QUANTIFICATION OF THE IMPACT OF IRRIGATION ON THE AQUIFER UNDERLYING THE VAALHARTS IRRIGATION SCHEME

By

RG Ellington

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Institute for Groundwater Studies
University of the Free State

Supervisor: Dr BH Usher

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Table of Contents:

Table of Figures:

Table of Tables:

1 INTRODUCTION

1.1 INTRODUCTION AND SCOPE OF INVESTIGATION

Irrigated land in South Africa currently amounts to approximately 1.3 million hectares. Agricultural water use is estimated to comprise the largest amount of water users in Southern Africa, with much of the region dependent on sufficient water of adequate quality for survival. The Vaalharts is the largest irrigation scheme in South Africa. Approximately 32 000 hectares of land is currently being irrigated. The salinity of the irrigated water has steadily increased over time (Herold and Bailey, 1996). Several research projects have been undertaken to determine the fate of added salts. The conclusion in these reports is that a very large proportion of the salts added to the subsurface due to irrigation are not returned to the surface water. A sink for these salts is therefore believed present. Research into the salt balance of the area and the effect of the salts on soils and crops have suggested that the majority of this salt is being leached through the soil and into the groundwater resources underlying the irrigated area. The underlying aquifer was believed to have a limited storage capacity. Once this capacity is exceeded, a flow reversal is expected. This process is likely to add a tremendous salt load (roughly estimated to be in the order of 100000t/annum (Herold and Bailey, 1996)) to an already stressed river system. The adverse effects of such an addition would be catastrophic to the irrigation scheme and the receiving aquatic environment. This thesis aims to determine the processes leading to the scenario outlined above.

1.2 AIMS

The aims of the thesis are the:

- Description of Vaalharts aquifer
- Determination of the Vaalharts aquifer characteristics
- Construction of a suitable conceptual model for the Vaalharts area
- Determination of water and salt balance for the Vaalharts Irrigation Scheme
- Determination of the impact of irrigation on the aquifer underlying the Vaalharts Irrigation Scheme

The major aim of this initiative is to answer the questions that previous reports involving the Vaalharts Irrigation Scheme raised. These reports involve the long-term salt balance, including the quantification of the aquifer at the Vaalharts Irrigation Scheme. In order to answer such broad questions, certain, more direct aims need to be addressed.

The first of these aims was the construction of a feasible conceptual model for the groundwater flow in the Vaalharts area. Once this has been adequately established, the groundwater response to irrigation in the Vaalharts Irrigation Scheme can be understood. In order for this to be attainable, a full understanding of the aquifer properties in the Vaalharts area needs to be gained.

In achieving this goal, a better understanding of the mechanics of salt migration in the Vaalharts Irrigation Scheme is possible. Once the mechanics of the groundwater and the salts are understood, the location of the salts, together with hypotheses structured by previous reports such as "The Long-Term Salt Balance of the Vaalharts Irrigation Scheme" by Herold and Bailey (1996) can be tested.

Figure 1 Diagram illustrating a pivot at the Vaalharts Irrigation Scheme

The following aim in this initiative is to conduct a complete water and mass balance for the Vaalharts Irrigation Scheme, involving the groundwater component and the role that this plays in the salinity of the Vaalharts system. These water and mass balances would also include the surface water contributions of the Vaal River and Harts River.

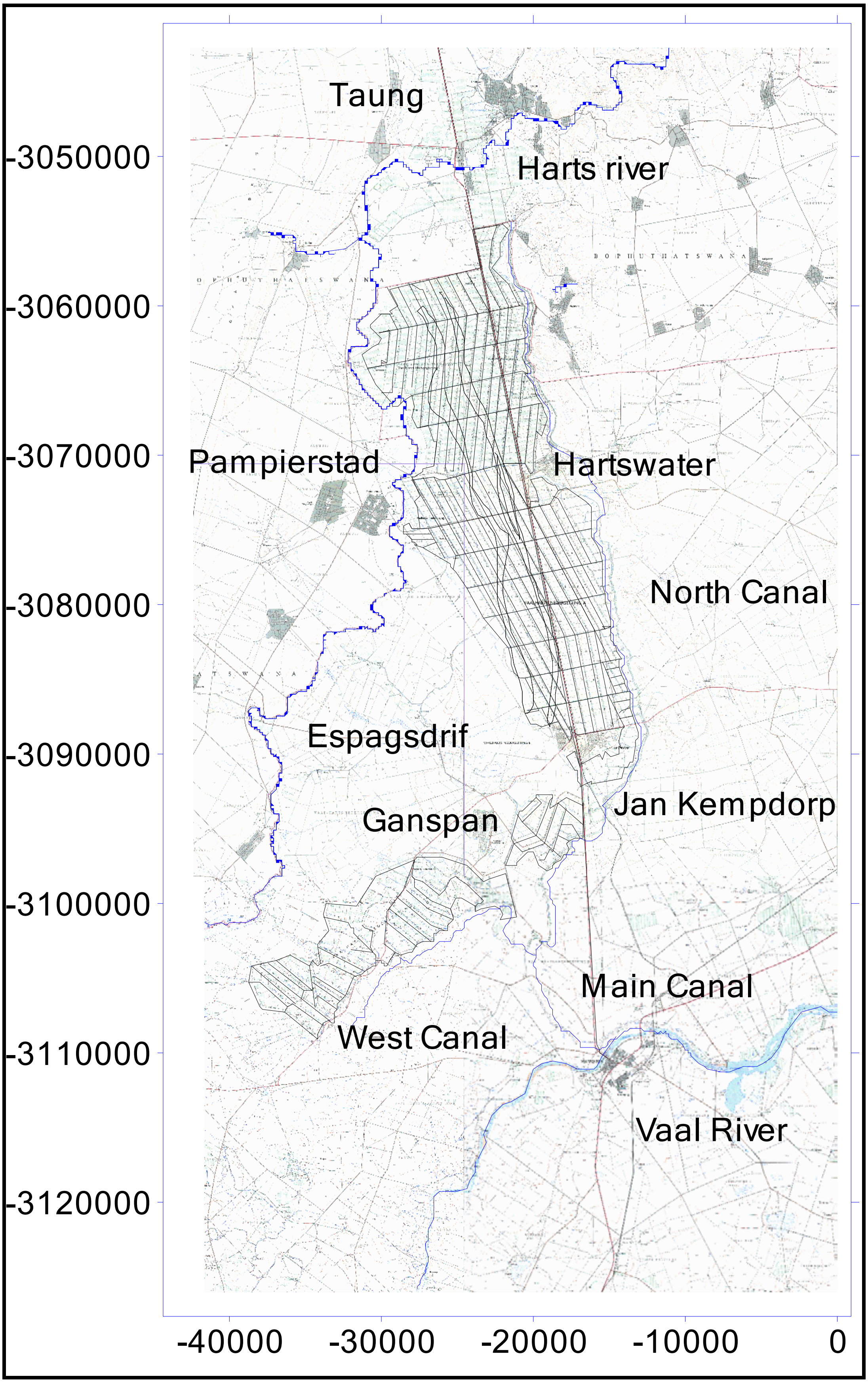


Figure 2: Map of the Vaalharts investigation area.

1.3 MOTIVATION FOR PROJECT

As mentioned, the Vaalharts Irrigation Scheme is the largest in South Africa, with approximately 32000ha currently being irrigated. This fact, combined with the fact that the salinity of the irrigation land has been increasing steadily over time, has prompted several research projects.

These research projects have studied the fate of the salts, with the conclusion that the majority of the salts added to the irrigation lands, have not been returned to the surface waters. This has led to the conclusion that the salts have been added to the groundwater. Water balances have suggested that the salts are being leached through the soils and into the groundwater resources below the irrigation area.

Figure 3: Illustration of the salts at the surface in the Ganspan area of Vaalharts (2002)

The expected problem from this leaching hypothesis is that the aquifer has a limited storage capacity. Once this storage capacity has been reached, an expected flow reversal of the salts to the surface is expected. This flow reversal is expected to return an approximate 100000t of salts per annum to an already stressed river system (Herold and Bailey, 1996). The effects of such an addition would be disastrous to the irrigation systems relying on the lower Vaal River.

1.4 METHODOLOGY

The project aimed to investigate the processes affecting the possible future groundwater flow reversal that was indicated by Herold and Bailey in 1996. These processes involve the geohydrology and related geology of the Vaalharts area, believed to be the salt sink in this equation.

The project investigated the rate of leakage from the irrigation soils and calcretes believed to be present in the Vaalharts basin through to the aquifer. The storage capacity of this aquifer also needed to be investigated, along with the possible salt load.

The groundwater was accessed in order to study the geohydrology of the aquifer. The project required the installation of in order to investigate the various aquifers separately. Combined with accessing the geohydrology, certain aquifer parameters needed investigation by means of conducting pump tests and slug tests.

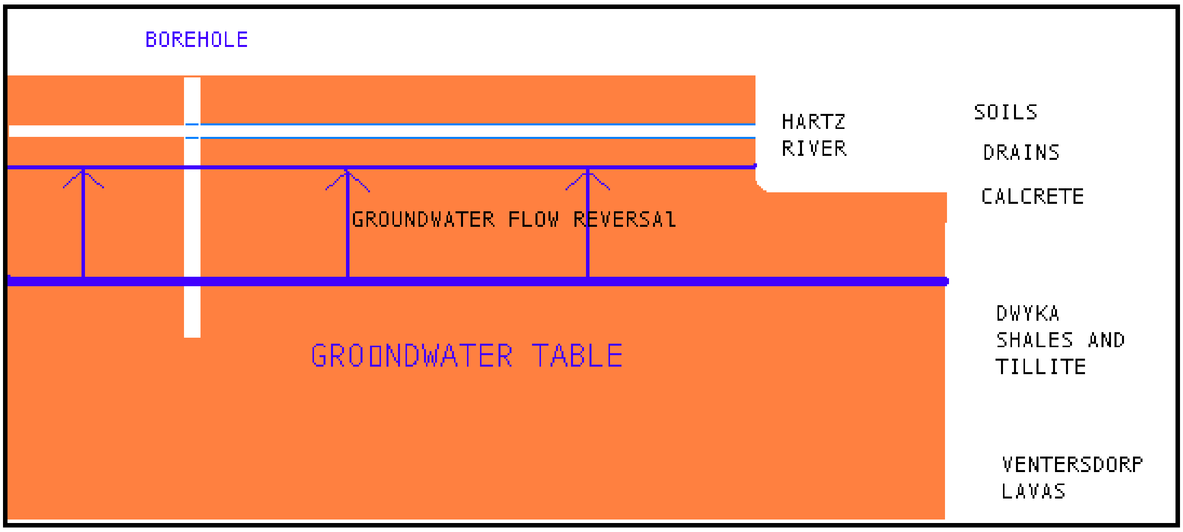


Figure 4: Diagram illustrating the conceptual idea surrounding the salts' flow reversal

The water levels needed to be measured over a period of time in order to understand the processes taking place within the aquifer. Combined with the collection of chemical data, hydrochemical profiling needed to be investigated across the Vaalharts Irrigation Scheme in order to gain a full understanding of the hydrochemistry.

From this information, viable conceptual models were constructed. Numerical modelling is vital in order to test different scenarios using simplified numerical models and empirical solutions.

The methodology steps are listed as follows:

- Literature and background information study
- Field reconnaissance
- Drilling of new boreholes and installation of piezometers
- Hydraulic testing of aquifer parameters
- Water level measurements
- Hydrochemical measurements
- Conceptual modelling of various test scenarios using simplified numerical models / empirical calculations
- Evaluation of magnitude of future impact

2 DESCRIPTION OF THE VAALHARTS IRRIGATION AREA

2.1 HISTORICAL OVERVIEW OF THE VAALHARTS IRRIGATION SCHEME

The initial movements towards an irrigation scheme in the Vaalharts began in 1881 – 1882 when Cecil John Rhodes, Prime Minister of the Cape Colony at the time, received the findings of the Irrigation Engineer. The Irrigation Engineer had surveyed the Cape Province for a suitable irrigation area (Herold and Bailey, 1996).

A soil survey that began in 1932, found that 36000ha of a possible 74000ha in the Vaalharts area was suitable for irrigation (Van Garderen, Louw and Rosenstrauch, 1934). The Vaalharts Government Water Scheme followed in 1933. The first irrigation plots were situated along the North Canal area, beginning at Jan Kempdorp in 1938, and moved in a northerly direction along the North Canal (Kriel, 1976). The North Canal section, stretching from Jan Kempdorp to Hartswater was completed in 1945. The West Canal area began development in the 1950's, with the first plots being allocated in 1957, while the last plots were allocated in 1966.

In the 1950's, it was found that farmers in this area took approximately three years to make full use of their plots, while from the 1960's onwards, it has taken approximately one year to fully utilise their land (Visser, 1992).

In the Vaalharts Irrigation Scheme, natural drainage has been found to be poor. This is attributable to the flat topographical gradient, and typical soil profiles found in the area. The upper, generally impermeable calcretes are found at depths varying between 0m and 5m (Gombar and Erasmus, 1976). According to Streutker (1977) the water table was found to be lying at approximately 24 metres below ground level (mbgl) for the period between 1935 and 1940, although it seems that no comprehensive borehole drilling to determine the water levels in the irrigation area were undertaken across the entire scheme (Herold and Bailey, 1996). No extensive measurement of the water levels seems to have been undertaken during the period of 1940's to 1970's. Streutker measured the water level in the Vaalharts Irrigation Scheme at approximately 1mbgl during the 1970's. An above-average rainfall in the years 1974, 1975 and 1976 seemed to contribute to waterlogging and a resultant severe loss in crop production across the Vaalharts Irrigation Scheme (Streutker, 1977). Localised waterlogging had occurred previously due to a so-called perched water table.

To combat waterlogging, a comprehensive network of 240 subsurface drains was installed between the years 1976 and 1979 at an approximate depth of 1.8mbgl. The drains were found to successfully control the water table, and in so doing, improve the crop yields. In 1976, prior to the drains' installation, approximately 3000ha of soils were saline or saline-sodic to a depth of 0.3mbgl. By the end of 1977, this had been reduced to approximately 1500ha, while in 1980; there remained approximately 1000ha of salt-affected soils (Herold and Bailey, 1996).

The irrigation canals, irrigation systems and internal and external drains have all seen improvements since 1971, resulting in a decrease of salt leaching (Herold and Bailey, 1996). Due to regular maintenance, and the elimination of trees on the banks of the canals, canal leakage decreased (Herold and Bailey, 1996). Correct manipulation of flow rate, length, width and slope of beds all resulted in a high irrigation efficiency (Streutker, 1977). Streutker didn't mention the degree of irrigation efficiency.

2.2 VAALHARTS-SPECIFIC LITERATURE

Much literature has been gathered and studied during the background analysis into this thesis. This literature comprises both hardcopy, and electronic texts. The information studied dealt with many different aspects of the Vaalharts problem.

Topics covered included fertilizers; groundwater modelling in similar situations; similar problems in other countries with general build-up of salts, and associated drop in water quality and crop production; water balance modelling with similar subsurface pipe drainage; soil and salt balances; crop water balances; the relation between geohydrology and agriculture and non-point source pollution problems.

This literature has been used in the construction of the Vaalharts conceptual model.

2.2.1 LONG TERM SALT BALANCE OF THE VAALHARTS IRRIGATION SCHEME

2.2.1.1 Background

Herold and Bailey published 'Long Term Salt Balance of the Vaalharts Irrigation Scheme' as a report to the Water Research Commission in 1996. The report dealt with the difference between the salts that have been applied to the irrigation area, and those measured in the surface waters. The initial reason for conducting the study was the fact that large-scale urban, industrial and mining developments in the Vaal River Catchment led to salinisation of the water supply to the Vaalharts Irrigation Scheme (Herold and Bailey, 1996).

