were identified. A conceptual model in the form of a N – S section through the Town compartment was compiled to illustrate the groundwater flow regime in the compartment. Based on the interpretation of the isotope data, shallow and deeper groundwater flow systems were identified. The shallow groundwater system is linked to meteoric water, whilst the deeper groundwater system appears to be linked to connate water. The Beaufort West Spring, a fracture guided artesian spring related to the contact of the Teekloof formation and the Town dyke, is linked to the confined deeper groundwater system, whilst the bulk of the municipal abstraction is from the shallow system.

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ABBREVIATIONS

AFYM	Aquifer Firm Yield Model
Al	Aluminium
ALK	Alkalinity
B	Boron
Br	Bromine
C	Carbon
Ca	Calcium
CFB	Cape Fold Belt
CGS	Council for Geosciences
ch	collar height
CIMERA	Centre of Excellence for Integrated Mineral and Energy Resource Analysis
CJ	Cooper Jacob
Cl	Chloride
DWS	Department of Water and Sanitation
EC	Electrical Conductivity
F	Fluoride
Fe	Iron
GIS	Geographical Information System

GRA II	Groundwater Resource Assessment Phase II
GMWL	Global Meteoric Water Line
H	Hydrogen
HCO_3	Bicarbonate
He	Helium
IAEA	International Atomic Energy Agency
IGS	Institute for Groundwater Studies
K	Potassium
KARIN	Karoo Research Initiative
KGEG	Karoo Groundwater Expert Group
km	kilometres
LIP	Large Igneous Province
ℓ/s	litres per second
m	metres
Ma	Million years
mamsl	metres above mean sea level
mbch	metres below collar height
mbgl	metres below ground level
Mg	Magnesium
mm	millimetres
mm/a	millimetres per annum
Mm^3/a	Million cubic metres per annum
Mn	Manganese
mS/m	milliSiemens per meter
mg/l	milligrams per litre
m^2/day	square metres per day
Na	Sodium
NaCl	Sodium Chloride
NGA	National Groundwater Archive
NH_4	Ammonia
NO_3	Nitrate
O	Oxygen
Ra	Radium
Rn	Radon
R^2	Correlation Coefficient
S	Storativity
SAWS	South African Weather Services
SO_4	Sulphate
T	Transmissivity
TBR	Tweeling Brandwag Renosterkop
TDS	Total Dissolved Solids
U	Uranium
UFS	University of Free State
UWC	University of the Western Cape
V	Vanadium
V-SMOW	Vienna Standard Mean Ocean Water
WGS84	Since the 1st January 1999, the official co-ordinate system for South Africa is based on the World Geodetic System 1984 ellipsoid, commonly known as

	WGS84, with the ITRF91 (epoch 1994.0) co-ordinates of the Hartebeesthoek Radio Astronomy Telescope used as the origin of this system. This new system is known as the Hartebeesthoek94 Datum.
WMA	Water Management Area
WMS	Water Management System
WRC	Water Research Commission
WR90	Water Resources of South Africa 1990
WR2012	Water Resources of South Africa 2012
3 – D	Three Dimensional
^{14}C	Carbon-14
^{222}Rn	Radon-222
^{226}Ra	Radium-226
^{238}U	Uranium-238
$\delta^{18}O$	Oxygen-18
δD	Deuterium
‰	per mil

1. Introduction

The research conducted herein originated through several consultancy reports compiled by this author from 2005 – 2008, as well as the author's contribution towards a Water Research Commission (WRC) project that started in 2008. The WRC Project, i.e. K5/1694/1, was conducted by a consortium of researchers with the main task to develop a sampling and monitoring protocol for radioactive elements in fractured rock environments (WRC, 2012). The consortium of researchers was Water Geoscience Consulting, Council for Geoscience (CGS) and the University of the Western Cape (UWC). The research outcomes were to support the implementation of the National Radioactive Monitoring Programme. The specific deliverables of Xu (et al, 2012) were as follows:

1) Re-evaluation of the results of earlier research findings on uranium speciation and the associated anomalies (i.e. anomalies in the aqueous environment) at the selected study area. This deliverable constituted Deliverable 1 of the project and included the literature and database review on physical – chemical characteristics of radioactive elements as well as a hydrocensus.
2) Application of recent advances to characterize flow regimes in fractured rock aquifer systems, with reference to 'tracing' the distribution of radio-active elements in fractured media. This deliverable constituted Deliverable 2 of the project and included the aquifer characterisation and delineation of groundwater flow regimes.
3) Development of local-scale sampling and monitoring protocol for radioactive elements in fractured rock formations. This deliverable constituted Deliverable 3 of the project.
4) Delineation of a groundwater protection zone around a selected study area with respect to an unstressed system taking into account the hydraulics, behaviour of selected radio-active elements, relevant policy documents, etc. This deliverable constituted Deliverable 4 of the project.

A large component of this dissertation deals mainly with "Deliverable 2: Aquifer characterisation and delineation of flow regimes" of Xu (et al, 2012), which supported the remainder of the deliverables within the broader study as mentioned above. It can be regarded as a reworked research product of Deliverable 2 of Xu (et al, 2012). The study strives to conceptualize the groundwater flow patterns within the fractured aquifers of Beaufort West by utilizing available data and information collected during a multi-phased fieldwork approach spanning over four years.

Under Xu (et al, 2012) several sites were investigated to select an appropriate location for detailed investigations. The site eventually selected was Beaufort West. To date extensive geohydrological work was conducted by the Beaufort West Municipality and Department of Water and Sanitation (DWS) starting in the 1970's. As a result of on-going exploratory drilling and monitoring by the Beaufort West Municipality and DWS since the 1970's geohydrological data is readily available for this area. The occurrence of radioactive elements in the Karoo Supergroup was first detected in the Karoo in 1964 during kimberlite exploration (Uramin, 2006). Early in 1970, an American exploration company embarked on systematic search of uranium in the Karoo which resulted in the discovery of uraniferous sandstone on a farm, Grootfontein 180, 20 km west of Beaufort West (Uramin, 2006). Subsequent to this uranium mineralisation was discovered on the Ryst Kuil farm (i.e. 40 km south of Beaufort West) in 1973. Following this discovery, the Geological Survey of South Africa undertook a detailed aerial-radiometric survey, which commenced in 1976, to delineate major uranium occurrences in the Main Karoo Basin. This resulted in the subdivision of the main Karoo Uranium Province into ten uraniferous provinces (Uramin, 2006).

Since the inception of Xu (et al, 2012), several other research studies have also been conducted in the Great Karoo. Murray (et al, 2012) produced a “Groundwater Planning Toolkit for the Main Karoo Basin”. The project aimed to identify favourable groundwater potential areas for bulk municipal water supplies. In identifying favourable groundwater areas, the focus was to develop a detailed transmissivity map of the Main Karoo Basin. Murray (et al, 2015) investigated “The Use of Chemistry, Isotopes and Gases as Indicators of Deeper Circulating Groundwater in the Main Karoo Basin”. The Shale Gas exploration projects conducted by Shell and Falcon are investigating deep seated shale gas reserves in the Karoo environment and its potential impacts on the groundwater system, both deep and shallow. As part of the on-going research, Shell appointed a group of consultants known as the Karoo Groundwater Expert Group (KGEG) to improve the understanding of Karoo Aquifers particularly relating to linkages of deep and shallow aquifer system. Under KGEG a Karoo Groundwater Atlas was produced. An Australian based company, Tasman, has also been exploring uranium reserves south of Beaufort West and have applied for mining rights for a few of their exploration areas. Although this research is cognisant of the aforementioned research projects and exploration (some of them on – going) that was undertaken since 2008, the main focus was not to acquire additional data but to contextualise this research within the main outcomes of more recent research projects.

A broad outline of the study area is presented in **Figure 1**. However, note that the delineation of the study area is further discussed in Section 4. The study area is defined by an area in and around the town of Beaufort West and fully covers the four main municipal well fields, as well as the areas in the south and southeast of town where new boreholes were drilled but not yet put in production. The study area can be accessed by the N1 highway between Cape Town and Johannesburg, the N12 highway from George in the south or the R61 road from Port Elizabeth. The study area is mainly drained by two main quaternary catchments, i.e. J21A and L11F. The Gamka River drains the J21A quaternary catchment in a south-westerly direction, whilst the Platdoring River drains the L11F quaternary catchment in a southerly direction. The four main municipal well fields are Brandwag (far northeast), Tweeling, Lemoenfontein and Town well fields. The Town well field supplies the majority of groundwater to the town. The volume of water from the Town well field amount to about 50% of the total groundwater supply. Further to this, the town uses surface water from the Gamka Dam. The ratio of groundwater to surface water usage is about 1:1.

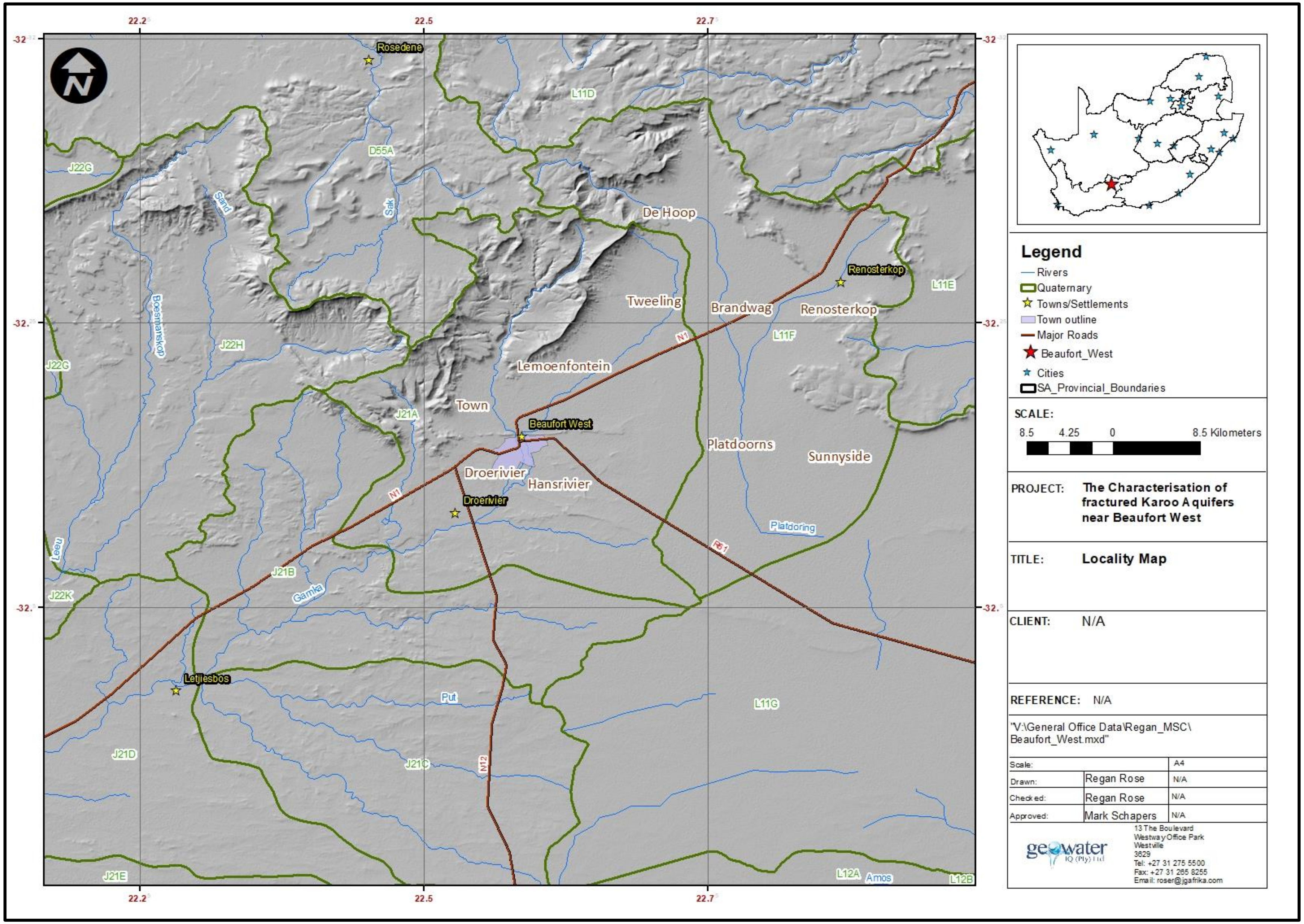

Figure 1: Locality of the study area

2. Aims and Objectives

The main aim of this dissertation is to develop a conceptual model of aquifer systems in Beaufort West and surrounding areas based on multi-faceted groundwater exploration approach, as well as report on aquifer types including settings of significant water-bearing structures. The specific objectives involve the following:

a) Delineation of the extent of the study area, taking into account the availability of data as well as the uranium occurrences.
b) An assessment of previous hydrogeological studies and interpretation of pumping test data and other data to provide field estimation of aquifer properties.
c) An assessment of structural, geological and geomorphologic setting of existing successful and unsuccessful boreholes.
d) Spatial characterisation of groundwater within the shallow aquifer.
e) An assessment of all available geochemistry data to assist with the development of a conceptual model.

3. Literature Review

Extensive groundwater exploration was initiated by DWS in the 1970's. Prior to this groundwater exploration was mainly limited to ad hoc borehole siting exercises that mainly focussed in areas close to Beaufort West town (Seward, 1988). Post 1970s regional reconnaissance type investigations were conducted by Boehmer (et al, 1970), Diettrich (1972), Campbell (1980), Vandoolaeghe (1985), Seward (1987), SRK (1998) and Rose (et al, 2007).

Boehmer (et al, 1970) conducted a regional geohydrological investigation and concluded that the best drilling targets are the fractured and weathered bedrock and dolerite contacts. They recommended that future investigations must focus in certain sections of the Town (Gamka) well field and Tweeling well field.

Diettrich (1972) expanded the previous investigation of Boehmer and De Bruin (1970) to areas west, north and northeast of Beaufort West. This investigation recommended that the Town well field is further optimised and that the Tweeling Brandwag Renosterkop (TBR) dyke is explored. Both Boehmer (et al, 1970) and Diettrich (1972) lacked quantitative estimation of potential groundwater availability, which resulted in large – scale drilling and aquifer testing from 1974 to 1979.

Campbell (1980) assessed all drilling and pump testing exercises conducted in the 1970s and investigated areas north, east and southeast of Beaufort West to define the extent and nature of groundwater occurrence and estimate the groundwater potential. According to Campbell (1980), the highest borehole yields were associated with the fractures in the Beaufort Group sediments. Based on average storage coefficients calculated from pump test data, a total of 112 Mm^3 of groundwater in storage was estimated over the area (Campbell, 1980). The average annual recharge over the same area was estimated at 12 Mm^3/a assuming 4% of annual rainfall (Campbell, 1980). The areas Brandwag, De Hoop and Renosterkop were recommended for further investigation.

Vogel (et al,1980) conducted research in isotopes to investigate the mode of recharge of the aquifers in and around Beaufort West. They concluded that recharge occurs both at the plains and escarpment, and that the recharge in the plains occur from direct rainfall recharge. However, since only 15 samples were taken, the results of the isotope study were deemed as not being representative of the entire area.

In an attempt to quantify the groundwater potential of aquifer units, Vandoolaeghe (1985) conducted an area wide geohydrological investigation to the north, northeast, east and south of Beaufort West. The results of this investigation is summarised in **Table 1**. From Table 1 the Brandwag well field shows the greatest potential with 2.0 Mm^3 of groundwater estimated. The groundwater potential for other aquifer units was estimated at well below the 1.0 Mm^3 mark. Other units to the east of Beaufort West (not included in Table 1) were also investigated, but the water quality at the time was considered too bad to be recognised as a viable option and requires desalination. Based on this information the Brandwag well field was proposed for well field development and augmentation (Vandoolaeghe, 1985).

Table 1: Estimated groundwater potential and storage per aquifer unit (Vandoolaeghe, 1985)

Aquifer Unit	Groundwater Potential (Mm^3)	Storage	Comments
1) Gamka/Town	0.75	2.5×10^{-3}	Unit recharges quickly following rainfall events
2) Kuilspoort			
a) Springfontein	Limited	Limited	
b) Lemoenfontein	0.25		
c) Tweeling	0.06		Unit is leaking to Lemoenfontein, recharges quickly
3) Hansrivier	Limited	Limited	Water quality marginal
4) Brandwag	2.0		High yielding boreholes; water quality good
5) Renosterkop	0.2		Water quality good

A gap in monitoring data was identified which was needed to provide a more reliable estimation of groundwater potential. Following the purchase by the municipality of the farm Brandwag, situated about 30 – 40 km northeast of Beaufort West, Seward (1988) initiated an extensive monitoring programme. Initially the monitoring network focussed mainly in areas northeast of Beaufort West and included Brandwag, Soetdoring and Renosterkop (Seward 1988). Future production and monitoring boreholes were also identified during this investigation.

As part of consultancy services rendered to the municipality SRK (1996) investigated the performance, management and future expansion of the Brandwag well field. As part of the long – term water supply assessment of the Brandwag well field, detailed hydrochemical and environmental isotope sampling were conducted in 1997. The resultant groundwater flow model and water balance calculations further confirmed that only 2% of annual recharge reaches the water table and that the rest is lost to evaporation or infiltrates to depths deeper than the boreholes or form part of a deeper flow system. The groundwater recharge to the Brandwag well field was estimated at about 0.66 Mm^3/a, and it was therefore concluded that further expansion of the Brandwag well field was limited (SRK, 1997). Additional work in 1998 calculated that the existing groundwater resources of the municipality had a combined sustainable yield of about 1.1 Mm^3/a (SRK, 1998). Further geophysical work west of Brandwag at Kuilspoort identified an offset of the TBR dyke. The latter work culminated in the drilling of two successful boreholes that now constitutes the Tweeling well field (SRK, 2000).

A decline in water levels was then noted at Brandwag well field in 2006 (Pers. Comm. Louw Smit[§]). This prompted an assessment of the water levels under more recent climatic conditions (Rose et al, 2005). The sustainable yield of Brandwag well field was revised and was subsequently significantly reduced to about 0.35 Mm^3/a, which suggested that the initial sustainable yield calculations provided by Vandoolaeghe (1985) were exaggerated. With this information and growing municipal water demands and below average rainfall a reconnaissance investigation to determine additional groundwater resources was undertaken (Rose et al, 2007). The reconnaissance investigation recommended that new well fields south of Beaufort West needed to be explored. The Hansrivier (southeast of Beaufort West) and Droerivier (southwest of Beaufort West) aquifer units were successfully explored in 2008 and 2009 and several boreholes in these well fields are available for use by the Beaufort West Municipality (GEOSS, 2011). The Hansrivier and Droerivier well fields, collectively known as the Southern well field, has an estimated sustainable yield of 0.86 Mm^3/a (GEOSS, 2011).

3.1 Groundwater Planning Toolkit for the Main Karoo Basin

A groundwater planning toolkit was developed under the WRC funded project by a consortium led by Groundwater Africa (Murray et al, 2011). The project aimed to identify favourable areas for groundwater potential in the Karoo basin for bulk municipal water supplies and provide a method for groundwater quantification. As part of

[§] Retired Town Engineer of Beaufort West Municipality identifying favourable areas for groundwater potential a detailed Transmissivity (T) map was produced mainly based on the observation that there is a direct correlation between borehole yield and T. The T approach was based on borehole yields and geology to produce a range of values for each hydrogeological domain. An Aquifer Firm Yield Model (AFYM) was produced under this project, which is based on monthly rainfall, recharge, evapotranspiration and baseflow to determine Aquifer Storage at any given month. The Aquifer Storage represents the upper limit of the groundwater resource. In addition, the Cooper Jacob (CJ) Well Field Model (based on Cooper Jacob approximation of the Theiss groundwater flow equation) was also developed to assist with distance between production boreholes. The outcome of the project identified areas of high permeability, and hence, favourable drilling targets to be associated with the following geological criteria:

- Dolerite dykes
- Dolerite ring structures
- Dolerite sill margins (inclined sheets)
- Thick alluvial deposits
- Folded and faulted formations

3.2 Karoo Groundwater Atlas

As part of the Shell Shale Gas Exploration project a Karoo Groundwater Atlas was produced to identify, assess and manage groundwater use related to shale gas exploration to preserve existing and future groundwater sources (SRK, 2012). The study aimed to achieve the following objectives:

- Understanding the hydrogeology of shale gas exploration precincts.
- Understanding the reliance of communities on groundwater in the Karoo.
- Estimation of the ecological sensitivities.
- Minimisation of environmental impacts of shale gas exploration.
- Identification of major and sole source aquifers.
- Development of a defensible strategy to inform shale gas exploration sites.
- Development of an interactive database with baseline data.

The geological and hydrogeological characterization was derived from the available geological maps and detailed geological borehole logs (shallow and deep boreholes) of DWS and the Petroleum Agency of South Africa (PASA). Three shale gas exploration precincts were identified of which the Central Karoo Precinct partially coincides with the study area. Existing data and information were used to assess and quantify several groundwater attributes for the compilation of regional hydrogeological maps and the development of a conceptual 3-D model. The attributes that are considered most important were:

- Aquifer yield
- Depth to groundwater
- Groundwater quality

- Dolerite intrusions
- Faults
- Folded lithologies
- Lithology
- Depth to main water strike
- Depth of weathering
- Soil type

Based on a ranking and weighting system employed in a similar fashion as the DRASTIC method the aquifer yield, depth to groundwater, groundwater quality and dolerite intrusions accounted for 60% of the weighting and are therefore regarded as the most significant to inform the shale gas exploration activities. Consideration zones were also broadly delineated for different hydrogeological domains. Vulnerability maps were also produced to assess the potential risk of the shale gas exploration to contamination, however the applicability of vulnerability maps for shale gas exploration was questioned since the potential threat is from the deep aquifer towards the shallow main aquifer (SRK, 2013). The work conducted under SRK (2012) and SRK (2013) allowed for the systematic development of a conceptual model for both shallow and deeper geological and hydrogeological systems.

3.2.1 Shallow Model

According to SRK (2013) the shallow model is represented by mainly the Beaufort Group sediments, alluvium, dolerite intrusions and weathered zones in the Main Karoo Basin. The main shallow aquifer is < 300 m in depth with the weathered zones estimated between 10 – 50 m in depth and the fractured zone between 100 – 160 m in depth. The aquifer yield, recharge and Electrical Conductivity (EC) improve from west to east, whilst the water levels become shallower from west to east. The latter is as a result of a higher ratio of sandstone and dolerite intrusions and a higher rainfall in an easterly direction (SRK, 2013). The shallow aquifer is the main source of water for municipalities and the sole source for communities.

3.2.2 Deep Model

The deep model is represented by several groups within the Karoo Supergroup succession, i.e. Beaufort Group (shale, mudstone, sandstone), Ecca Group (shale, mudstone, some sandstone), Dwyka Group (tillite), which stratigraphically overlies either the Cape Supergroup or Basement Granite (SRK, 2013). The geological strata within the Karoo Supergroup are mainly horizontal except for those areas adjacent to the Cape Fold Belt (CFB) where fracture development is limited due to the successive layers of shale and mudstone. The Karoo sediments thicken towards the south due to the influence of the CFB. The Karoo dolerite outcrops south of Beaufort West and from there is trending in a south-easterly direction. Permeability along the dolerite dykes is dependent on the host rock with intrusion contact zones in sandstone generally more permeable than in mudstone. The permeability is also likely to decrease with depth as sediment load increases causing compaction and closure of fractures as confirm with a deep PASA borehole with limited fractures at depth. Three zones of groundwater occurrence are identified (SRK, 2013):

1. Main shallow aquifer (< 300 m, as described in previous paragraph)
2. Intermediate Zone (300 – 1000 m)
3. Deep Zone to Basement (> 1000 m)

The groundwater salinity is expected to increase with depth due to slow groundwater movement and longer residence time. It was found that the major east to west trending faults are deep seated and could connect through the Karoo sediments to basement. Similarly kimberlite fissures are deep rooted and straight, and if connected to dolerite dykes, could be deeply connected. The estimated depth of shale gas horizons varies between 1000 – 3450 m (SRK, 2013).

3.3 Shell Shale Gas Exploration

As part of a Shell funded project to investigate the viability of shale gas exploration activities in the western, central and eastern Karoo, a group of experts known as KGEG was formed in 2011. Several studies have since been completed. Van Tonder (et al, 2013) investigated the potential impacts of shale gas fracking on groundwater in the Karoo Basin of South Africa. The study concluded that the Karoo Basin is under artesian conditions, which implies that pollutants will always try to migrate upwards. Based on the temperature of warm water springs the upward velocities of water are relatively high. The cubic law was used to estimate upward leakage rates from gas well during production and after production when pressures are likely to rebuild due to natural artesian conditions of Karoo formations. The results show that an area of 300 ha could be contaminated over a 30-year period in a downstream groundwater flow direction. For an abstraction borehole drilled along a fault or dyke structure intersecting the fracked area, the results predict that the pollutant will reach the borehole in less than two months if the borehole is situated 6km from the well pad. The model further predicted that the total impact of fracking is a function of the total area that will be fracked (Van Tonder et al, 2013).

Utilising data of 24 deep boreholes drilled in the Karoo during the 1960’s during Soekor’s oil exploration, as well as data on thermal springs, Rosewarne (et al, 2013) produced a map indicating the northern limit of the Cape Fold Belt Basin beneath the Karoo sediment cover (**Figure 2**). The study was conducted to improve the understanding of deeper aquifers and associated groundwater occurrences and their possible interconnection with shallow aquifers.

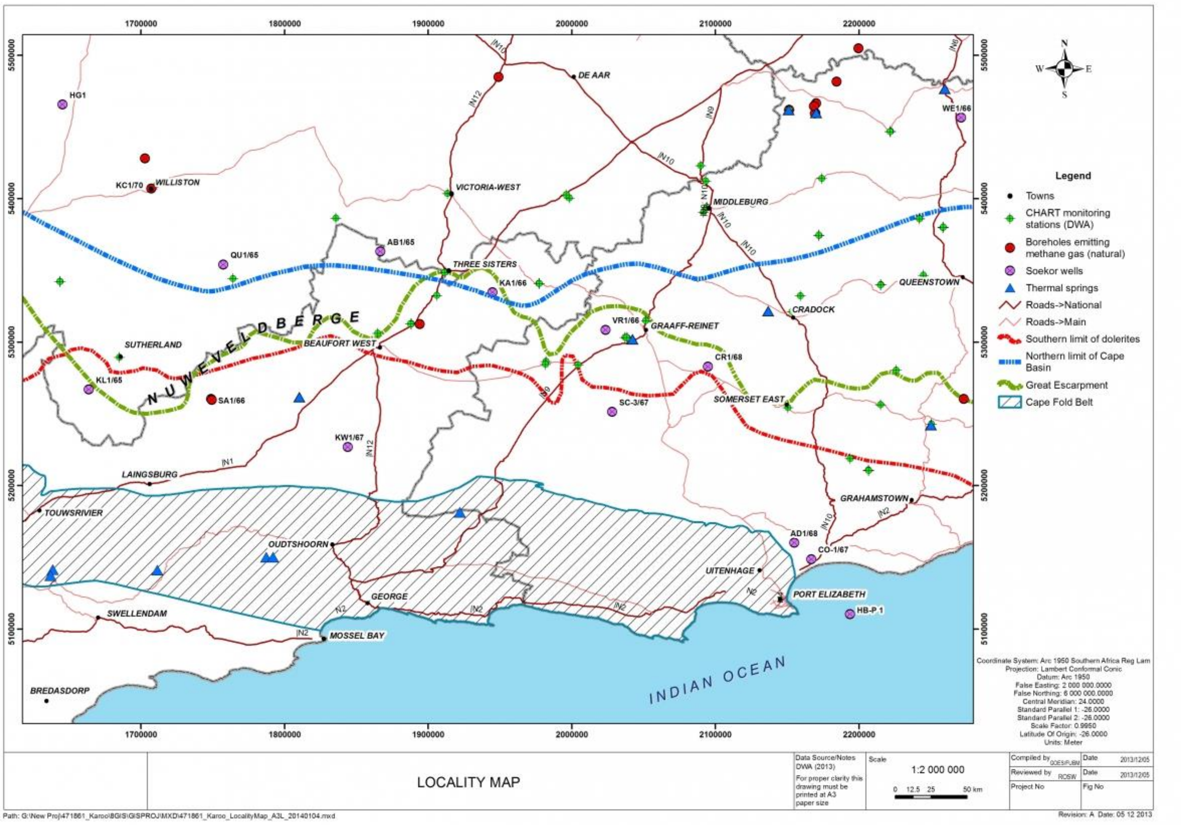

Figure 2: Map indicating northern limit of Cape Fold Belt (Rosewarne et al, 2013)

Conceptual north to south cross – sections were also produced through studies by Rosewarne (et al, 2013) and Van Tonder (et al, 2013). The north to south cross – section from George to Fraserburg is provided in **Figure 3** after Rosewarne (et al, 2013). The main features are as follows:

- Rocks of the Cape Supergroup are highly folded and faulted within the Cape Fold Belt on the southern margin of the Karoo Basin and the sub-outcrop of these rocks (the Witteberg Group) extends almost as far north as Fraserburg;
- Deep-seated (thousands of metres) groundwater circulation takes place along faults within the Cape Supergroup rocks, as evidenced by thermal springs with temperatures of up to 62°C (Brandvlei);
- The influence (structure and deep groundwater circulation) of the Cape Fold Belt extends into the southern Karoo, probably up to the Great Escarpment, and the southern limit of dolerite intrusions runs parallel to and just to the south of the escarpment;
- Recharge on the exposed Cape Supergroup rocks in the Langeberg, the presence of these rocks at depth below the Karoo rocks, deep groundwater circulation and fracturing in the Dwyka Tillite related to the Cape Fold Belt are possible key factors giving rise to the artesian groundwater encountered in some of the SOEKOR wells to the south of the Great Escarpment;
- This groundwater is likely to be confined by the Lower Ecca formations, which is where the shale gas is postulated to occur;

- The highest TDS measured during drilling of the SOEKOR wells was 10 000 mg/L, which is only an order of magnitude higher that some groundwaters from the shallow aquifer. However, the TDS of deep groundwater may increase to the north of the Great Escarpment away from the influence of the Cape Supergroup rocks/Cape Fold Belt.