Herold and Bailey constructed and calibrated a hydro-salinity simulation model and used this to complete the missing information regarding the historical flow and water quality records. The model was also used to simulate the long-term behaviour of the Vaalharts system. The results of this model confirmed to the researchers that the Vaalharts aquifer was acting as a salt sink that had accumulated approximately 66% of the total dissolved salts contained in the irrigation water since its commissioning in the 1930's. This equates to an annual load of 100000t (Herold and Bailey, 1996).

Herold and Bailey began working on the hypothesis that the water had been percolating slowly from the semi-pervious calcrete layer to a deeper aquifer, where the salts were being stored. The authors believed that, although there were limited groundwater data for the Vaalharts area, the available data supported their hypothesis.

The return flow that Herold and Bailey expected to occur would add an additional 100000t/annum to the Harts River. This would place additional stress on the downstream river system, have an effect on the downstream irrigation areas such as the Orange-Riet system (Du Preez *et al*, 2000).

The research found that the complete effect of the drainage system on the TDS load was inconclusive. The drains were installed from the 1970's through to the 1980's in approximately 40% of the irrigated lands (Herold and Bailey, 1996). Drains are still being installed to this day. The research also suggested that the long-term influence of the rainfall fluctuations had a greater effect on the irrigation return flow volume and the TDS load than the drainage system.

2.2.1.2 Calibration

2.2.1.2.1 Upper Harts Subsystem

Herold and Bailey decided upon using the Schweizer-Reneke Dam (Wentzel Dam) and the area immediately downstream from that for the Upper Harts sub-system to calibrate the hydrosalinity model. Their model also accounted for the urban abstractions from the Wentzel Dam. In the catchment, a salt wash-off sub-model only areas contributing to runoff were used, while all areas that were not contributing to runoff were excluded from use in this model (Herold and Bailey, 1996).

The areas surrounding the Wentzel Dam used flood irrigation as an irrigation method, while the areas near to the Bloemhof Dam began to use sprinkler, centre-pivot and drip irrigation practices. These irrigation practices illustrate varying irrigation efficiencies and return flow factors (Herold and Bailey, 1996). The flood irrigation, for instance, uses a larger volume of water than pivot irrigation.

Herold and Bailey obtained a relatively good fit between their observed and modelled monthly TDS loads, although, by their own account, the period of comparison was relatively short. They believed that the TDS concentrations were not as good as the TDS load comparisons; due to differences that occurred during low flow conditions. This was expected to be due to the semi-arid catchment flow generally coming to a halt during the winter months, when almost no rainfall occurs (Herold and Bailey, 1996).

2.2.1.2.2 Middle Harts Subsystem

Herold and Bailey used the area surrounding the Vaalharts Irrigation Scheme for their Middle Harts sub-system. This area included the North and West Canals, the three gauges, namely C3H007 (Espagsdrif), C3R002 (Spitskop Dam) and C3H013 (Lloyds). They also used two salt wash-off sub-models. They again only used the effective catchment areas that illustrated effective runoff.

In the irrigation sub-model RR11; only the flow was calibrated, as there was no observed TDS measurement. RR11 and RR12 are part divisions of the Upper Harts catchment. The hydro-salinity model, WQT, was modified so that growth in return flow and efficiency could be incorporated into the irrigation sub-model. It was necessary to make this adjustment due to the drains that were installed from 1976 until 1979, and then, as a result of the drought, were plugged from 1983 until 1986. It was found that the observed and modelled TDS concentrations were very similar. They also found that the modelled TDS concentrations fell quite steeply after the flood events in 1975 and 1988.

Insufficient data were available for the West Canal, forcing the modelled data to be negligible. Only the floods were recorded for 1975 and 1988. The return flows were twice those for the North Canal due to lesser return flows in the West Canal.

Herold and Bailey found certain inconsistencies between the modelled and observed data, although with the more important stations C3H003 and C3R002 there was a relatively good correlation between the modelled and observed values. This fact gave good weighting to the data obtained by the model to complete the missing data in the flow data, return flow data and TDS data.

2.2.1.3 CONCLUSIONS

Herold and Bailey were unable to gain certain information relating to their study. This information included data on crops and areas under irrigation that had to be interpolated and extrapolated. They simulated missing water supply quality data from before the 1970's by using their Vaal River model. They used the hydro-salinity water quality model WQT to calibrate for both the Upper and Middle Harts Catchments. They calibrated these models up to, and including the year 2030. Herold and Bailey did not expect a good correlation between the observed and modelled values. The relation between these values was however sufficient for a reasonable approximation.

The investigation made estimates of the amount of water percolating through to the groundwater by subtracting the calculated annual return flows to the Harts River from the estimated total irrigation losses. The results that Herold and Bailey achieved ranged from 33 x $10^6 m^3$ to 63 x $10^6 m^3$ per annum. This large range in results was attributed to the type of calculation made.

While investigating the possible groundwater storage of the geology in the North Canal area, the researchers hypothesised two possibilities. The first hypothesis was that the calcretes were sufficiently porous to allow percolation to a deeper aquifer, and the second was that the calcretes were sufficiently impermeable to hinder percolation to a deeper aquifer. They did not investigate the storage directly, and concluded that further investigation would be necessary.

In studying the model calibration, Herold and Bailey concluded that 66% of the salts had not been accounted for in their salt and water balances, and assumed that these salts had moved into the groundwater. In a previous investigation, completed by Herold and Muller, it was concluded that 80% of the salts had been unaccounted for, based upon the data available to them, up to the end of September 1984 (Stewart *et al*, 1987). Although their values vary, both reports concluded that the groundwater had 'accepted' the salts (Herold and Bailey, 1996).

In concluding their research on the long-term salt balance of the Vaalharts, Herold and Bailey (1996) predicted the future TDS balance. They illustrated two possible options. The first was continuing with current conditions until the year 2030, when the groundwater would be expected to have an accumulated TDS load of 60%. The second option assumed that irrigation practices would improve and included increased water allocations, and predicted a TDS load of 59% in the groundwater.

In their conclusions, Herold and Bailey (1996) also believed that the subsurface drains had little effect upon the return flows. It was believed that the wet and dry hydrological years had a greater effect. Extraneous factors such as excessive irrigational practices, water restrictions and plugging of drains during drought also had a greater effect upon irrigational return flows than the subsurface drains.

2.2.2 THE DISA HYDROSALINITY MODEL

Gorgens, Jonker and Beuster of the Department of Civil Engineering at the University of Stellenbosch developed the DISA hydro-salinity model. The model was applied to the Vaalharts Irrigation Scheme as a part of its eventual refinement (Gorgens *et al*, 2001). The reason for this application was that the DISA model needed to be applied to a summer rainfall region, and had only previously been applied to a winter rainfall region in the Breede River irrigation scheme. The developers of the model were looking at certain processes such as surface runoff, deep percolation and artificial drainage.

The Vaalharts Scheme was used for external verification of the DISA model. They considered a period of five seasons enough for full verification. The period used was October 1988 until April 1991: a period of three summer seasons and two winter seasons.

In this evaluation of the DISA model; the model underestimated the salt concentrations, while simultaneously overestimating the flow conditions. Various possible reasons were considered for this error. One of these possibilities was that the salts were leaching to a deeper aquifer, as previously hypothesised by Herold and Bailey (1996). Another possibility of this error in the model's results was that there was an incorrect simulation of artificial drainage.

The researchers eventually concluded that the phenomenon could be attributed to the fact that the simulated volume of tailwater, described as water not abstracted from the canals for irrigation, which enters the Harts River, was too great. The relatively low TDS concentration was affecting the final TDS measured further down the Harts River. The reason for these high volumes of tailwater entering the Harts River was attributed to incorrect monthly irrigation supply water distribution.

2.3 GEOLOGY

2.3.1 INTRODUCTION

The Hartswater Group Lithostratigraphy:

Rocks of the Bothaville Formation unconformably overlie the Hartswater Group, and is best developed near the towns Hartswater and Taung. The distribution of the Hartswater Group can be seen in Figure 5 below. The Hartswater Group is comprised of two formations, namely the lower Mhole Formation and the upper Phokwane Formation. The names given to these formations have been derived from the tributaries of the Harts River (Kent and de Grys, 1980).

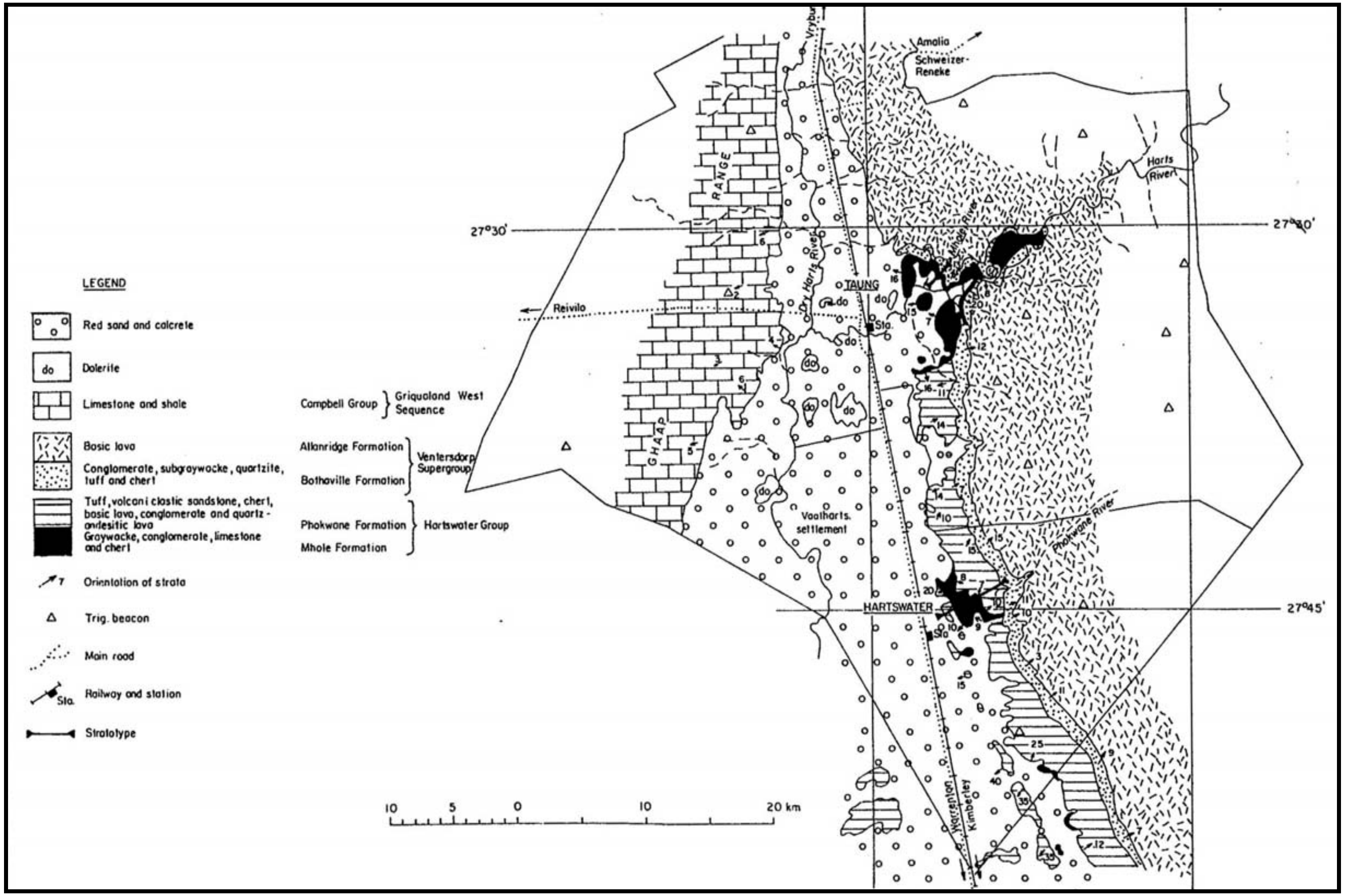


Figure 5: Geology of the Hartswater Group

The lower Mhole Formation has a maximum thickness of 120m. It is comprised of a granite-pebble conglomerate overlain by an alternating succession of tuffaceous sediments, arkose and chert with locally developed lenses of stromatolitic limestone (Kent and de Grys, 1980). In the Taung area, the succession can be further developed into conglomerates and overlying sediments. The overlying sediments seem to pinch out in the south towards Hartswater with the conglomerate present in the Hartswater area (Kent and de Grys, 1980).

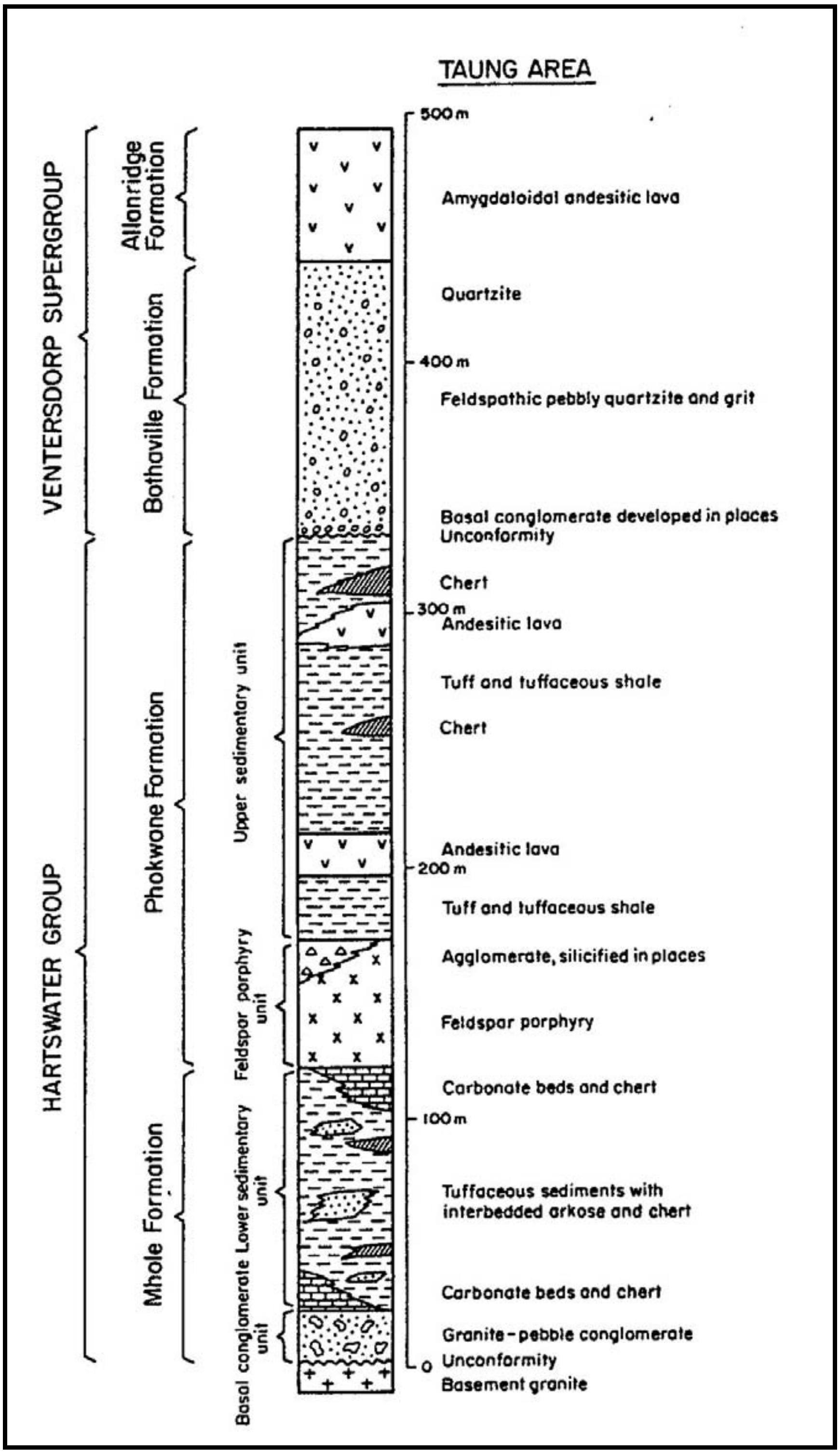


Figure 6: Lithostratigraphy for the Taung area of the Hartswater Group

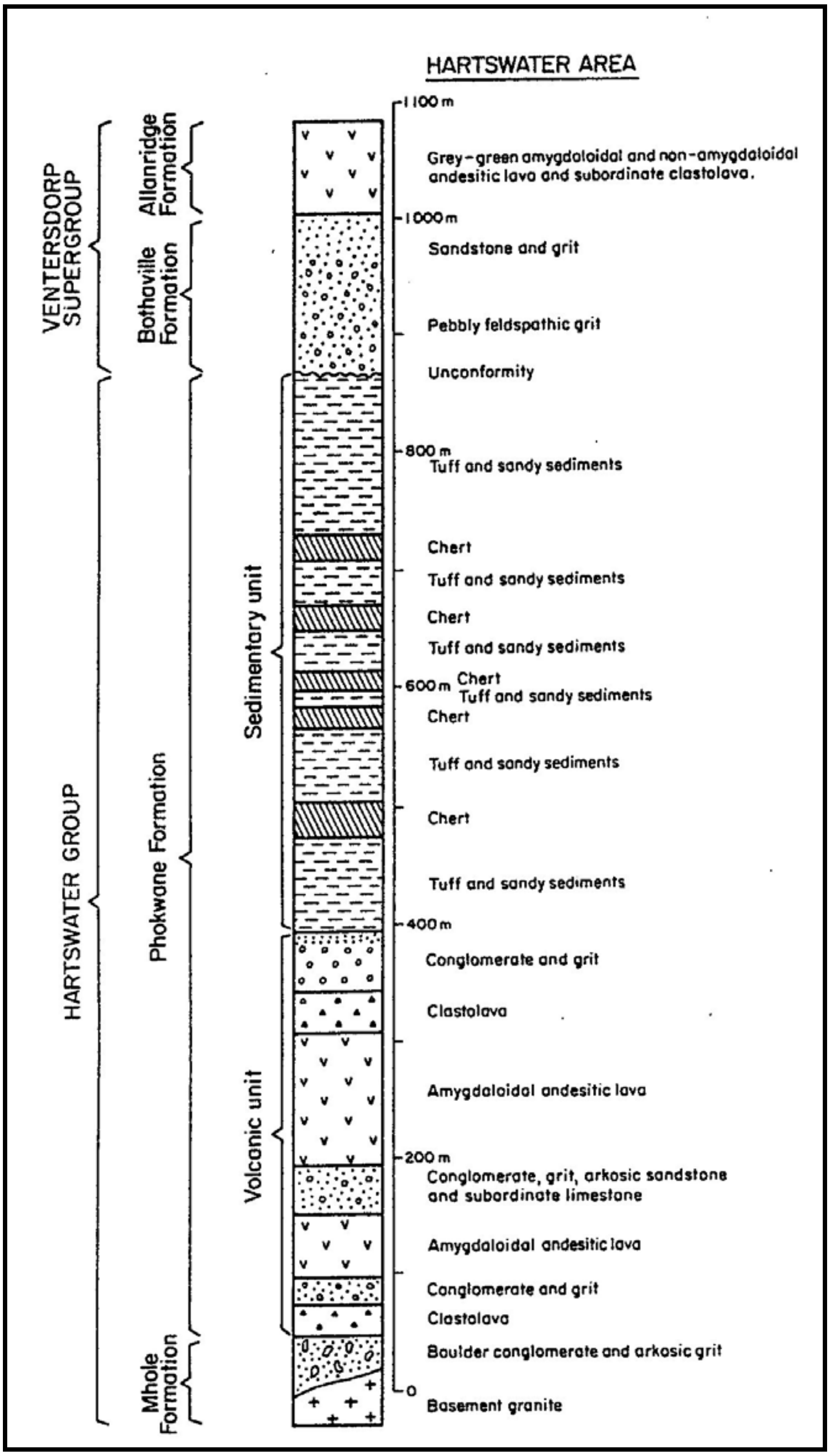


Figure 7: Lithostratigraphy for the Hartswater area of the Hartswater Group

The upper Phokwane Formation lies conformably on the top of the Mhole Formation, and comprises alternating successions of volcanic and sedimentary materials that can be divided into two discrete units. In the Taung area, the Formation commences at the base with quartz-feldspar porphyry with occasional well-developed flow banding. This is overlain by tuff and tuffaceous shale together with layers of andesites and cherts (Kent and de Grys, 1980). In the Hartswater area, the geology is very similar to that in the Taung area, although the feldspar porphyry is replaced by interbedded conglomerates and grit, in addition to sandy sediments (Kent and de Grys, 1980).

A marked conformity separates the Phokwane Formation from the Bothaville Formation in both areas, with the Bothaville Formation comprising an upward-fining succession of conglomerate, pebbly feldspathic grit, sandstone and quartzite, overlain by a monotonous succession of amygdaloidal andesite lavas (Kent and de Grys, 1980).

2.3.2 VAALHARTS IRRIGATION SETTLEMENT (GEOLOGICAL SETTLEMENT)

The report discussed the geology of the Vaalharts area and was compiled by Temperley in 1967. Temperley differentiated between the Harts River system and the Dry Harts River system. The Vaalharts, as we know the area, is fed by the Harts River, while the Dry Harts River feeds the irrigation scheme to the north of Taung. Temperley therefore refers to the two systems as the combined Harts-Dry Harts Valley.

2.3.2.1 Soil

The soils in the area are said to be “exceptional” as they are described as being Kalahari sand. A normal feature of the Kalahari sands in this area, in the Harts-Dry Harts Valley is that there is a stratum of calcrete, described by Van der Merwe in personal communication to Temperley, as a B-horizon of the Kalahari sands in this area. Temperley believes that the calcretes developed in a peculiar manner, in that they developed from below, and not from above as usual. Temperley believes that developed by ‘deposition from soil water that moved upwards under capillarity from slightly calcareous rock and subsoil below’ (Temperley, 1967). It was further believed that the waterlogging that occurred in the area is a result of the characteristics of the Kalahari sands and associated calcretes in the area.

2.3.2.2 Geological Structure

2.3.2.2.1 Geological Structure of the Valley

The Harts – Dry Harts (HDH) Valley runs in a north – south direction due to the fact that the majority of formational boundaries and structural lines such as faults run in the same direction, while the regional dip is low and in a mainly westerly direction.

The HDH valley was excavated from pre – Karoo rocks during pre – Karoo times and because of the fact that the Valley lies just north of the main Karoo outcrop, the Dwyka series has been preserved. The Dwyka is now confined to the valley pediments (Temperley, 1967). The Dwyka is apparently thickest between the two Valley slopes, and thins out towards these slopes. According to Temperley, Ventersdorp lavas form the upper eastern Valley sides, while dolomites form the upper western valley sides.

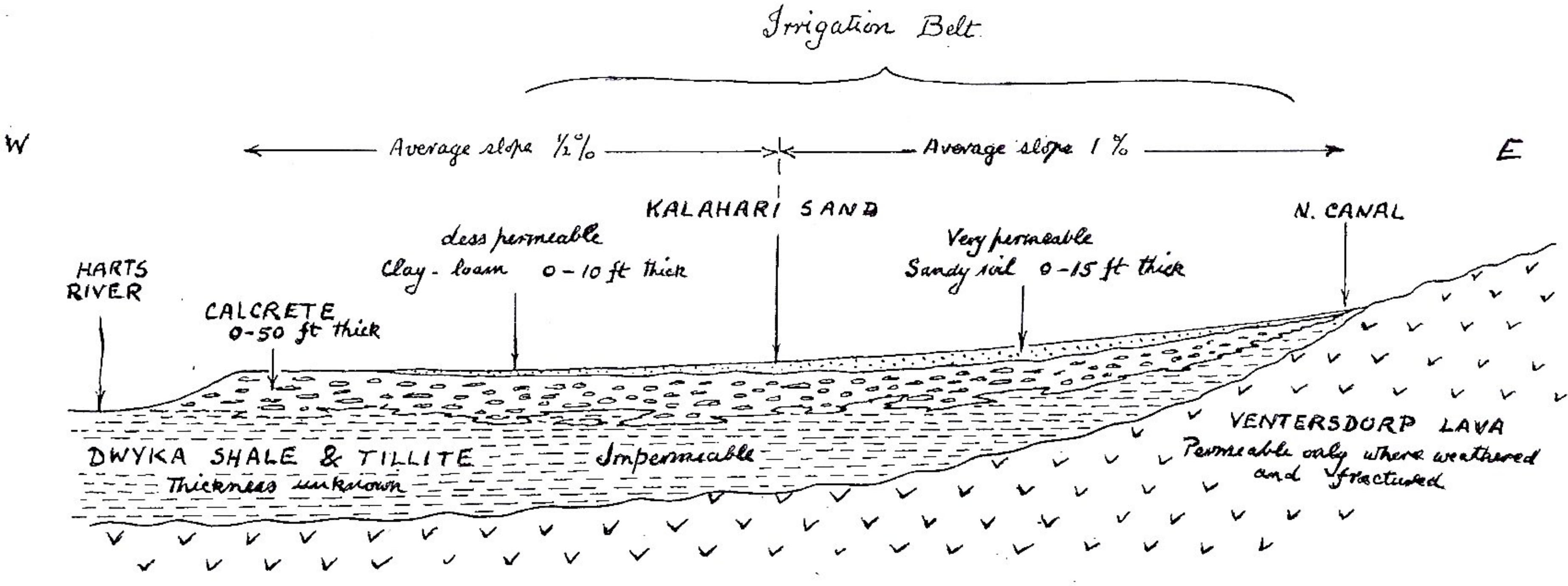


Fig. 5. Geological section across the North Canal area of the Vaal-Harts Irrigation Settlement. Generalized and largely inferred. Residual and alluvial deposits omitted.

Figure 8: Conceptual geology as described by Temperley (Temperley, 1967)

2.3.2.2.2 Ventersdorp System:

Temperley quoted the Geological Commission Maps (1907 – 1908) as stating that the greater part of the Ventersdorp Series, that outcrops in the Vaalharts area as either volcanic or minor intrusive rocks where the majority of the volcanics are pyroclasts, and basic (Temperley, 1967).

2.3.2.2.3 Black Reef and Dolomite Series:

The Black Reef Series is said to consist of similar rocks to the Ventersdorp Series, although no dolerite is mentioned and instead of conglomerates, flagstones are present. A flagstone is 'a rock, such as a micaceous sandstone or shale, that can be split along bedding planes into suitable slabs for flagging' (Lapidus, 1990). Drilling experience gained during this thesis (Section 4.1) indicates these flagstones to be shales. Where unfractured, the Black Reef series can be as impermeable as the Ventersdorp, and as similar faulting has occurred as with the Ventersdorp, the transmission of groundwater will take place in the same manner.

2.3.2.2.4 Dwyka Series:

In this area, Dwyka shales and tillites occur. There are also outcrops of dolerite present that have eroded the shales (Temperley, 1967). The Dwyka tillites and shales are generally impermeable rocks except where decomposed by weathering or fracturing by faults has occurred. The depth of Dwyka weathering is also very limited, especially where the Dwykas are not exposed, but are rather covered by Kalahari sands and calcretes (Temperley, 1967). Groundwater in the Dwyka is among the most highly mineralised groundwaters to be found in South Africa (Temperley, 1967).

2.3.2.2.5 Calcrete:

According to Temperley, the maps prepared prior to the construction of the Vaalharts Irrigation Scheme indicate that a formation of calcrete lies between the bedrock (notably Dwyka shales and tillites) and the Kalahari sands (Temperley, 1967). The calcrete, due to its age, is now experiencing weathering in the form of cracks, so that, although the hand specimen may seem impermeable, the calcretes act as a large sponge between the largely impermeable bedrock and the highly permeable Kalahari sands (Temperley, 1967).

2.3.2.2.6 Causes of Waterlogging:

Groundwater is proposed to play a very small part in the waterlogging of the Vaalharts Scheme. The waterlogging is said to be due to the excessive accumulation of irrigation water in the soils.

2.3.2.2.7 Causes of Salinisation:

Salinisation in the Vaalharts area is said to contain factors additional to the waterlogging. These factors are:

- Especially high mineral content in Dwyka aquifer

- Vertical circulation between irrigation water and mineralised sub - calcrete water
- Climate with high evaporation-rainfall ratio

2.3.3 THE GEOLOGY OF AREA 2724D (ANDALUSIA)

This MSc thesis by Liebenberg, entitled ‘Die Geologie van Gebied 2724D (Andalusia), discusses the geology of the Vaalharts written in 1977.

There are four main groups in the area, namely, in descending order of chronological age, Kraaipan Formation, Ventersdorp Group, Griqualand-West Succession and Dwyka Formation. These groups vary in age from pre-Cambrian to Carboniferous. To the east of the Vaalharts area is the Cape Valley geology, consisting of the Ventersdorp Group, while to the west of the Vaalharts is the Ghaap Plateau consisting of the Griqualand-West Succession.

Erathem	Period	Lithology	Formation	Group	Supergroup
Cenozoic	Quaternary	Calcrete, Aeolian sand, Alluvial gravel, and Alluvium			
Mesozoic	Jurasic	Dolerite		Post-Karoo	
Paleozoic	Carboniferous	Tillite, Shales, Sandstone and Mudstone	Dwyka Formation		Karoo Supergroup
	Cambrian-Devonian	Diabase	Post-Ventersdorp to Pre-Karoo		
		Dolomite and Limestone	Ghaap plateau -Dolomite Formation		
		Dolomitic Limestone, Shale and Quartzite	Schmidtdrif Formation	Cambell Group	Griqualand-West Succession
	Middle pre-Cambrian	Shale, Limestone and Mudstone			
Pre-Cambrian		Limestone, Mudstone, Shale and Tuff			
		Basic Lava	Allanridge Formation		
		Conglomerate, Tuff, Tuffite, Quartzite and Subgraywacke	Bothaville Formation	Ventersdorp group	
		Basic Lava, Pyroclastic Breccia, Conglomerate, Quartzite, Sandstone and Shale	Rietgat Formation		
		Andesitic Lava and Ignimbrite	Makwassie Formation		
		Granite Conglomerate, Graywacke, Conglomerate, Limestone, Chert and Chertified Shale	Kameeldoorns Formation		
		Foliated Granite			
	Lower Pre-Cambrian	Banded Ironstone and Greenstone	Kraaipan Formation		

Table 1: Table illustrating the stratigraphy in the Vaalharts area

2.3.4 SUMMARY OF GEOLOGY

The geology within the Vaalharts valley appears to be predominantly Karoo sedimentary, although the pre-Cambrian basement geology appears igneous. Aeolian Kalahari sands largely overlie the Vaalharts valley. Also of Quaternary age are calcretes and alluvial gravels. Below these Quaternary sediments lie shales, tillites and mudstones. The pre-Cambrian igneous lithologies are largely divided between basic lavas of the Ventersdorp Group and granites of the Kameeldoorns Formation.

During drilling investigations (Section 4.1) the shales were found to be thicker in the north of the Vaalharts, while more clays, calcretes and gravels were found to the south.

2.4 GEOHYDROLOGY

2.4.1 HYDROGEOLOGICAL INVESTIGATION FOR WATER PROVISION TO COMMUNITIES AND SCHOOLS IN THE HARTSVALLEI FROM GROUNDWATER RESOURCES

This is a technical report from the Department of Water Affairs and Forestry (Vermaak *et al*, 2002) on geophysical investigations, drilling work, and aquifer parameter tests conducted in the Vaalharts area.