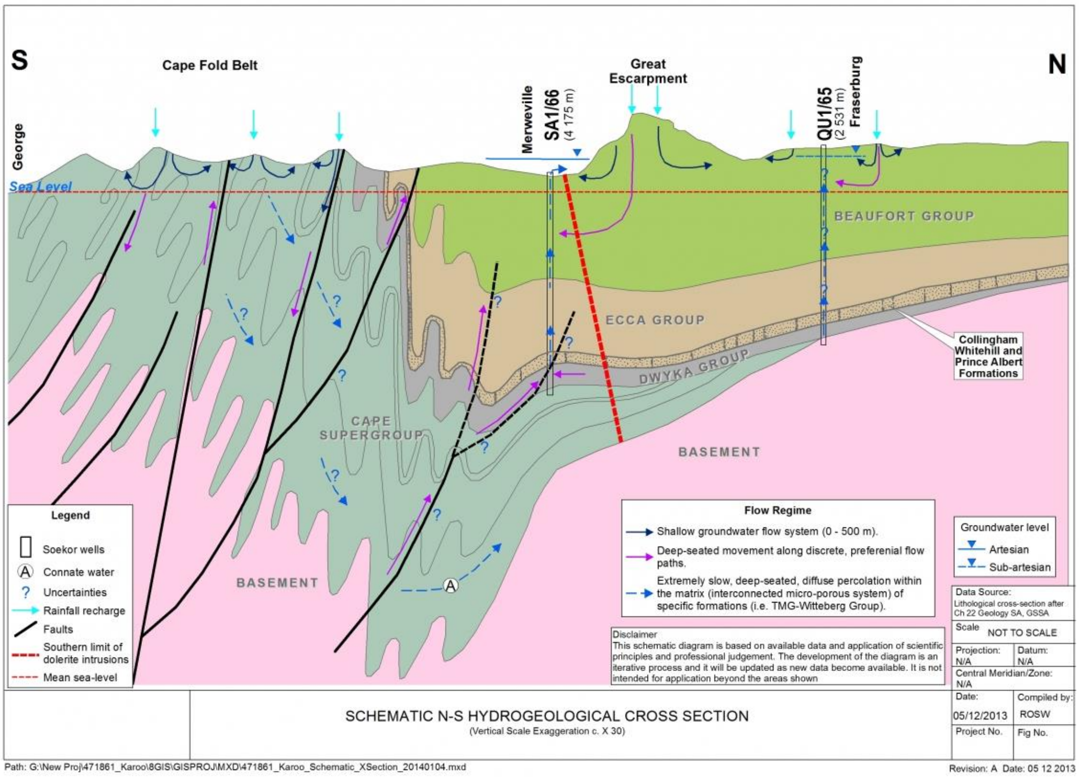

Figure 3: North to south cross – section from George to Fraserburg (Rosewarne et al, 2013)

3.4 Groundwater Indicators

A study launched by the WRC in 2015 investigated the use of chemistry, isotopes and gases as indicators of deeper circulating groundwater in the Main Karoo Basin. The study strived to characterise the deeper groundwater component because it is anticipated that fracking will create conduits through which deeper groundwater can migrate, and if the deeper groundwater is of poor quality, it will impact negatively on shallow groundwater. Although no boreholes were found suitable for sampling deep formations the existence of warm springs was used as the closest approximation. The study area focussed along the central and southwestern Karoo Basin. The outcomes of the study showed that several indicators can be used to differentiate between deep and shallow groundwater systems. The latter indicators are summarised in **Table 2**.

Table 2: Deep and shallow groundwater indicators within the Main Karoo Basin (Murray et al, 2015)

	Deep Groundwater	Shallow Groundwater
Indicators	NaCl type	Ca-Mg-HCO^3 type;
	> 25 degrees Celsius	< 25 degrees Celsius
	Low ^3H, ^{14}C;	Moderate ^3H, High ^{14}C;
	Low $^{36}Cl/Cl$ and $^3He/^4He$	Higher $^{36}Cl/Cl$ and $^3He/^4He$
	Low NO^3, Mg	Variable NO^3
	Lower ^{18}O & ^2H than in shallow groundwater	Higher ^{18}O & ^2H than in deep groundwater
	Low Alkalinity	High Alkalinity
	Low U and V	High U and Rn
	Low Rn and Ra	Low F and Br
	High F	Low methane and He gas
	High methane and He gas	
	High B	

The study went a step further by providing a provisional list of determinands with concentrations as guidance for differentiating deep from shallow aquifer systems. The list includes threshold concentrations for each determinands.

3.5 Cimera Karin Project

The Centre of Excellence for Integrated Mineral and Energy Resources Analysis (CIMERA) under the auspices of the Karoo Research Initiative (KARIN) conducted core drilling at Willowvale in the Eastern Cape Province to explore the geology and shale gas potential (De Kock et al, 2016). The geological interpretation is a narrow zone of crustal shortening towards the south in close proximity with the CFB resulting in the northward thinning of the Karoo basin and asymmetrical basin shape. The depositional environment changes from glacial fill at the base (Dwyka Group) to fluvial deltaic (Ecca Group) to terrestrial fluvio – lacustrine (Beaufort Group) to fluvial and aeolian (Stormsberg Group). Sedimentation ended at about 183 Ma with the emplacement and extrusion of Karoo Large Igneous Province (LIP) represented by the outpouring of at least 1400 m of basaltic lavas (Drakensberg Group), which have subsequently become feeder networks of dolerite sills and dykes. The deep drilling intersected the lower Balfour Formation of the Beaufort Group (with abundant sills), the Ecca Group (Waterford, Fort Brown, Ripon, Collingham, Whitehill and Prince Albert formations from top to bottom) and Dwyka Group. A total depth of 2353 m was achieved when drilling was aborted 14.7 m into the Dwyka Group. The Whitehill Formation, i.e. the main target for shale gas extraction although its potential is mainly unquantified, was intersected at about 2294 m.

3.6 Similar Studies

Similar studies to the one proposed herein were conducted by Adams (et al, 2001), Eilers (et al, 2015) and Harkness (et al, 2017). Adams (et al, 2001) investigated the chemical evolution of groundwater in the Western Karoo to provide insight into the interaction of water with the environment. Descriptive statistics of the hydrochemistry, as well as stable isotopes were used to provide an understanding of hydrochemical processes. The study identified salinization, mineral precipitation and dissolution, cation exchange and human activity as the main processes influencing the groundwater chemistry. The stable isotopes indicated the occurrence of infiltrated evaporated water giving rise to saline groundwater. Further to this, the localised topographic effect was provided as the overriding factor in controlling the groundwater chemistry as follows:

- Higher lying areas have a $CaHCO_3$ type water
- Topgraphically flat areas have a NaCl type water
- Areas where localised damming occurs provide saline soils, which leach into groundwater during recharge events.

Talma (1981) noted a trend in groundwater chemistry from $CaHCO_3$ to NaCl associated with greater ^{14}C age in parts of the Karoo basin. Adams (et al, 2001) noted a similar evolutionary trend in the groundwater in the Western Karoo from $CaHCO_3$ to $CaSO_4$ to NaCl through cation/anion exchange processes.

A geochemical baseline study was conducted by Eilers (et al, 2015) to differentiate deep and shallow groundwater based on the decay of uranium associated with the Karoo sediments. The Beaufort and Stormsberg Groups host Karoo uranium deposits known as the Karoo Uranium Province with uranium mineralisation highest in Molteno Formation of the Stormsberg Group, followed by the Adelaide Subgroup of the Beaufort Group, which in turn is followed by the Elliot Formation of the Stormsberg Group. The most stable isotope associated with uranium is ^{222}Rn, which is a decay product of ^{226}Ra, and in turn a decay product of ^{238}U. The results showed that deep groundwater, as defined by sub – thermal water as an initial proxy, contained low uranium and low ^{222}Rn. The shallow groundwater, owing to the fact that it contains higher O^2 and alkalinity that increases uranium solubility, contains high ^{222}Rn as a result of the decay of uranium and subsequent absorption into the shallow aquifer due to the presence of oxic fractures. The presence of dolerite intrusions, which comprise 30% of the Karoo Basin thickness, creates preferential flow mechanism for the rise of deep poorer quality water into fresh shallow aquifers.

Harkness (et al, 2017) assessed the groundwater chemistry at eight different sampling regions across the Karoo Basin for gas and water chemistry. The overall groundwater chemistry composition was summarised as follows:

- Low salinity Ca – Mg – HCO_3 type water (Type A)
- Low salinity Na – HCO_3 – Cl type water (Type B)
- Relative high salinity Na – Cl type water (Type C)

Based on mean residence time calculations Type A water (10^2 years) is significantly younger than Type B water (10^4 years), which in turn is younger than Type

C water (10^5 years). AC water types were also identified and attributed to direct mixing of deep saline water and fresher shallow groundwater. The stable isotopes analysis indicated that shallow groundwater is controlled by evaporation in arid conditions, whilst saline groundwater was diluted by apparent fossil meteoric water under wetter climatic conditions.

4. Research Formulation

Recent studies mentioned in Section 3 utilised geochemistry indicators (inorganic and isotopes) to differentiate between shallow and deep groundwater. The shale gas exploration studies in particular focused more on regional scale assessments. The opportunity existed to apply these methods on a local well field scale. The current local scale studies have been mainly limited to consultants' reports with resource management limited to basic well field scale monitoring and interpretation. The problem with the current local scale approach is that well fields are operated on a "sustainable yield" level based on available fracture storage. Lateral inflows and outflows are not considered. The field work conducted at Beaufort West municipal well fields presented an opportunity to utilise available data and information to spatially characterise the groundwater, as well as to delineate a) flow directions, and b) potential compartments (due to the presence of dolerite dykes and sills) in the shallow aquifer (i.e. < 300 m as defined by SRK (2013)). A better understanding of the flow dynamics is essential to improve the overall resource management and subsequent decision making. It must be noted though that the research used existing data. The research did not attempt to expand the existing database or to collect additional data.

5. Methodology

Through several phases of data collection and field visits a systematic approach was adopted towards the development of a comprehensive groundwater database and conceptual model of groundwater flow within the fractured Karoo aquifer/s. Several projects were conducted by this author from 2005 – 2008 as part of the consultancy services rendered to the Beaufort West Municipality. The field visits included several individual geohydrological assessments and consultants' reports produced by this author that are all packaged into this dissertation. The latter geohydrological reports included the following:

- A review of the municipal well field operation (Rose et al, 2005).
- Investigating the possibility of utilising treated sewage water for a possible waterfront development on the Springfontein Dam (Rose et al, 2006a).
- Borehole camera investigations of problematic boreholes within the municipal well fields (Rose et al, 2006b).
- Investigating the interaction of groundwater and surface water in the Springfontein Dam area (Rose et al, 2006c).
- Hydrochemical sampling of the municipal well fields (Rose et al, 2007a).

- Optimization of groundwater abstraction in Beaufort West municipal well field (Rose et al, 2007b).
- Reconnaissance field investigation to identify new well fields for future augmentation (Rose et al, 2007c).
- Exploratory siting, drilling and pump testing of new fields south of Beaufort West (Rose et al, 2008).
- Aquifer characterisation and groundwater flow regimes of Karoo aquifers in Beaufort West (Rose, 2008)

Initially, all municipal well fields were visited in 2005 to capture their coordinates, check the current borehole infrastructure, take photos of each borehole, and to measure the water level and EC where possible. General comments were also made of each borehole's performance and/or problems experienced. All previous hydrogeological data were acquired from private consultants, municipal and DWS databases.

The hydrochemical sampling of the municipal well fields involved the sampling of about 12 production boreholes that were operational at the time. Two hydrochemical sampling runs were conducted in April 2006 and November 2006 respectively. The sampling was conducted in accordance with the sampling guide provided by Weaver (1992) and later updated by Weaver (et al, 2007). Samples were submitted to Bemlab in Somerset West and Ithemba in Johannesburg for macro – chemical (major cations and anions) and isotopes (oxygen 18, deuterium and tritium) respectively. The sampling and subsequent laboratory analyses were aimed at determining the status of groundwater quality and groundwater types, as well as to understand hydrological processes involved in groundwater flow.

Additional groundwater and surface water were sampled in August 2006 close to the Springfontein Dam north of the town to investigate the possible connectivity of surface water in the Springfontein Dam and groundwater. Macro – chemical (major cations and anions) and isotope (oxygen 18 and deuterium) sampling were conducted at selected sites near the Springfontein Dam area. This included the sampling of the Beaufort West Spring situated next to (i.e. downgradient of) the Springfontein Dam.

A surface water balance study was also conducted towards end – 2006 to investigate the possibility of utilizing the surface water in the Springfontein Dam for a waterfront development, or to supplement the surface water in the Springfontein Dam with treated sewage water during low flows. During this investigation the hydrology of the catchment was studied using WR 90 mean annual runoff data to produce an estimate of the possible surface runoff into the Springfontein Dam. Samples of the treated sewage data were also taken at the sewage treatment plant and at the golf course (since the golf course is using treated sewage water for irrigation purpose).

Borehole camera inspections at problematic boreholes were also conducted in 2006 with the assistance of a DWS (Geohydrology, Pretoria) borehole camera unit and team. Four boreholes were investigated to determine the cause of the declining borehole yields. They are G29858KA and G29858P (both in the Brandwag well field), as well as G29947A and G29946D (both in the Town well field).

Due to the continuous declining borehole yields in the Brandwag well field (particularly over the eastern part of this well field) alternative drilling sites were investigated in the western part of the Brandwag well field as temporary solution. The declining water levels is mainly due to local over – pumping and subsequent dewatering[**]. Electrical resistivity geophysical method as well as the magnetic method was employed to site a borehole on the contact of the TBR Dyke and Teekloof sediments. Although the geophysics provided one site for borehole drilling, the drilling of this site never occurred due to concerns that the Brandwag well field is already over – utilized. This nevertheless provided valuable geophysical information of this contact zone.

The optimization of groundwater abstraction in Beaufort West municipal well field involved groundwater balance calculations to identify areas of surplus or deficit groundwater. The available time series water levels were used to conduct a statistical time series analysis and forecasting using Statistica (version 5.1) software. The forecasting was compared with the water balance calculations. From the forecasting analysis, varying trends have been observed for the individual boreholes. Generally, the boreholes in the Town well field indicated improving (recovering) future trends, whilst that of Brandwag, Tweeling and Lemoenfontein well fields indicated declining trends.

The reconnaissance field investigation conducted in 2007 constituted an initial hydrocensus over an area of approximately 5 – 10 km east, south and west of Beaufort West town. The data generated during the hydrocencus were used in conjunction with all other existing geohydrological data, including DWS and municipal data to spatially identify new areas for potential well field development. This investigation produced short, medium and long term solutions for future augmentation.

During the latter parts of 2007 and 2008 the exploratory siting and drilling of boreholes in the southwest and southeast of the town commenced as part of the short term solutions provided in the reconnaissance investigation. The farms Droerivier, Hansrivier and Steenrotsfontein were investigated. Aerial photographic interpretation preceded the surface geophysical exploration to identify significant geological structures for drilling. In areas associated with dolerite dyke intrusions the magnetic method was used not only to locate the dolerite contacts but also to determine the orientation of the dyke. The proton magnetometer instrumentation was used for this purpose. In areas associated with faulting and fracturing within the Beaufort Group sediments, the

[**] Botha (et al, 1998) attributes this observation to deformation within the borehole caused by collapse of bedding plane fractures.

electromagnetic geophysical method, using the ABEM WADI apparatus, was used to identify conductive zones within predominantly sandstone and shale horizons. Five boreholes were drilled in Droerivier, two in Steenrotsfontein and two in Hansrivier. During drilling the blown out rock samples were taken at 1m intervals to assess the rock formation (i.e. rock type, minerals, degree of fracturing, iron staining, etc.). This information was later used to produce borehole logs per borehole using the Winlog software (version 1.0). The two most successful boreholes, both situated at Hansrivier, were pump tested in 2008.

During each of the aforementioned groundwater assessments the data were systematically collated into a comprehensive MS Access and GIS database respectively. Collectively, the data were derived from a variety of different sources, including the following:

- DWS's NGA database.
- DWS's WMS database.
- A private Excel - based database of Mr. Piet Havenga of DWS.
- Technical reports of SRK Consulting (SRK, 1997; SRK, 1998)
- Technical reports of this author (Rose et al, 2005; Rose et al, 2006a; Rose et al, 2006b; Rose et al, 2006c; Rose et al, 2007a; Rose et al, 2007b; Rose et al, 2007c; Rose et al, 2007d; Rose et al, 2008).
- The Beaufort West Municipality's GEOMON database.
- Boreholes drilled for the Beaufort West Municipality in 2008.
- Hydrocensus information of January 2007 (Rose et al, 2007).
- Hydrocensus information of UWC conducted in May 2008.

In accordance with DWS's standard descriptors for geosites the data were systematically populated during each individual groundwater assessment to ultimately create a 'mega' database for Beaufort West (DWS, 2004). The data included basic borehole data (i.e. coordinates, elevation, borehole depth, etc.), water levels, water chemistry (i.e. major anions, cations, trace elements, EC, pH, stable isotopes), borehole yields (i.e. blow yields and tested yields), transmissivity (T) and storativity (S). Groundwater use data were limited to the municipal well fields since there are limited private water use data. Where possible the data were continuously verified in the field for correctness.

The available data were used to conceptualise the groundwater flow in fractured aquifer/s in Beaufort West. The initial research constituted Deliverable 2 of the Xu (et al, 2012) and included two main parts, i.e. aquifer characterization and delineation of groundwater flow paths. A GIS approach was used to spatially identify trends in a variety of datasets so that subareas with similar characteristics can be grouped into groundwater compartments or flow paths (flow regimes). The point source data were overlain on 1:250 000 geological map of the area to determine the possible relationship of each dataset with the geology. Maps were generated to assist with the spatial characterization of the individual datasets, as well as to interpret the groundwater flow regime and associated recharge and chemical processes in the secondary aquifers. The available water level data were interpolated using the Baysian interpolation technique in the Tripol software acquired from the Institute for Groundwater Studies (IGS) at the University of Free State (UFS). The interpolated data were then exported to the Surfer 10 software for contouring and vectoring purposes. The contours and vectors were exported as shapefiles for the final map compilation in ARC GIS 10.5. Both the contours and vectors were overlain on the 1:250 000 geology of the area for the delineation of groundwater flow paths. This allowed for the separation of the secondary Karoo Aquifer into different compartments. A conceptual flow model of the Town Compartment was used to illustrate the groundwater flow regime in these individual aquifer units. A geological cross – section was also produced to further illustrate the groundwater flow regime.

6. Delineation of Study Area

Groundwater has been used for domestic and agricultural purposes since the early nineteenth century from one spring in the town (Willis, 2014). Several farmers were dependent on the water allocation from the spring through a system of water turns via a furrow (Pers. Comm. Louw Smit). Today the same furrow still exists flowing in a southerly direction along Bird Street. Extensive groundwater exploration was then conducted by DWS in the 1970's which covered an area up to 30 km north, northeast and east of Beaufort West (IDP, 2010). More recently in 2008 groundwater exploration shifted to the south of town. As a result of extensive groundwater exploration over a 50 year period over 300 boreholes have now been drilled. Some of these boreholes have become production boreholes for the town's water supply, whilst several other boreholes are used as part of the town's monitoring network. As a result of over 20 years of groundwater monitoring a comprehensive groundwater database has now been established that includes water levels, water quality, volume of groundwater abstraction and rainfall. Note that the areas in the south of town have particular relevance to the study since they coincide at least partially with the uranium mining areas.

Beaufort West has both groundwater and surface water sources for their municipal water supply. Although all rivers in the area are non – perennial rivers, the Gamka Dam, situated north of the town in the Nuweveld Mountains, dams the rainfall runoff from the Gamka River during a predominantly summer rainfall season. The annual usage from the Gamka Dam is approximately 1.9 Mm^3 (Umvoto, 2011). Groundwater usage is from several well fields in the north, northeast and south of the town. These well fields abstract approximately 1.9 Mm^3 per annum of groundwater. The well fields are situated within a radius of 40 km from the town. The furthest well field is the Brandwag well field (situated about 40 km northeast of the town), followed by Tweeling well field (situated about 30 km northeast of town), which in turn is followed by Lemoenfontein well field (situated about 20 km northeast of town) and the Town well field that extends from the town to about 10 km north of town. The new well fields recently explored in the south are Hansrivier (situated 10 km southeast of town) and Droerivier (situated 5 km southwest of town), collectively known as the Southern well field. Due to the strategic importance of groundwater, groundwater monitoring is critical to sustain the lifespan of these well fields.

Two main indicators determined the outline of the study area. They are 1) occurrences of uranium in the area, and 2) data availability. Uranium exploration in the Beaufort West area has been active for a number of years. Evidence of this is the number of exploratory boreholes that exist in the southeast, south and southwest of the town. These exploratory boreholes are different to the conventional water boreholes since they are often very narrow in diameter (between 90 mm and 120 mm) and shallow, with maximum depths above the regional water table. Hence they can sometimes be mistaken for dry water boreholes. Several of the latter boreholes occur on the farms Hansrivier, Quaggasfontein, Steenrotsfontein and Blydskap, situated 5 to 20 km south of Beaufort West. Although the extent of the uranium mining areas are unknown due to the confidentiality of the mining companies currently in operation, the areas that are reportedly actively mining the uraniferous sandstone are in the vicinity of Rietkuil (in the southwest) and Ryst Kuil (in the southeast). Note that during the May 2008 hydrocensus none of these areas were visited due to access.

The study area is therefore limited to areas where access was permitted or generally where data is available. Due to this author’s previous involvement as groundwater consultant to the Beaufort West Municipality from 2005 to 2009, the bulk of the data relates to the municipal well fields and adjacent exploratory areas. These areas include the town’s well fields in the north and northeast (up to 40 km northeast of town), 40 km east of the town including the farm Sunnyside, 30 km south of the town up to the farm Blydskap. Although the areas south of Beaufort West were only recently re – visited for possible exploratory purposes, they also include old and existing mining properties that were not accessible for data collection. As a result of this, large gaps in the spatial spread of point source data exist along the southern areas. However, the areas in the south were included as part of the study area since they include the uranium mining areas, which was part of the scope of the broader Xu (et al, 2012) study.

7. Climate

The study area is dominated by cold and dry winters and hot and wet summers (Willis, 2014). Winter and summer temperatures of below 0°C and above 40°C respectively are not uncommon. During winter snow falls along the escarpment are often associated with the low temperatures. The rainfall is highly variable across the Great Karoo, with < 100 mm recorded in the north – western Karoo and increases to about 400 mm along the eastern parts of the Karoo (Willis, 2014). Although the area receives some rain during the winter, the bulk of the rainfall occurs in summer in the form of thunderstorms that transforms the dry rivers into rapidly raging torrents for short periods (IDP, 2010). According to South African Weather Services (SAWS) rainfall data for the

De Hoop rainfall station, situated about 40 km northeast of Beaufort West, the long term annual average rainfall is about 268 mm/a of which the peak rainfall months are from January to April (**Figure 4**). The latter annual average rainfall is consistent with the 260 mm/a provided by Diettrich (1972).

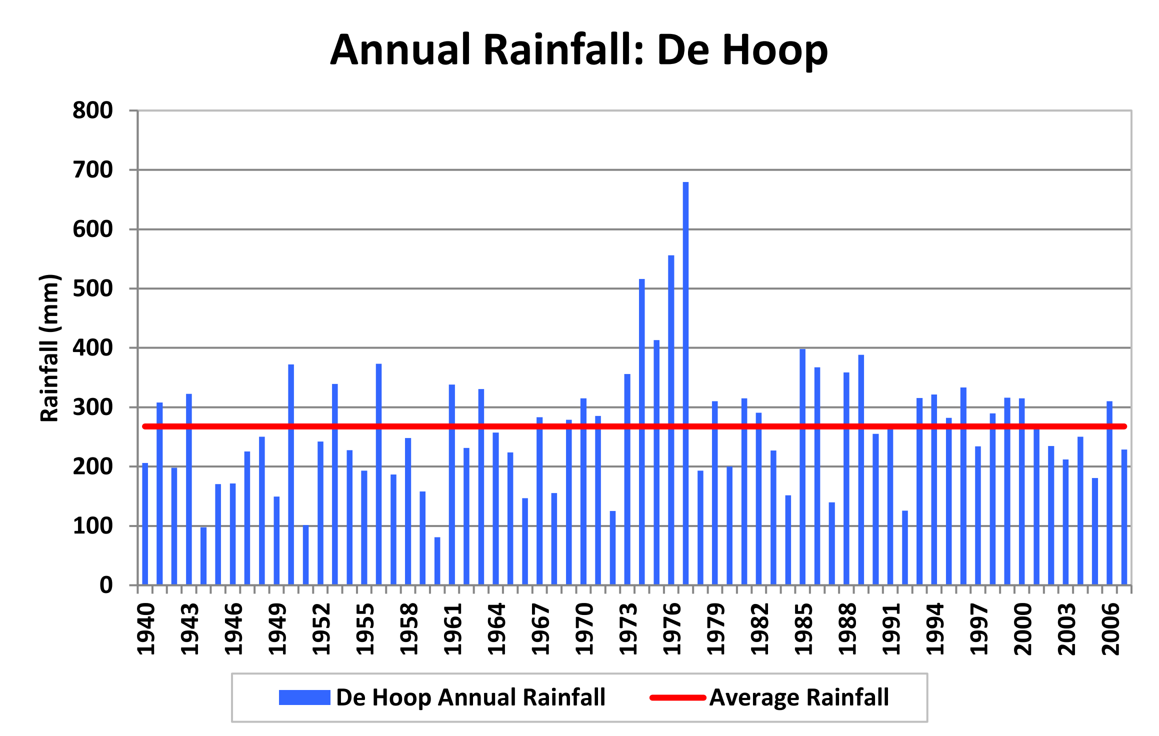

Figure 4: Long term annual rainfall

8. Hydrology

The study area generally slopes from north to south and forms the headwaters of J21A and L11F quaternary catchments respectively. The J21A catchment, comprising of the main Gamka River and its tributary the Kuilspoortspruit River, drains south – westwards through Beaufort West town and forms part of the broader Gouritz Water Management Area (WMA). The L11F catchment, comprising of the main Platdoring River and its tributary the Renosterspruit River, drains southwards and forms part of the Fish to Tsitsikamma WMA. The drainage channels are mainly characterised by alluvium filled dried up river beds that only flows during or shortly after heavy showers. The only surface water source in the area is the Gamka Dam, situated in the Nuweveld Mountain north of Beaufort West. The Gamka Dam has a capacity of about 1.9 Mm^3 and is currently used for municipal supply in Beaufort West, contributing to about 45% of the total municipal water (Umvoto, 2011).

The topography is generally controlled by the presence of resistant dolerite sills and dykes that form a cap rock to the less resistant Beaufort Group sediments. The Nuweveld Mountain in the north forms an east to west escarpment with dolerite sill capping on top and in between sediments. The elevation at the Gamka Dam is approximately 1150 mamsl. The slopes are generally convex in shape owing to the positive weathering processes associated with the dolerite sills in particular. The flat plains to the south of the Nuweveld Mountain is characterised by wide flat lying areas that stretch over tens of kilometres. The average elevation in Beaufort West is approximately 850 mamsl.

9. Regional Geology

The regional geology is dominated by the Karoo Supergroup that was deposited in the Karoo Basin with a surface area of 200,000 km^2 (CGS, 2005; Aarnes et al, 2011). The Karoo Supergroup was formed through sedimentation within an intracratonic, foreland basin on Gondwanaland, during the Carboniferous, Permian, Triassic and early Jurassic ages, about 300 Ma to 160 Ma ago (Truswell, 1970). Catuneanu (et al, 2005) describes the Karoo Basin as a retro – arc foreland basin behind the Cape Fold Belt. The main Karoo Basin covers a large part of the central and eastern parts of South Africa, and according to Du Toit (1954), the Karoo Basin has a maximum thickness in the southern parts of the Northern Cape Province and Lesotho. In accordance with Tankard et al (1982), the succession of rocks comprising the Karoo Supergroup is shown in **Figure 5**.

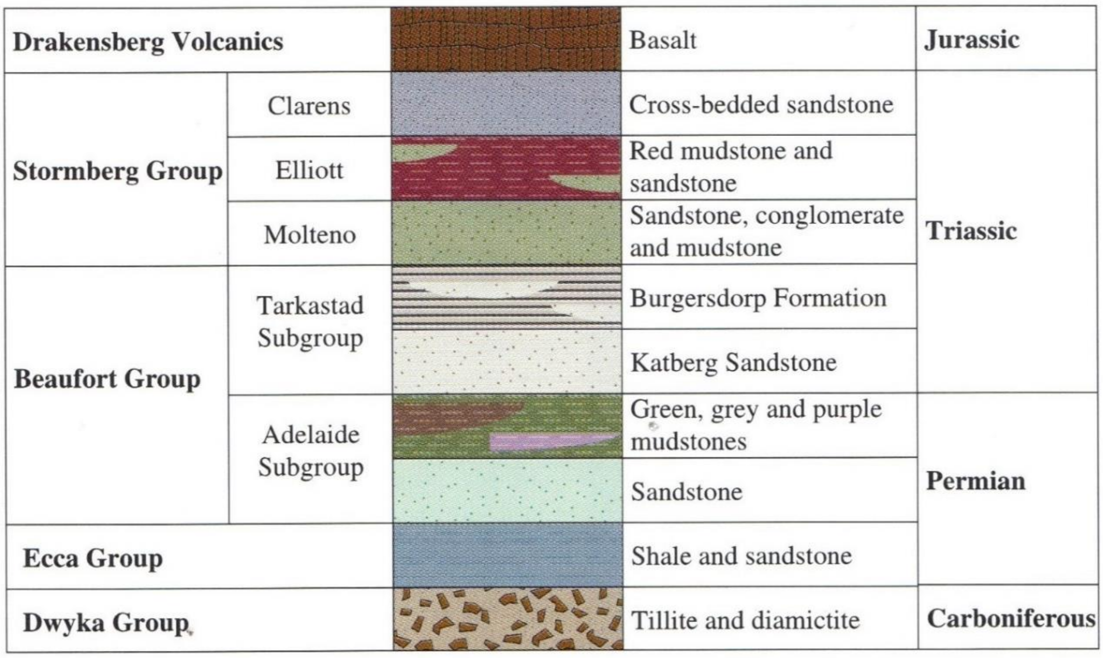

Figure 5: The Karoo Supergroup (Tankard, et al, 1982)

The base of the Karoo Supergroup is represented by the Dwyka Group. The sedimentation of the Dwyka Group occurred when Gondwanaland migrated over the South Pole during the Carboniferous Age (Johnson et al, 2006; Botha et al, 1998). The Dwyka sediments consist mainly of diamictite and massive tillite deposited under conditions of glaciation (Botha et al, 1998). The Dwyka Group were deposited on older Precambrian granitic rocks in the north and sedimentary rocks associated with the Cape Fold Belt in the southern parts of the Karoo Basin, respectively. The Ecca Group stratigraphically overlies the Dwyka Group (CGS, 2005). The Ecca Group, deposited under a series of marine and deltaic conditions during early Permian Age (286 – 248 Ma), consists mainly of shale and sandstone (Johnson et al, 2006; Botha et al, 1998). The thickness of the Ecca Group varies from about 600 m in the north of the Karoo Basin to 1500 m in the south of the Karoo basin (Botha et al, 1998).