Areas that were investigated for groundwater were Windsorton, Ganspan, Spitskop, Bullhill and Raeipella. Geophysical investigations were carried out in these areas using a magnetometer and the electromagnetic method. Boreholes sited with magnetic methods, such as the magnetometer and the electromagnetic method requires the presence of iron within the structures. Dolerites, Karoo shales and coals also contain iron, although the shales and coals cannot be used to site water. The dolerite is an igneous rock that is intruded into the already present sedimentary rocks, such as the shales. This intrusion creates a fracture zone around the dolerite creating a zone of high transmissivity. The dolerites are sited to drill into this transmissive zone to gain higher water yields. Vaalharts does not seem to have a large dolerite presence, although literature indicates that there is dolerite present within the valley.

Boreholes were drilled using an air-percussion drill at a borehole diameter of 0,165m. The depth of boreholes drilled varied between 30m and 90m. The water-strikes in the area varied between 16m and 78m.

The testing of the boreholes was carried out using a submersible pump, and were analysed using the FC program (developed by Van Tonder, 1998). The FC Program is an Excel based software package incorporating various geohydrological-related mathematical equations. The FC Program includes ‘different types of pumping tests’ (Van Tonder *et al*, 2002). The best method to obtain fractured rock aquifers is the application of a 3-dimensional numerical flow model, the data required for these numerical flow models is however not always available. The FC Program therefore applies an analytical approach to analyse pump test data. Analytical pump tests used in this program allow the determination of fractured rock aquifer parameters such as the hydraulic conductivity, transmissivity and storativity.

The blow yields determined from pumping tests of boreholes drilled across the area varied between having no yield, and 4,7l/s in the Spitskop area. The tested yields indicated that sustainable yields of between 0.1l/s and 5.5l/s were available in the area.

The water levels were measured between 21.94mbgl, and 1.25mbgl. The water levels in the Vaalharts Irrigation Scheme area measured between 9.56mbgl and 1.25mbgl during this study of Vermaak *et al*, (2002).

The electrical conductivity was measured between 80mS/m and 113mS/m.

2.4.2 VAALHARTS DRAINAGE

Gombar and Erasmus, 1976 compiled the report entitled 'Vaalharts Ontwateringsprojek' for the Department of Mines. It deals with the geochemistry and aquifer parameters of the groundwater in the Vaalharts Irrigation Scheme. The authors also determined a water balance for the area.

2.4.2.1 Water Balance

The water balance constructed by Gombar and Erasmus (1976) is much outdated as compared to present conditions. At the stage at which the report was compiled, only 10% of the canals were actually cemented.

An historical figure to bear in mind was that 40% of the then allocated water for irrigation, was being lost to groundwater. This equates to a value of 63Mm^3/annum.

2.4.2.2 Natural Groundwater Flow

According to Gombar and Erasmus during this report, the average hydraulic conductivity for the entire North Canal area was 7.4m/d during their time of testing. This equates to an average transmissivity of 70m^2/d, using their average aquifer thickness. Gombar and Erasmus thereafter calculated the average groundwater gradient towards the river as being 0.0059m/m. The storativity calculated by the authors, as an average of their pump tests results amounted to an average of 12.4%, or 0.124.

2.4.2.3 Chemistry

The average TDS measured by the authors, over the nineteen boreholes tested, was 1005mg/l. This TDS value equates to an approximate electrical conductivity of 132 mS/m.

2.4.2.4 Comparison to Current Research

The area that Gombar and Erasmus (1976) used for the area of the North Canal, used largely for their evapotranspiration and rainfall calculations was 280000ha, while the value calculated during this research for the North Canal, West Canal and the area between these irrigation areas and the Harts River, was only 72000ha. This value is almost a quarter of that used by Gombar and Erasmus (1976), and would greatly affect the volumes of water used for their water balance. Also, the volume of irrigation water being allocated at the time of the investigation by Gombar and

Erasmus (1976) was only 150Mm^3/annum-approximately half of the current allocation to the North and West Canal areas.

The values calculated by Gombar and Erasmus for the storativity was in the order of 10^{-01}, while storativity values determined during this research indicates the storativity to be in the order of 10^{-03}.

Transmissivity values determined by Gombar and Erasmus (1976) were 70m^2/d, while transmissivity values determined during this research averaged at 75m^2/d for the North Canal area. These values compare similarly.

2.4.3 QUANTIFICATION OF LEAKANCE FROM CANALS IN THE NORTH CANAL AREA, VAALHARTS IRRIGATION SCHEME

This report by Van Wyk and Esterhuyse (1993), entitled ‘Kwantitatiewe beraming van die lekkasies in landerye by vyf toevoervore op die Noordkanaal-Vaalharts waterskema’ discusses the leakance from canals and the associated salinisation in the North Canal area of the Vaalharts Irrigation Scheme. In achieving their objective, the authors measure leakance from these canals at that time and the geohydrology of the area.

The geology discussed in the report is very similar to that found in both literature and drilling operations during this research. The majority of the work conducted by the authors took place on the boundary of the southern North Canal area. The gravels were believed to be a product of the Kalahari sands and basement geology. The basement geology found during this thesis was basic lavas, while the authors encountered both basic lavas and granites.

Water level gradients were determined at each canal studied, and varied between 0.0002 and 0.02. The water level gradient used during this research was an average of the water levels measured during this thesis. The water level gradient used during this thesis is calculated the same as that used by Gombar and Erasmus (1976).

The boreholes drilled during this investigation were relatively shallow, with the deepest borehole being 15m. The yields delivered by these boreholes varied between 0.05l/s and 3l/s, confirming the variations found during this research. Hydraulic conductivities measured during this project were between 0.045m/d and 6.25m/d. Storage of 2.77×10^{-03} was determined by Rudolph, van Meeker en Genome.

The aquifer parameters described by Van Wyk and Esterhuyse (1993) relate favourably to values determined during this thesis. The hydraulic conductivities and storativities determined during this thesis are similar to those determined by Rudolph, van Niekerk en Genote for this area of the Vaalharts.

Leakance from the incoming canals varied between 0.2m^3/d/1000m and 425m^3/d/1000m.

2.4.4 EFFECT OF WATER QUALITY ON IRRIGATION FARMING ALONG THE LOWER VAAL RIVER: THE INFLUENCE ON SOILS AND CROPS

Du Preez *et al* compiled this report to the Water Research Commission in 2000. The report revolves around the fact that the Vaal River is the recipient of poor water quality from industrial, mining and agricultural activities along the Vaal River. These activities result in high salt contents being added to the Vaal River system. In the lower courses of the Vaal River, where the water is mainly used for irrigation, the salt content often leads to salinisation and crop damage (Du Preez *et al*, 2000).

The aims of the project were to:

- Investigate changes in Vaal River water quality in the past and predict future trends
- Assess the effects of these changes
- Evaluate effect of these changes on irrigated crops
- Conduct survey of typical salt profiles in various soil types
- Investigate applicability of various salinity models for soil-crop systems (Du Preez *et al*, 2000)

The aims of this project were reached by studying the water quality data, the soil quality, crop yields, and various salinity models. The areas investigated included Vaalharts, Spitskop, Wildeklawer, Zandbult and Jackson.

The authors decided to use DWAF water quality data for the years 1971 to 1997 to study the changes in quality of Vaal River irrigation water. The data collected was divided into the following segments:

- Vaal River
- Harts River
- Modder River
- Riet River
- Orange River

The following annual EC (mS/m/annum) increases were expected to occur over a 50-year period in the river segments mentioned, if the flow patterns remained constant:

- H2 (Harts River segment below Vaalharts Irrigation Scheme): 6.82
- V4 (Vaal-Orange confluence): 2.32
- H1 (Schweizer-Reineke Dam to Taung): 1.58
- R3 (Riet-Vaal confluence): 1.23
- V2 (Vaal-Harts confluence): 0.98
- V1 (Vaalharts weir): 0.54
- Remaining segments had predicted annual EC increases of less than 0.25.

(Du Preez *et al*, 2000).

The authors predicted, that the extrapolated EC values over 50 years would see estimated values of 460mS/m in the Vaal-Orange confluence, 190mS/m in the Harts River segment below the Vaalharts Irrigation Scheme, and 198mS/m in the Riet-Vaal confluence.

The soil types were classified in the Vaalharts, Spitskop, Wildeklawer, Zandbult and Jackson areas. The Vaalharts was classified as having sandy and clayey soil types, irrigated with water from the Vaal River at the Vaalharts Weir. They found that removal of salts was higher in sandy soil types (approximately 60%) than in clayey soil types (approximately 20%). In cases where virgin soil types contained less than 4.0t salts ha^{-1} m^{-1}, irrigation resulted in an increase of salt content of the irrigated soils. The irrigated soils contained 1.3 to 8.9 times more salts than their unirrigated counterpart soils (Du Preez *et al*, 2000).

Crops grown in the areas of study consist of 84% wheat, Lucerne, maize, groundnuts and cotton, with a variety of fruits comprising the remaining 16% of the area. The authors encountered no ill effect on crop yields when the best quality water was used for irrigation. A 20% reduction in crop yield was encountered on salt sensitive crops when the long-term average water quality was used from segments H2 (area below Vaalharts Scheme) (Du Preez *et al*, 2000).

The salinity models used for fulfilling the aims of this project were the Aragues (Aragues, 1996) and Szabolcs (Szabolcs, 1986) approach to empirical mass balance, and the more mechanical SWB model (Annandale *et* al, 1998). The SWB model allowed local support from the University of Pretoria.

This report is of particular interest to the quantitative determination of the salt balance for the groundwater component of processes in the Vaalharts. It explains many of the agricultural processes occurring within the Vaalharts and offers an alternate viewpoint on the interaction between the surface water and agriculture in this system.

This report was used to gather information on the soil-water balance models conducted on the Vaalharts. The effect the Vaal River on Vaalharts irrigation is paramount. The Vaal River water used for irrigation in the Vaalharts is the largest source of salts entering the Vaalharts system. The incoming irrigation water adds approximately 130000t/annum salts to the Vaalharts system. This report provides emphasis for the importance of irrigation efficiency in the Vaalharts. This can be extrapolated to the other irrigation schemes in the lower reaches of the Vaal River.

2.5 AVAILABLE DATA FOR THE AREA

The search for groundwater accessibility yielded a poor response during this investigation. The problem was that where present, the majority of boreholes were equipped with mono-pumps. The presence of these mono-pumps prevented easy access to groundwater levels, and chemistry data could not be accessed at specific depths, and only by use of a pumped sample.

There were a total of 41 of diamond prospecting boreholes drilled in earlier years, although all have either been blocked by rocks, or ploughed up, and destroyed in this manner.

Data have since been accessed from the National Groundwater Database, allowing information on borehole positions, borehole construction, groundwater level data, and pump-test information. In addition to NGDB data, data have also been acquired from the Department of Water Affairs and Forestry. These data not only supply an amount of groundwater data, including chemistry and water levels, but also surface water quality of the dams and rivers in the area.

The DWAF and NGDB information is presented and discussed in the sections that follow.

2.6 RAINFALL

The following diagrams discuss the rainfall in the Vaalharts Irrigation Scheme over the past 67 years.

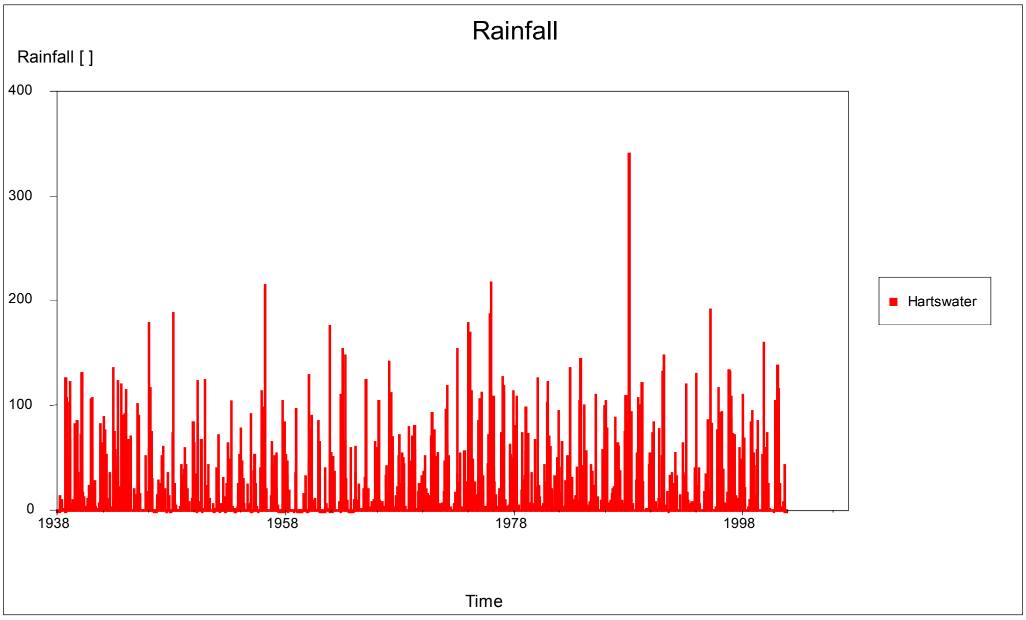


Figure 9: Time-series graph illustrating the rainfall measured at Hartswater over the past 67 years

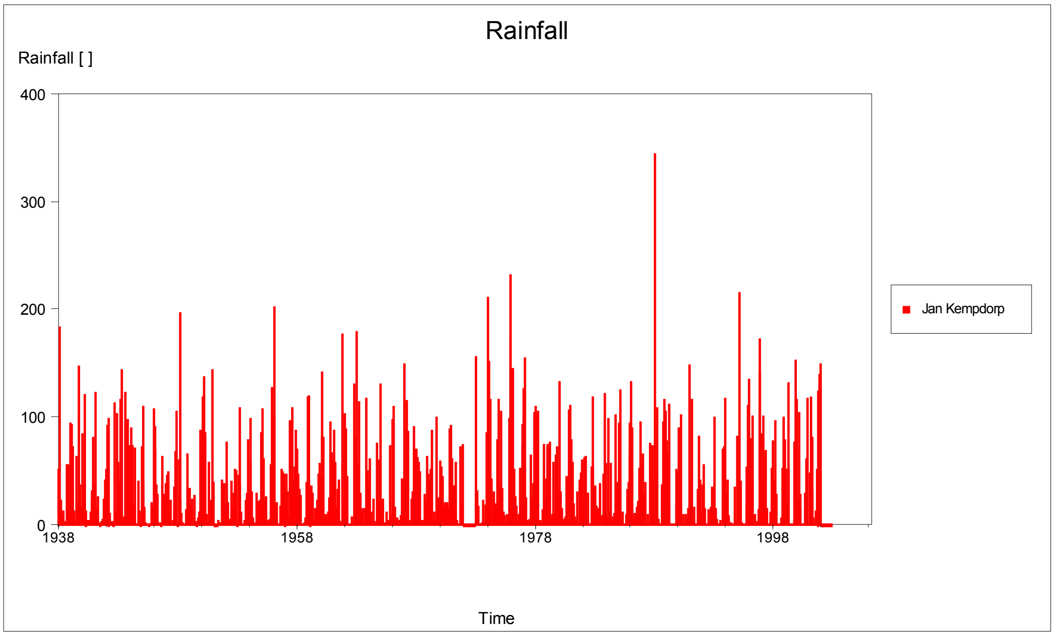


Figure 10:Time-series graph illustrating the rainfall measured at Jan Kempdorp over the past 67 years

In the above two diagrams, namely Figure 9 and Figure 10, it can be seen that the rainfall patterns for the Jan Kempdorp and Hartswater stations are very similar. The average rainfall for these two stations is however, different. The average rainfall for

Hartswater is 416mm/annum over the past 67 years, while Jan Kempdorp has an average rainfall of 445mm/annum, giving the Vaalharts Basin an approximate average of 430mm/annum. Seasonal variations and annular cycles are present in these patterns, although long-term averages were determined to be preferable for use in water balance calculations.