Fluvial sedimentation during late Triassic and early Jurassic formed the Beaufort Group, which stratigraphically overlies the Ecca Group and consists of two subgroups, i.e. the Adelaide Subgroup and Tarkastad Subgroup. According to the CGS (2005), the regional surface geology of Beaufort West is mainly dominated by the Adelaide Subgroup of the Beaufort Group (**Table 3**). The Adelaide Subgroup of late Permian age (i.e. 260 Ma) consists of the older Abrahamskraal Formation and younger Teekloof Formation of alternating bluish - grey mudstone and grey very fine to medium grained sandstone (Chevalier et al, 2001). The Abrahamskraal Formation can be up to 2500 m thick whereas the Teekloof Formation can be up to 1400 m thick (Chevalier et al, 2001). According to Chevalier (et al, 2001) the sandstone units were formed by lateral migration of meandering rivers, whereas the mudstone units were formed by deposition in a flood plain and lacustrine environment. The Tarkastad Subgroup of early Triassic Age is divided into the older Katberg Formation, which consists mainly of thick layers of coarse sandstone with bright coloured shales and mudstones, and the younger Burgersdorp Formation, which consists of brightly coloured red, blue and green mudstones (Botha et al, 1998). A braided and meandering stream depositional environment has been ascribed to the Beaufort Group sediments (Botha et al, 1998). The braided stream deposits tend to produce sheetlike, wedge – shaped sandstone layers intermingled with shale lenses. According to Tankard (1982), the meandering stream deposits tend to produce horizontal layers of alternating sandstone, siltstone and mudstone.

Table 3. Surface geology of Beaufort West and surrounding area (Rose, 2008)

Group	Subgroup	Formation	Intrusives	Lithology	Age
				Alluvium	Recent
				Calcrete and hard pan	
			Dykes/sills	Dolerite	Jurassic
Beaufort	Adelaide	Teekloof		Mudstone	Permian
		Abrahamskraal		Sandstone	

Due to renewed uplift of the Cape Fold Belt during the Triassic Age (230 – 193 Ma) resulted in the aridisation of the basin where sediments were again deposited in four smaller basins in Southern Africa (Catuneanu et al, 2005; Botha et al, 1998). One of these basins formed over an area that stretches from the northern parts of the Eastern Cape Province into Lesotho and the Free State and KwaZulu – Natal Provinces (Botha et al, 1998). The Stormberg Group represents the youngest group of the Karoo Supergroup and consists of the Molteno, Elliot and Clarens Formations (in order of decreasing age) (CGS, 2005). The Molteno Formation is characterised by six depositional cycles, each cycle coarsening towards its base, i.e. conglomerate and coarse sandstone at its base, followed by fine – grained sandstone and shales with coal seams (Botha et al, 1998). Due to its wedge like structure, the Molteno Formation varies greatly in thickness from a maximum of 640 m at Maclear in the southeast Karoo Basin to 30 m in the northeast Karoo Basin. The Elliot Formation consists mainly of red mudstone and medium to fine – grained sandstone in a wedge like depositional basin with a maximum thickness of 500 m in the south to 20 m in the north (Botha et al, 1998). Following the deposition of the Elliot Formation, aeolian processes dominated, to produce sediments related to aeolian sand, playa lakes and sheet flood deposits of the Clarens Formation (Tankard, 1982). The aeolian sand sedimentation produced the fine to very fine – grained, cross – bedded units of up to 10 m thick, whilst the storm floods and subsequent wadi formation type sedimentation produced medium to fine – grained sandstone (Botha et al, 1998). Fine – grained sandstones with a high clay content are associated with playa lake deposits (Botha et al, 1998).

Widespread volcanism ended the Karoo sedimentation during early Jurassic Age (Tankard et al, 1982). According to Botha (et al, 1998), the magmatic activity is divided into two phases, i.e. an extrusive phase associated with the outpour of Drakensberg lavas, as well as the intrusive phase associated with numerous linear dolerite dykes and kimberlites in the Karoo formations. The intrusion of dolerite dykes resulted in the formation of fractures and contact metamorphism within the sedimentary host rock (Aarnes et al, 2011).

In the Beaufort West and surrounding areas, Jurassic age dolerite dykes and sills intruded into the fractures of the Beaufort Group sediments over a period of extensive magmatic activity over the entire Southern African subcontinent during the Gondwanaland break-up (Chevalier et al, 2001), resulting in a network of dolerite dykes, sills and even inclined sheets in the study area (**Figure 6**). According to Rose (2007) the two main dykes are:

1. E – W trending dyke stretching from the Nuweveld Mountains north of the Gamka Dam in an easterly direction cutting across the farms Tweeling, Brandwag and Renosterkop, otherwise called the TBR – dyke by SRK (1997), terminating into an interpreted dolerite ring structure on the farm Renosterkop.
2. E – W trending dyke cutting through the town of Beaufort West.

In addition, there are also other smaller dykes like the Droerivier dyke (i.e. southeast – northwest dyke north of Droerivier) and Hansrivier dyke (i.e. a small north – south dyke at Hansrivier). Furthermore, there are dolerite sills that cover mainly the mountain tops as cap rock. The interpreted dolerite ring structure on the farm Renosterkop (northeast of Beaufort West) is described by Chevalier (et al, 2001) as saucer-like inclined dolerite sheet. A large part of the area especially in the lower lying areas is also covered by calcrete and hard pan deposits (CGS, 2005) possibly as a result of secondary weathering of the Karoo sediments. Alluvium covers the river valleys of predominantly ephemeral streams.

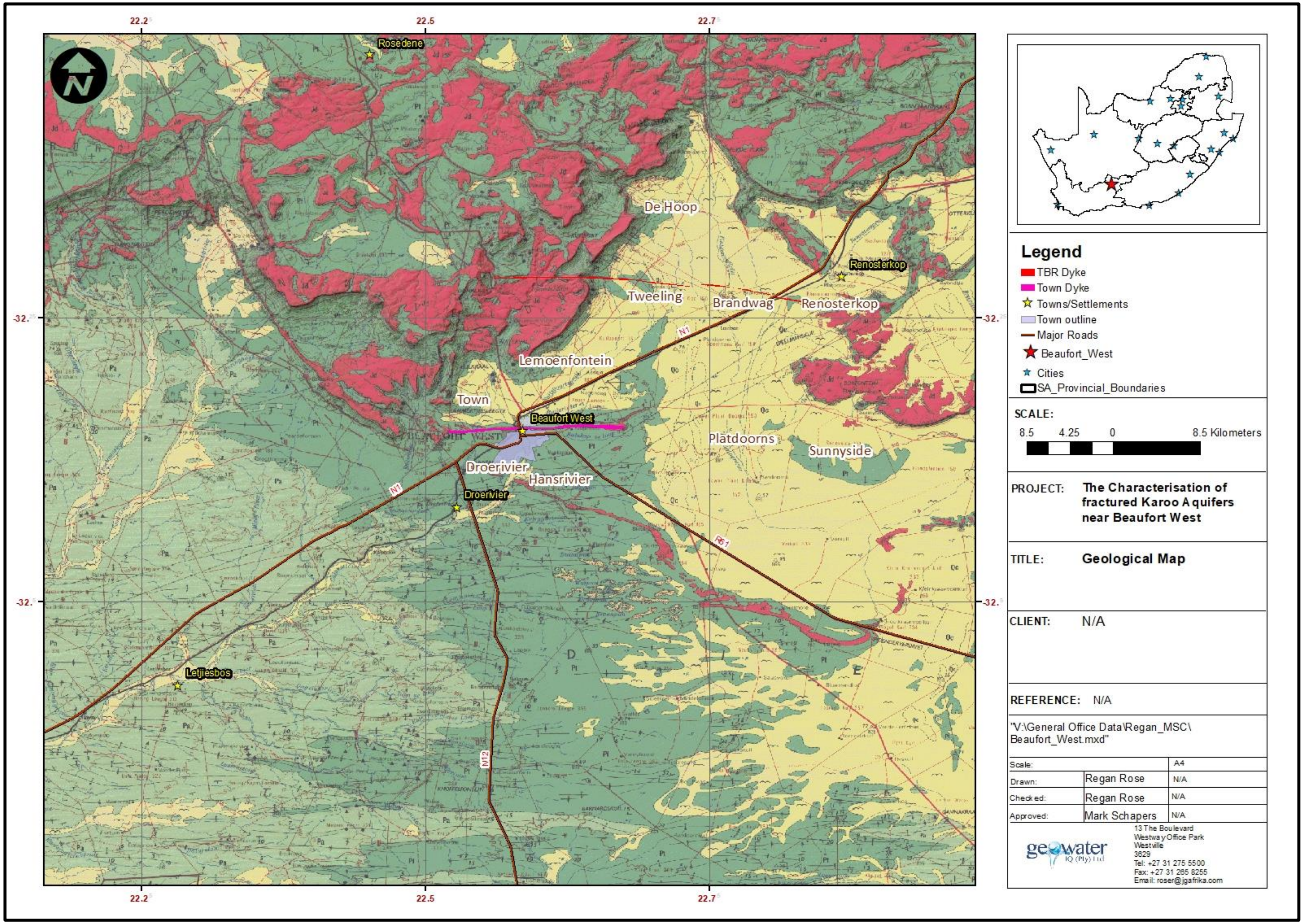

Figure 6: Geology of the study area (CGS, 2005)

10. Regional Hydrogeology

According to the 1:500 000 hydrogeological map series Sheet 3122 of Beaufort West fractured rock aquifers (secondary aquifers) cover most of the surface area around Beaufort West, although a combination of intergranular and fractured rock aquifers also exists in the area (DWS, 2002). The fractured rock aquifer, associated with the Beaufort Group sediments, tends to produce high yielding boreholes > 5.0 ℓ/s particularly in areas overlain with thick alluvium deposits (WR, 2012)[††]. The borehole yields tend to decline to 0.5 – 2.0 ℓ/s over large areas south and west of Beaufort West (WR, 2012). The fractured nature of the Beaufort Group sediments is due to the brittle nature of the rocks in response to deformational processes. Generally, the Beaufort Group sediments have low primary porosities, but the secondary porosity is well developed and is associated with weathering, minor folding, fracturing, faulting and jointing (SRK, 1997). According to SRK (1997), high groundwater potential exists at the dolerite / sediment contact zones, the mudstone / sandstone contact zones, as well as the fractured sandstone (i.e. particularly where the proportion mudstone: sandstone ratio is small). The borehole yields associated with the Adelaide Subgroup (Beaufort Group) vary dependent on the arenaceous: argillaceous ratio of the rock content (SRK, 1997). A high arenaceous: argillaceous ratio suggest that the rock is more rigid than plastic, which aids the development of brittle failure when exposed to external forces and results in the formation of fractures within the predominantly arenaceous rocks. Conversely, a low arenaceous: argillaceous ratio suggest that the rock is more plastic and less rigid, and is likely to bend rather than break when exposed to external forces and generally results in less fracture development and lower borehole yields.

The intergranular and fractured aquifer is represented in the area by the dolerite sills and dykes, which exhibit a dual porosity. Due to the in-situ weathering nature of dolerite it develops a dual porosity within the upper weathered and lower fractured zone respectively. The borehole yields associated with the intergranular and fractured aquifer is generally in the range of 0.1 – 0.5 ℓ/s (WR, 2012). It must be noted though that not all dolerite sills and dykes behave in this way but it is described as such in the 1:500 000 hydrogeological map. Dolerite is more commonly associated with a fractured aquifer where the fractured contact zones of the dolerite and the Karoo sediments are the main water bearing target.

Locally the alluvium within dried up river beds and plains also constitute a primary aquifer, however on the 1:500 000 scale provided by WR (2012), it is not regarded as a major aquifer. The alluvium in turn acts as storage reservoirs for recharged water from rain events and recharges the underlying formations (SRK, 1998). The regional hydrogeological map is provided in **Figure 7**.

[††] The Groundwater Resources Assessment Phase II (GRA II), initially conducted by DWS in 2005, was updated by Water Resources 2012.

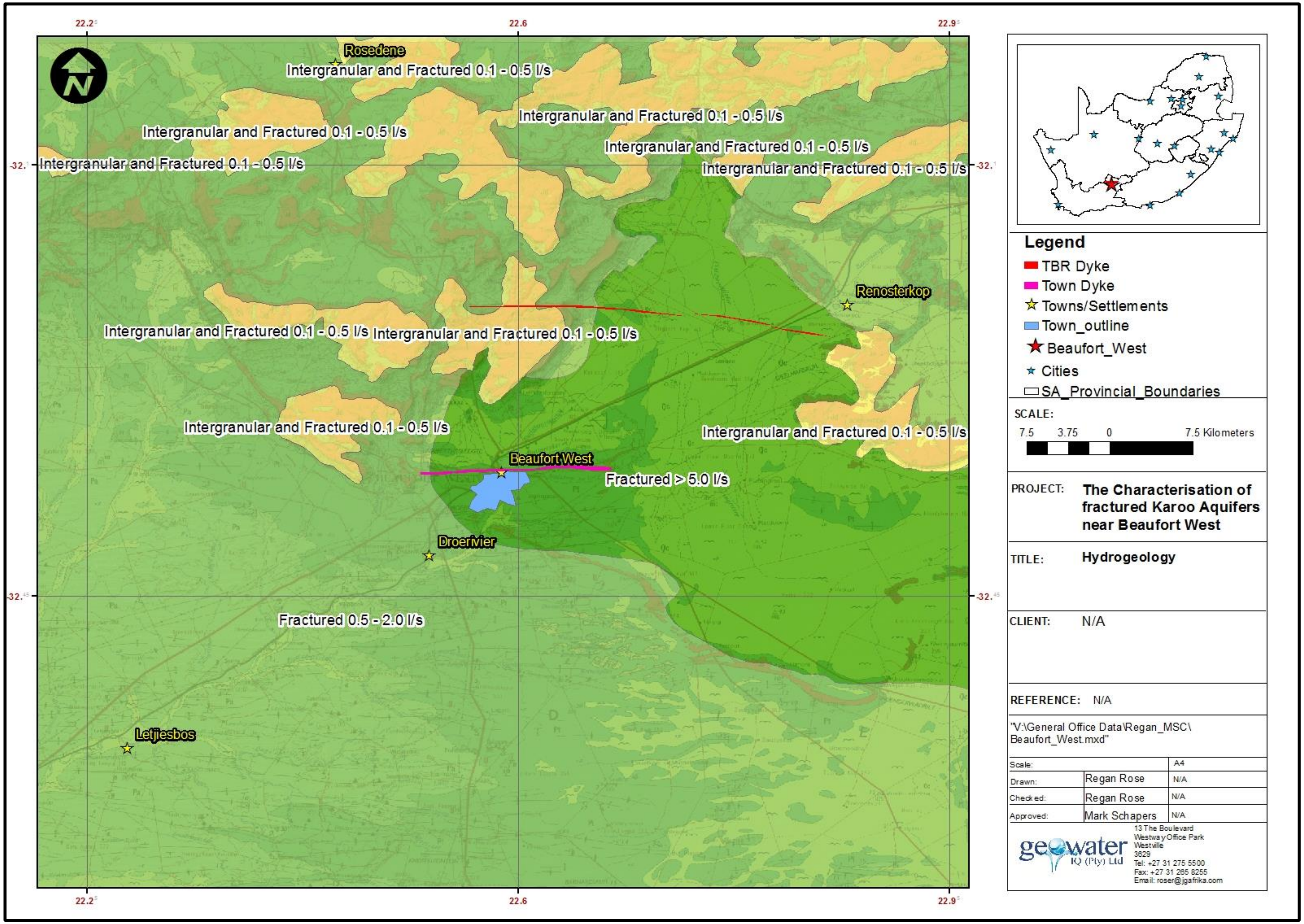

Figure 7: Hydrogeological Map (WR, 2012)

The groundwater quality varies greatly over the study area. Using the EC as overall groundwater quality indicator there is a gradual deterioration of groundwater quality in a south – easterly direction (WR, 2012) (**Figure 8**). The best groundwater quality (i.e. 0 – 70 mS/m) occurs in the north along the Nuweveld Mountains, whilst the poorest groundwater quality (i.e. >1000 mS/m) occurs about 30 km southeast of Beaufort West. Most of the area around Beaufort West generally has good to moderate (70 – 300 mS/m) groundwater quality. The observed groundwater quality distribution may reflect local groundwater recharge conditions.

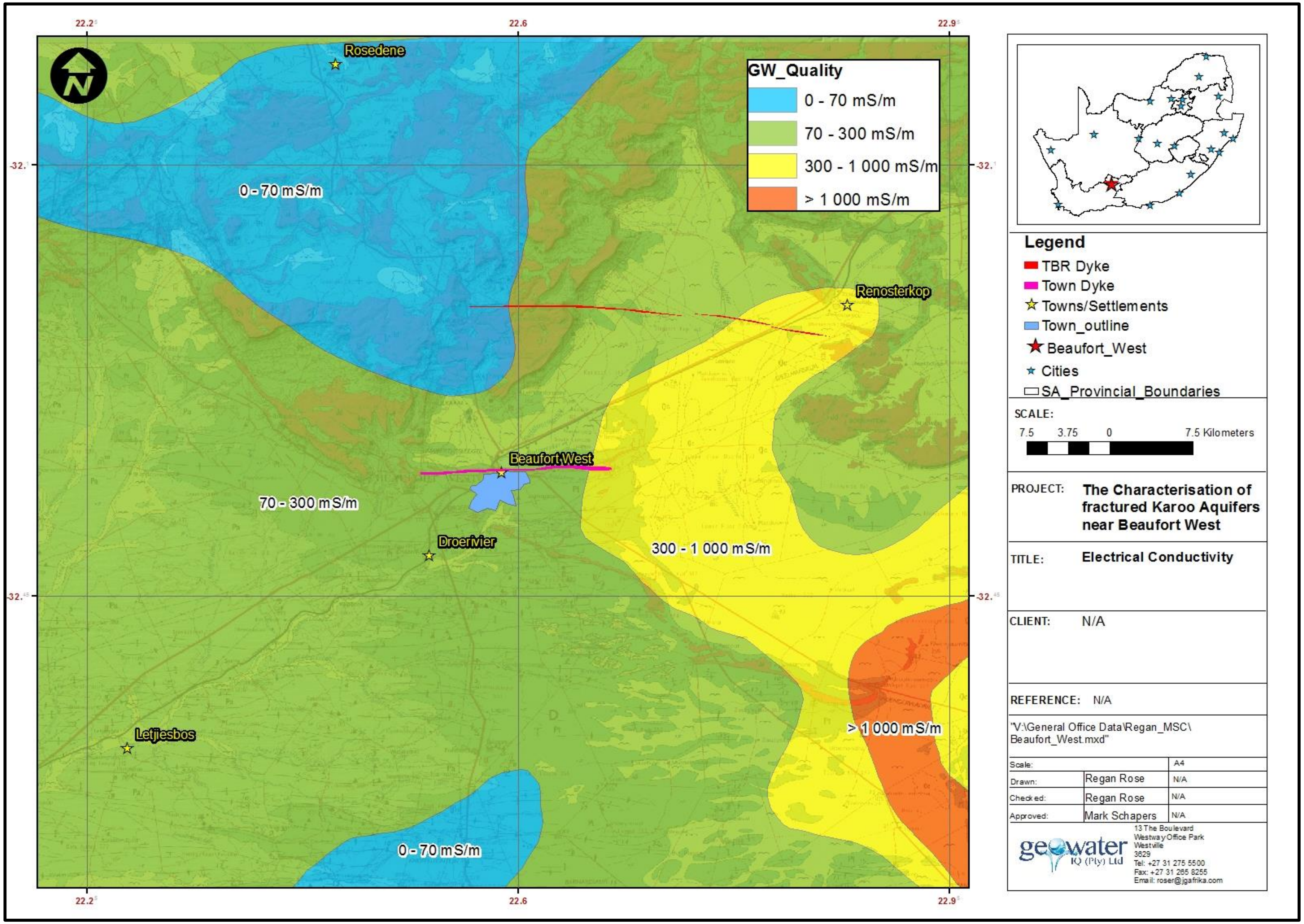

Figure 8: Groundwater Quality (WR, 2012)

Current abstraction (discharge) in the area comes from the municipal and agricultural sectors. According to DWS's Water Authorisation and Registration Management System (WARMS); groundwater use is 3.36 Mm^3/annum for J21A and 1.23 Mm^3/annum for L11F respectively (DWS, 2005). The municipal groundwater usage from Beaufort West Municipality is about 2.0 Mm^3/annum.

According to WR (2012), the mean recharge for the quaternary catchments J21A and L11F is 1.76% and 2.32% of total rainfall respectively, which is equivalent to approximately 3.46 Mm^3 and 3.79 Mm^3 for these two quaternary catchments respectively. The study area covers the majority of these two quaternary catchments. The groundwater recharge over the study area is spatially variable (**Figure 9**). Higher recharge (> 10 mm/a) is expected in the north along the Nuweveld mountain, whilst there is a gradual decrease towards the south and southwest. The groundwater recharge is a minimum in the southwest where < 1 mm/annum is expected (WR, 2012). It must be noted though that the WR (2012) recharge was derived mainly from the chloride mass balance method which assumes vertical rainfall recharge in the area above it. This is not always the case as in some cases recharge occurs some distance from the well fields and/or discharge areas. However, for the purpose of this dissertation the recharge is deemed sufficient to indicate the spatial distribution.

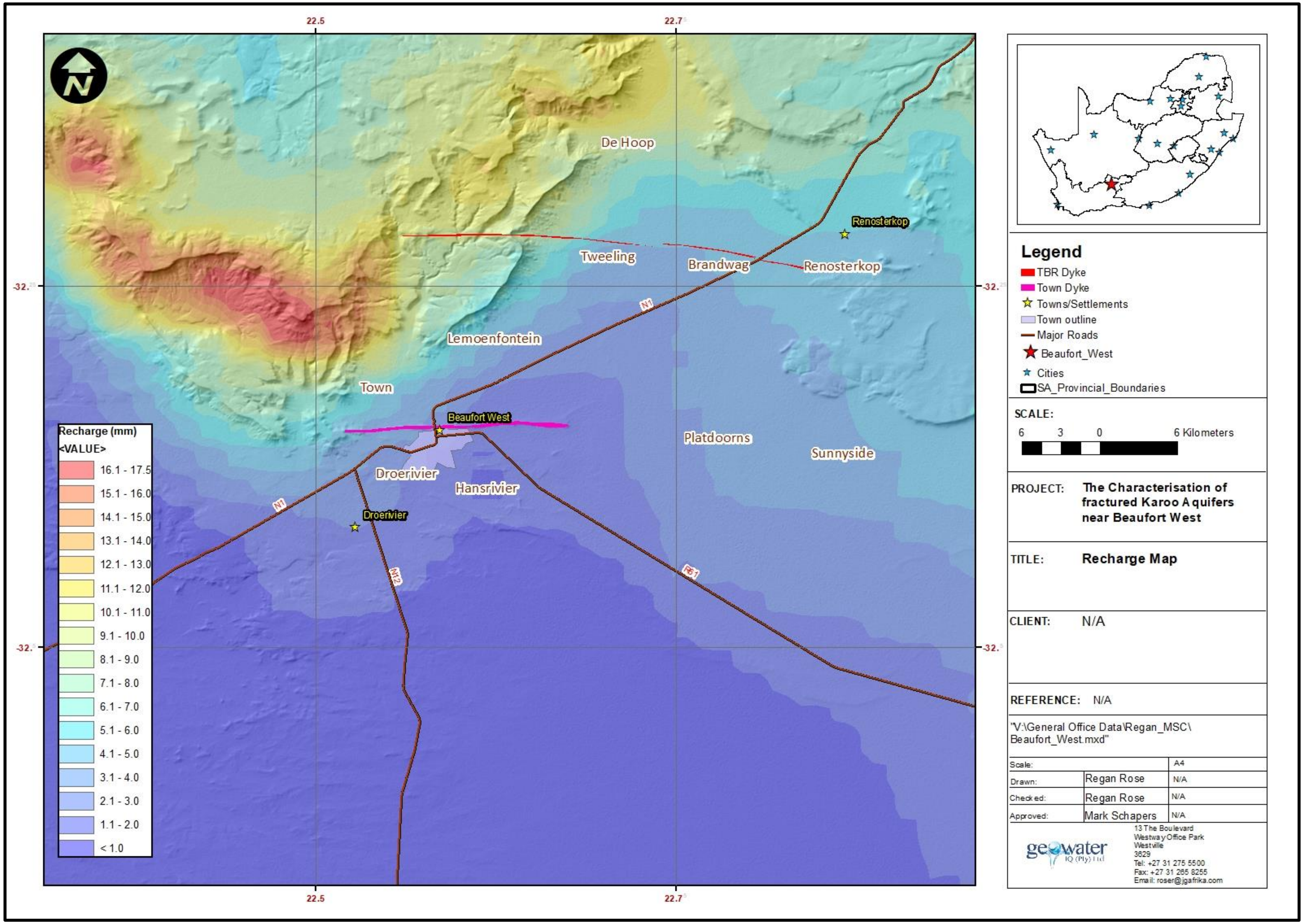

Figure 9: Groundwater recharge of the study area (WR, 2012)

11. DATA ANALYSIS AND TRENDS

11.1 Aquifer Properties

Borehole pump tests of existing successful boreholes were conducted on a needs basis as requested by the Beaufort West Municipality from 2006 to 2008 or whenever new boreholes were drilled. For this dissertation the pump test data had the main purpose of determining T and S values of the fracture zones. Of lesser importance for this dissertation is the determination of the sustainable yields of boreholes and therefore it will not be discussed in too much detail. The pump tests did however determine sustainable yields based on identification of the main fracture (or water strike) and subsequently available drawdown. The boreholes that were pump tested during this period were Brandwag_5, DR_5, G29877L_new, HK_NDA, HR_10 and HR_13. The raw pump test data is provided in **Appendix A**. The summary tables of the respective borehole analyses utilising the FC Method[‡‡] are provided in **Appendix B**. Additional pump test data were acquired from a variety of sources to compile a map of transmissivity (T) and storativity (S). The sources include historical reports (DWS and SRK Consulting) and the NGA. Furthermore, it must also be noted that the T and S values adopted were derived from different authors using different scientific interpretation methods. The spatial distribution of T and S are shown in **Figure 10** and **Figure 11** respectively. The data is limited mainly to the municipal well field areas, which reflects the areas most extensively explored over the past 50 or so years. The T and S values represent the average horizontal T and S values within the fracture zones at the respective localities.

[‡‡] An Excel-based software product produced by the Institute for Groundwater Studies at the University of Free State

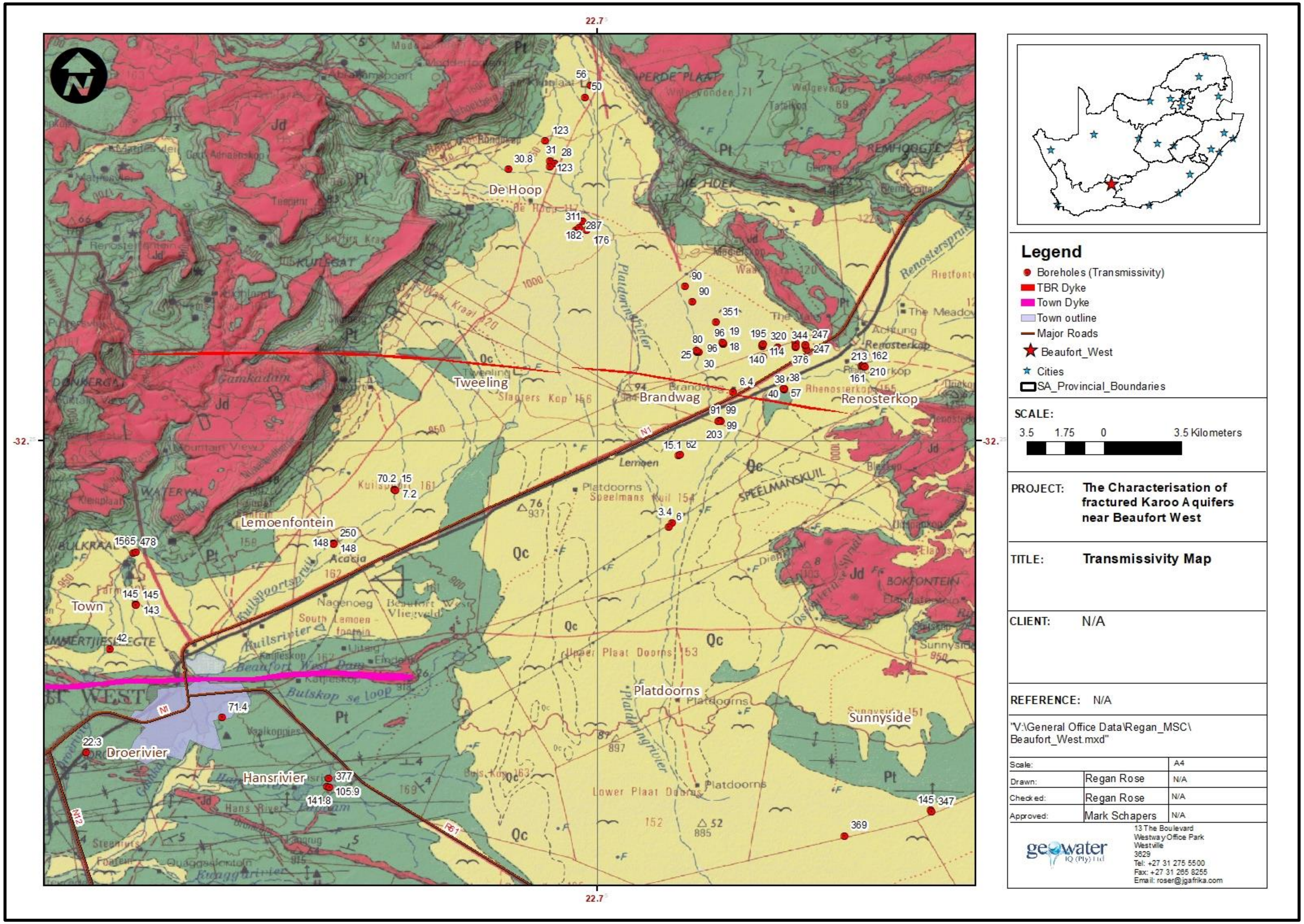

Figure 10: Spatial distribution of transmissivity (T in m²/day) within the underlying aquifer

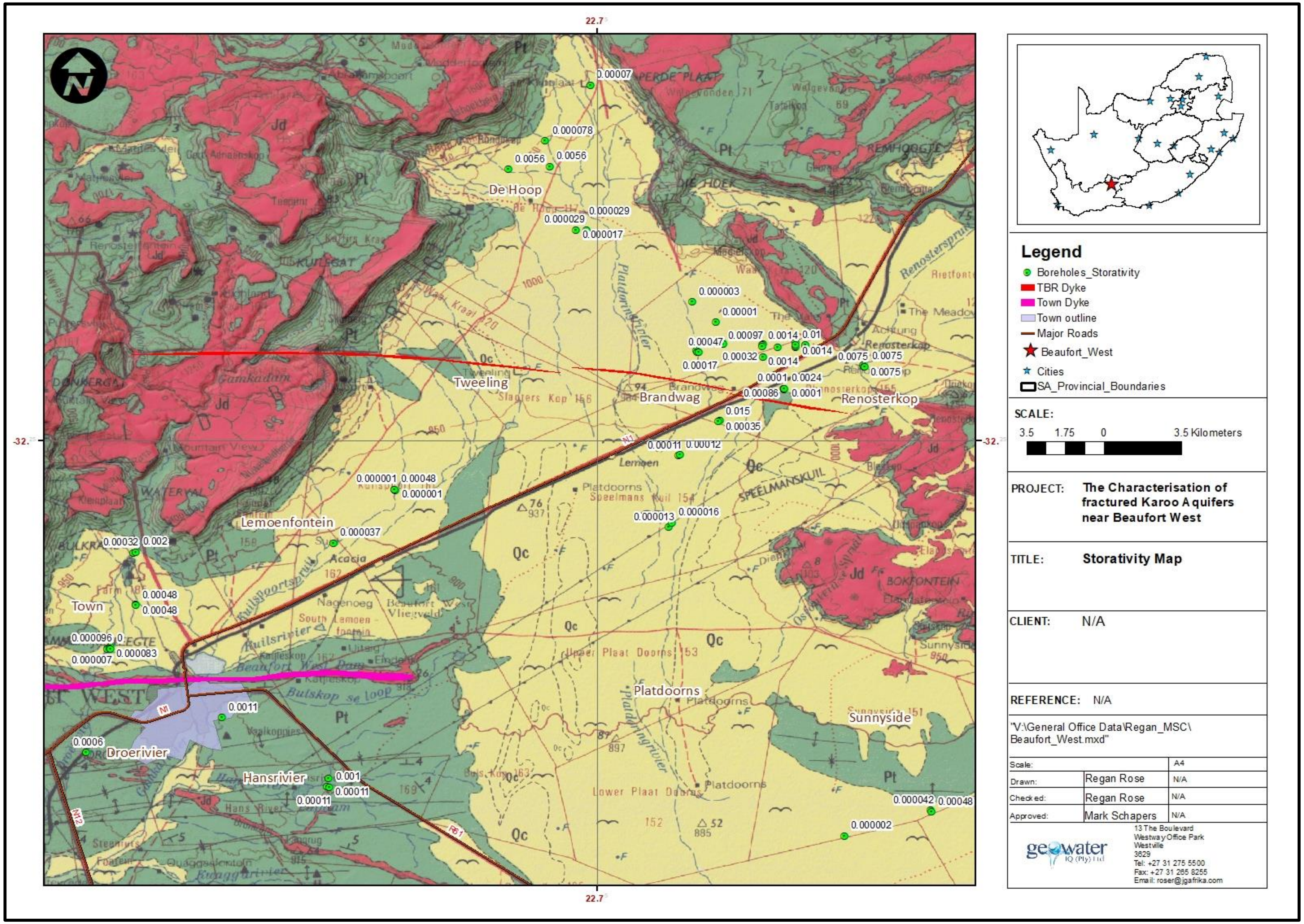

Figure 11: Spatial distribution of storativity (S dimensionless) within the underlying aquifer

The T and S values vary greatly over the study area (**Table 4**). Within the Brandwag well field higher T and S values are observed in the eastern side of the well field where T is > 200 m^2/day and S between 1 x 10^{-2} – 1 x 10^{-3}. The western side of the Brandwag well field is somewhat different to the eastern side, where T is generally < 200 m^2/day and S is between 1 x 10^{-4} – 1 x 10^{-5}. In the north at De Hoop T varies between 30 – 300 m^2/day, whilst S values are in the 1 x 10^{-5} range (although isolated patches occur where S is in the range of 1 x 10^{-3}). At Platdoorns (south of Brandwag well field) the T values vary greatly from < 10 m^2/day to > 200 m^2/day, whilst the S values are in the 1 x 10^{-5} range. At the Lemoenfontein well field the T varies from > 100 m^2/day – 250 m^2/day, whilst the S values are in the 1 x 10^{-4} – 1 x 10^{-5} range. The Town well field, Droerivier and Hansrivier generally have S values that range from 1 x 10^{-3} – 1 x 10^{-4}, although the T values vary from about 40 to > 400 m^2/day for the Town well field to < 10 m^2/day for Droerivier and > 300 m^2/day for Hansrivier.

Table 4: Summary of T and S in the study area

Subarea	Average borehole depth (m)	T (m^2/day)	S (dimensionless)
Brandwag east	67	>200	0.01 - 0.001
Brandwag west	81	<200	0.0001 - 0.00001
De Hoop	75	30 - 300	0.001 - 0.00001
Platdoorns	81	<10 - >200	0.00001
Lemoenfontein	66	100 - 250	0.0001 - 0.00001
Town well	56	40 - >400	0.001 - 0.0001
Droerivier	101	<10	0.001 - 0.0001
Hansrivier	58	>300	0.001 - 0.0001
Sunnyside	68	100 - 360	0.00001 - 0.000001

No clear correlation is visible between the observed T values and the geology. A general field observation is that boreholes drilled on the dolerite contact zones are higher yielding than those drilled in the sediments of the Teekloof formation. A case in point is two boreholes drilled on the farm Hansrivier on the contact of a dolerite dyke that produced sustainable borehole yields more than 10 ℓ/s. Although the latter observed T were well in excess of 300 m^2/day, it is no different to other areas in the municipal well fields (Town and Brandwag well fields) associated with the fractured sediments of Teekloof formation (in the absence of any dolerite dykes). The degree of fracturing seems to dictate the successfulness of boreholes rather than the lithology itself. However, note that the arenaceous units tend to produce better borehole yields and water quality than the shale, siltstone or mudstone units, probably due to its larger pore sizes and effective porosity.

The degree and interconnectivity of the fracturing is possibly best displayed by the hydraulic diffusivity (i.e. T/S) distribution, which is highly variable over the study area.

T/S = hydraulic diffusivity

An example is the Brandwag well field area where S values vary between 1×10^{-2} and 1×10^{-7}. Local dewatering that has been reported in the Brandwag well field is likely to be related to areas with low S particularly in the east of the well field where there is competition with other users (i.e. agriculture). The latter observation must not be seen in isolation of recharge and lateral inflows.

Considering that borehole yield and S shows a very weak correlation ($R^2 = 0.002$) (**Figure 12**), a significantly higher correlation (albeit still relatively low) can be observed between borehole yield and T ($R^2 = 0.2264$) (**Figure 13**), suggesting that the borehole yield is more dependent on T than on S.

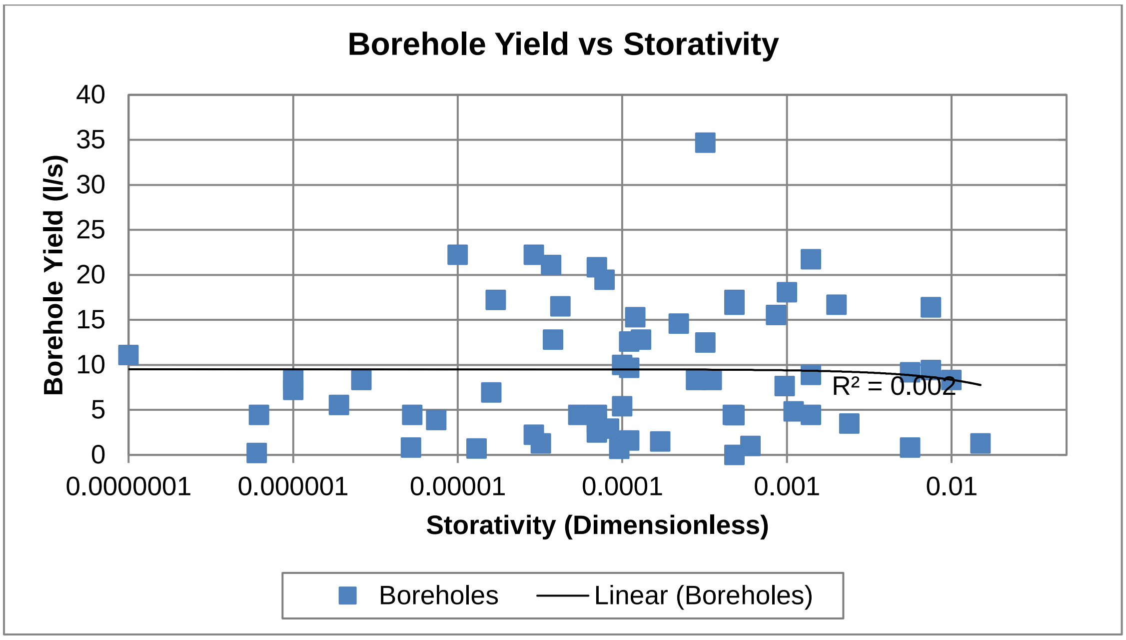

Figure 12: Borehole Yield vs S

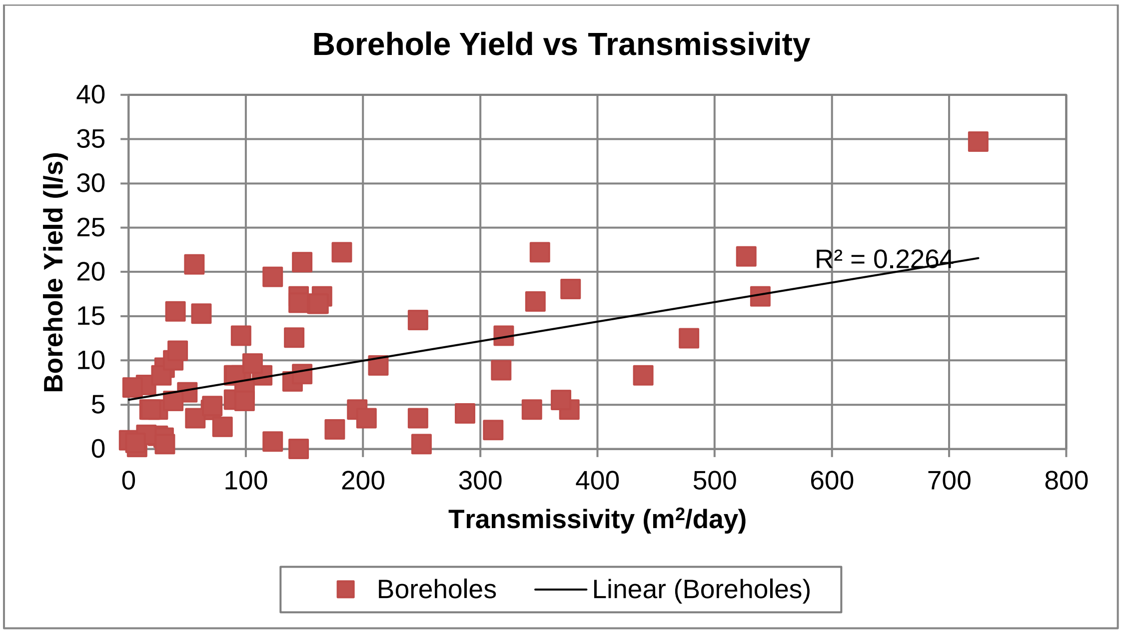

Figure 13: Borehole Yield vs T

The correlation between borehole yield and T is further highlighted in **Table 5**. The available data from 37 boreholes with T > 100 m^2/day indicate that about 70% of these boreholes produced borehole yields > 5.0 ℓ/s. When T = 10 – 100 m^2/day about 60% of boreholes produce borehole yields > 5.0 ℓ/s, whilst for T < 10 m^2/day about 75% of boreholes produce borehole yields < 2.0 ℓ/s. Although there is no clear relation between borehole yield and the lithology, the high yielding boreholes (> 5 ℓ/s) that are present in all municipal well field areas are more related to the occurrence of secondary flow paths in the different formations, e.g. Teekloof formation versus fracturing on the contact of the Teekloof formation and dolerite dykes and sills.

Table 5: Transmissivity and borehole yields

Transmissivity Categories	Total no. of records	No. of records with borehole yields >5.0 l/s	%	No. of records with borehole yields 2.0 – 5.0 l/s	%	No. of records with borehole yields <2.0 l/s	%
T>100m²/d	37	26	**70.27**	8	21.62	3	8.11
T >10m²/d but <100m²/d	28	17	**60.71**	7	25.00	4	14.29
T<10m²/d	4	1	25.00	0	0.00	3	**75.00**

The spatial distribution of borehole yields is shown in **Figure 14**.

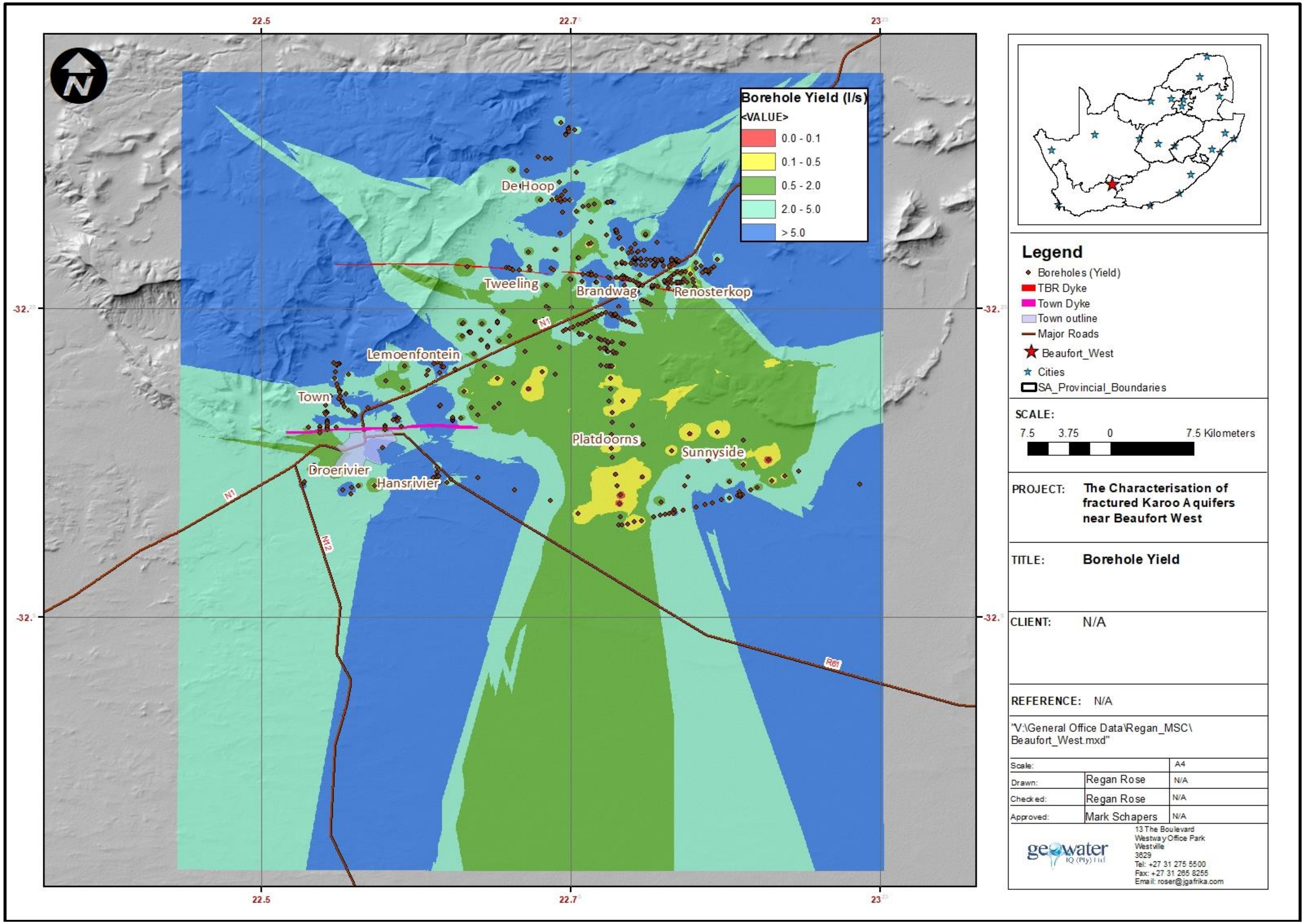

Figure 14: Spatial distribution in borehole yield

11.2 Water Chemistry

11.2.1 Spatial Trend

Water chemistry information was collated from previous sampling rounds in 1997 and 2006 (April 2006 and November 2006). This includes both macro – chemical (major anions and cations) as well as stable isotope data. During a hydrocensus in 2008 additional boreholes were sampled and analysed for major anions, cations and trace elements. The latter data is provided in **Appendix C**. Additional water chemistry data were also acquired from the DWS's WMS database. All the available macro – chemical time series data is provided in **Appendix D**.

The macro – chemical laboratory results were used to construct chemical diagrams for further interpretation. The Aquiworx software (version 2.5.2.0) was used to compile the chemical diagrams. Further to this, all EC values were captured into a comprehensive GIS database for map display purposes. At each point the most recent EC value was used for contouring to display the spatial variation in EC. The results are shown in **Figure 15**. Figure 15 shows there is a general increase in EC from northwest to southeast over the area. The latter trend supports the WR (2012) spatial distribution of EC in Section 9. The lower ECs (< 150 mS/m) in the north coincide with the Nuweveld Mountains which represents the main recharge area. Higher ECs are observed over the central parts of the map extent where the EC reaches a maximum (> 520 mS/m) about 15 km east of Beaufort West as well as the eastern part of Brandwag well field. The former area is a narrow strip that stretches southwards from the N1 highway to the R61 (from Beaufort West to Aberdeen). This area also coincides with an area associated with surficial calcrete deposits, however there is no clear correlation between the elevated EC and calcrete deposits. The area east of Brandwag is associated with an area that is currently being heavily exploited, both for municipal and agricultural purposes. This area is characterised by slow recharge and large distance from the recharge area along the TBR Dyke. In the far eastern part of the map (i.e. Sunnyside) an area of lower ECs (< 150 mS/m) are also observed, which might further suggest a local recharge area with a westerly groundwater flow component.

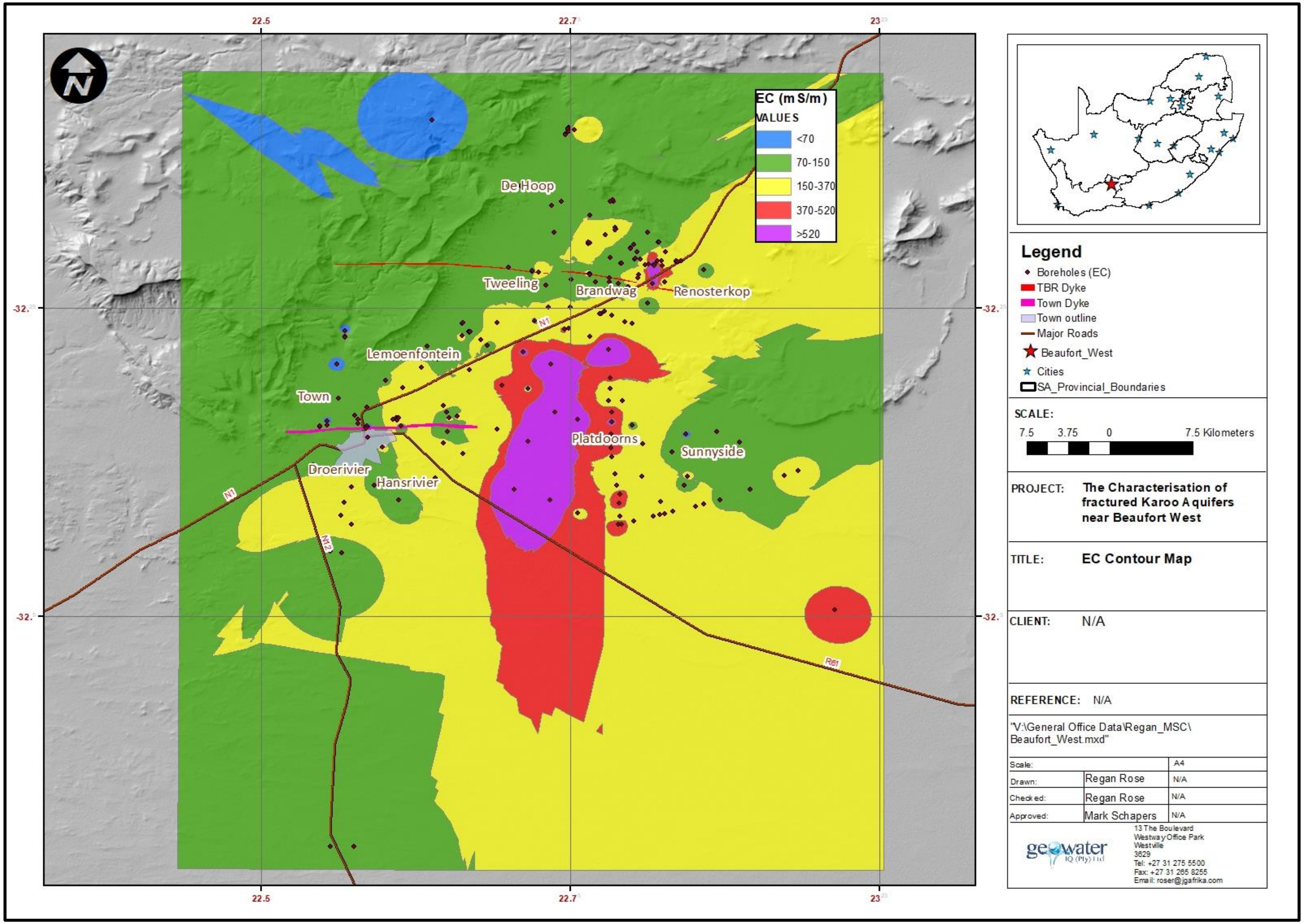

Figure 15: EC contours

11.2.2 Macro – chemistry

Using the data of the April 2006 sampling round the samples analysed plot between two end – members Ca – Mg - HCO_3 and Ca – Mg – SO_4 – Cl (**Figure 16**). It is interesting to note that the boreholes located close to the main recharge area, i.e. the Nuweveld Mountains north of the town of Beaufort West (Rose et al, 2006a), are closer to the Ca – HCO_3 end – member (e.g. Waterval, Fontein, G29947A, Noordeinde Suid, G29879BC), whereas those located further away from the main recharge area are closer to the Ca – Mg – SO_4 – Cl end – member (e.g. all the boreholes in the Brandwag and Tweeling well fields). Hence there is a strong correlation between distance from the recharge area and groundwater chemistry.

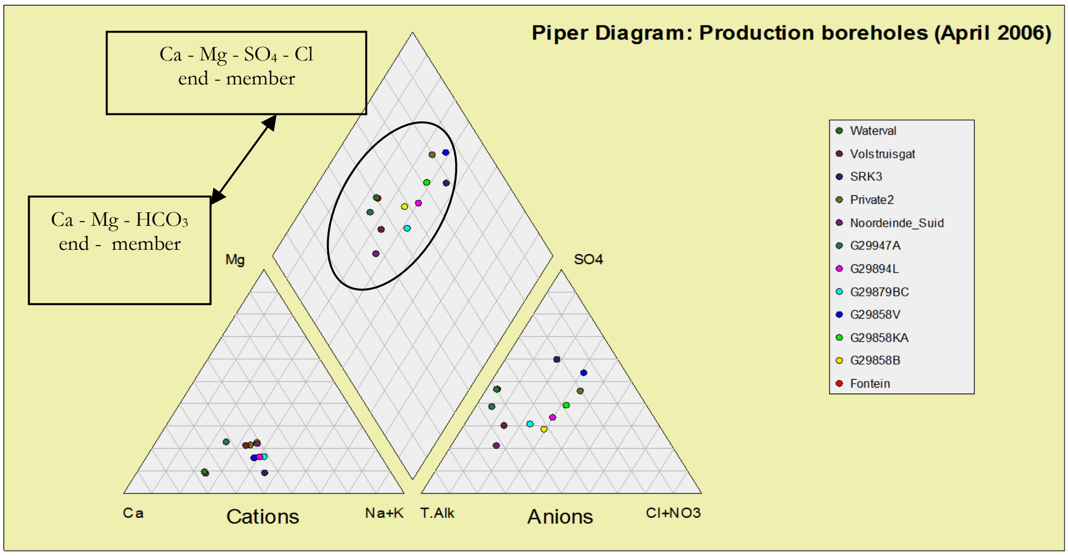

Figure 16: Piper diagram (April 2006)

Comparing the November 2006 data, the groundwater chemistry remained basically the same as in April 2006 (**Figure 17**). The only noticeable exception is that of Fontein, which plots much closer to the Ca – Mg - HCO_3 end – member than in April 2006. Interestingly, this shift in groundwater chemistry was accompanied by a significant decline in EC from 90 mS/m in April 2006 to 51 mS/m in November 2006. The latter could signify an important seasonal recharge event.

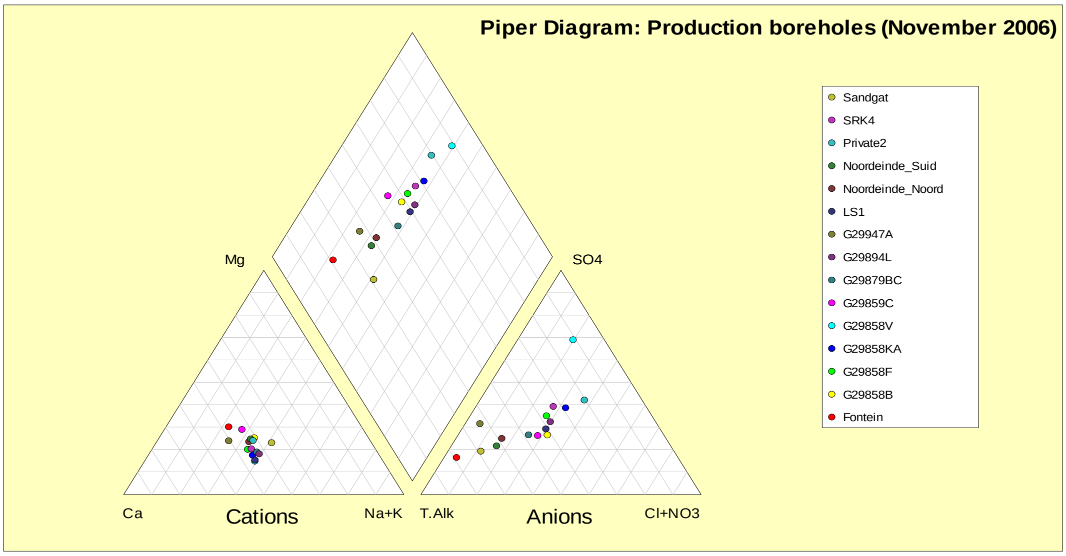

Figure 17: Piper diagram (November 2006)

When all samples are plotted on the Piper diagram a good correlation between EC and dominant water type can be observed (**Figure 18**). The high ECs (> 150 mS/m) plot closer to the Ca – Mg – SO_4 – Cl end – member, whilst the lower ECs (< 150 mS/m) plot closer to the Ca – Mg - HCO_3 end – member. The latter observation can be related to distance from the recharge area. The greater the distance for groundwater to travel, the more interaction with the rock will occur, which in turn will result in an increase in EC (salinity) and consequently a change in dominant ions from Ca – Mg - HCO_3 to Ca – Mg – SO_4 – Cl. The latter observation compares well with Adams (2001) cation/anion exchange theory.

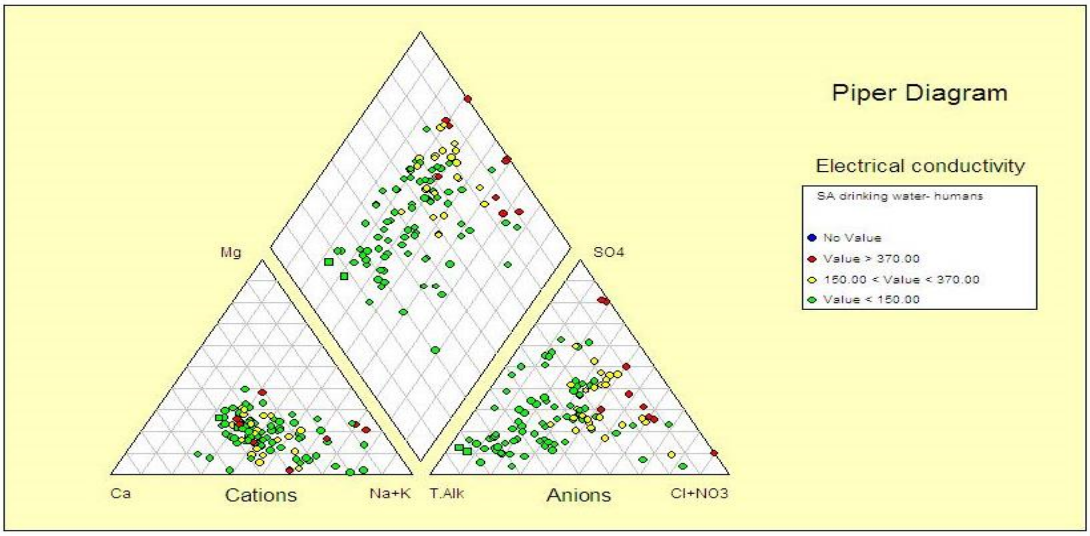

Figure 18: Piper diagram for all samples

In terms of trends, the EC at most boreholes is reasonably stable over the last ten years of monitoring (**Figure 19**). The notable exceptions are G29858V (No.9) and G29858B (No.8) in the Brandwag well field. In the case of G29858V (No.9) the EC increased by 149 mS/m, from 126 mS/m in June 1997 to 275 mS/m in November 2006§§. The EC at G29858B (No.8) increased steadily from 82 mS/m in 1996 to 134 mS/m in November 2006. However, it must be stressed that such large increases in EC does not apply to the entire Brandwag well field, and appear to be very localized. At Private 2 (No.12) the EC decreased substantially from 270 mS/m in 1997 to 215 mS/m in November 2006, whilst the ECs at G29858KA (No.1), G29894L (No.2) and G29859C (No.6) revealed minor increases or decreases (< 10 mS/m) over the last 10 years of monitoring.