2.7 GROUNDWATER LEVELS

The water levels illustrated below are acquired from the National Groundwater Database (NGDB). The data viewed are from the entire Vaalharts valley area, and are not specific to the irrigation area. The water levels illustrated below have been collected since 1900 until 1950.

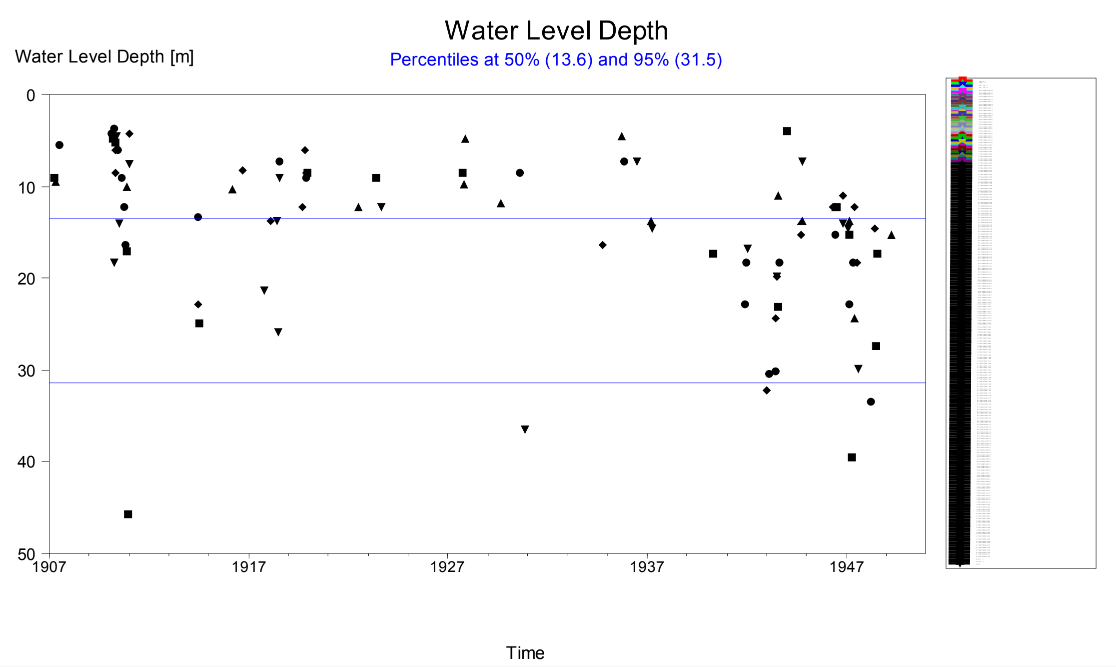


Figure 11: Time-graph of the water level elevations in the Vaalharts area.

In Figure 11 it can be seen that the water levels vary drastically over time. Although much of the recently acquired waterlevel data indicate that the waterlevel stands at approximately 2m below surface, according to the data shown above, the water levels in the Vaalharts valley vary between 1,50mbgl and 46mbgl.

The average water level for this area, since 1900, stands at approximately 10,35m below surface level, with 50% of the water level data falling above 6,50m below ground level. It is also important to note that the water levels have remained relatively constant throughout the study period of 102 years, indicating the historical water level in the area, and what influence the irrigation actually has on the Vaalharts area.

The above NGDB data illustrate how much data exists, but at the same time how little time-series data exists for the Vaalharts area. This is a major drawback for understanding the hydraulic interactions, and illustrates the importance of the monitoring system established in the current project. It is also important to note that water levels of 3.5mbgl were measured in the irrigation area as early as 1910. This data disagrees with Streutker (1977) where he indicates that average water levels during the 1940's were as low as 24mbgl in the Vaalharts Irrigation Scheme.

2.8 WATER QUALITY

The water quality data discussed in this section of the thesis refers to data acquired from the DWAF, NGDB and various reports regarding the Vaalharts Irrigation Scheme and its water quality. Water quality parameters that have been illustrated in this section include the electrical conductivity, pH, sulphates and total dissolved solids.

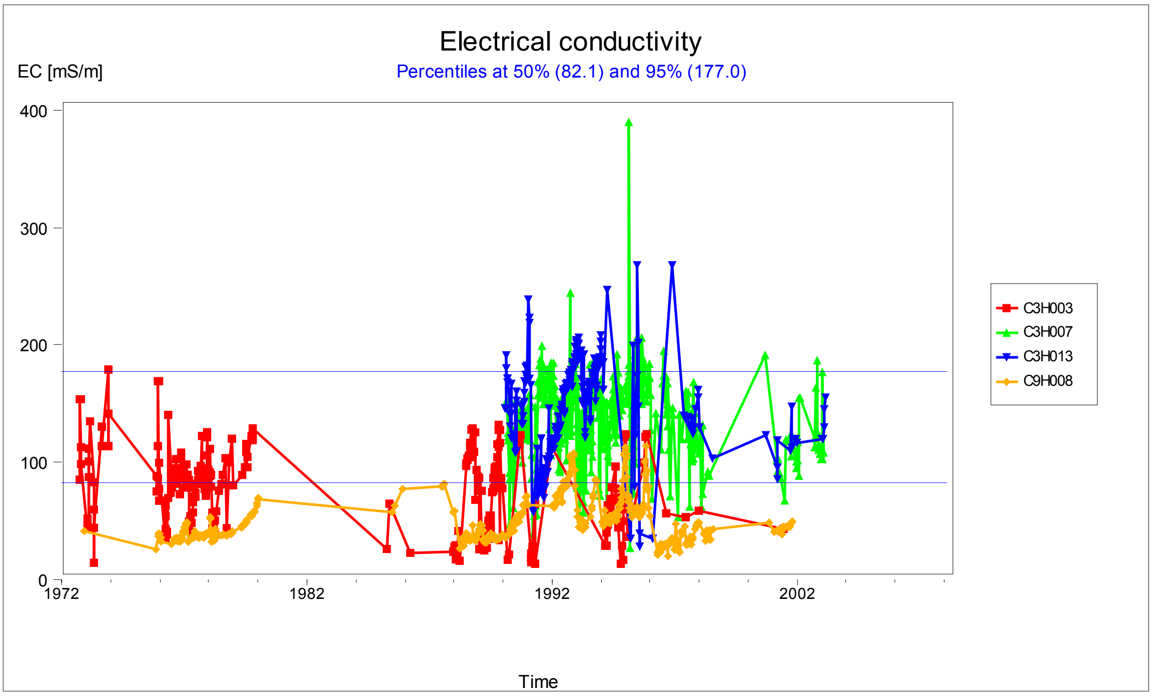


Figure 12: Time-graph of the electrical conductivity of the Vaalharts surface water samples.

In the above diagram, Figure 12 a time-series graph of the electrical conductivity of the Vaalharts surface water is shown. The surface water samples illustrated are for sample points C3H003 (Taung), C3H007 (Espagsdrif, downstream of the Vaalharts), C3H013 (Harts River at Spitskop) and C9H008 (Vaalharts barrage at Vaal River).

The electrical conductivity's of the surface waters illustrated indicate the incoming versus the outgoing water at the Vaalharts Irrigation Scheme. The average EC of the surface water entering the system is 47mS/m. The average EC measured at Taung, upstream of the Vaalharts Irrigation Scheme on the Harts River is 72mS/m, while at Espagsdrif flow station, downstream of Vaalharts, the EC has an average of 137mS/m. The long term average EC of the flow station at the Spitskop Dam on the Harts River is 145mS/m. These surface water average electrical conductivity values indicate that there is a nett increase of 65mS/m being seen in the Harts River below the Vaalharts Irrigation Scheme.

Long-term time-series data for the groundwater within the Vaalharts Irrigation Scheme were unavailable in the National Groundwater Database. The following data from a report by Gombar and Erasmus (1977) illustrates the historical groundwater TDS values within the Vaalharts Irrigation Scheme.

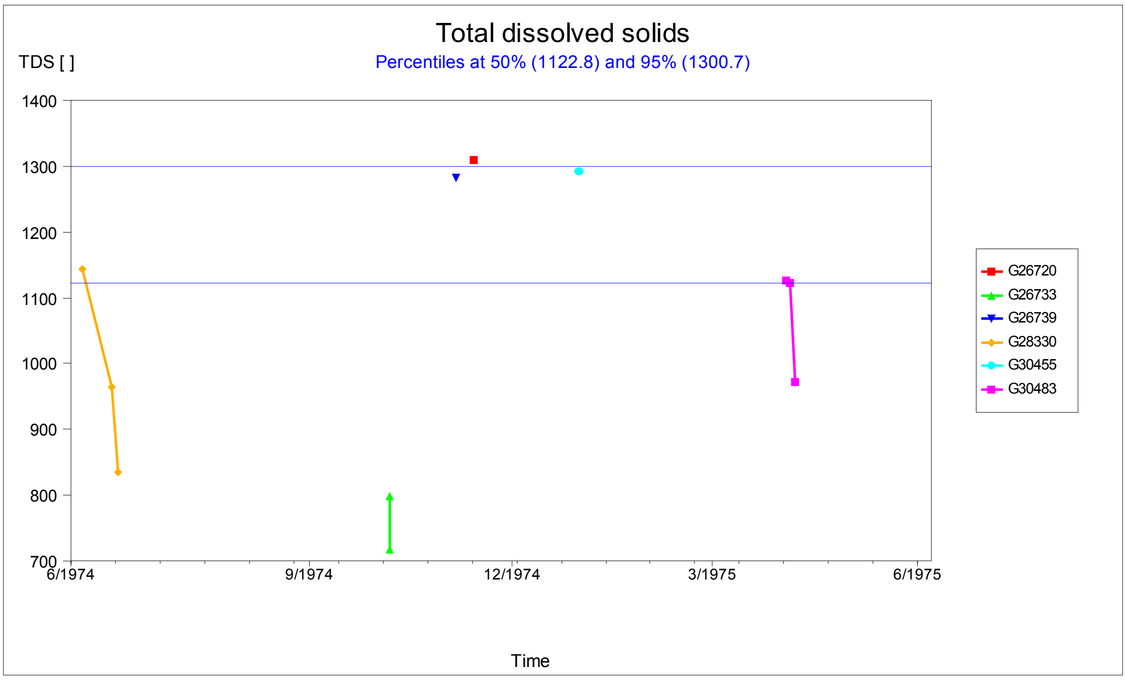


Figure 13: Diagram illustrating TDS values for boreholes sampled in 1976

In the above diagram, Figure 13, TDS values for six boreholes sampled by Gombar and Erasmus (1976) are illustrated. It is interesting to note that the average TDS value for these six boreholes, 27 years ago, was 1005mg/l, while the present average is 1350mg/l. This denotes an average annual increase of 13mg/l in the groundwater. This data will be revisited in Section 6.2(Salt Balance). These TDS values measured by Gombar and Erasmus give us a clear indication of the historical groundwater quality within the Vaalharts Irrigation Scheme.

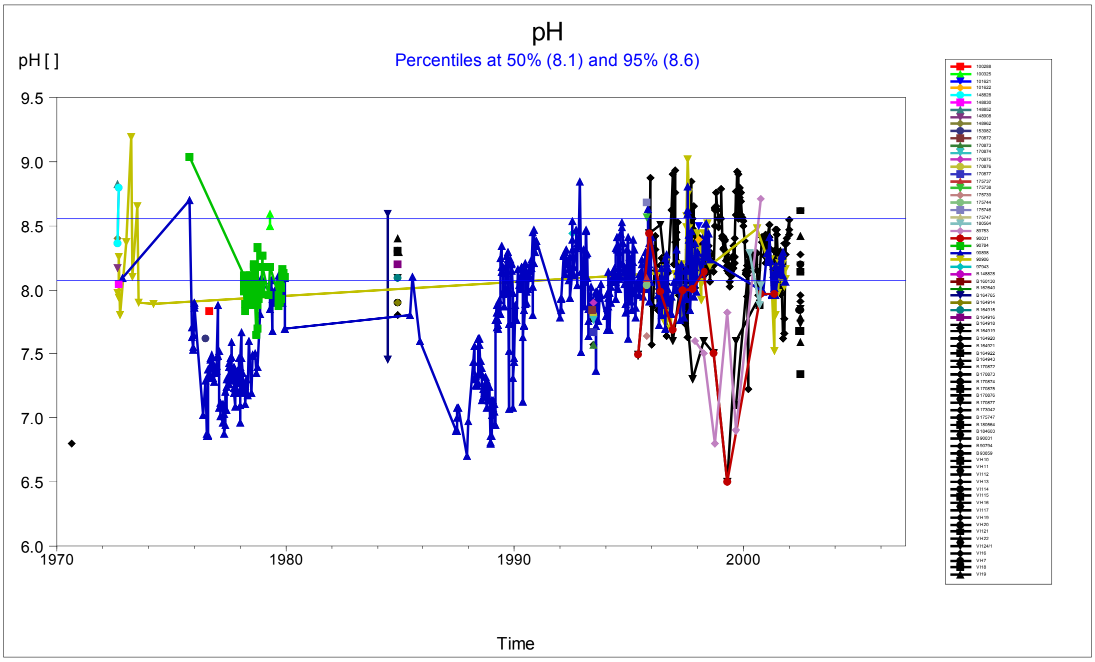


Figure 14: Time–series graph of the pH – values at the Vaalharts Irrigation Scheme

In the above diagram; Figure 14; a time-series graph of the pH - values found in the waters at the Vaalharts Irrigation Scheme is shown. In this diagram, it can be seen that the average pH-value has been rising since the 1980’s. The pH - values are similar for the period from 1970 to 1987; although not much data appear between 1980 and 1984. Station A101772 (blue line) shows an increase in the pH - value is the measuring point upstream of the Vaalharts Irrigation Scheme used for irrigation water.

Although there are variations in this data over time, the integrity of previous results’ sampling methods cannot be verified, although a general trend can be seen in much of the data. What is important to note, regarding this pH information from the Vaalharts area, is that all the pH - values have remained generally constant within the boundaries of the expected alkalinity.

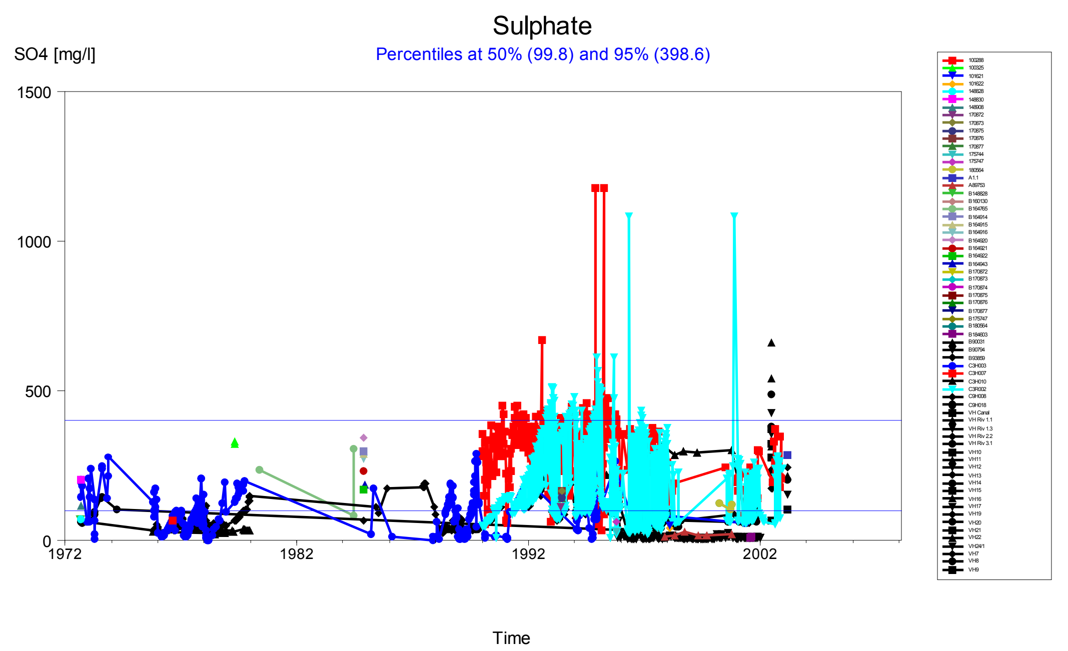


Figure 15: Time–series graph for the sulphate values from samples taken from both the surface- and groundwater in the Vaalharts area

In the above diagram, Figure 15, a time-series graph of the sulphate values in the Vaalharts area is illustrated (NGDB, 2002). It should be remembered that sulphates are commonly associated with fertilizers such as potassium sulphate (K_2SO_4) and ammonium sulphate [(NH_4)2SO4]. As can be seen in the above diagram, sulphates upwards of 300mg/l are quite common. These sulphate values can be found in both the groundwater and surface water samples.