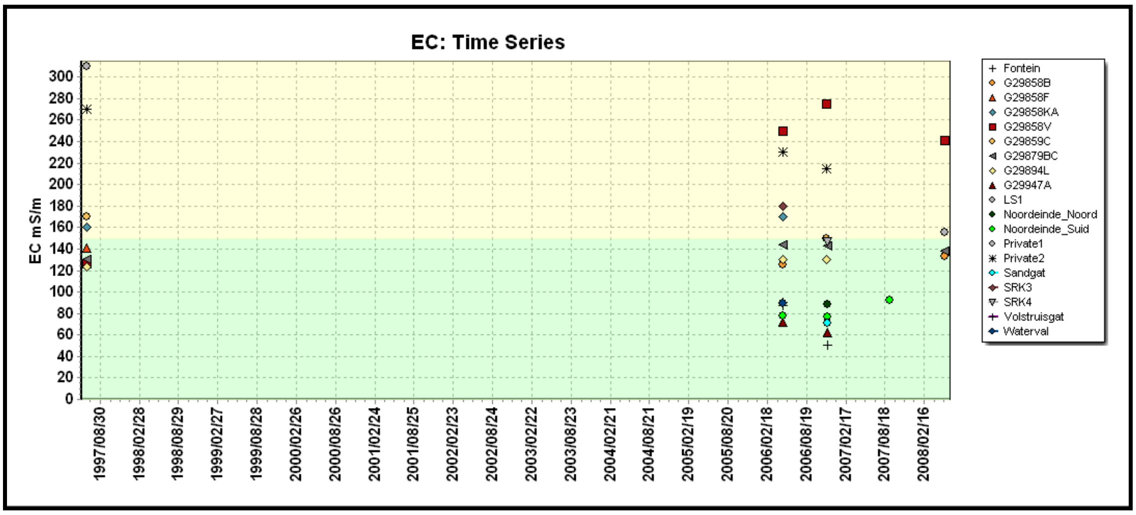

Figure 19: EC trend at some municipal boreholes

The Tweeling and Lemoenfontein well fields are also relatively stable in terms of EC with only minor changes in EC being observed over the 10 years of monitoring. Similar to the Brandwag well field the increase / decrease in EC is very site specific. For example, LS1 (Lemoenfontein_South) showed a slight decrease in EC from 165 mS/m in 1997 to 154 mS/m in November 2006, whilst at G29879BC (Lemoenfontein_North) there is a slight increase in EC from 130 mS/m in 1997 to 143 mS/m in November 2006.

The best groundwater (using EC as an indicator) is currently observed in the Town well field, where ECs are generally less than 100 mS/m. The most recent sampling results have even shown signs of declining ECs (improving water quality) in the Town well field. The trend in water quality correlates well with water level observations at all well fields. For example in the Brandwag well field deteriorating water quality (EC) was observed at G29858KA and G29858B where declining water levels were observed. For the remainder of the Brandwag well field, relatively stable water quality (EC) has been achieved and possibly linked to the relatively stable water levels, although it must be noted that even these water levels are very slowly declining. Overall the areas showing deteriorating water quality are localized and possibly relate to local over – abstraction.

§§ Note the 1997 sampling was carried out in June and the 2006 sampling was carried out in April and November, so exact seasonal comparisons cannot be made.

11.2.3 Stable Isotope Analysis

Table 6 shows the results of the isotope data analysed at Ithemba Laboratory in Johannesburg. These results were used to characterise the isotopic composition of the groundwater at certain localities to enhance the conceptual understanding of groundwater flow.

Table 6: Summary of available isotope data

Sample ID	Borehole	δD‰	δ^{18}O‰
Bulkraal	G29947A	-27.60	-4.70
Waterval (Bh)	Waterval/HB21_45	-27.20	-4.50
Waterval (Fontein)	Fontein	-27.20	-4.60
B-wag 9	G29858V	-33.40	-5.10
B-wag 2	G29894L	-34.50	-5.90
B-wag 12	Private2	-31.40	-5.20
SRK3	SRK3	-34.20	-5.70
LN	G29879BC	-28.40	-4.90
NES	Noordeinde_Suid/HB921_43	-3.70	-0.70
VOL	G29946D/Volstruisgat	-30.50	-4.90
B-wag 8	G29858B	-35.60	-5.90
NEN	Noordeinde_Noord/HB21_41	-12.30	-2.17
BW_Spring	BW_Spring	1.40	0.07
BW_Manor2	BW_Manor2	-2.90	-0.75
BW_Manor3	BW_Manor3	-5.10	-1.09
BW_Manor4	BW_Manor4	-7.00	-1.37
S-Dam_4	S-Dam_4	-12.30	-2.29

From Table 7, δD was plotted against δ^{18}O for interpretation. The resultant graph in **Figure 20** shows that all the samples plot on what appear to be an evaporation line defined by Equation 1:

$$\delta D = 6.04\,\delta^{18}O + 1.28 \quad \text{(Eq. 1)}$$

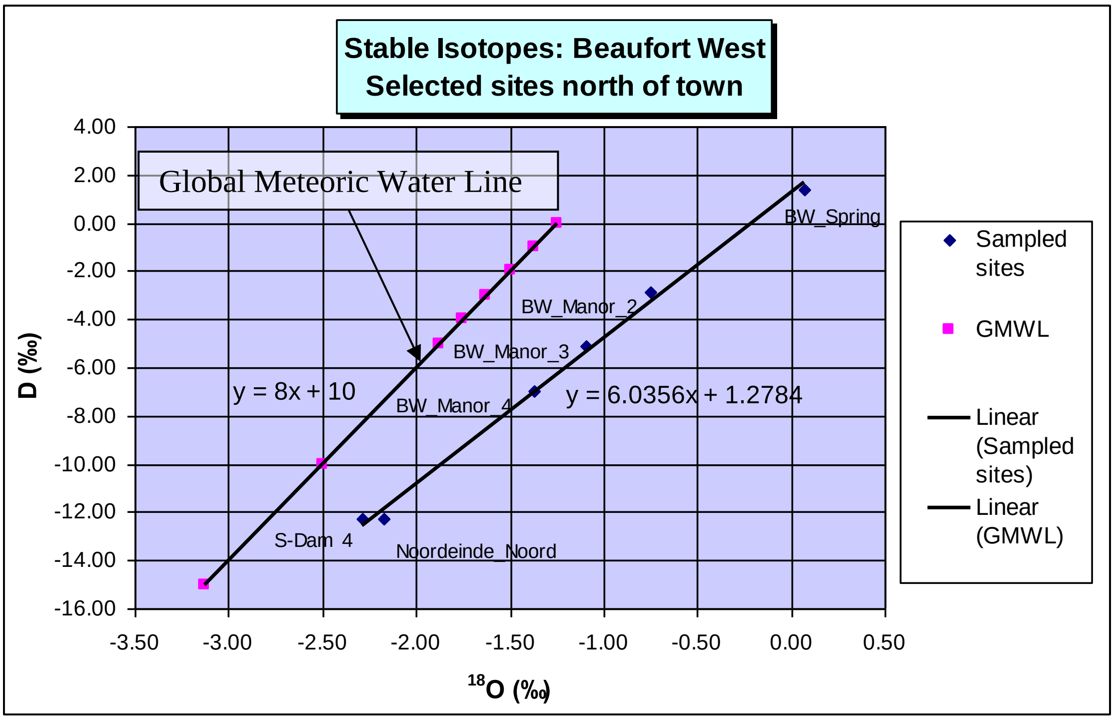

Figure 20: δD vs δ^{18}O for the selected sites

Rainfall samples from Cape Town International Airport (i.e. average of mean annual average from 1996 – 2001), as well as rainfall data from the International Atomic Energy Agency (IAEA) show a mean δ^{18}O of –2.59 ‰, and a mean δD of –7.67 ‰ and a mean d-excess around 13 ‰. The d-excess (indicative for the local climatologically conditions like temperature, latitude, altitude, rainfall amount effects) for Cape Town International Airport shows light isotopic composition in comparison to the Global Meteoric Water Line (GMWL) due to moisture formation at high latitudes or enhanced/repeated moisture recycling in the rain.

The evaporation line shows a smaller slope (6.04) than the GMWL provided by Craig (1961) and is defined by Equation 2:

$$\delta D \quad = \quad 8\,\delta^{18}O + \quad 10 \qquad \text{(Eq. 2)}$$

The latter indicates that the water that recharged the aquifer experienced enhanced evaporation losses in surface water bodies (the residual surface water is enriched in heavier isotopes). Hence the isotopic composition points towards influences of indirect recharge via surface water bodies or mixing of recharging groundwater with connate water. BW_Spring plots very close to the isotopic composition of seawater given as zero per mil (0 ‰) for both δD and δ^{18}O according to Vienna Standard Mean Ocean Water (V-SMOW), and is likely to be indicative of connate (Drever, 1988). However, the latter is not consistent with observations from the macro – chemistry since a Na – Cl dominant water was expected rather than the observed Ca – HCO_3. The latter is also not consistent with Murray's (et al, 2015) deep groundwater indicators. However, this could also imply that chemical reaction with the host rock is occurring.

The isotopic composition of the groundwater at the three private boreholes at Beaufort Manor guest house is slightly lighter than at the BW_Spring and fall in the range of δD between -2 and -5 ‰, and $\delta^{18}O$ between -0.5 and -1.5 ‰. It is interesting to note that Noordeinde_Noord (sample NEN) and S-Dam_4 have similar isotopic compositions (i.e. lighter than all the other sites, but still relatively enriched in heavy isotopes), which could represent the average surface water isotopic signature. If the latter is correct, it would then imply that Noordeinde_Noord is receiving indirect recharge from the surface water of the Gamka River.

Unfortunately, no rainfall isotope data could be sourced of Beaufort West rainfall to allow further interpretation of the data. However, if regional isotopic data are added to April 2006 sampling round, 3 main groups can be identified, i.e. lighter isotopic composition, heavier isotopic composition and intermediate isotopic composition (**Figure 21**). From Figure 20 it is assumed that the isotopic signature of the rainfall prior to evaporation must have been in the region of $\delta^{18}O$ = -5 ‰ and δD = -30 ‰, defined by the intersection of the GMWL and evaporation line.

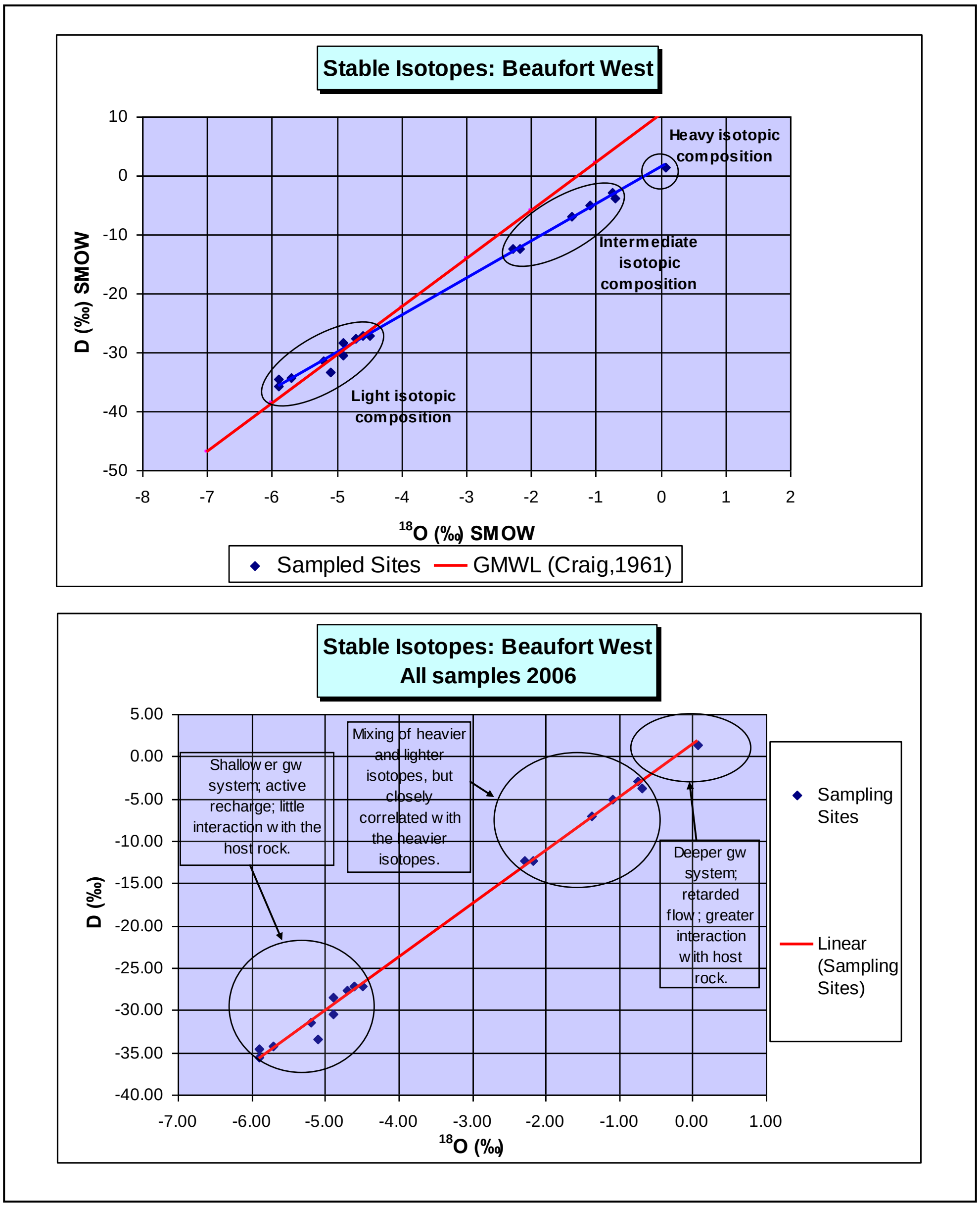

Figure 21: δD vs δ^{18}O for all Beaufort West sites in 2006

The lighter isotopic composition (i.e. δ^{18}O < -5 ‰ and δD < -25 ‰) includes most borehole sites sampled in Brandwag, Tweeling, Lemoenfontein and upper Town well fields. The observed lighter isotopic compositions is likely to be indicative of active recharge along the Nuweveld Mountains (rainout effect, precipitation gets "lighter" on its way inland). Hence for Brandwag and Tweeling well fields this could mean active recharge along the TBR dyke. There appear to be little water-rock interaction and it could be a relatively shallow groundwater system typically meteoric water. Some of the upper Town well field boreholes (i.e. Waterval, Fontein, G29947A/Bulkraal) plot close to the origin of the evaporation line which could be related to the shallow groundwater levels over this part of the Town well field.

The heavier isotopic composition (i.e. δ^{18}O 0.07 ‰ and δD 1.4 ‰) is associated with the BW_Spring. Due to an increase in δ^{18}O it is expected that there is a greater water-rock interaction which could further imply more stagnant flow which is possibly related to deeper groundwater system typically connate water ($\delta^{18}O$ 0.0 ‰ and δD 0 ‰). The presence of the BW_Spring is likely to be a regional groundwater discharge point that is probably driven by the northerly inclined orientation of the Town dyke.

An intermediate isotopic composition (i.e. $\delta^{18}O$ between -0.5 and -2.5 ‰ and δD between -2 and -12 ‰) indicates mixing of the lighter and heavier isotopes. These include all the boreholes and other sampling sites (with the exclusion of BW_Spring) at the lower end of the Town well field (including the private boreholes at Beaufort Manor guest house). Although a mixing model is identified for these sites, the results show that they are closely correlated with the heavier isotopic composition. Therefore, it is anticipated that upward leakage from the deeper groundwater system is occurring. Further to this it is debatable whether S-Dam_4 is part of the intermediate group as it could be more related to the regional surface water isotopic composition that has also undergone some mixing. The vast difference in EC (i.e. 31 mS/m) at S-Dam_4 compared to that of the lower Town well field boreholes (i.e. > 80 mS/m) could strongly support the latter statement.

12. Groundwater Flow Paths

The available water level information was used to produce a water level contour map for the delineation of groundwater flow paths over the study area. About 200 boreholes have water level data. These points were used to contour the groundwater levels on a regional (coarse) and local scale (detailed). At each point the most recent measured water level was used for interpolation.

A regional – scale groundwater contour map was produced in ARC GIS and is provided in **Figure 22**. From Figure 22 the regional groundwater flow pattern is generally from north to south. The piezometric heads vary from > 1500 mamsl in the north coinciding with the Nuweveld Mountains to about 800 mamsl in the south coinciding with the flat lying plains. Note that only 4 points were sourced with piezometric head information above 1300 mamsl – these points are all situated in the mountainous areas in the north. However, the spatial distribution of the boreholes in the flatter lying areas is sufficient to confirm the regional groundwater flow paths from north to south.

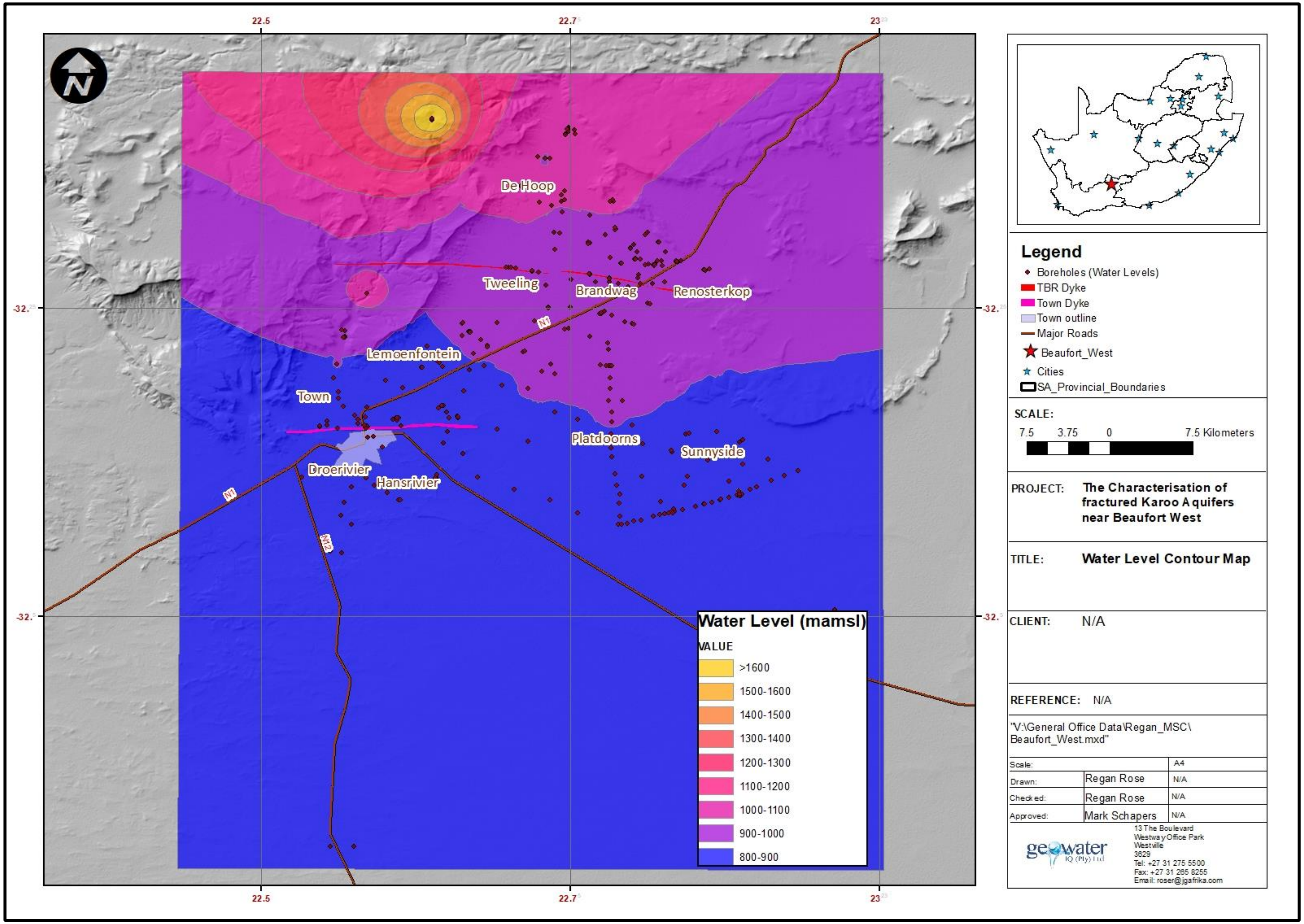

Figure 22: Regional groundwater flow paths

A local scale groundwater contour map was also produced using the interpolation software, i.e. Tripol. Tripol is an interpolation program that estimates values for random variables from a given set of regionalised variables. Tripol includes the following:

1) Computation of a semi – variogram for a set of data points.
2) Fitting of a mathematical function to the semi – variogram
3) Estimation of values for any set of random data from the given set of data points.

Tripol implements 3 interpolation methods, i.e. Distance Weighting, Kriging and Bayesian Estimates. Kriging and Bayesian Estimates do not only yield an estimate of the random variable, but also an error in the estimate. For Kriging and Bayesian Estimation, a semi – variogram is required to estimate the manner in which the mean values of the known dataset behave over the region. A mathematical function is then fitted to the semi – variogram values to obtain certain parameters that are needed for the interpolation by Kriging and Bayesian Estimation. The same 200 boreholes (used for the regional contour map) with groundwater level data were again used for the Tripol software program together with over 5000 unknown points for the interpolation. The applicability of the Bayesian Estimation technique was tested prior to conducting the interpolation method. The available water levels within the grid were plotted in graph format against the elevation (topography). A correlation of about 99% (R2) was obtained, which implies that the technique is applicable (**Figure 23**).

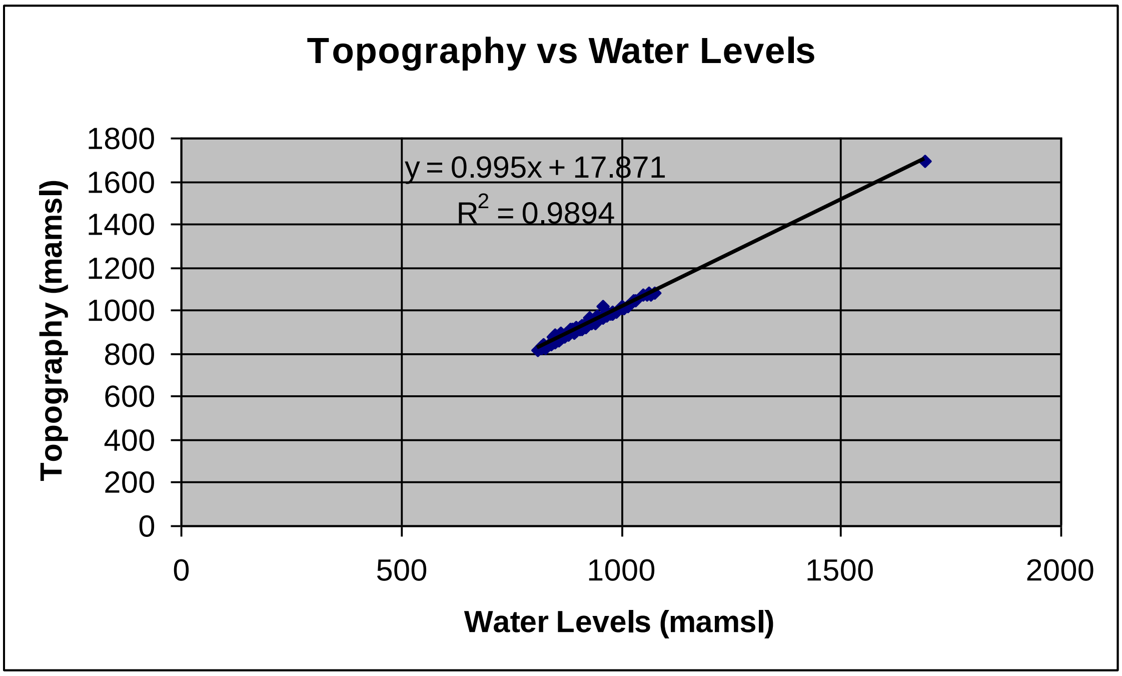

Figure 23: Plot of Topography versus Water Levels

Utilising the Bayesian estimation technique within the Tripol software, the mathematical function used to fit the semi – variogram produced a correlation coefficient of about 80.6%. At the end of the interpolation Tripol provided the solution in a grid format that was imported into the Surfer 8.0 software package for contouring purposes.

A contour map with contour intervals of 5 m was produced within an ARC GIS format (**Figure 24**). The 5 m groundwater contours provided important information of the groundwater flow characteristics. Note that areas above 1010 mamsl were not contoured as there is very limited data above this elevation that would otherwise also make the map look too "crowded". It is also not sure how the aquifers with piezometric heads of over 1300 mamsl are linked to those below 1000 mamsl over such a relatively small distance. Hence it is likely that the boreholes in the Nuweveld Mountains could be linked to topographically higher aquifers. Distinct groundwater flow patterns were identified. Although the general groundwater flow direction is from north to south the dolerite dykes have a strong influence on the local groundwater flow conditions. This is best shown by the groundwater contours that straddle almost perpendicular to the strike of the dolerite dykes, implying that the groundwater flow is parallel to the strike of the dykes. Hence, the dykes (i.e. Town dyke, TBR dyke, Hansrivier dyke and Droerivier dyke) are essentially interpreted as groundwater barriers that effectively compartmentalise the groundwater flow. Due to the presence of offsets along the TBR dyke, lateral flow across the dyke can occur at these offsets as is evident on the contour map.

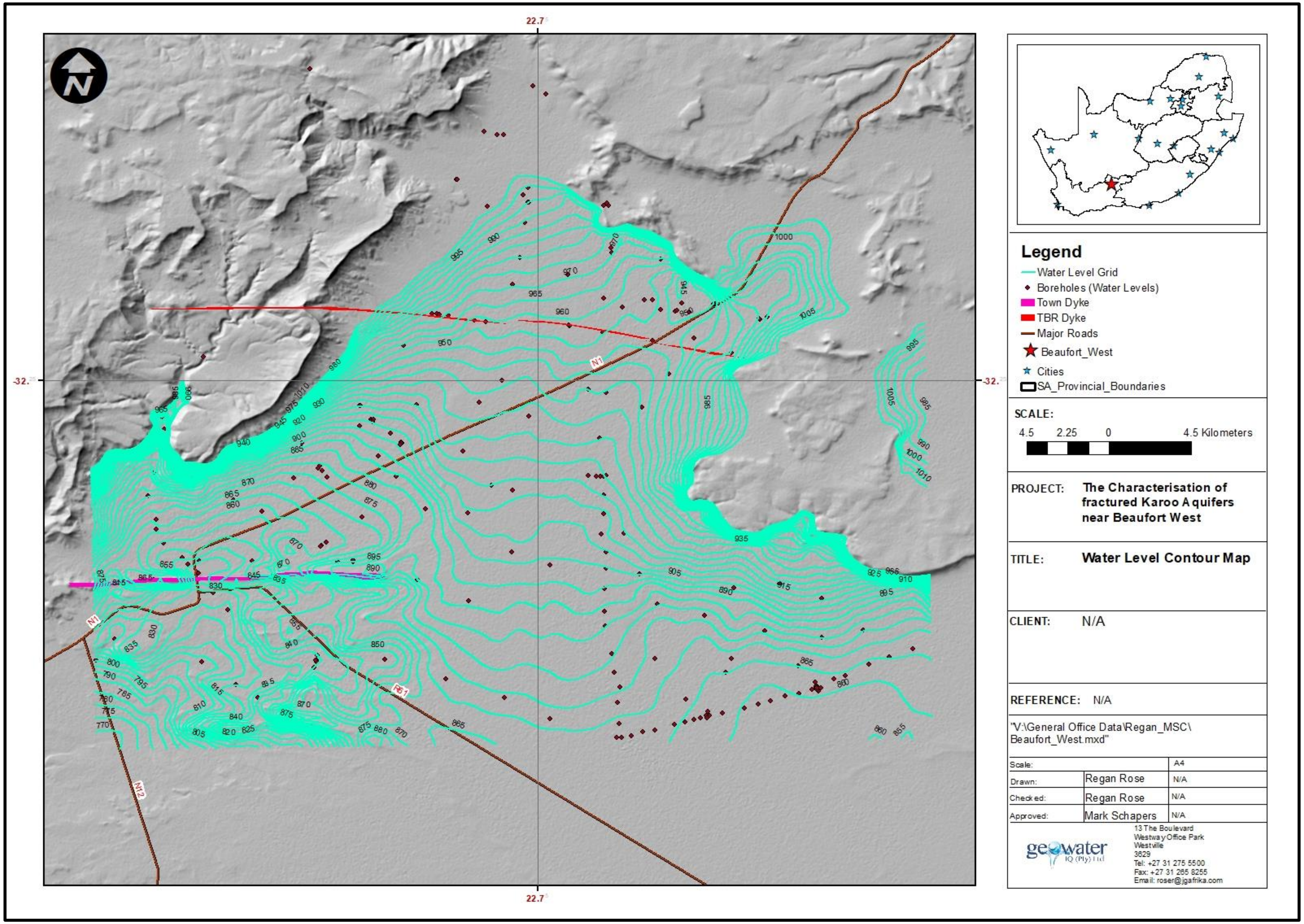

Figure 24: Groundwater level contours with 5 m intervals

The further development of a groundwater flow net enabled the identification of capture zones. The capture zones were manually identified using a simple approach: Where two arrows point away from each other a groundwater boundary (capture zone) is defined. Based on this approach several groundwater compartments were highlighted over the study area (**Figure 25**). These groundwater compartments are the Brandwag compartment, Tweeling compartment, Sunnyside compartment, Platdoorns compartment, Town compartment, Hansrivier compartment and Droerivier compartment. Although no groundwater level data were sourced for the areas in the far south and southeast of the study area, and although these areas were initially not included into the Tripol grid, it was decided not to exclude them from the study since they overlap with large parts of the current active uranium mines. A simple extrapolation approach was then used to subdivide these areas into groundwater compartments based on 2 principles:

- The general groundwater flow direction is from north to south.
- Dolerite dykes are groundwater barriers.

Utilizing the extrapolation approach, the areas in the south and southeast were subdivided into the Quaggasfontein compartment, whilst the Platdoorns compartment was extended southwards up to the dyke (probably same dyke as Droerivier dyke) along the south-eastern boundary of the study area.

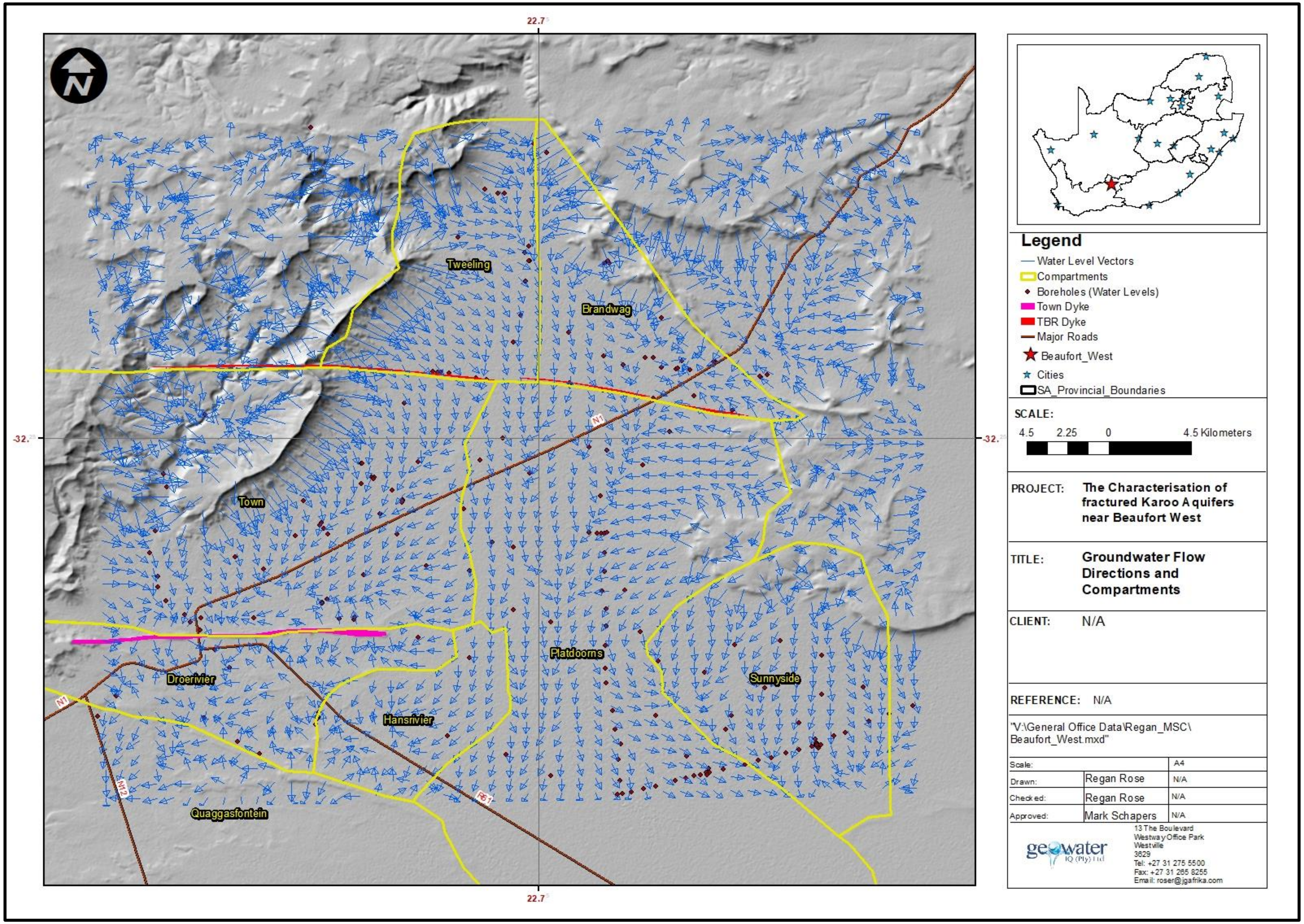

Figure 25: Groundwater flow directions and compartments

The Brandwag compartment is the furthest northeast compartment in the study area. The compartment is demarcated in the north, northeast and east by a prominent mountain range, whilst in the south the compartment is demarcated by the TBR dyke. The westernmost boundary is demarcated at a point where all groundwater is flowing exactly north – south, with no easterly component of flow (possibly a constant head boundary). Local recharge is from the northeast and north. Based on the interpretation of the groundwater level contours, no groundwater seems to be reaching the Brandwag compartment from the west along the TBR dyke. The latter statement contradicts previous assessments by SRK (1997). Although the EC is poor (along the eastern side of this compartment), this phenomena is very localised and probably aided by local dewatering of the aquifer. The observation of declining water levels in this area in 2008 suggests that local dewatering is likely. Therefore, although there is a groundwater component flowing from the east (i.e. from Renosterkop), this might have been caused by local over – pumping resulting in poorer quality groundwater being drawn in from the east. The borehole yields in this compartment are generally above 5.0 ℓ/s, and seldom below 2.0 ℓ/s.

The Tweeling compartment is situated west of the Brandwag compartment. Its southernmost boundary is the TBR dyke, whilst the western and northern boundaries are the Nuweveld mountain. The eastern boundary coincides with an area identified as a constant head boundary. Groundwater flow is mainly eastwards along the TBR dyke and southwards from the Nuweveld mountains (i.e. local recharge area). Some groundwater flow across the TBR dyke is expected towards the Platdoorns and Town compartments.

The Sunnyside compartment is the compartment in the extreme east of the study area. It is characterised by predominantly southerly groundwater flow from the mountainous area north of the farm Sunnyside to a dyke south of Sunnyside that appears to be a ring - like feature. The mountains at Sunnyside are also regarded as a local recharge area. Towards the southwest of this compartment some leakage is expected from the Platdoorns compartment. The groundwater quality in this compartment is much fresher than in the Platdoorns compartment with variable borehole yields > 5.0 ℓ/s reported here.

The Platdoorns compartment is a large compartment that stretches from the TBR dyke in the north to the Droerivier dyke in the southeast of the study area. A local recharge area is identified in the northeast of this compartment coinciding with the mountains south of Renosterkop, from where groundwater is flowing initially in a westerly direction, then changing to a southerly direction as it approach the middle region within this compartment. Although the TBR dyke is mainly seen as an impermeable barrier, some leakage is expected across this dyke from the Brandwag compartment since the dyke is offsetting. This compartment generally has elevated ECs (> 300 mS/m) and poor borehole yields (< 2.0 ℓ/s) which further makes it a unique compartment.

The Town compartment has the Town dyke as its southernmost boundary, however some groundwater flow across this dyke towards the Droerivier compartment is also expected. In the north and west the Nuweveld Mountain provides the main recharge area. The extent of the capture zone could extend for kilometres into the Nuweveld mountain, hence the northernmost boundary of this compartment is not well defined. For the purposes of this study the TBR dyke that outcrops in the Gamka Pass north of town is used as the northernmost boundary. Groundwater generally flows from the north and northeast towards the southwest (town). Very good groundwater quality (< 150 mS/m) is generally encountered in the west along the Gamka river. Declining water levels are also known to recover quickly after rainfall events which further indicate good active recharge in this area. Groundwater quality in the eastern side of this compartment has slightly higher EC (70 – 300 mS/m), but could indicate greater travel distances from the recharge area.

The Hansrivier compartment is situated east of the Droerivier compartment. It is separated from the Droerivier compartment by the presence of the Hansrivier dyke, i.e. a small north – south dyke on the farm Hansrivier. Recent magnetic data showed that the Hansrivier dyke is not laterally extensive to the north and that it is cut off in the vicinity of borehole HR_14 on the farm Hansrivier. Hence north of HR_14 it is likely that some mixing occur with the fresher Droerivier compartment. The Hansrivier compartment drains from the north, east and southeast towards the west up to the Hansrivier dyke. Local recharge might also occur from the southeast within this compartment, but this can be confirmed with more groundwater level data in the south and southeast of this compartment. Based on field measurements the groundwater quality east and west of the Hansrivier dyke is distinctly different, i.e. > 150 mS/m east of the Hansrivier dyke and < 100 mS/m west of the Hansrivier dyke. Hence the Hansrivier dyke is generally regarded as a groundwater barrier.

The Droerivier compartment is situated south of the town. Based on the groundwater level contours the groundwater is draining from the north and northeast towards the southwest. The Gamka river is likely to be the main driving force behind this. Some leakage is expected across the Town dyke that will generally feed this compartment. The Town dyke marks the northernmost boundary of this compartment, whilst the Droerivier dyke is the southernmost boundary of this compartment. The groundwater quality is generally good (EC < 150 mS/m) particularly in close proximity to town, but tends to become poorer away from town towards the south and southwest.

The Quaggasfontein compartment spans the area in the southwest of the study area. The compartment is defined in the north and northeast by the Droerivier dyke, whilst in the south and west the boundary is defined by the study area boundary. The area is characterized by small open folds within the Teekloof Formation. In the southeast of the compartment there are several small dried up pans. Although there are very limited data in the south of this compartment, the general groundwater flow direction is assumed to be from north to south based on observations of the regional groundwater flow pattern. Hence it is also expected that the groundwater ECs will increase from north to south.

13. Conceptual Model

The interpretation of the chemistry results contributed significantly towards the development of a conceptual model over an area from north to south through Beaufort West town (**Figure 26**). Spatial information of boreholes, topography and geology (available borehole logs) were used in conjunction with the chemistry data to compile the conceptual model. The analysis of the isotope data showed three isotopically different water types. Firstly, the distinctly different isotopic signature of the Beaufort West spring compared to the Brandwag, Tweeling, Lemoenfontein and upper Town well field boreholes might suggest a multi-layered fractured rock aquifer system (**Figure 27**). The Beaufort West spring is likely to be structurally controlled by the Town Dyke that is outcropping along a prominent east-west ridge that trend through the northern parts of the town. The Town Dyke is relatively steeply inclined towards the north. Hence, the Beaufort West spring discharges water that is likely to be related to a deeper regional flow system dominated by connate water. Although the latter is not consistent with the macro-chemistry, it is anticipated that there is some water – rock interaction taking place. This needs to be further investigated. Secondly, the deeper regional flow system appears to leak upwards into the shallower groundwater flow system (essentially the fractured sandstone and porous alluvium) along the northern periphery of the town, resulting in the mixing of connate and meteoric water along the lower Town well field. Thirdly the boreholes at Brandwag, Tweeling, Lemoenfontein and upper Town well field abstract groundwater from the upper shallow groundwater system associated with the fractured sandstone, siltstone and mudstone. However, these boreholes are not linked to the deeper groundwater system as they are topographically much higher and further away from the Beaufort West spring.

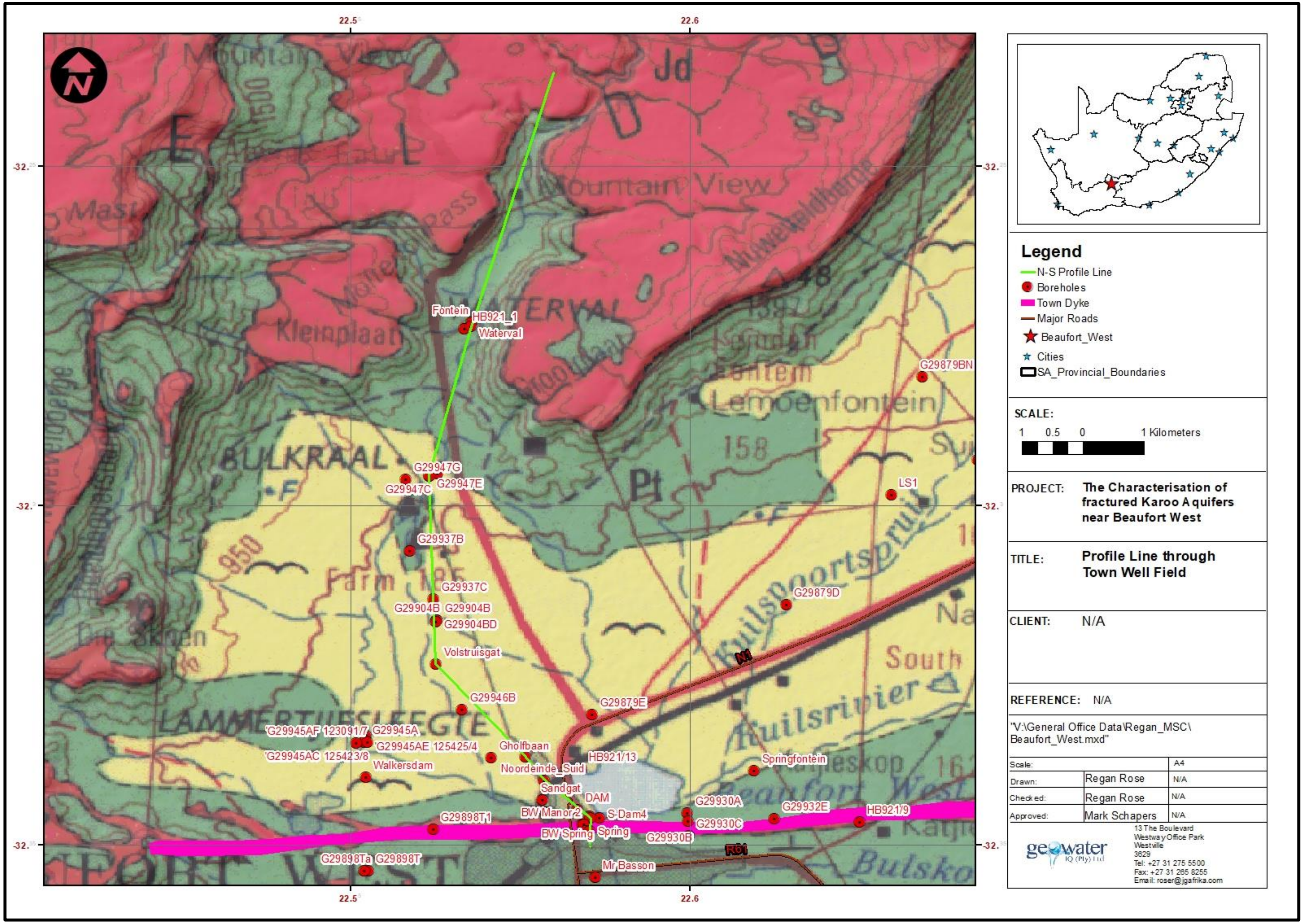

Figure 26: Profile line through a section of the Town well field (Rose, 2008)

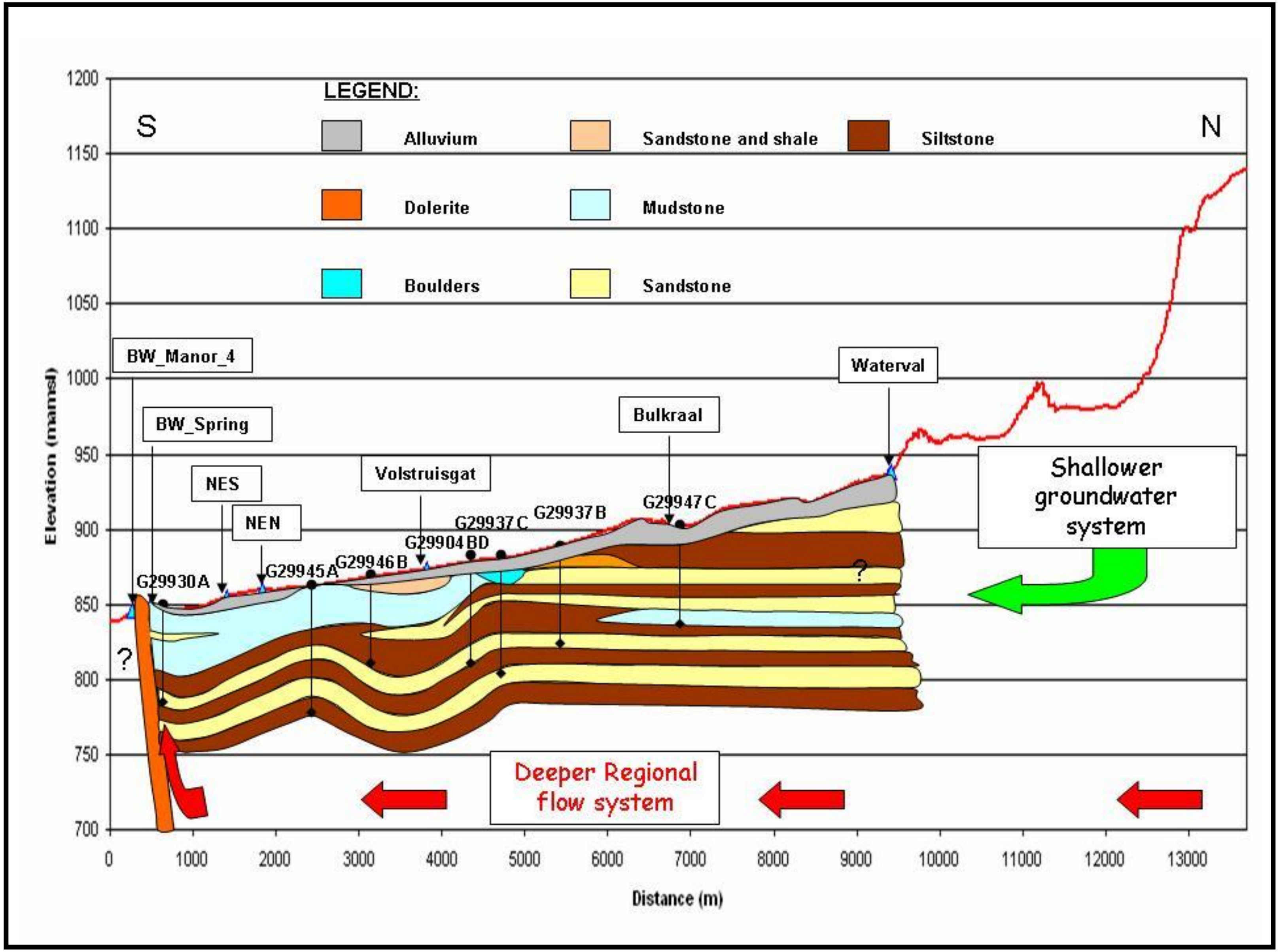

Figure 27: Conceptual model of Beaufort West Town Well Field (Rose, 2008)

14. Discussion

The study conducted herein used all available data and information collected over at least three decades to characterize the occurrence of groundwater and delineate flow paths within the fractured aquifers in and surrounding Beaufort West. Groundwater data were acquired from a variety of sources including:

- DWS's NGA database.
- DWS's WMS database.
- Beaufort West Municipality's GEOMON database.
- A private Excel - based database of Mr. Piet Havenga of DWS.
- Technical reports of SRK Consulting.
- Technical reports compiled by this author from 2006 – 2008.
- Boreholes drilled and pump tested by this author from 2006 – 2009 for the Beaufort West Municipality.
- Hydrocensus data conducted by this author from 2006 – 2009.
- Hydrocensus data conducted by UWC in May 2008.

The May 2008 hydrocensus attempted to cover areas in the south of Beaufort West where data is sparse. However, during the latter hydrocensus it was learnt that large parts of the areas in the south is inaccessible since they have been earmarked for mining purposes. This resulted in large gaps in the data in the south of the study area, practically limiting the initial study area to areas where there is data. All data were lumped into a GIS – based format to produce a variety of different maps. These maps assisted with the spatial characterization of the individual datasets. The datasets used for this study are geology, recharge, borehole yields, T, S, EC and water levels. The spatial characterization assisted with identifying trends in the groundwater data so that subareas with similar groundwater characteristics can be grouped into groundwater compartments.

Firstly, as expected there is a good correlation between borehole yields and transmissivity. High yielding (> 5 ℓ/s) boreholes are present in the municipal well field areas, although there is no clear distinction between the borehole yields and the geology, i.e. fracturing in the Teekloof formation versus fracturing on the contact of the Teekloof formation and dolerite dykes and sills. The degree of fracturing seems to dictate the successfulness of boreholes rather than the lithology. However, note that the sandstone rich units tend to produce better borehole yields and quality than the shale, siltstone or mudstone units. The degree and interconnectivity of the fracturing is possibly best displayed by the hydraulic diffusivity (T/S), which is highly variable and mainly dependent on the variability of S since T is fairly constant. An example is the Brandwag well field area where storativity values vary between 1×10^{-2} and 1×10^{-7}. Local dewatering that has been reported in the Brandwag well field is likely to be related to areas with low storativities particularly in the east of the well fields where there is competition with other users (i.e. agriculture). The latter observation must not be seen in isolation of recharge and lateral inflows. Future groundwater management decisions must therefore not only be based on observation of T, but a combination of T, S and recharge.

Secondly, there is a good correlation between recharge (amount and mode) and EC. The areas with lower ECs (< 100 mS/m) generally have either higher recharge rates or more localised recharge or a combination of the two. The inverse is observed for poorer quality groundwater (EC > 200 mS/m), where the recharge is likely to be less and more delayed within the unsaturated zone.

A groundwater level contour grid was compiled over the study area to assist with the identification of groundwater flow paths. These flow paths contributed significantly in the delineation of groundwater compartments, originating from dolerite intrusions. The groundwater compartments are the Brandwag, Tweeling, Sunnyside, Platdoorns, Town, Hansrivier, Droerivier and Quaggasfontein compartments. All the groundwater compartments seem to correlate well with spatial observations of EC and recharge. Based on the regional groundwater flow direction from north to south, and the assumption that dolerite dykes act as groundwater barriers, the Quaggasfontein and southern parts of the Platdoorns compartment were extrapolated southwards due to the unavailability of data.

A conceptual model through a N – S section through the Town compartment was compiled to illustrate the groundwater flow regime in a typical Karoo fractured rock compartment. Chemistry data (macro – chemical and isotope) were used to support the conceptual model. Based on the interpretation of the isotope data shallow and deeper groundwater flow systems were identified. The shallow groundwater system is linked to meteoric water, whilst the deeper groundwater system is linked to a connate water source. The current municipal groundwater abstraction is from the shallow groundwater system. The Beaufort West Spring, situated on the contact of the Teekloof formation and the Town dyke, is linked to the deeper groundwater system. The Town dyke has a strong structurally controlled influence on the deeper groundwater flow system since it forces the deeper groundwater upwards. The Town dyke is therefore seen as an aquiclude (i.e. impermeable groundwater barrier).

15. Recommendations

The following recommendations are provided:

- ✓ Conduct a hydrocensus in the areas within a radius of about 20 km south, southeast and southwest of Beaufort West town. Owners of properties in this area must be notified in advance to allow for quick and easy access.
- ✓ Conduct additional isotope and chemistry sampling in the south within a 20 km radius.
    - Future groundwater sampling in and around Beaufort West must include the sampling and analysis of uranium.
    - Conduct a ^{222}Rn isotope study and compare with current results to further confirm the deep groundwater flow model.
- ✓ Acquire additional groundwater data from private companies and mines in the area.
- ✓ Acquire additional data on recently drilled deep boreholes by CGS.
- ✓ Conduct a numerical groundwater flow model of the area.

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- ✓ Dr. Yazeed Van Wyk of the WRC.
- ✓ Dr. Kevin Pietersen of SLR Consulting.
- ✓ Ms. Rooseda Peters of DWS.
- ✓ Mr. Piet Havenga retired Hydrogeologist of DWS.
- ✓ Mr. Louw Smit, retired Town Engineer of the Beaufort West Municipality.

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APPENDIX A: RAW PUMP TEST DATA

BOREHOLE: Brandwag_5						
Step Test Data			CDT Data Q = 4.00 l/s		Recovery	
Time (min)	Drawdown (m)	Q (l/s)	Time (min)	Drawdown (m)	Time (min)	Drawdown (m)
1	0.3	1.64	1	0.65	1	8.9
2	0.34	1.64	2	0.7	2	8.72
3	0.37	1.64	3	0.82	3	8.56
5	0.44	1.64	5	0.99	5	8.38
7	0.48	1.8	7	1.55	7	8.18
10	0.55	2.01	10	1.99	10	7.8
15	0.66	2.01	15	2.2	15	7.25
20	0.75	2.02	20	2.41	20	6.7
30	0.84	2.02	30	2.63	30	6.4
40	0.91	2.02	40	2.68	40	5.64
50	0.99	2.02	60	2.82	60	5
60	1.1	2.01	90	2.88	90	4.26
61	1.22	2.01	120	2.95	120	3.99
62	1.35	3.89	150	3.2	150	3.7
63	1.44	3.89	180	3.45	180	3.49
65	1.55	3.95	210	3.7	210	3.29
67	1.66	3.95	240	3.96	240	3
70	1.78	4	300	4.4	300	2.8
75	1.86	4	360	4.62	360	2.61
80	1.95	4.03	420	4.84	420	2.4
90	2.1	4.03	480	5.01	480	2.2
100	2.2	4.01	540	5.15	540	2
110	2.26	4.01	600	5.32	600	1.9
120	2.32	4.01	720	5.43	720	1.61
121	2.4	4.01	840	5.67	840	1.32
122	2.52	4.89	960	5.78	960	1.25
123	2.64	4.89	1080	5.86		
125	2.8	5.6	1200	6.03		
127	3.02	5.6	1320	6.15		
130	3.22	5.98	1440	6.26		
135	3.64	5.98	1560	6.69		
140	3.82	6	1680	6.83		
150	4.1	6	1800	7.01		
160	4.38	6.04	1920	7.2		
170	4.9	6.04	2040	7.41		
180	5.55	6	2160	7.62		
181	6.3	6	2280	7.8		
182	6.75	6	2400	7.96		
183	7	8	2520	8.1		
185	7.21	8	2640	8.19		
187	7.3	8	2760	8.3		
190	7.38	8	2880	8.4		
195	7.51	8.02	3000	8.51		
200	7.6	8.02	3120	8.6		
210	7.76	8.01	3240	8.82		
220	7.87	8.01	3360	9		
230	8	8.03	3480	9.14		
240	8.2	8.03	3600	9.22		
			3720	9.34		
			3840	9.2		
			3960	9.2		
			4080	9.25		
			4200	9.25		
			4320	9.25		

BOREHOLE: DR_5						
Step Test Data			CDT Data Q = 6.07 l/s		Recovery	
Time (min)	Drawdown (m)	Q (l/s)	Time (min)	Drawdown (m)	Time (min)	Drawdown (m)
1	0.45	2.5	1	0.86	1	37.07
2	0.49	2.5	2	0.98	2	23.89
3	0.54	2.5	3	1.07	3	13.76
5	0.57	2.5	5	1.16	5	4.31
7	0.59	2.5	7	1.23	7	3.08
10	0.61	2.5	10	1.36	10	2.96
15	0.64	2.5	15	1.5	15	2.83
20	0.69	2.5	20	1.61	20	2.75
30	0.73	2.5	30	1.7	30	2.63
40	0.75	2.5	40	1.8	40	2.56
50	0.78	2.5	60	1.93	60	2.4
60	0.8	2.5	90	2.06	90	2.27
61	1.05	5.4	120	2.19	120	2.17
62	1.13	5.4	150	2.34	150	2.07
63	1.24	5.4	180	2.5	180	1.99
65	1.32	5.39	210	2.68	210	1.89
67	1.38	5.39	240	2.83	240	1.82
70	1.45	5.41	300	3.02	300	1.7
75	1.52	5.41	360	3.35	360	1.57
80	1.56	5.41	420	3.98	420	1.46
90	1.62	5.41	480	4.92	480	1.39
100	1.66	5.42	540	6.13	540	1.3
110	1.69	5.42	600	9.28	600	1.22
120	1.73	5.41	720	15.97	720	1.07
121	2.25	8.33	840	22.1	840	0.91
122	2.61	8.33	960	26.36	960	0.78
123	2.7	8.33	1080	28.96	1080	0.64
125	2.79	8.32	1200	30.92	1200	0.53
127	2.83	8.32	1320	32.74	1320	0.28
130	2.93	8.34	1440	34.28	1440	0.13
135	2.96	8.34	1560	37.02	1560	0
140	2.99	8.33	1680	39.62		
150	3.03	8.33	1800	42.21		
160	3.06	8.35	1920	44.02		
170	3.11	8.35	2040	45.86		
180	3.15	8.34	2160	47.72		
181	3.87	12.51	2280	50.58		
182	3.98	12.51	2400	53.3		
183	4.25	12.51	2520	59.02		
185	4.46	12.52	2640	68.01		
187	4.82	12.52	2760	74.16		
190	6.5	12.51	2880	79.86		
195	8.8	12.51				
200	9.49	12.5				
210	11.08	12.5				
220	13.54	12.51				
230	19.04	12.51				
240	24.15	12.51				
241	32.1	15.14				
242	37.48	15.14				
243	44.18	15.14				
245	49	15.13				
247	53.21	15.13				
250	56.1	15.14				
255	61.46	15.14				
260	66.18	15.14				

BOREHOLE: G29877L_new						
Step Test Data			CDT Data Q = 4.00 l/s		Recovery	
Time (min)	Drawdown (m)	Q (l/s)	Time (min)	Drawdown (m)	Time (min)	Drawdown (m)
1	0.78	0.89	1	2.8	1	10.69
2	0.88	0.89	2	3.8	2	9.07
3	1.1	0.89	3	4.72	3	8.81
5	1.2	1.02	5	6.6	5	7.95
7	1.31	1.02	7	8.12	7	7..37
10	1.39	1.05	10	9.45	10	6.96
15	1.47	1.05	15	10.34	15	6.2
20	1.56	1.05	20	10.62	20	5.7
30	1.73	1.05	30	11.25	30	5.03
40	1.86	1.03	40	11.73	40	4.48
50	1.96	1.03	60	12.32	60	3.9
60	2	1.05	90	12.65	90	3.35
61	2.51	2.1	120	12.97	120	2.99
62	2.7	2.1	150	13.24	150	2.74
63	2.87	2.1	180	13.4	180	2.48
65	3.1	2.04	210	13.56	210	2.31
67	3.26	2.04	240	13.72	240	2.15
70	3.37	2.04	300	13.96	300	1.86
75	3.52	2.04	360	14.25	360	1.59
80	3.7	2.06	420	14.45	420	1.3
90	3.88	2.06	480	14.62	480	1.04
100	4.04	2.07	540	14.8	540	0.91
110	4.26	2.07	600	15	600	0.75
120	4.45	2.08	720	15.15	720	0.51
121	5.06	2.99	840	15.3		
122	5.75	2.99	960	15.37		
123	6.4	3.57	1080	15.59		
125	7.36	4	1200	15.98		
127	7.75	4	1320	16.07		
130	8.25	4.06	1440	16.09		
135	8.83	4.06	1560	16.19		
140	9.26	4.01	1680	16.25		
150	9.96	4.01	1800	16.31		
160	10.27	4	1920	16.39		
170	10.61	4	2040	16.48		
180	10.84	4.05	2160	16.53		
181	12.98	5.22	2280	16.57		
182	14.01	5.22	2400	16.61		
183	15.02	5.22	2520	16.64		
185	16.07	6.07	2640	16.66		
187	17.1	6.07	2760	16.69		
190	19.94	6.07	2880	16.7		
195	22.33	6.07	3000	16.73		
200	25.64	6.05	3120	16.75		
210	31.94	6.05	3240	16.76		
220	34.47	6.07	3360	16.78		
230	36.2	6.07	3480	16.83		
240	38.51	6.07	3600	16.85		
241	40.5	7.6	3720	16.87		
242	42.88	7.6	3840	16.88		
243	44.95	7.6	3960	16.89		
245	49.1	8	4080	16.91		
247	58.05	8	4200	16.93		
250	67.1	7.99	4320	16.94		
255	76.07	7.99				
260	87	8.01				
265	87	7				
267	87	6.95				
270	87	6.9				