2.8.1 INTERPRETIVE DIAGRAMS

Various methods are used to interpret chemical data. When gathering raw data, it is important to interpret these data in a manner that would make geohydrological relationships understandable. It is therefore important to show patterns of variability between different water types in a particular area, such as the Vaalharts valley, and identify geochemical processes that are taking place.

Trilinear diagrams are generally used for such water classification. Examples of such diagrams are the Piper Diagrams and Expanded Durov Diagrams. Other diagrams that may be used to interpret chemical data are Stiff Diagrams and SAR (Sodium Adsorption Ratio) Diagrams. Interpretation diagrams that will be used in this section, for the background information chemical data are Piper Diagrams and Expanded Durov Diagrams.

A Piper diagram uses the major anions and cations and plots them in one trilinear diagram. This is achieved by calculating their relative percentage to the other anions or cations. The two points, namely anion and cation are then extended to an above diamond, where the water classification is possible. The disadvantage of a Piper diagram is that the relative percentages of the anions and cations are plotted.

An Expanded Durov Diagram is similar to a Piper Diagram in that relative percentages of the anions and cations are plotted, namely three for the anions and three for the cations. The Expanded Durov Diagram consists of nine plots for the anions and cations. It is important to note that a Piper Diagram plots the relative proportions of the various anions and cations.

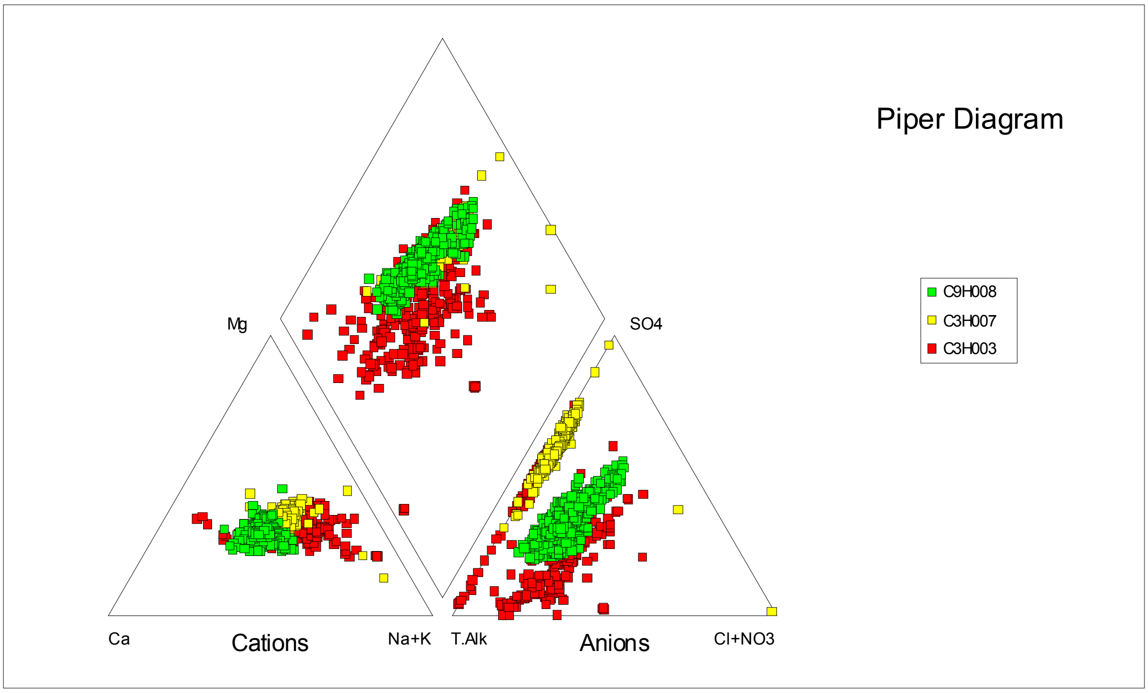


Figure 16: Piper Diagram illustrating the major cations and anions for the surface water chemistry in the Vaalharts area

In this diagram for the surface water chemistry, sample points C9R008, C3H003 and C3H007 have been used.

In Figure 16 trends between the three sample points' water qualities can be seen. It is interesting to note, that while C3H007 is a combination of the two other water samples illustrated, the anions show no clear relationship among each other. The cations plot within the same fields, with water from the Taung station tending towards the Na+K field.

Water samples taken at station C3H007, downstream from the Vaalharts Irrigation Scheme on the Harts River, indicate an anion trend towards the sulphates. This could be due to either fertilizers, or sulphates in the incoming Vaal River water.

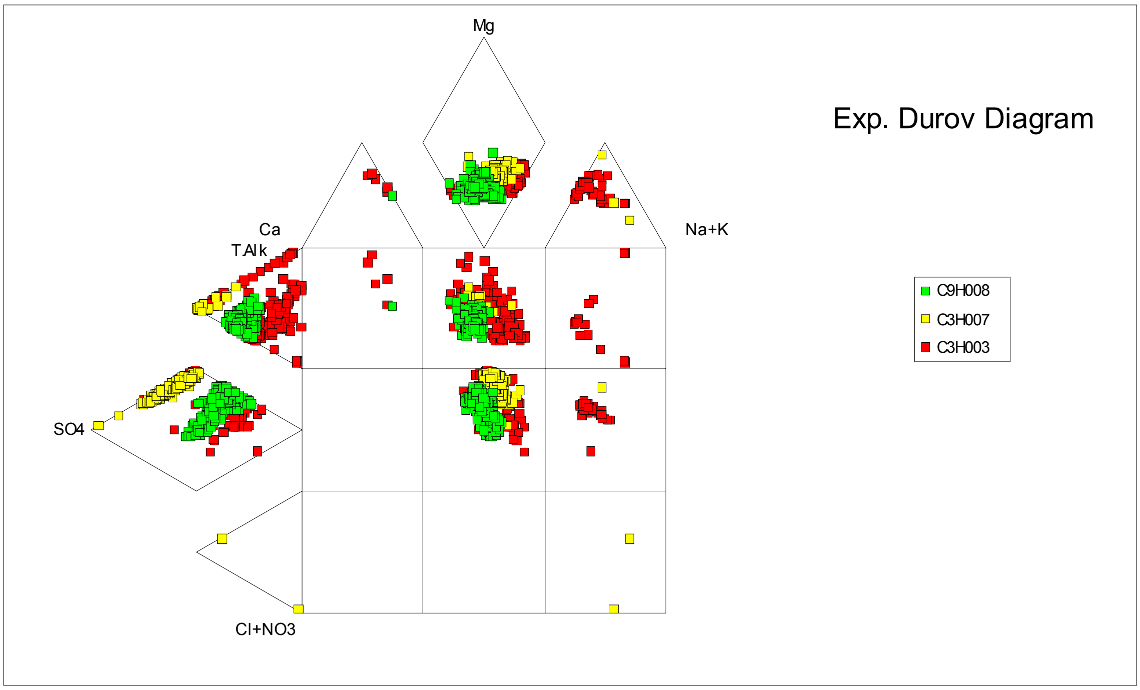


Figure 17: Expanded Durov Diagram for the surface waters present in the Vaalharts area

In Figure 17 an Expanded Durov Diagram of the surface waters in the Vaalharts area is illustrated.

The Expanded Durov Diagram above illustrates a dominance of magnesium cations and sulphate anions. In later investigations, it seems evident that the magnesium is a result of the highly mineralised shales, while the sulphate is a result of the incoming Vaal River water. Further investigation into this theory is made in Section 4.5.3.

The samples that have plotted in the centre of the diagram illustrate relatively high sulphate values. These sulphates cannot only be because of Vaalharts Irrigation Scheme additions, as the higher sulphate value samples can be seen in the water entering the system at both the Vaalharts barrage on the Vaal River and at Taung, upstream on the Harts River. This may be resultant of the upstream irrigation, mining and industrial activities on Harts and Vaal Rivers.

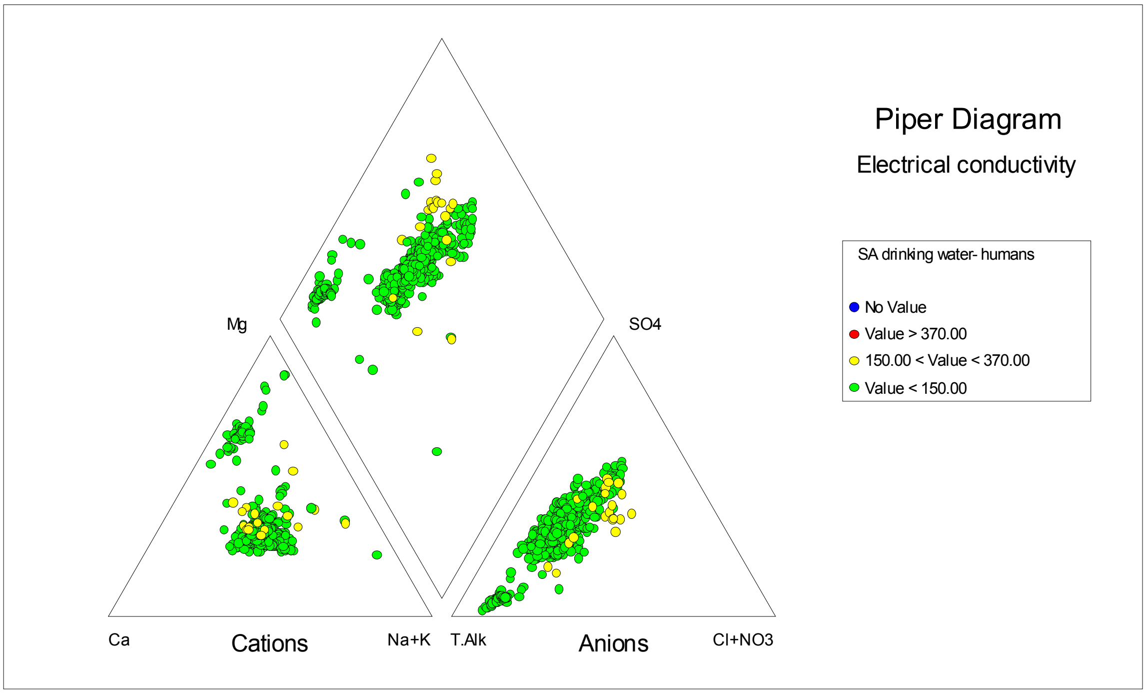


Figure 18: Piper Diagram of the groundwater samples for the Vaalharts area

In the above diagram, Figure 18, a Piper Diagram illustrates the various groundwater types present in the Vaalharts.

In the cation field, a large number of non-dominant cations are present, although a significant number of magnesium cations are also present. A number of samples also plot between the magnesium, sodium and potassium cations.

In studying the anion fields, bicarbonate is the major anion present. The field runs from the bicarbonate through to a line almost equidistant between the sulphate, chloride and nitrate anion fields. If the values for the cations and anions are projected through to the main diamond, the majority of the waters plot within the calcium - sodium cation facies, and evenly between the chlorite-sulphate-bicarbonate and bicarbonate-chloride-sulphate anion facies.

The anions present in Figure 18 above show similar results to those shown of the surface water samples in Figure 16. The surface water samples of flow station C9R008 and C3H003 shown in Figure 16 plot similarly to the groundwater anions and cations shown in Figure 18. The similarity between the incoming surface water and the groundwater within the Vaalharts Irrigation Scheme is a possible indication of the recharge from irrigation water to the Vaalharts aquifer.

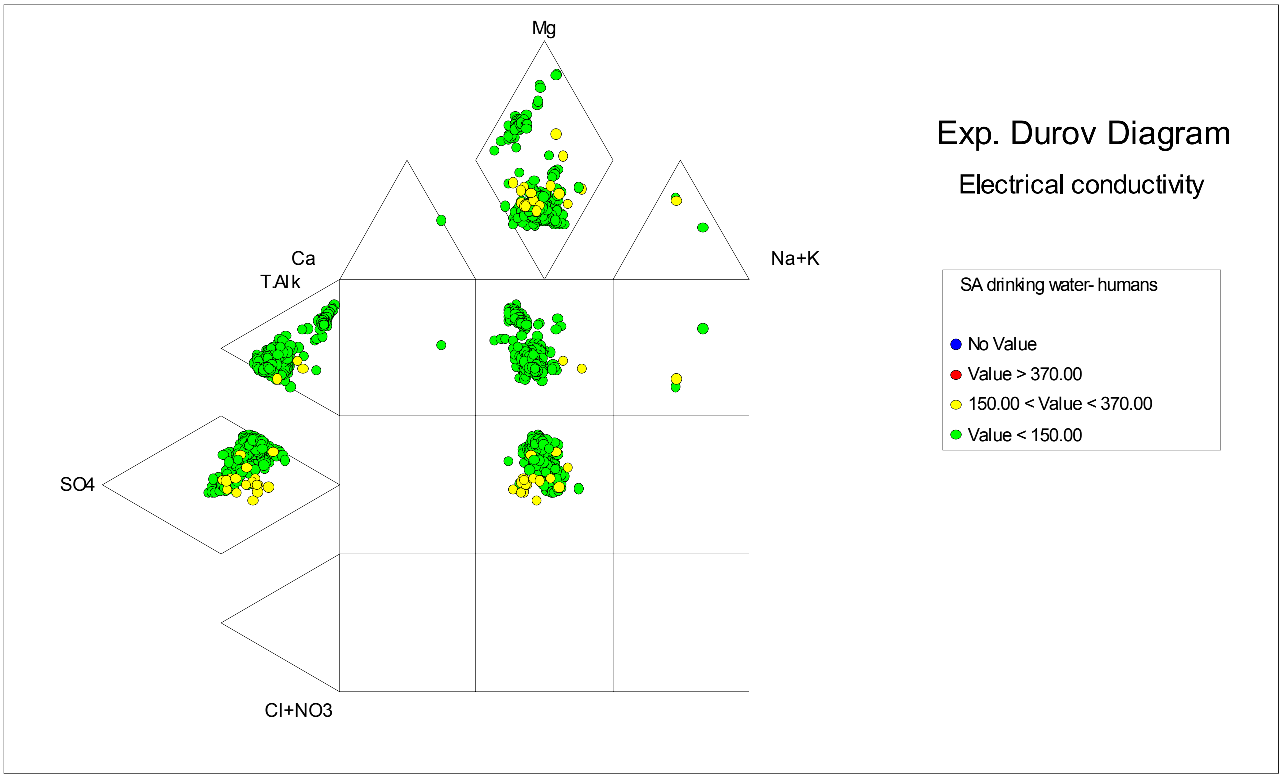


Figure 19: Expanded Durov Diagram illustrating the various concentrations for groundwater samples taken in the Vaalharts area

In the above diagram, Figure 19, an Expanded Durov Diagram has been plotted illustrating the various concentrations of the chemistry of the groundwater samples taken in the Vaalharts area.