BOREHOLE: HK_NDA						
Step Test Data			CDT Data Q = 8.13 l/s		Recovery	
Time (min)	Drawdown (m)	Q (l/s)	Time (min)	Drawdown (m)	Time (min)	Drawdown (m)
1	0.47	3.45	1	1.39	1	1.98
2	0.51	3.45	2	1.54	2	1.63
3	0.55	3.45	3	1.65	3	1.52
5	0.6	3.46	5	1.73	5	1.47
7	0.62	3.46	7	1.79	7	1.42
10	0.64	3.46	10	1.85	10	1.38
15	0.65	3.46	15	1.99	15	1.32
20	0.65	3.45	20	2.05	20	1.3
30	0.67	3.45	30	2.08	30	1.26
40	0.67	3.45	40	2.12	40	1.22
50	0.68	3.45	60	2.15	60	1.17
60	0.68	3.45	90	2.17	90	1.13
61	1.27	6.03	120	2.2	120	1.08
62	1.28	6.03	150	2.23	150	1.04
63	1.3	6.03	180	2.25	180	1.01
65	1.33	6.05	210	2.27	210	0.98
67	1.36	6.05	240	2.29	240	0.95
70	1.38	6.04	300	2.32	300	0.91
75	1.4	6.04	360	2.36	360	0.87
80	1.42	6.03	420	2.4	420	0.83
90	1.43	6.03	480	2.44	480	0.81
100	1.45	6.04	540	2.47	540	0.79
110	1.45	6.04	600	2.49	600	0.77
120	1.45	6.04	720	2.56	720	0.74
121	2.58	9.51	840	2.61	840	0.71
122	2.6	9.51	960	2.67	960	0.68
123	2.67	9.51	1080	2.74	1080	0.65
125	2.78	9.52	1200	2.78	1200	0.61
127	2.83	9.52	1320	2.8	1320	0.58
130	2.83	9.52	1440	2.8	1440	0.55
135	2.93	9.52	1560	2.8	1560	0.53
140	2.95	9.53	1680	2.81	1680	0.53
150	2.98	9.53	1800	2.81	1800	0.53
160	3.01	9.52	1920	2.82	1920	0.52
170	3.03	9.52	2040	2.82	2040	0.52
180	3.05	9.53	2160	2.84	2160	0.51
181	3.4	12.02	2280	2.86	2280	0.49
182	3.47	12.02	2400	2.87	2400	0.47
183	3.51	12.02	2520	2.89	2520	0.46
185	3.55	12.03	2640	2.93	2640	0.44
187	3.58	12.03	2760	2.96	2760	0.43
190	3.6	12.02	2880	2.98	2880	0.41
195	3.63	12.02	3000	3.01	3000	0.39
200	3.65	12.01	3120	3.03	3120	0.37
210	3.67	12.01	3240	3.06	3240	0.35
220	3.68	12.02	3360	3.08	3360	0.33
230	3.7	12.02	3480	3.1	3480	0.32
240	3.73	12	3600	3.12	3600	0.3
241	4.3	14.88	3720	3.15	3720	0.29
242	4.37	14.88	3840	3.18	3840	0.27
243	4.5	14.88	3960	3.2	3960	0.26
245	4.6	15.04	4080	3.22	4080	0.25
247	4.65	15.04	4200	3.25	4200	0.24
250	4.69	15.25	4320	3.27	4320	0.23
255	4.73	15.25				
260	4.77	15.24				
270	4.8	15.24				
280	4.84	15.25				
290	4.86	15.25				
300	4.88	15.25				

BOREHOLE: HR_10						
Step Test Data			CDT Data Q = 15.25 l/s		Recovery	
Time (min)	Drawdown (m)	Q (l/s)	Time (min)	Drawdown (m)	Time (min)	Drawdown (m)
1	0.16	2.98	1	0.58	1	2.46
2	0.17	2.98	2	1.09	2	2.38
3	0.18	2.98	3	1.25	3	2.33
5	0.19	2.98	5	1.34	5	2.27
7	0.19	3.2	7	1.39	7	2.23
10	0.19	3.2	10	1.4	10	2.18
15	0.2	3.22	15	1.42	15	2.14
20	0.21	3.22	20	1.44	20	2.09
30	0.22	3.22	30	1.48	30	2.04
40	0.22	3.22	40	1.53	40	2
50	0.25	3.21	60	1.59	60	1.93
60	0.28	3.21	90	1.67	90	1.86
61	0.36	5.76	120	1.76	120	1.8
62	0.39	5.76	150	1.83	150	1.73
63	0.45	6.45	180	1.87	180	1.7
65	0.48	6.45	210	1.92	210	1.64
67	0.5	6.46	240	1.96	240	1.61
70	0.51	6.46	300	2.03	300	1.55
75	0.51	6.45	360	2.08	360	1.47
80	0.47	6.45	420	2.13	420	1.38
90	0.48	6.46	480	2.19	480	1.37
100	0.6	6.46	540	2.24	540	1.26
110	0.51	6.44	600	2.29	600	1.2
120	0.52	6.44	720	2.38	720	1.1
121	0.73	9.43	840	2.45	840	1
122	0.75	9.43	960	2.52	960	0.92
123	0.77	9.43	1080	2.59	1080	0.81
125	0.79	9.42	1200	2.63	1200	0.72
127	0.79	9.42	1320	2.67	1320	0.76
130	0.82	9.43	1440	2.7	1440	0.69
135	0.84	9.43	1560	2.73	1560	0.66
140	0.86	9.41	1680	2.74	1680	0.62
150	0.88	9.41	1800	2.76	1800	0.59
160	0.9	9.42	1920	2.8	1920	0.57
170	0.91	9.42	2040	2.83	2040	0.55
180	0.93	9.43	2160	2.87	2160	0.54
181	1.14	12.75	2280	2.92	2280	0.62
182	1.18	12.75	2400	2.96	2400	0.5
183	1.2	12.75	2520	2.98	2520	0.49
185	1.23	12.75	2640	3.02	2640	0.47
187	1.24	12.73	2760	3.06	2760	0.45
190	1.25	12.73	2880	3.06	2880	0.43
195	1.27	12.73	3000	3.07	3000	0.42
200	1.29	12.73	3120	3.07	3120	0.42
210	1.31	12.74	3240	3.1	3240	0.41
220	1.33	12.74	3360	3.11	3360	0.4
230	1.36	12.75	3480	3.12	3480	0.39
240	1.39	12.75	3600	3.14	3600	0.39
241	1.59	15.71	3720	3.16	3720	0.38
242	1.62	15.71	3840	3.17	3840	0.36
243	1.65	15.71	3960	3.19	3960	0.35
245	1.66	15.73	4080	3.22	4080	0.34
247	1.68	15.73	4200	3.25	4200	0.33
250	1.69	15.74	4320	3.28	4320	0.32
255	1.71	15.74				
260	1.73	15.72				
270	1.75	15.72				
280	1.78	15.72				
290	1.8	15.72				
300	1.82	15.72				

BOREHOLE: HR_13						
Step Test Data			CDT Data Q = 10.05 l/s		Recovery	
Time (min)	Drawdown (m)	Q (l/s)	Time (min)	Drawdown (m)	Time (min)	Drawdown (m)
1	0.35	3.4	1	1.78	1	1.6
2	0.37	3.4	2	1.83	2	1.56
3	0.38	3.4	3	1.86	3	1.55
5	0.39	3.41	5	1.9	5	1.53
7	0.39	3.41	7	1.93	7	1.51
10	0.4	3.41	10	1.96	10	1.48
15	0.41	3.41	15	1.98	15	1.46
20	0.42	3.42	20	1.99	20	1.44
30	0.43	3.42	30	2.02	30	1.39
40	0.43	3.42	40	2.04	40	1.36
50	0.44	3.42	60	2.06	60	1.3
60	0.44	3.42	90	2.09	90	1.24
61	0.78	6.53	120	2.13	120	1.2
62	0.81	6.53	150	2.16	150	1.16
63	0.83	6.53	180	2.2	180	1.14
65	0.85	6.51	210	2.24	210	1.12
67	0.87	6.51	240	2.28	240	1.09
70	0.89	6.52	300	2.33	300	1.05
75	0.92	6.52	360	2.36	360	1.01
80	0.94	6.53	420	2.39	420	0.98
90	0.96	6.53	480	2.43	480	0.95
100	0.98	6.52	540	2.47	540	0.92
110	1.02	6.52	600	2.5	600	0.89
120	1.05	6.52	720	2.53	720	0.86
121	1.49	9.24	840	2.55	840	0.83
122	1.55	9.24	960	2.58	960	0.81
123	1.59	9.24	1080	2.6	1080	0.78
125	1.61	9.25	1200	2.6	1200	0.76
127	1.63	9.25	1320	2.6	1320	0.73
130	1.65	9.24	1440	2.6	1440	0.71
135	1.66	9.24	1560	2.63	1560	0.68
140	1.68	9.25	1680	2.68	1680	0.66
150	1.69	9.25	1800	2.72	1800	0.65
160	1.69	9.25	1920	2.75	1920	0.64
170	1.69	9.25	2040	2.78	2040	0.62
180	1.7	9.24	2160	2.83	2160	0.61
181	2.07	12.27	2280	2.88	2280	0.6
182	2.15	12.27	2400	2.88	2400	0.59
183	2.22	12.27	2520	2.88	2520	0.57
185	2.3	12.26	2640	2.88	2640	0.56
187	2.42	12.26	2760	2.87	2760	0.54
190	2.46	12.25	2880	2.87	2880	0.54
195	2.48	12.25	3000	2.88	3000	0.53
200	2.49	12.28	3120	2.89	3120	0.52
210	2.51	12.28	3240	2.9	3240	0.51
220	2.53	12.28	3360	2.91	3360	0.5
230	2.54	12.28	3480	2.93	3480	0.5
240	2.55	12.28	3600	2.95	3600	0.49
241	2.96	14.88	3720	2.96	3720	0.48
242	3.03	14.88	3840	2.98	3840	0.48
243	3.06	14.88	3960	2.99	3960	0.46
245	3.07	15.47	4080	3	4080	0.46
247	3.08	15.47	4200	3.01	4200	0.45
250	3.1	15.47	4320	3.02	4320	0.45
255	3.12	15.47				
260	3.14	15.46				
270	3.15	15.46				
280	3.16	15.47				
290	3.17	15.47				
300	3.18	15.47				

APPENDIX B: PUMP TEST SUMMARY SHEETS

Summary — Main — Brandwag_5

Applicable	Method	Sustainable yield (l/s)	Std. Dev	Early T (m^2/d)	Late T (m^2/d)	S	AD used
☑	Basic FC	1.74	1.21	45	6.4	1.10E-03	10.0
☐	Advanced FC			45	6.4	1.00E-03	10.0
☑	FC inflection point	0.37	0.28				3.0
☑	Cooper-Jacob	1.20	0.77		17.7	8.02E-03	10.0
☑	FC Non-Linear	1.39	1.22				10.0
☑	Barker	0.54	0.33	K_f = 201	S_s =	1.01E-03	10.0
	Average Q_sust (l/s)	1.05	0.58	b = 2.00	Fractal dimension n =	1.50	

Recommended abstraction rate (L/s): 1.05 for 24 hours per day

Hours per day of pumping: 12 — 1.49 L/s for 12 hours per day

Amount of water allowed to be abstracted per month: 2721.6 m^3

Borehole could satisfy the basic human need of: 3629 persons

Is the water suitable for domestic use (Yes/No):

Summary — Main — DR_5

Applicable	Method	Sustainable yield (l/s)	Std. Dev	Early T (m^2/d)	Late T (m^2/d)	S	AD used
☑	Basic FC	0.02	0.02	109	0.3	6.60E-04	6.0
☐	Advanced FC			109	0.3	1.00E-03	6.0
☑	FC inflection point	0.19	0.16				6.0
☑	Cooper-Jacob	0.06	0.04		1.0	1.52E-02	6.0
☑	FC Non-Linear	4.65	4.10				6.0
☑	Barker	0.00	0.00	K_f = 938	S_s =	2.78E-04	6.0
	Average Q_sust (l/s)	0.99	2.05	b = 15.00	Fractal dimension n =	0.48	

Recommended abstraction rate (L/s): 0.99 for 24 hours per day

Hours per day of pumping: 12 — 1.40 L/s for 12 hours per day

Amount of water allowed to be abstracted per month: 2566.08 m^3

Borehole could satisfy the basic human need of: 3421 persons

Is the water suitable for domestic use (Yes/No): Yes

Summary — Main — G29877L_new

Applicable	Method	Sustainable yield (l/s)	Std. Dev	Early T (m^2/d)	Late T (m^2/d)	S	AD used
☑	Basic FC	1.93	0.85	16	15.1	1.10E-04	21.0
☐	Advanced FC			16	15.1	1.00E-03	21.0
☐	FC inflection point	1.50	0.68				15.6
☑	Cooper-Jacob	1.80	1.16		21.8	1.58E-06	21.0
☑	FC Non-Linear	0.57	0.50	10.0		1.01E-03	26.0
☑	Barker	2.12	1.04	K_f = 39	S_s =	1.70E-04	21.0
	Average Q_sust (l/s)	1.60	0.70	b = 0.14	Fractal dimension n =	2.14	

Recommended abstraction rate (L/s): 1.60 for 24 hours per day

Hours per day of pumping: 12 — 2.26 L/s for 12 hours per day

Amount of water allowed to be abstracted per month: 4147.2 m^3

Borehole could satisfy the basic human need of: 5530 persons

Is the water suitable for domestic use (Yes/No): Yes

Summary | Main | **HK_NDA**

Applicable	Method	Sustainable yield (l/s)	Std. Dev	Early T (m^2/d)	Late T (m^2/d)	S	AD used
☑	Basic FC	3.11	1.75	383	71.4	1.10E-03	5.7
☐	Advanced FC			383	71.4	1.00E-03	5.7
☑	FC inflection point	2.87	1.36				2.9
☑	Cooper-Jacob	5.76	3.73		260.8	1.59E-02	5.7
☑	FC Non-Linear	7.68	6.77				10.0
☑	Barker	4.77	3.96	K_f = 100	S_s =	1.60E-04	5.7
	Average Q_sust (l/s)	4.84	1.99	b = 3.70	Fractal dimension n =	1.95	

Recommended abstraction rate (L/s)	4.84	for 24 hours per day	
Hours per day of pumping: 12	6.84	L/s for 12	hours per day
Amount of water allowed to be abstracted per month	12538.39	m^3	
Borehole could satisfy the basic human need of	16718	persons	
Is the water suitable for domestic use (Yes/No)	Yes		

Summary | Main | **HR_10**

Applicable	Method	Sustainable yield (l/s)	Std. Dev	Early T (m^2/d)	Late T (m^2/d)	S	AD used
☑	Basic FC	11.82	6.70	636	141.8	1.10E-04	10.9
☐	Advanced FC			636	141.8	1.00E-03	10.9
☐	FC inflection point	3.93	2.21				1.6
☑	Cooper-Jacob	16.04	10.38		265.1	8.96E-04	10.9
☑	FC Non-Linear	8.41	7.42				10.9
☑	Barker	14.03	9.30	K_f = 100	S_s =	1.60E-04	10.9
	Average Q_sust (l/s)	12.58	3.27	b = 5.00	Fractal dimension n =	1.89	

Recommended abstraction rate (L/s)	12.58	for 24 hours per day	
Hours per day of pumping: 12	17.79	L/s for 12	hours per day
Amount of water allowed to be abstracted per month	32600.73	m^3	
Borehole could satisfy the basic human need of	43468	persons	
Is the water suitable for domestic use (Yes/No)	Yes		

Summary | Main | **HR_13**

Applicable	Method	Sustainable yield (l/s)	Std. Dev	Early T (m^2/d)	Late T (m^2/d)	S	AD used
☑	Basic FC	9.51	5.15	733	105.9	1.10E-04	12.2
☐	Advanced FC			733	105.9	1.00E-03	12.2
☑	FC inflection point	4.59	1.77				2.6
☑	Cooper-Jacob	14.37	9.30		267.5	1.51E+02	12.2
☑	FC Non-Linear	9.35	8.24	553.0		1.00E-03	12.2
☑	Barker	10.46	6.20	K_f = 1902	S_s =	1.60E-04	12.2
	Average Q_sust (l/s)	9.66	3.49	b = 1.00	Fractal dimension n =	1.76	

Recommended abstraction rate (L/s)	9.66	for 24 hours per day	
Hours per day of pumping: 12	13.66	L/s for 12	hours per day
Amount of water allowed to be abstracted per month	25038.72	m^3	
Borehole could satisfy the basic human need of	33385	persons	
Is the water suitable for domestic use (Yes/No)	Yes		

APPENDIX C: LABORATORY DATA

BemLab (Pty) LTD
2002/017933/07
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Report No.: **WT1904/2008**

ANALYSES REPORT

Gaathier Mahed
Universiteit van Weskaapland

Date received: 19/05/2008
Date tested: 21/05/2008

Origin	Lab. No.	pH	EC mS/m	Na	K	Ca	Mg	Fe	Cl	CO_3	HCO_3	SO_4	B	Mn	Cu	Zn	P	NH_4-N	NO_3-N
												mg/l							
Blydskap 1	1904	7.7	127	152.9	6.7	73.4	24.9	**0.08**	150.7	108.4	251.1	94	0.55	**0.00**	**0.01**	**0.03**	0.04	1.75	8.16
Blydskap 2	1905	7.6	99	87.9	8.7	80.0	23.6	**0.09**	88.1		382.8	48	0.34	**0.00**	**0.00**	**0.02**	0.00	1.72	10.95
Brandwag 8	1906	7.7	133	105.6	1.8	114.3	42.1	**0.07**	130.4	120.5	265.1	174	0.13	**0.00**	**0.00**	0.08	0.00	1.74	3.16
Brandwag 9	1907	7.9	241	249.8	2.0	232.7	37.0	**0.13**	263.5	114.5	125.6	654	0.42	0.22	**0.00**	**0.06**	0.00	1.75	0.64
Hansrivier 10	1908	7.7	189	166.2	6.6	158.0	47.7	**0.14**	264.4	93.4	260.3	232	0.23	**0.00**	**0.00**	0.24	0.00	1.73	12.60
Lemoenfontein Noord	1909	7.7	138	126.9	2.5	132.0	31.0	**0.09**	115.4	135.5	367.5	162	0.22	**0.00**	**0.00**	0.11	0.08	1.54	3.88
Lemoenfontein Wes	1910	7.7	155	131.8	2.8	157.8	31.8	**0.09**	173.6		427.2	197	0.21	**0.00**	**0.00**	**0.02**	0.00	1.43	2.54
Meyerspoort 1	1911	7.4	56	60.6	3.7	45.9	10.5	**0.09**	35.2		246.5	36	0.10	**0.00**	**0.01**	**0.01**	0.00	1.46	1.81
Mr Basson	1912	7.7	124	135.2	4.3	87.0	32.7	**0.10**	77.5		627.8	42	0.30	2.59	**0.00**	**0.01**	0.05	1.58	0.41
Nigrini Farm 1	1913	2.5	669	132.1	3.6	169.4	51.9	**0.08**	243.2		0.0	142	0.28	**0.02**	**0.00**	**0.01**	0.00	1.56	280.40
Nigrini Farm 2	1914	7.7	415	286.0	3.1	388.6	135.1	**0.16**	868.0	90.4	185.3	548	0.30	**0.00**	**0.00**	**0.03**	0.00	1.40	50.60
Schrfont 1	1915	7.6	83	74.5	2.7	96.4	16.5	**0.08**	52.9		381.2	65	0.12	**0.00**	**0.01**	**0.01**	0.00	1.40	3.66
Schrfont 2	1916	7.6	87	68.5	3.0	94.4	18.9	**0.15**	65.2	96.4	300.1	52	0.11	**0.00**	**0.01**	0.11	0.00	1.27	3.83
Spring	1917	2.3	977	61.3	4.4	70.0	18.4	**0.13**	33.5		0.0	50	0.18	**0.02**	**0.00**	**0.01**	0.08	1.34	328.40
Steenrotsfontein 1	1918	7.8	262	330.4	3.6	183.7	60.7	**0.12**	349.8		600.2	357	0.60	**0.00**	**0.00**	**0.02**	0.07	1.47	69.60
Steenrotsfontein 2	1919	7.7	405	390.8	9.8	392.5	78.3	**0.13**	621.2		583.3	607	0.67	0.05	**0.00**	0.14	0.03	1.28	3.85
Tweeling	1920	7.8	137	131.4	2.7	141.1	29.1	**0.15**	107.5		336.8	263	0.23	**0.01**	**0.00**	**0.03**	0.00	1.34	1.11
Windpomp 1	1921	7.8	119	131.4	2.2	126.1	4.8	**0.08**	111.0		396.6	84	0.26	0.04	**0.00**	**0.05**	0.00	1.19	10.44
Methods#		W05	W04	W01	W01	W01	W01	W01	W07	W06	W06	W01	W01	W01	W01	W01		W02	W03

Values in **bold** is smaller than the lowest quantifiable concentration.
#Refer to BemLab work instructions - Accredited methods identified by reference number

Sample conditions
Samples in good condition.

Statement
The reported results may be applied only to samples recieved. Any recommendations included with this report are based on the assumption that the samples were representative of the bulk from which they were taken. Opinions and recommendations are not accredited.

Dr. W.A.G. Kotzé (Director)
....
for BemLab

23-05-2008
....
Date

Enquiries: Dr. W.A.G. Kotzé
Arrie van Deventer

APPENDIX D: TIME SERIES CHEMISTRY DATA

Table 7: Time series chemistry data

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
G29858B	05/04/2006	7.60	125	800	105.0	35.0	107.0	0.90	264.0	134.0	172.0				0.00	0.00	
G29858B	21/05/2008	7.70	133		114.3	42.1	105.6	1.80	385.6	130.4	174.0	3.16			0.07	0.00	1.74
G29858F	30/06/1997	7.40	141	902	126.0	31.6	136.0	2.10	213.0	138.0	570.6	1.30	0.80	0.04		0.00	
G29858KA	30/06/1997	7.40	160	1024	146.0	35.6	145.0	2.50	234.0	193.0	623.2	0.70	0.80	0.00		0.01	
G29858KA	05/04/2006	7.50	170	1088	160.0	33.0	156.0	2.40	247.0	200.0	326.0				0.00	<0.05	
G29858O	30/06/1997	7.90	100	640	69.4	27.3	109.0	0.90	304.0	71.0	201.6	0.60	1.10	0.00		0.00	
G29858P	30/06/1997	7.50	149	954	140.0	47.1	108.0	1.30	295.0	184.0	375.3	4.50	0.50	0.00		0.00	
G29858V	30/06/1997	7.70	126	806	96.5	20.6	156.0	1.20	219.0	87.0	561.0	0.09	1.00	0.00		0.07	
G29858V	05/04/2006	7.30	250	1600	247.0	52.0	244.0	2.40	206.0	307.0	708.0				0.13	0.17	
G29858V	22/11/2006	7.60	275		269.0	51.0	272.0	1.90	168.0	226.0	1011.0	0.00	0.96				
G29858V	21/05/2008	7.90	241		232.7	37.0	249.8	2.00	240.1	263.5	654.0	0.64			0.13	0.22	1.75
G29859C	30/06/1997	7.20	170	1088	153.0	65.7	118.0	1.20	337.0	211.0	480.5	5.10	0.50	0.02		0.01	
G29859C	22/11/2006	7.70	150		135.0	54.0	102.0	1.40	352.0	152.0	193.0	4.60	0.56				
G29872D	30/06/1997	7.50	160	1024	146.0	58.8	121.0	1.60	349.0	183.0	430.5	7.10	0.50	0.00		0.00	
G29879BC	30/06/1997	7.10	130	832	97.6	36.6	140.0	2.60	280.0	146.0	355.3	4.60	0.60	0.00		0.00	
G29879BC	05/04/2006	7.50	144	922	128.0	30.0	148.0	2.60	339.0	125.0	219.0				0.06	<0.05	
G29879BC	23/11/2006	7.70	143		123.0	32.0	127.0	2.50	347.0	124.0	180.0	3.80	0.93				
G29879BC	21/05/2008	7.70	138		132.0	31.0	126.9	2.50	503.0	115.4	162.0	3.88			0.09	0.00	1.54
G29894L	30/06/1997	7.80	123	787	100.0	32.1	118.0	2.20	240.0	150.0	322.3	0.30	0.40	0.00		0.00	
G29894L	05/04/2006	7.60	130	832	116.0	26.0	124.0	2.10	233.0	139.0	209.0				0.00	0.00	
G29894L	22/11/2006	7.80	130		112.0	28.0	121.0	1.60	239.0	139.0	196.0	0.52	0.52				
G29896K	30/06/1997	7.60	144	922	140.0	27.7	124.0	1.50	230.0	207.0	352.3	0.09	0.30	0.00		0.00	
G29914A	30/06/1997	7.50	84	538	55.5	25.9	84.0	8.30	283.0	62.0	447.7	5.50	0.40	0.00		2.72	
G33542	30/06/1997	7.50	154	986	137.0	42.7	123.0	1.00	242.0	242.0	378.7	0.09	0.60	0.00		0.00	
G33544	30/06/1997	7.60	90	576	92.6	8.1	91.0	2.00	213.0	49.0	286.4	2.00	1.10	0.00		0.00	

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
LS1	21/05/2008	7.70	155		157.8	31.8	131.8	2.80	427.2	173.6	197.0	2.54			0.09	0.00	1.43
Private1	30/06/1997	7.20	310	1984	274.0	123.0	227.0	2.10	306.0	610.0	974.9	2.70	0.70	0.01		0.00	
Private2	30/06/1997	7.40	270	1728	243.0	101.0	201.0	1.90	287.0	511.0	580.2	2.50	0.70	0.00		0.00	
Private2	05/04/2006	7.80	230	1472	224.0	66.0	203.0	1.80	248.0	297.0	533.0				0.00	0.00	
Private2	22/11/2006	7.70	215		184.0	63.0	177.0	2.20	235.0	309.0	460.0	1.40	0.76				
SRK3	05/04/2006	7.50	180	1152	176.0	21.0	206.0	1.70	215.0	133.0	569.0				0.27	0.13	
Noordeinde_Suid	05/04/2006	7.60	78	499	68.0	22.0	69.0	1.70	250.0	47.0	81.0				0.00	0.00	
Noordeinde_Suid	09/08/2007	7.90	92		78.0	29.0	69.0	1.60	272.0	61.0	100.0	1.80	0.73				0.00
Noordeinde_Suid	23/11/2006	7.40	77		66.0	23.0	60.0	1.60	233.0	42.0	76.0	1.40	0.73				
Noordeinde_Noord	23/11/2006	7.50	88		78.0	25.0	69.0	1.50	257.0	49.0	103.0	2.00	0.71				
Waterval	05/04/2006	7.50	89	570	129.0	11.0	54.0	1.10	240.0	14.0	214.0				0.06	0.12	
Fontein	05/04/2006	7.40	90	576	127.0	10.0	55.0	0.90	241.0	15.0	217.0				0.00	0.08	
Fontein	23/11/2006	7.30	51		50.0	19.0	28.0	0.60	207.0	10.0	40.0	0.00	0.37				
Volstruisgat	05/04/2006	7.50	87	557	82.0	23.0	68.0	1.20	247.0	47.0	129.0				0.00	0.00	
G29947A	05/04/2006	7.60	72	461	79.0	21.0	44.0	1.10	211.0	17.0	141.0				0.00	0.00	
G29877L_new	04/09/2007	7.30	232		238.0	16.4	267.3	1.40	289.4	345.1	529.0	0.00			0.11	0.35	0.00
DR_5	16/05/2008	7.80	149		152.3	33.1	93.6	3.50	261.8	198.3	146.0	13.16			0.06	0.00	0.32
HR_10	16/05/2008	7.70	194		151.3	45.0	164.7	6.40	246.5	267.0	229.0	10.64			0.71	0.65	0.00
HR_10	21/05/2008	7.70	189		158.0	47.7	166.2	6.60	353.7	264.4	232.0	12.60			0.14	0.00	1.73
HR_13	16/05/2008	7.80	195		161.5	44.3	163.5	6.80	344.5	250.3	243.0	13.29			0.06	0.01	0.09
HK_NDA	16/05/2008	7.80	166		120.8	32.3	179.0	2.90	338.4	195.6	218.0	7.64			0.01	0.00	0.00
Blydskap 1	21/05/2008	7.70	127		73.4	24.9	152.9	6.70	359.5	150.7	94.0	8.16			0.08	0.00	1.75
Blydskap 2	21/05/2008	7.60	99		80.0	23.6	87.9	8.70	382.8	88.1	48.0	10.95			0.09	0.00	1.72
Meyerspoort 1	21/05/2008	7.40	56		45.9	10.5	60.6	3.70	246.5	35.2	36.0	1.81			0.09	0.00	1.46
Mr Basson	21/05/2008	7.70	124		87.0	32.7	135.2	4.30	627.8	77.5	42.0	0.41			0.10	2.59	1.58
Nigrini Farm 1	21/05/2008	2.50	669		169.4	51.9	132.1	3.60	0.0	243.2	142.0	280.40			0.08	0.02	1.56

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
Nigrini Farm 2	21/05/2008	7.70	415		388.6	135.1	286.0	3.10	275.7	868.0	548.0	50.60			0.16	0.00	1.40
Schrfont 1	21/05/2008	7.60	83		96.4	16.5	74.5	2.70	381.2	52.9	65.0	3.66			0.08	0.00	1.40
Schrfont 2	21/05/2008	7.60	87		94.4	18.9	68.5	3.00	396.5	65.2	52.0	3.83			0.15	0.00	1.27
STR_1	21/05/2008	7.80	262		183.7	60.7	330.4	3.60	600.2	349.8	357.0	69.60			0.12	0.00	1.47
STR_2	21/05/2008	7.70	405		392.5	78.3	390.8	9.80	583.3	621.2	607.0	3.85			0.13	0.05	1.28
Tweeling	21/05/2008	7.80	137		141.1	29.1	131.4	2.70	336.8	107.5	263.0	1.11			0.15	0.01	1.34
Windpomp 1	21/05/2008	7.80	119		126.1	4.8	131.4	2.20	396.6	111.0	84.0	10.44			0.08	0.04	1.19
Sandgat	23/11/2006	7.60	71		52.0	20.0	70.0	1.80	249.0	29.0	65.0	1.40	1.00				
SRK4	23/11/2006	7.50	147		136.0	37.0	127.0	2.50	256.0	155.0	289.0	0.96	0.73				
G29947A	05/04/2006	7.60	72	461	79.0	21.0	44.0	1.10	211.0	17.0	141.0				0.00	0.00	
G29947A	23/11/2006	7.50	62		64.0	18.0	38.0	1.00	201.0	14.0	95.0	0.00	0.40				
BW Spring	09/08/2007	7.80	80		81.0	23.0	60.0	4.80	355.0	22.0	44.0	0.00	1.00				0.00
BW Manor 2	09/08/2007	7.40	93		71.0	24.0	95.0	4.50	350.0	39.0	77.0	0.67	1.20				0.00
BW Manor 3	09/08/2007	7.50	95		76.0	18.0	103.0	2.90	345.0	42.0	81.0	0.99	1.30				0.00
BW Manor 4	09/08/2007	7.50	99		40.0	1.0	181.0	0.78	342.0	44.0	84.0	0.47	1.20				0.00
S-Dam4	09/08/2007	7.60	31		32.0	10.0	14.0	4.50	127.0	3.1	18.0	0.29	0.31				0.10
89701	18/10/1994	7.22	179	1179	148.6	41.2	142.9	3.54	249.3	221.8	306.5	2.03	0.87				0.02
89701	10/04/1995	7.72	159	1155	154.7	39.3	144.9	3.66	257.2	196.3	294.9	1.43	1.06				0.04
89701	05/12/1995	8.12	217	1309	169.5	35.4	189.3	4.23	241.6	250.1	360.0	1.12	0.49				0.02
89701	20/05/1996	7.85	159	1066	139.2	34.2	139.7	3.49	236.9	213.7	239.9	1.45	0.94				0.02
89701	13/11/1996	7.90	164	1268	169.8	37.0	166.3	2.96	246.1	231.4	354.4	1.16	0.64				0.02
89701	06/05/1997	7.88	162	1119	150.3	37.5	146.6	2.89	235.5	254.4	234.5	0.91	0.66				0.02
89701	12/11/1997	7.10	157	1117	152.8	39.9	135.6	2.55	269.1	185.6	256.2	3.47	0.67				0.02
89701	12/11/1997	7.92	157	1121	149.5	46.4	132.1	2.59	267.2	194.4	253.5	3.53	0.71				0.02
89701	21/05/1998	7.20	137	1026	140.8	38.4	114.0	2.52	282.4	158.9	204.4	5.00	0.67				0.02
89701	23/09/1998	6.90	148	1055	136.9	42.5	118.9	2.76	274.9	174.9	220.0	5.04	0.97				0.05