The majority of the groundwater samples' chemistry plots within the fields of bicarbonate-magnesium, or in the centre field, where no dominant cations or anions are present. This is interesting, as the surface water samples plot within the same fields. Other samples are also found within the calcium-bicarbonate and bicarbonate-sodium fields.

The Expanded Durov diagrams of Figure 17 and Figure 19 indicate the possible interaction between the surface- and groundwater. This adds further support that the surface water is recharging the aquifer. The surface- and groundwater would therefore illustrate similar trends.

2.9 HYDROCENSUS RESULTS

A hydrocensus was conducted within the Vaalharts Irrigation Scheme at the initiation of this research project. Literature indicated that 41 diamond-prospecting boreholes had been drilled during the 1970's. It was hoped that these boreholes could provide access to the aquifer. During a hydrocensus inspection to locate these boreholes, all were found to either be destroyed by farming practices, or have been blocked by stones.

A second hydrocensus across the Vaalharts Irrigation Scheme to discover domestic boreholes was conducted. The results of the investigation needed to deliver access to water levels, depth-varying chemistry, and provide the ability to conduct aquifer parameter tests within the boreholes. The extent of domestic boreholes in the Vaalharts seemed to be limited. The boreholes that were discovered during this hydrocensus proved to be equipped with mono-pumps, and had been encased in concrete for fear of destruction and theft. In total, 22 boreholes were discovered. Only pumped samples were possible from these boreholes, although these were still able to provide chemistry.

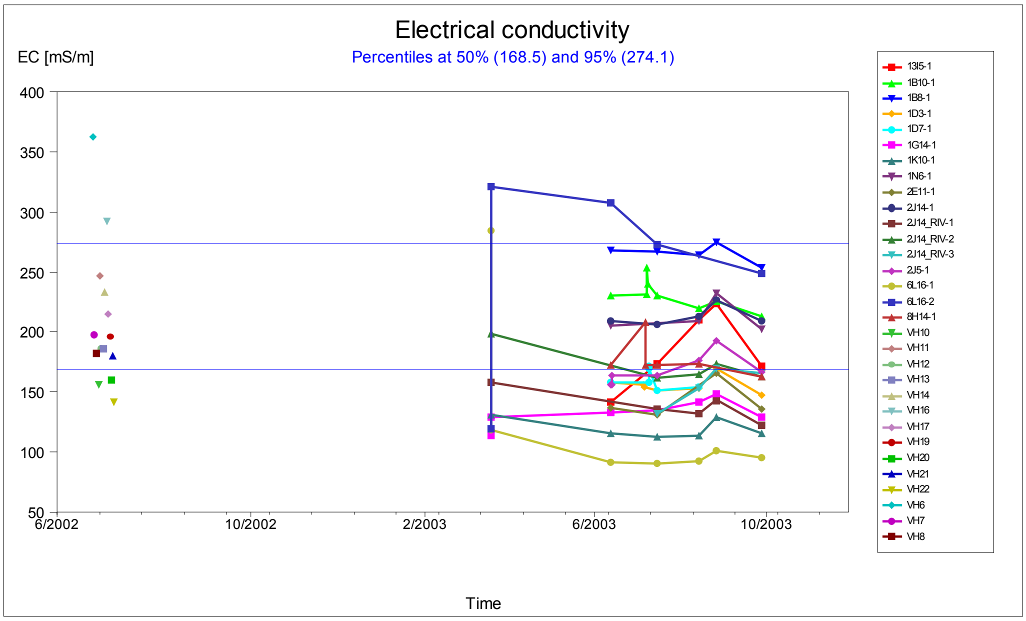


Figure 20: Electrical conductivity of hydrocensus boreholes and boreholes drilled during this research

In Figure 20, the electrical conductivity of the boreholes sampled during the hydrocensus are compared with that of the samples of the boreholes drilled during this research project. The hydrocensus boreholes were sampled during 2002. The hydrocensus boreholes illustrate a range of electrical conductivities between 140mS/m and 360mS/m. The more recent samples illustrate a range of electrical conductivities between 90mS/m and 320mS/m. The hydrocensus boreholes' EC therefore falls within the same EC range as that of the boreholes drilled during this research project.

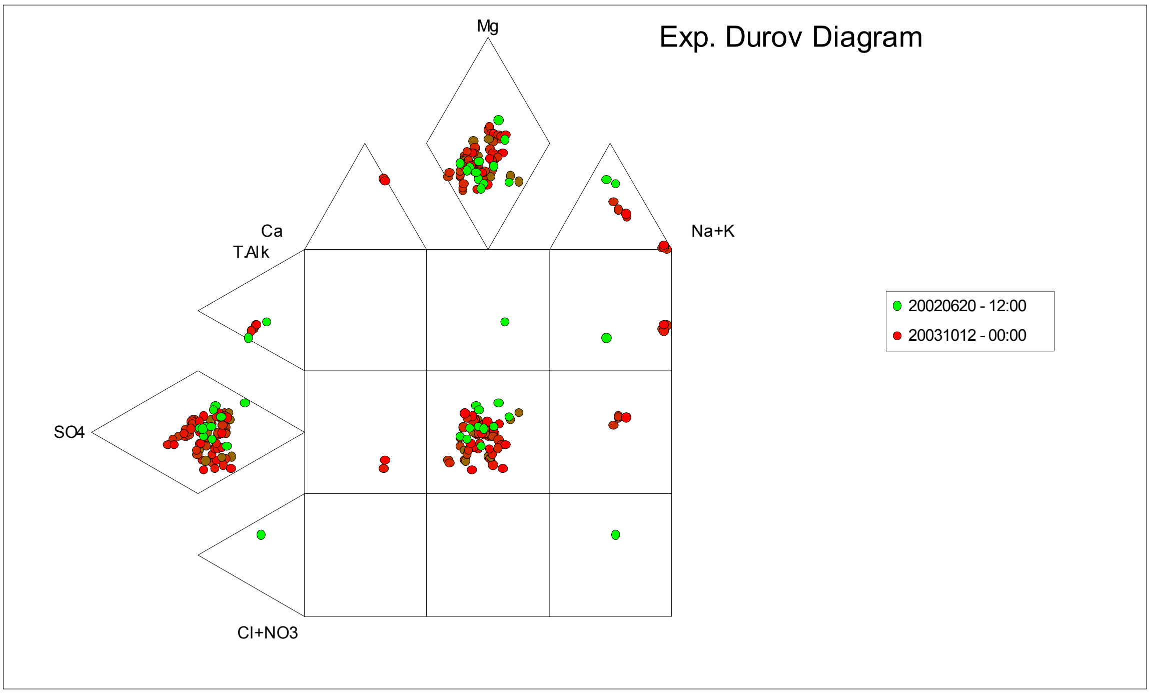


Figure 21: Expanded Durov Diagram for the hydrocensus boreholes and those drilled during this research project

In Figure 21 above, a combination of boreholes drilled during this research project and those sampled during the hydrocensus are illustrated. The boreholes sampled during the hydrocensus are illustrated in green, while the more recently drilled boreholes are illustrated in red. The majority of boreholes plot as magnesium-sulphate waters. Both the natural geology and the incoming Vaal River water explain this phenomenon. The shales present in the Vaalharts seem to be highly mineralised in magnesium, while the incoming Vaal River water is appears relatively high in sulphate concentrations. This theory is addressed in Section 4.5.3

There are a few outlying samples though. Borehole VH6, in the north of the North Canal area, is classified as sodium-chloride water. Borehole VH6 also has the highest measured electrical conductivity of all the samples with an EC of 360mg/l. The presence of sodium can possibly be attributed to the use of fertilizers and pesticides.

3 INITIAL CONCEPTUAL MODELS

3.1 PRIOR CONCEPTUAL MODELS

3.1.1 INTRODUCTION

As previously mentioned, the ultimate reason for conducting this project is to discover the location of unaccounted salts in the Vaalharts Irrigation Scheme area. This question of the salts' location arose following a report delivered by Herold and Bailey in 1996.

Herold and Bailey completed a hydro-salinity simulation model for the Vaalharts system, and their findings concluded that there was a variation between the salts being applied to the Vaalharts system, and the salts that were being measured in the surface waters downstream of the system. There was also an historical salt balance model used by Herold and Bailey (1996). Herold and Bailey 's historical salt balance was originally constructed for the North Canal area by Streutker (1977). Streutker's salt balance was conducted for the North Canal area for the years 1959 to 1966. The mean annual results for Streutker's salt balance are shown as follows:

- Salt in Irrigation Water = 41000t (V = 142.1; C = 288)
- Salt in Fertilizers = 8200t
- Salt in Drainage Water = 7300t (V = 10.41; C = 704)
- Salt removed by Plants = 6500t

Where: V = water volume in Million Cubic Meters
C = TDS Concentration in mg/l

The above figures imply that 40924t of the salts in the irrigation water, added to the 8184t of salts in the fertilizers were added to the system, while 7322t of salts in the drainage water were subtracted from the system, together with a further 6480t. This implies that between the years 1959 and 1966, when no enforced drainage was in place, there was a mean annual addition of 35306t of salts to the system.

Herold and Bailey's constructed and calibrated hydro-salinity simulation model indicated that the Vaalharts groundwater system was acting as a salt sink that had accumulated approximately 66% of the total dissolved salts contained in the irrigation water since the Vaalharts' commissioning in the 1930's (Herold and Bailey, 1996).

The reason for the finding was that the salts being applied to the Vaalharts system were not seen in the Harts River downstream of the Irrigation Scheme. It was expected that, as the drainage canals flow from the Vaalharts Irrigation Scheme into the Harts River, these salts should be seen in the TDS values of the surface waters. This was not the case. The difference in the salt balance led Herold and Bailey to construct certain hypotheses.

3.2 HYPOTHESES OF PROCESSES BY HEROLD AND BAILEY

Herold and Bailey (1996) hypothesized the various processes taking place in the Vaalharts Irrigation Scheme. Their hypothesis of processes was as follows: From dams, the water was supplied to a canal, and in turn to the irrigation area. From here, the water is supplied via various secondary and tertiary canals to the many plots and farm dams; Water was calculated to be lost to seepage and evaporation from the canals and the farm dams; During these processes, water was added to the system via rainfall; The total water loss was divided as follows: evaporation, surface runoff, evapotranspiration, lateral seepage to veld, deep percolation to groundwater.

The drains were installed to maintain the water level below that of the root zone and accounts for a specific amount of the groundwater. This drainage water is conveyed towards the Harts River over the main supply canals.

Drainage below the root zone that was not intercepted by the subsurface drains was hypothesized to flow to the groundwater system, which was said to possibly consist of a perched aquifer and a deeper aquifer. Herold and Bailey (1996) hypothesized that water from the perched aquifer would then gradually flow, together with its solutes, towards the river, or the nearest main drain. The remainder of the water that was not intercepted by the subsurface drainage was believed to have percolated down towards the deeper aquifer, and apparently result in the "gradual filling of this deeper water table" (Herold and Bailey, 1996).

Herold and Bailey (1996) further hypothesized that once this deeper watertable had filled, there would be a "rapid increase in the rate at which water discharges towards the river via direct seepage and the subsurface drains" (Herold and Bailey, 1996). In adding to this, Herold and Bailey stated, "whereas before a substantial proportion of the TDS load contained in the irrigation water would have been trapped in the deeper groundwater zone, from then onwards a rough balance would be maintained between the TDS loads entering via the irrigation water and returning to the river" and would "…result in increased salinisation of the river" (Herold and Bailey, 1996).

Herold and Bailey believed that if the flow of the "lower groundwater" was "…unimpeded, then over a long period of time, the accumulated TDS load could begin to return to the surface water" (Herold and Bailey, 1996). They also believed that, in the Vaalharts, if such pathways existed, the geology present in the Vaalharts area, namely the Dwyka shales and tillites would have such low permeability that the flow rate of water would be restricted.

Herold and Bailey therefore seem to have seen the Dwyka shale and tillite aquifers as a basin, where water could essentially only flow into from directly above, and was unable to escape laterally, or in other words, flow towards the river along a natural gradient. The permeability was believed to be too low, disabling sufficient quantities of water to be released.

The conclusions drawn by Herold and Bailey (1996) regarding a two-system aquifer are addressed in Section 4.2.4.1.

4 FIELD STUDY AND DATA COLLECTION

4.1 INTRODUCTION

The drilling phase of this research resulted from the hydrocensus conducted in the Vaalharts Irrigation Scheme. Boreholes providing direct access to the groundwater proved to be non-existent. It was necessary to drill a network of boreholes across the Vaalharts Irrigation Scheme to determine aquifer parameters and gain an understanding of the geology in the Vaalharts.

4.2 DRILLING

4.2.1 GENERAL

The need for drilling was made evident by the relative lack of accessibility to open boreholes, as the majority of boreholes are covered by cement blocks fitted with mono-pumps. The accessibility to depth profiles was therefore non-existent, allowing only pumped samples from the mono-pumps, giving no information as to the correlation between the water being tested and the various lithologies.

After meeting with the DWAF in the Kimberly offices, they kindly agreed to provide a drilling rig for this project. The benefit to the DWAF, and the Water Users Association in the Vaalharts, is that a groundwater monitoring system for the Vaalharts area can be established through these activities. After completion of this project, the ongoing monitoring of the groundwater system will be possible.

Figure 22:DWAF drilling rig and support vehicles used in the Vaalharts project

The drilling method used was air percussion, with the boreholes being drilled to a diameter of 0.165m. This diameter was decided upon due to the necessity to conduct various aquifer parameter tests. This diameter of boreholes allows various aquifer parameter tests to be conducted, including pump tests, slug tests, and tracer tests. In several of these boreholes, piezometers were installed so that the possibility of multiple aquifers and depths can be assessed for the hydraulic and hydrochemical response.

Figure 23: Example of a log taken during the drilling stage of the research project

The boreholes were drilled from the beginning of March 2003 until the end of May 2003.

4.2.2 LOCATION OF BOREHOLES

There were a total of 17 boreholes drilled across the Vaalharts Irrigation Scheme, of which 3 were located on the riverbanks of the Harts River, and the remaining 14 were drilled on the plots. The boreholes drilled on the banks of the Harts River were positioned as such to test a hypothesis of bank storage in the Vaalharts Irrigation Scheme. The boreholes were located across the span of the Vaalharts in order to give an accurate representation of the geology and aquifer characteristics throughout the area of study.