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
89701	23/04/1999	7.94	153	1069	148.6	43.9	109.8	2.87	284.8	175.4	217.5	5.19	0.78				0.02
89701	06/05/2000	7.73	175	1216	174.5	41.8	135.0	2.94	281.6	219.8	284.3	3.15	0.62				0.02
89701	20/09/2000	8.58	168	1099	150.1	38.7	137.3	3.21	263.9	201.6	231.7	3.20	0.58				0.02
89701	25/05/2001	8.00	163	1124	156.6	41.4	135.5	2.79	263.1	215.1	237.1	3.03	0.63				0.02
89701	20/09/2001	7.86	169	1059	87.8	43.1	141.1	3.25	263.0	207.9	240.0	3.23	0.65				0.02
89701	19/04/2002	7.97	157	1153	151.2	46.0	134.0	3.61	273.3	195.0	271.7	3.83	0.67				0.04
89701	15/09/2002	8.00	171	1175	159.9	37.9	144.2	2.55	266.7	226.3	266.7	2.59	0.66				0.04
89701	01/05/2003	7.81	171	1196	159.6	38.9	150.0	2.55	249.0	190.2	345.8	1.02	0.94				0.02
89701	26/09/2003	7.66	172	1176	175.0	34.5	125.9	2.71	259.2	206.9	307.5	1.47	0.70				0.02
89701	14/05/2004	8.13	182	1267	186.8	36.0	171.0	2.85	251.0	228.5	330.2	1.14	0.73				0.02
89701	07/10/2004	7.94	173	1210	165.9	31.0	157.0	2.78	261.8	224.7	302.7	1.35	0.75				0.02
89701	02/06/2005	7.82	165	1153	159.0	36.4	143.0	2.72	254.2	194.1	300.9	1.16	0.68				0.02
89701	08/09/2005	8.27	167	1106	149.2	33.2	143.3	2.74	240.8	193.1	286.4	0.96	0.70				0.04
89701	04/05/2006	7.96	164	1218	159.8	35.2	160.6	2.79	250.7	215.9	334.5	0.68	0.75				0.02
89701	13/09/2006	8.08	153	1054	137.3	35.2	137.8	2.60	238.3	171.1	274.7	0.86	0.66				0.07
89701	09/05/2007	8.33	190	1197	151.6	37.0	159.6	2.60	235.6	231.8	323.3	0.47	0.70				0.12
89701	20/09/2007	8.26	125	926	128.1	28.2	120.6	2.66	210.6	144.0	236.0	1.95	0.71				0.14
89939	18/10/1994	7.41	57	409	54.8	16.7	25.9	0.53	192.9	11.4	63.2	0.14	0.53				0.02
89939	10/04/1995	8.20	62	497	64.7	20.5	30.5	1.62	244.0	9.2	71.2	0.15	0.69				0.02
89939	05/12/1995	8.35	72	540	81.5	18.4	39.1	2.02	230.1	10.9	106.0	0.18	0.30				0.02
89939	20/05/1996	7.87	629	513	72.5	18.3	34.8	0.15	231.4	11.8	92.2	0.08	0.46				0.02
89939	13/11/1996	8.01	67	550	84.9	16.3	36.4	0.88	238.6	10.7	108.4	0.20	0.33				0.02
89939	06/05/1997	7.61	54	417	57.9	18.1	26.9	0.73	195.4	14.8	59.0	0.11	0.32				0.02
89939	12/11/1997	8.02	58	469	63.1	19.9	31.9	0.80	221.0	15.6	67.0	0.10	0.31				0.02
89939	21/05/1998	7.61	48	407	53.2	17.6	26.9	0.53	205.3	11.1	46.3	0.09	0.30				0.02
89939	23/09/1998	7.80	43	348	46.7	16.5	24.8	0.52	166.7	13.3	41.5	0.06	0.51				0.05

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
89939	23/04/1999	7.76	54	451	61.8	19.5	28.6	0.73	226.1	13.6	50.9	0.06	0.33				0.02
89939	08/10/1999	8.01	58	456	58.5	20.4	29.6	0.71	227.5	13.0	55.4	0.18	0.29				0.02
89939	06/05/2000	7.71	53	403	52.0	20.2	27.9	0.64	181.7	26.9	52.5	0.17	0.33				0.02
89939	20/09/2000	7.94	54	406	53.0	18.7	29.0	0.75	191.7	22.2	48.1	0.07	0.36				0.02
89939	25/05/2001	8.65	58	464	61.3	22.8	31.7	0.66	219.7	23.4	55.7	0.11	0.31				0.09
89939	20/09/2001	8.36	61	460	29.5	43.4	28.5	0.78	223.9	20.3	63.4	0.13	0.29				0.04
89939	19/04/2002	7.85	70	558	74.8	29.1	34.5	0.77	257.1	27.4	77.3	0.11	0.31				0.02
89939	15/09/2002	7.93	67	495	67.9	23.0	29.3	0.74	215.4	25.4	84.5	0.33	0.30				0.04
89939	30/04/2003	8.04	58	435	51.9	20.6	28.8	0.54	212.6	18.8	54.4	0.06	0.34				0.08
89939	26/09/2003	7.70	53	402	52.6	19.5	26.9	0.72	201.0	16.7	39.5	0.08	0.30				0.02
89939	14/05/2004	7.98	65	514	67.5	24.8	33.9	0.81	256.6	16.4	57.3	0.06	0.44				0.02
89939	06/10/2004	7.96	77	614	113.0	8.9	47.4	0.91	226.8	17.0	149.9	0.06	0.50				0.04
89939	01/06/2005	7.93	64	540	66.4	27.0	34.6	0.83	287.2	16.1	44.7	0.04	0.34				0.02
89939	07/09/2005	7.96	72	516	77.8	11.2	53.2	0.93	131.7	16.4	194.4	0.04	0.45				0.02
89939	04/05/2006	8.19	88	720	124.1	13.1	54.0	0.83	235.9	17.2	222.0	0.04	0.49				0.02
89939	12/09/2006	8.32	53	388	50.2	16.2	26.9	0.52	187.8	13.8	50.0	0.09	0.61				0.05
89939	09/05/2007	8.24	80	625	104.2	10.6	48.3	0.89	232.0	18.0	159.8	0.04	0.51				0.09
89939	18/09/2007	7.97	97	710	126.9	9.3	66.5	0.96	212.2	18.3	228.7	0.04	0.58				0.11
91174	07/01/1976	7.86	150		82.0	44.0	167.0	7.95	234.6	206.0	194.0	9.29	0.60				
91175	28/01/1976	7.73	76		42.0	8.0	101.0	18.90	167.3	57.0	123.0	0.75	1.16				
91176	03/02/1976	8.09	64		25.5	11.4	88.0	7.51	176.6	65.8	49.4	1.69	0.39				
91177	09/02/1976	7.85	113		30.7	2.3	187.1	12.70	133.5	254.4	34.0	0.02	1.94				
91178	10/02/1976	7.87	86		59.0	36.2	68.4	3.80	243.0	93.5	48.4	7.63	0.29				
91182	06/04/1976	8.17	65	454	55.7	23.6	35.5	2.51	172.7	49.8	39.6	8.24	0.41				0.02
91183	14/05/1976	8.13	89	600	56.8	7.0	108.2	1.48	131.2	36.4	229.2	0.02	0.76				0.02
91184	09/07/1976	7.65	119	823	64.5	26.2	138.2	4.05	238.8	114.5	149.1	7.76	0.95				0.02

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
91185	07/07/1976	7.60	189	1236	121.7	23.4	229.3	6.68	153.7	218.4	404.6	9.68	1.86				0.02
91772	03/07/1978	7.90	433	2908	183.8	91.6	652.8	35.76	307.7	961.4	586.8	4.30	1.22				0.06
93974	11/01/1985	8.56	46	413	39.1	19.2	33.8	3.24	195.9	26.0	9.8	9.52	0.28				0.04
94748	08/01/1987	8.00	114	777	77.4	36.0	109.4	1.62	191.8	126.1	174.7	3.81	0.84				0.04
94748	23/02/1988	8.01	134	892	96.2	54.7	99.7	0.86	215.8	172.4	176.6	6.24	0.84				0.02
94748	27/02/1989	6.88	95	535	21.8	37.7	98.1	1.88	80.6	166.3	107.9	0.25	0.32				0.90
94748	27/02/1990	7.48	90	589	40.4	31.1	98.4	1.62	144.7	151.0	87.1	0.68	0.25				0.02
94748	14/03/1991	8.09	124	921	104.4	52.6	94.5	0.87	252.9	162.5	172.3	5.45	0.87				0.02
94748	17/03/1992	7.95	116	923	104.5	53.0	88.3	0.78	270.5	154.3	166.3	5.57	0.77				0.08
94749	13/01/1987	7.70	112	711	69.6	32.3	107.9	5.97	127.8	155.2	182.3	0.24	0.43				0.04
94749	24/02/1989	7.64	120	842	94.1	34.6	107.7	2.74	211.4	155.1	189.3	0.10	0.45				0.06
94749	27/02/1990	7.69	40	323	25.4	8.3	47.1	1.89	158.1	27.8	18.3	0.02	0.70				0.11
94749	15/03/1991	8.16	97	780	94.3	32.5	96.0	2.49	209.7	146.1	152.4	0.04	0.44				0.02
94749	17/03/1992	8.07	124	911	113.7	38.5	106.2	2.63	237.1	167.7	192.6	0.02	0.52				0.04
94750	29/01/1987	7.80	130	904	112.7	22.3	133.2	5.21	160.8	118.5	307.4	1.69	1.52				0.04
94750	26/02/1988	8.01	111	726	76.8	38.9	87.3	1.73	178.9	124.0	176.1	0.29	1.29				0.02
94750	26/02/1988	7.97	120	775	86.0	33.8	110.3	2.69	177.0	148.2	176.7	0.12	0.44				0.02
94750	24/02/1989	7.61	111	765	75.6	44.8	89.9	1.96	202.2	133.7	166.7	0.94	1.28				0.02
94750	27/02/1990	7.69	86	594	35.6	36.4	91.6	2.91	177.4	117.1	92.0	0.16	0.45				0.70
94750	15/03/1991	8.22	115	773	55.2	12.5	170.7	0.58	132.7	122.3	248.2	0.02	1.67				0.02
94750	17/03/1992	7.94	149	1036	69.9	6.9	249.2	0.85	121.5	119.3	439.6	0.02	1.96				0.02
95329	24/02/1988	7.97	76	530	65.6	6.6	82.1	2.03	183.6	35.1	111.0	0.43	1.33				0.07
95329	27/02/1989	7.55	75	535	64.2	5.8	79.3	1.72	194.0	38.5	106.0	0.20	1.46				0.02
95329	27/02/1990	7.85	74	595	66.3	7.0	87.5	1.98	206.0	42.3	135.3	0.67	0.52				0.02
95329	13/03/1991	8.15	106	879	140.0	5.0	119.0	0.99	150.0	41.0	389.0	0.02	1.42				0.02
95329	18/03/1992	8.48	120	946	155.5	3.1	114.7	0.91	169.6	59.1	404.0	0.02	1.23				0.02

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
95330	24/02/1988	8.20	135	941	136.2	36.7	95.9	3.00	221.5	148.8	223.5	5.72	0.97				0.05
95330	27/02/1989	6.76	453	3968	559.3	65.4	556.0	6.30	86.1	325.3	2340.9	1.68	1.84				0.07
95330	27/02/1990	7.77	165	1162	135.8	26.2	190.7	3.69	200.0	160.5	361.3	8.75	1.43				0.02
95330	13/03/1991	7.88	533	4587	538.6	16.5	911.0	4.05	33.1	459.0	2613.4	0.09	3.36				0.07
95331	24/02/1988	8.11	149	1002	110.0	59.8	119.7	0.78	216.2	201.7	231.8	3.18	0.49				0.02
95331	27/02/1989	7.08	50	320	27.0	11.7	53.9	1.34	106.4	90.3	2.0	0.36	0.39				0.39
95331	26/02/1990	7.81	57	327	28.3	14.3	54.6	0.84	65.0	122.1	26.0	0.08	1.32				0.16
95331	13/03/1991	8.15	77	558	66.3	15.8	74.3	0.87	182.4	86.5	89.9	0.32	0.49				0.06
95331	16/03/1992	8.51	72	498	61.0	11.9	66.3	0.75	176.3	67.3	75.5	0.02	0.46				0.02
95332	25/02/1988	7.97	158	999	113.5	48.1	144.0	1.60	190.8	259.5	189.2	2.14	0.67				0.04
95332	23/02/1989	7.64	227	1366	162.8	69.7	173.5	1.94	222.8	406.8	261.0	4.08	0.55				0.02
95332	26/02/1990	7.63	202	1326	136.3	69.9	178.2	2.79	210.9	396.6	272.5	2.71	0.22				0.27
95332	15/03/1991	7.99	175	1319	158.5	70.9	173.9	2.21	207.8	420.5	222.1	3.74	0.77				0.02
95332	16/03/1992	8.12	219	1353	172.7	70.3	167.9	2.22	239.6	386.7	242.5	3.99	0.56				0.06
95332	09/11/2005	7.76	240	1433	172.3	85.0	175.6	2.67	185.7	482.5	260.9	6.05	0.43				0.02
95332	17/10/2007	7.70	212	1369	173.7	65.1	164.6	2.01	258.0	395.9	235.7	3.76	0.46				0.12
95333	25/02/1988	8.11	151	1021	123.9	44.6	130.0	2.42	246.3	202.0	209.5	1.62	0.62				0.73
95333	23/02/1989	7.61	136	973	106.5	41.1	131.1	2.62	263.2	185.8	184.4	0.09	0.59				0.02
95333	26/02/1990	8.15	98	635	19.8	38.8	127.4	2.68	148.5	199.8	64.3	0.05	0.81				0.05
95333	15/03/1991	8.04	118	934	95.9	41.0	127.8	2.11	225.8	205.3	173.6	2.70	0.65				0.02
95333	16/03/1992	8.20	127	885	86.2	40.4	122.3	2.08	240.4	177.1	160.8	0.45	0.48				0.06
149652	24/05/1976	7.83	73	528	51.9	18.6	76.7	3.43	174.2	46.6	113.4	0.97	0.42				0.25
149829	16/06/1976	6.76	149	1036	133.2	52.4	97.2	6.54	236.4	125.3	259.9	16.40	0.62				0.06
149830	16/06/1976	7.79	193	1307	162.1	45.1	161.4	27.31	184.7	216.9	439.1	6.40	0.66				0.73
152898	04/03/1976	7.91	408	2621	266.9	200.8	302.1	23.37	267.6	802.1	636.3	14.14	0.67				0.14
155589	14/03/1977	7.78	130	923	116.8	22.5	133.5	0.95	234.0	129.9	232.3	0.09	0.78				0.02

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
155589	23/03/1977	7.99	111	800	103.8	23.1	97.1	0.64	242.7	95.3	169.4	3.23	0.60				0.02
156565	20/09/1977	7.63	117	708	73.9	12.0	118.0	0.15	166.8	95.8	203.4	0.08	0.62				0.02
156565	07/11/2005	7.88	78	651	74.1	18.3	81.3	4.31	307.8	46.7	48.4	0.38	0.65				0.02
156565	08/05/2006	8.21	73	571	48.6	20.6	79.0	4.08	258.9	46.3	55.8	0.04	0.59				0.08
156565	15/10/2007	8.34	97	591	28.3	17.5	94.0	5.16	289.0	54.9	37.8	0.04	0.69				0.09
156578	21/09/1977	7.48	76	565	67.8	17.1	64.0	2.51	250.4	50.7	46.6	2.29	0.69				0.02
156578	07/11/2005	7.85	77	646	81.6	18.8	62.8	3.06	322.1	35.8	41.8	2.01	0.66				0.02
156578	06/11/2006	8.27	56	417	26.7	15.3	69.8	3.01	154.1	35.9	72.1	1.30	0.55				0.08
156578	15/10/2007	7.62	77	639	86.2	17.5	59.5	2.33	317.4	34.8	48.2	0.56	0.65				0.08
164085	12/04/1984	7.90	131	974	136.9	22.8	126.6	1.05	246.9	113.8	269.9	0.17	0.58				0.05
164085	30/04/1984	7.71	127	943	121.8	19.1	133.8	0.96	226.6	110.2	277.8	0.44	0.63				0.02
164085	07/11/2005	7.80	68	485	55.2	16.4	52.1	2.77	233.0	35.8	37.9	0.04	0.54				0.02
164892	17/12/1984	7.60	125	733	87.0	58.9	68.8	2.26	119.4	211.1	124.4	7.87	0.05				0.40
166259	02/02/1987	7.50	129	785	51.1	15.6	169.4	30.37	105.6	209.0	176.4	0.57	2.20				0.04
166259	24/02/1988	8.06	197	1158	140.0	78.1	116.5	1.91	250.3	282.7	214.5	4.21	0.56				0.04
166259	27/02/1990	7.90	195	1230	161.0	85.8	117.4	2.56	202.0	343.7	257.5	3.22	0.89				0.04
166259	13/03/1991	8.22	188	1320	171.1	84.0	117.2	2.31	293.4	335.0	239.4	2.82	0.55				0.02
166259	18/03/1992	8.24	183	1220	157.2	62.1	122.0	1.55	282.2	290.8	239.9	0.44	0.63				0.06
166613	01/03/1988	7.78	174	1153	121.6	7.9	242.9	1.66	145.8	222.4	375.1	0.44	1.67				0.02
166613	23/02/1989	7.43	193	1178	121.5	7.8	236.7	1.25	167.0	224.8	378.4	0.44	1.78				0.02
166613	26/02/1990	7.88	173	1186	111.4	9.6	255.7	1.62	156.0	234.8	380.7	0.39	0.54				0.02
166613	15/03/1991	8.16	141	1140	116.7	7.2	242.7	1.23	156.7	228.1	347.5	0.67	1.99				0.02
166613	19/03/1992	8.06	251	1758	189.9	95.2	260.1	1.20	224.5	579.0	351.4	1.46	0.46				0.06
166614	24/02/1988	8.34	211	1347	185.1	70.9	136.7	1.76	283.4	255.9	328.9	4.81	0.69				0.02
166614	27/02/1989	7.96	205	1392	182.1	72.3	132.3	1.79	321.6	245.3	342.9	5.18	0.59				0.07
166614	27/02/1990	7.81	177	1335	165.6	68.6	127.9	2.02	344.7	220.8	299.6	6.42	1.27				0.04

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
166614	16/03/1992	8.34	182	1284	160.3	68.0	127.3	1.48	338.9	215.7	276.0	4.91	0.60				0.06
166615	25/02/1988	8.06	154	987	118.1	43.1	134.2	1.08	188.8	242.1	212.9	1.05	0.41				0.04
166615	23/02/1989	6.61	113	620	23.7	36.4	139.9	1.84	52.1	244.4	109.1	0.24	0.22				0.16
166615	26/02/1990	7.33	99	536	24.3	21.6	133.4	1.71	17.6	256.1	76.8	0.08	0.11				0.02
166615	15/03/1991	8.18	78	459	19.6	14.7	129.9	1.31	18.8	256.9	12.2	0.18	0.31				0.04
166615	16/03/1992	8.10	116	628	37.2	31.6	129.4	1.26	45.3	255.6	116.7	0.05	0.31				0.40
166616	25/02/1988	4.45	135	637	80.8	27.4	112.6	2.66	5.4	400.9	4.0	0.09	0.15				1.29
166616	23/02/1989	7.43	357	2201	133.3	101.5	475.4	2.67	191.6	760.0	483.5	1.76	0.53				2.22
166616	26/02/1990	7.22	150	769	80.7	39.0	126.2	3.58	46.1	439.9	20.0	0.02	0.60				1.89
166616	16/03/1992	8.04	230	1350	215.0	61.9	148.8	0.95	170.7	463.9	250.8	0.02	0.24				0.06
166617	25/02/1988	8.43	213	1397	181.5	84.6	136.6	0.62	327.3	243.2	340.6	2.22	0.46				0.04
166617	23/02/1989	7.76	206	1390	162.8	82.7	132.9	0.77	320.5	239.3	370.6	2.25	0.45				0.08
166617	26/02/1990	7.93	156	1121	104.6	63.5	134.2	0.98	289.5	184.6	265.8	3.10	0.36				0.06
166617	12/03/1991	7.73	141	1145	111.8	68.3	135.7	0.72	305.3	185.8	257.3	2.88	0.67				0.02
166617	16/03/1992	8.31	175	1284	155.3	70.0	132.6	0.64	375.1	184.8	268.0	3.30	0.52				0.06
166617	07/11/2005	7.61	119	867	72.0	49.1	113.1	0.82	266.8	124.7	172.8	1.99	0.36				0.02
166618	26/02/1988	8.06	134	881	106.0	16.9	149.9	1.53	185.5	166.1	213.7	0.06	0.57				0.02
166618	24/02/1989	7.67	132	936	114.1	20.5	146.2	1.56	205.6	167.5	233.5	0.23	0.52				0.02
166618	27/02/1990	7.87	128	942	115.3	28.0	124.9	2.14	241.2	176.4	200.7	0.12	0.34				0.04
166618	15/03/1991	8.27	128	938	119.2	21.7	144.4	1.34	203.8	189.8	211.5	0.15	0.56				0.02
166618	17/03/1992	8.18	126	918	120.4	22.7	127.7	1.33	223.2	175.5	197.9	0.02	0.46				0.06
166619	26/02/1988	7.78	95	554	13.5	37.0	111.1	3.97	163.3	168.4	14.8	1.26	0.25				0.49
166619	27/02/1989	7.58	98	625	19.6	40.5	112.4	8.28	202.6	176.5	2.0	4.06	0.27				0.05
166619	27/02/1990	7.56	96	661	21.5	41.5	112.4	8.46	210.6	179.2	5.4	7.71	1.32				0.04
166619	15/03/1991	8.15	121	856	83.2	45.3	110.3	2.44	223.2	184.5	138.5	4.25	0.48				0.02
166619	17/03/1992	8.08	141	990	98.1	56.1	120.9	0.60	246.5	204.1	194.5	3.18	0.58				0.04

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
166619	19/03/1992	8.24	161	1166	125.4	5.9	244.8	1.11	162.2	225.8	361.5	0.35	1.81				0.04
166620	26/02/1988	7.69	113	644	62.6	34.8	101.9	2.47	124.0	212.3	74.2	0.92	0.42				0.02
166620	27/02/1989	7.79	135	931	112.8	45.1	103.0	2.28	222.1	198.2	179.5	4.21	0.61				0.04
166620	27/02/1990	7.93	144	1020	134.8	48.7	104.8	2.81	253.8	189.8	198.0	6.90	0.56				0.02
166620	13/03/1991	8.27	136	946	117.3	47.7	96.6	1.88	249.8	174.8	178.8	5.41	0.66				0.02
166620	17/03/1992	8.27	124	998	131.1	43.6	101.6	2.23	273.8	168.6	191.6	5.60	0.77				0.06
166621	26/02/1988	8.01	101	683	90.3	7.4	108.8	1.16	197.4	100.7	125.4	1.82	0.49				0.04
166621	27/02/1989	7.79	125	888	115.0	31.1	106.1	1.52	238.9	151.9	172.3	4.21	0.56				0.02
166621	27/02/1990	8.14	119	917	115.7	32.8	107.8	1.83	260.0	150.3	170.3	4.59	0.53				0.02
166621	13/03/1991	8.19	99	713	95.4	9.5	106.2	1.17	209.5	107.5	128.4	1.98	0.56				0.02
166621	17/03/1992	8.08	112	783	110.5	9.8	108.7	1.33	205.2	140.9	151.7	2.13	0.48				0.05
166622	26/02/1988	8.11	157	1067	138.3	54.0	116.0	0.93	248.0	201.4	222.6	6.88	0.62				0.02
166622	27/02/1989	7.87	154	1123	142.0	59.5	107.7	1.20	287.7	215.1	214.8	7.15	0.57				0.06
166622	27/02/1990	8.06	159	1187	144.9	67.2	112.1	1.57	317.2	219.1	224.6	6.70	0.39				0.02
166622	13/03/1991	8.09	291	2238	244.0	28.1	399.6	2.38	157.7	248.5	1109.4	2.73	1.94				0.02
166622	17/03/1992	8.31	173	1165	142.3	64.4	111.9	1.01	308.7	215.7	226.0	5.93	0.45				0.06
166623	29/02/1988	7.74	160	1073	132.3	13.8	192.1	1.56	142.1	190.7	366.8	0.46	0.77				0.02
166623	24/02/1989	7.67	133	1002	125.5	21.2	139.8	3.81	227.3	96.2	331.0	1.36	0.77				0.04
166623	27/02/1990	7.80	114	848	63.0	14.5	168.4	2.25	210.0	120.1	219.9	0.55	0.55				0.06
166623	14/03/1991	8.28	116	833	71.8	10.7	170.7	1.36	182.9	116.2	237.5	0.10	0.89				0.02
166623	18/03/1992	7.85	514	4751	559.9	14.3	945.0	3.27	67.9	427.8	2713.8	0.09	3.48				0.06
166624	29/02/1988	8.01	284	1525	194.1	86.1	206.7	12.44	148.5	701.6	121.2	4.85	0.51				0.04
166624	24/02/1989	7.52	241	1312	77.3	56.1	286.4	6.33	183.8	581.9	72.1	1.51	0.57				0.08
166624	26/02/1990	7.95	224	1258	85.2	62.4	270.8	6.44	154.7	564.6	78.4	0.07	1.61				0.04
166624	14/03/1991	8.34	258	1502	173.2	81.3	203.9	11.75	166.9	680.6	118.1	6.48	0.55				0.02
166624	19/03/1992	8.30	240	1508	175.7	82.0	205.0	12.12	186.9	669.3	110.5	5.54	0.66				0.07

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
166625	29/02/1988	8.29	943	6193	174.3	336.0	1520.3	0.15	332.7	1753.0	1990.9	2.63	1.39				0.02
166625	23/02/1989	7.90	618	3756	136.1	174.0	889.9	1.93	287.7	1184.9	999.5	3.79	1.00				1.13
166625	26/02/1990	8.13	747	5545	119.3	276.4	1423.6	4.76	348.0	1530.8	1751.3	3.05	0.55				0.02
166625	14/03/1991	8.34	633		162.5	258.9	1324.7	3.75	596.0	1513.6	1551.2	2.27	1.75				0.02
166625	19/03/1992	8.50	732	5778	127.2	249.6	1427.2	3.33	667.7	1532.3	1607.8	3.33	1.49				0.08
166627	04/03/1988	8.11	86	578	50.9	23.0	81.4	7.47	235.5	59.8	44.2	5.32	0.57				0.05
166627	24/02/1989	7.84	83	613	55.1	24.0	79.3	7.57	259.4	61.4	45.6	5.20	0.56				0.02
166627	27/02/1990	7.84	78	639	48.8	24.3	84.6	8.01	275.0	60.9	49.8	5.58	1.34				0.43
166627	14/03/1991	8.10	76	592	51.6	22.8	79.3	7.68	256.4	56.6	38.6	5.10	0.54				0.02
166627	18/03/1992	8.29	110	856	75.3	9.6	175.2	1.14	182.5	116.4	254.0	0.02	1.23				0.02
169759	09/06/1992	8.10	146	889	70.4	45.7	144.1	2.56	193.6	255.0	125.7	1.98	0.52				0.02
170306	01/02/1993	1.00	3840	5497	132.6	42.1	142.1	9.58	2.0	4503.3	666.3	0.04	0.84				0.12
170306	07/11/2005	7.43	123	889	101.2	42.0	103.9	2.63	219.2	155.6	197.2	4.33	0.56				0.02
170306	15/10/2007	7.60	65	417	46.6	9.4	72.0	1.06	70.5	72.1	127.2	0.22	1.17				0.08
200000227	26/06/2001	8.54	124	952	19.8	36.9	199.4	2.84	353.2	77.0	178.5	1.15	2.09				0.06
1000005307	08/09/2003	7.60	199	1356	104.2	48.5	237.9	3.80	407.1	262.5	192.5	2.18	0.76				0.02
1000005309	08/09/2003	7.70	31	214	24.3	7.6	20.4	1.36	98.9	17.0	13.1	2.07	0.32				0.02
1000005311	08/09/2003	7.61	128	938	107.7	28.2	136.0	1.49	318.4	176.8	96.9	0.43	0.71				0.02
1000005313	08/09/2003	7.77	108	761	87.1	14.2	113.1	2.92	288.0	86.8	93.5	2.44	0.90				0.02
1000005315	09/09/2003	7.68	73	543	66.3	15.9	60.6	1.63	236.4	49.4	54.5	1.37	0.53				0.04
1000005317	09/09/2003	7.79	91	682	62.1	5.8	123.7	2.28	266.6	63.2	98.0	0.11	1.21				0.07
1000005319	09/09/2003	7.44	157	1001	146.7	16.6	145.7	1.77	241.3	241.7	117.4	8.20	0.49				0.02
1000005321	09/09/2003	7.84	98	743	91.3	17.3	104.7	2.03	282.9	100.8	75.5	1.33	0.81				0.02
1000005323	09/09/2003	7.61	93	678	76.9	18.1	90.0	1.19	254.0	104.8	69.4	1.52	0.66				0.02
1000005325	09/09/2003	7.93	89	680	80.7	15.5	82.3	1.78	291.6	66.5	72.2	1.07	0.70				0.02
1000005327	09/09/2003	7.52	82	648	77.7	13.8	87.1	3.11	286.8	49.6	59.3	1.63	0.72				0.02

Site Name	Date	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	ALK mg/l	Cl mg/l	SO_4 mg/l	NO_3 mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	NH_4 mg/l
1000011055	08/11/2005	7.78	21	139	15.9	5.3	12.0	0.53	68.5	7.0	9.7	1.11	0.19				0.02
1000011055	07/11/2006	7.87	25	196	25.3	7.9	19.2	0.56	93.4	7.0	21.9	0.04	0.17				0.11
1000011055	15/10/2007	7.42	102	754	71.9	28.4	113.8	0.58	244.4	94.6	145.6	0.11	0.60				0.08
1000011055	16/10/2007	7.21	27	190	24.7	8.1	14.1	0.36	96.6	7.2	17.0	0.11	0.22				0.06
1000259865	07/11/2006	7.92	93	685	54.7	20.4	120.7	2.28	239.5	85.5	107.6	0.21	0.68				0.08

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