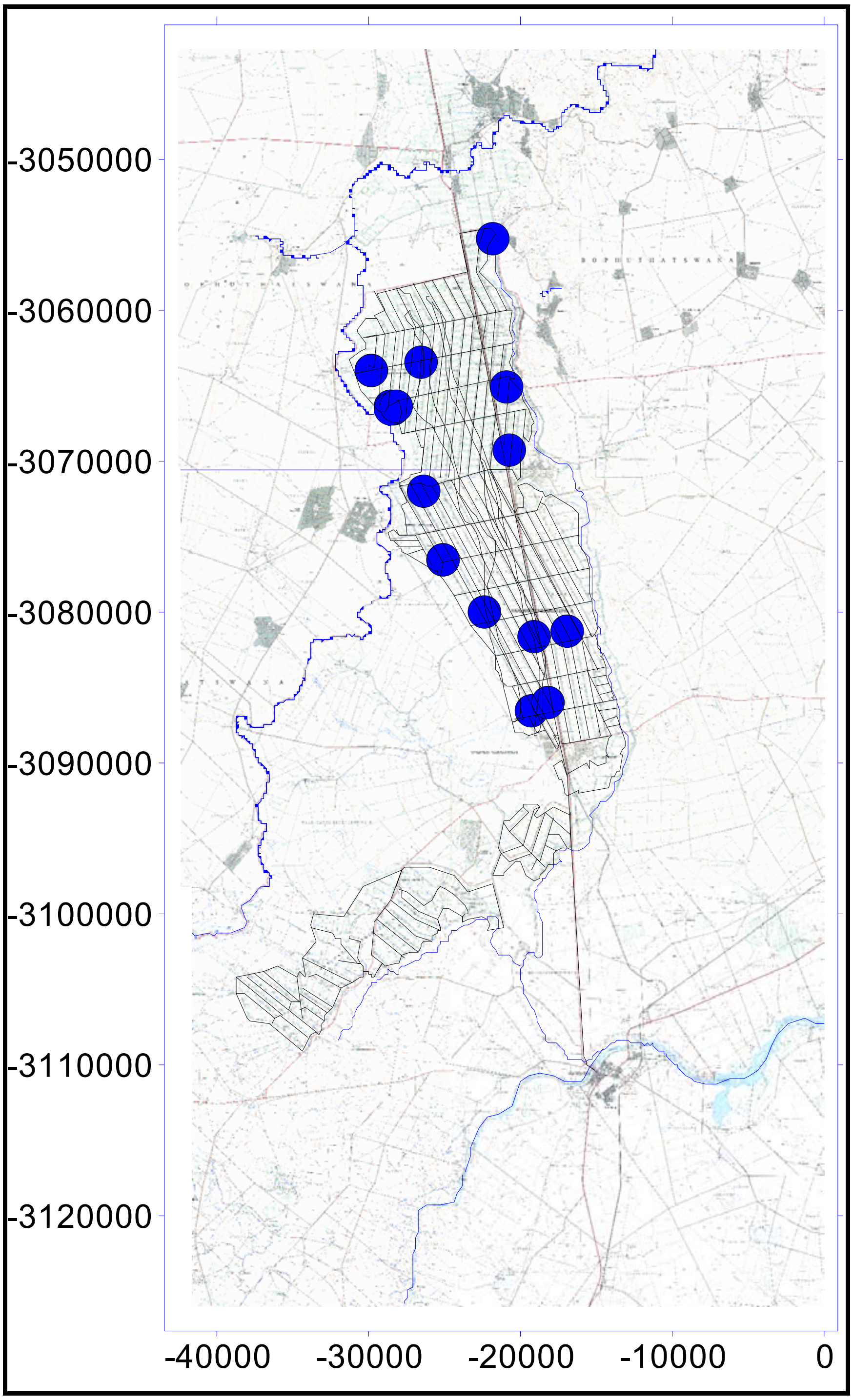


Figure 24: Diagram illustrating the relative locations of the boreholes drilled in the Vaalharts Irrigation area during this project

4.2.3 BOREHOLE DESCRIPTION

Of the 17 monitoring boreholes drilled during this project, the first 7 boreholes were drilled to random depths until they reached the lava bedrock, while the remaining 10 boreholes were drilled to a depth of approximately 20m. The reasoning behind drilling to the lava bedrock was that a complete geology and groundwater profile would then be possible, including a correlation between these two.

In total 544m were drilled during this research. The depths of boreholes are as follows:

Table 2: Table illustrating the boreholes drilled in the Vaalharts Irrigation Scheme during this project

BOREHOLE	PLOT	DEPTH DRILLED	X CO - ORDINATE	Y CO - ORDINATE	Z CO-ORDINATE
1B10-1	1B10	24m	-19270.63	-3086558.94	1129
1B8-1	1B8	41m	-18186.34	-3086061.92	1136
1D3-1	1D3	20m	-16902.00	-3081306.00	1150
1D7-1	1D7	20m	-19117.00	-3081598.00	1126
2E11-1	2E 11	70m	-22418.70	-3080045.31	1106
1G14-1	1G14	26m	-25106.40	-3076609.90	1089
8H14-1	8H14	20m	-26404.00	-3072037.00	1068
13I5-1	13I5	20m	-20826.00	-3069373.00	1109
2J5-1	2J5	20m	-20925.00	-3065159.00	1139
2J14-1	2J14	20m	-28164.26	-3066382.16	1082
2J14_RIV-1	2J14	20m	-28528.00	-3066451.00	1073
2J14_RIV-2	2J14	20m	-28476.00	-3066510.00	1073
2J14_RIV-3	2J14	20m	-28515.00	-3066510.00	1072.5
1K10-1	1K10	101m	-26521.00	-3063526.00	1106
6L16-1	6L16	42m	-29831.96	-3063997.08	1081
6L16-2	6L16	36m	-29877.37	-3063980.57	1081
1N6-1	1N6	20m	-21799.00	-3055307.00	1123

Once the initial 7 boreholes had been drilled to within the basement geology, it was decided to drill the following boreholes to a depth of 20m. The depth of 20m was decided upon based on the geology encountered during the first 7 boreholes. This indicated to us that necessary aquifer parameters and geochemistry could be gained from boreholes of this depth.

4.2.3.1 BOREHOLE LOGS

The borehole logs taken during the drilling phase of this project in the Vaalharts Irrigation Scheme are all quite similar, although all borehole logs do have slight variations as would be expected if one considers the geological processes that have taken place in the Vaalharts valley (refer to Section 2.3). The borehole logs have all been plotted using the Windows Interpretation System for Hydrogeologists software (WISH)(Lukas, 1998).

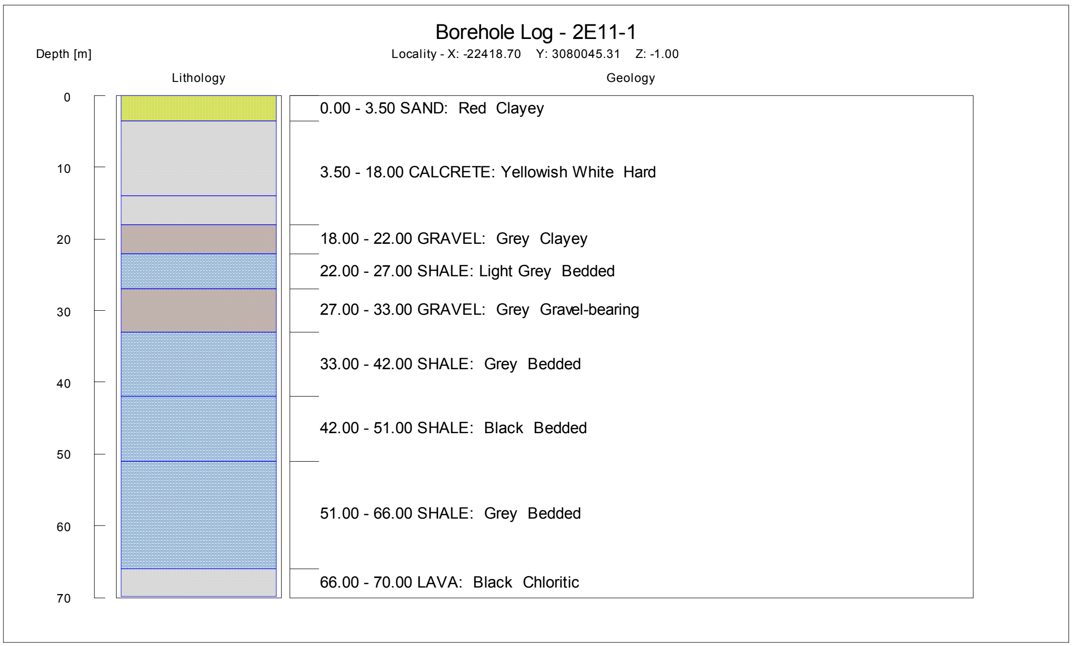


Figure 25: Borehole log for Borehole 2E11-1

In the above diagram, Figure 25, borehole 2E11-1, a typical lithology for the geology found in the Vaalharts is seen. The topsoils vary in depth between 3.5m, as seen in this example, and a maximum depth of 12.5m. The topsoils vary between being sandy, silty or clayey in composition.

The calcrete layer, where present, varies in depth between 0m and 16m. The degree of weathering within the calcrete also varies. The calcretes visible on the surface seem to have developed a small degree of fracturing, while those below the surface are relatively fresh and dense.

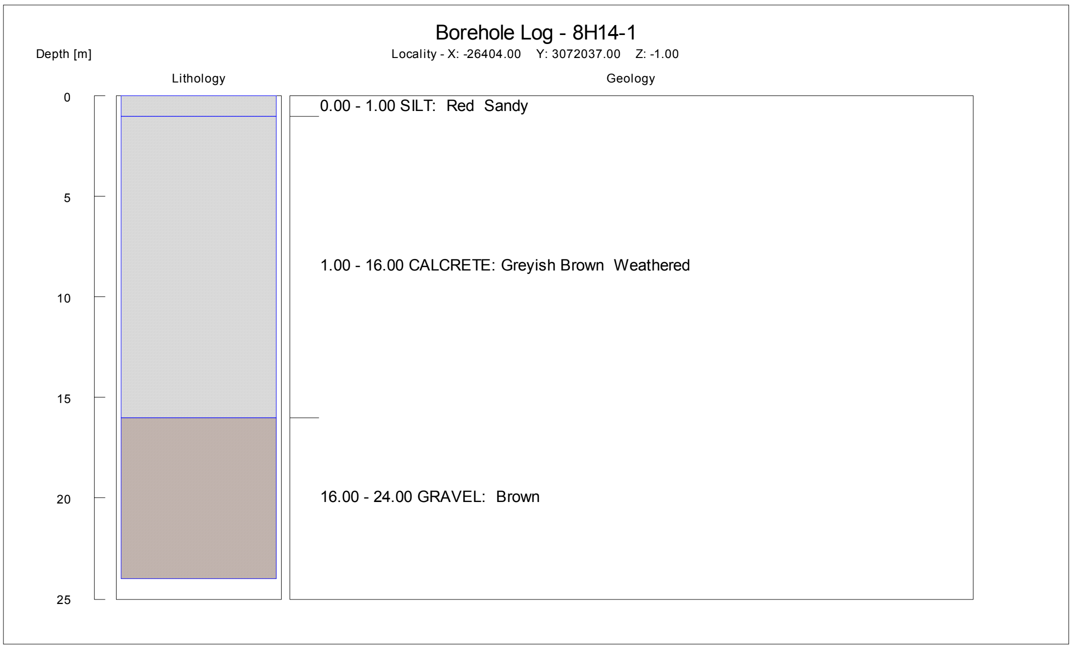


Figure 26: Borehole log taken from borehole 8H14-1 illustrating the depths of calcretes that can be seen in the Vaalharts Basin

The gravels that are seen in the Vaalharts area vary in position and depth. They can be seen above the shales. They generally consist of alluvial wash of pre-Karoo rocks, although more localised gravels can also be found. They seem to lie in lenses, scattered across the Vaalharts valley. The gravels vary between 1m and 4m in thickness.

The Dwyka shales that are found in the Vaalharts are generally continuous. The shales themselves vary in terms of colour, grain size, and depth. The shales vary in shades of grey, while black shales can also be found. Some black shale is mineralised with amounts of chlorite, whereas other shales are devoid of visible minerals. The grain size distribution of the shales varies between being very fine-grained, fine-grained, and medium-grained. The depths of shales can also vary. Shales may be found to be 88m thick, as is the case in borehole 1K10-1, while shales may be non-existent as in borehole 1B10-1's log.

Seven of the seventeen boreholes were drilled until they reached the Ventersdorp lavas. The boreholes include the two boreholes drilled on plot 6L16, and those drilled on plots 2E11, 1B10, 1B8, 1G14, 1D7, and 1K10. The depths at which the lavas were encountered in these boreholes varied between 8m, as is the case with borehole 1D7-1, and 98m as with borehole 1K10-1. The lavas appeared to be rather mineralised, with chlorite being largely present. The lavas encountered were extremely dense, and seemed to act as an aquiclude to the above aquifer.

Figure 27: The DWAF drill used in the Vaalharts

4.2.4 BOREHOLE CONSTRUCTION

All boreholes drilled during this research were drilled to a diameter of 0.165m. The boreholes were predominantly cased with a 4mm steel casing, although three of the boreholes drilled on the banks of the Harts River were cased with Johnson screens. Furthermore, three of the seventeen boreholes drilled during this research were equipped with piezometers. In all boreholes, casing and screens used for the borehole construction were slotted to allow free flow of groundwater through the boreholes and accurate groundwater investigation. The boreholes were slotted from a metre below the depth of the Kalahari sands to disallow clogging of the borehole from these sands.

Table 2 illustrates the borehole depths. Boreholes were drilled to depths of between 20m and 101m. As previously mentioned, this is believed to give a clear indication of aquifer mechanics and groundwater chemistry in the Vaalharts.

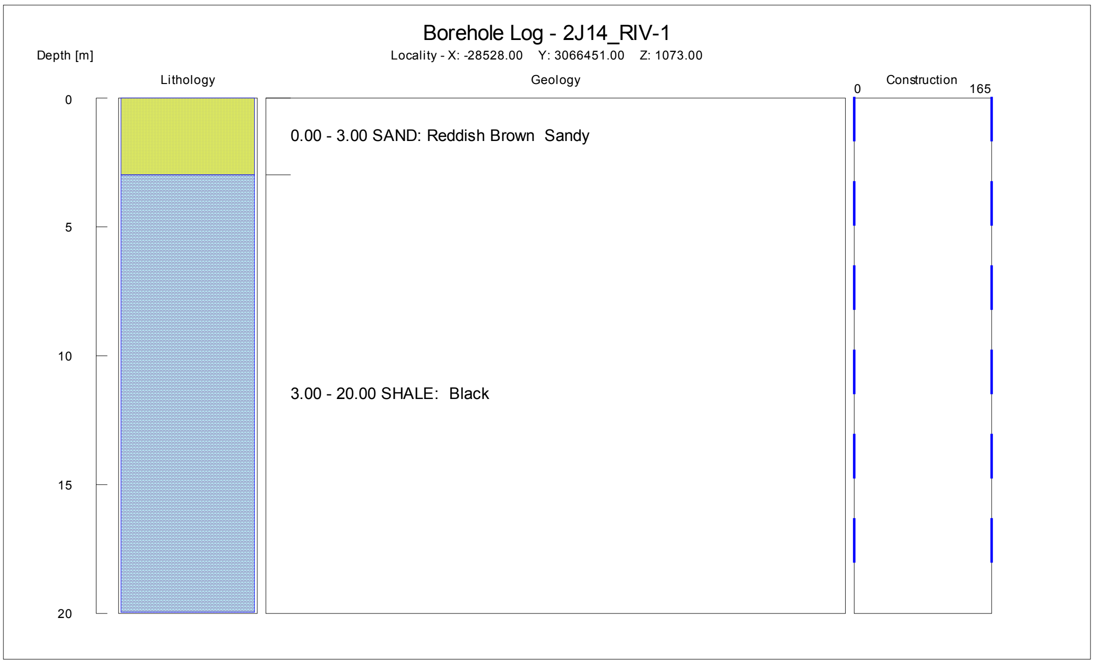


Figure 28: Diagram of borehole 2J14_RIV-1 illustrating the borehole construction

An illustration of the construction is seen in Figure 28.

4.2.4.1 PIEZOMETERS

'A piezometer is an open-ended pipe, placed in a borehole that has been drilled to a desired depth in the ground. The bottom tip of the piezometer is fitted with a perforated or slotted screen, 0.5 to 1m long, to allow the inflow of water' (Krusemann and de Ridder, 1994).

Piezometers were installed in three boreholes across the North Canal area. The boreholes used are believed to deliver an accurate representation of the general geology in the Vaalharts. The piezometers were installed to test the conceptual model of Herold and Bailey (1996), where they assumed there to be two aquifers in the Vaalharts-an upper, perched aquifer relating to the calcretes, and a deeper aquifer. The presence of two such aquifers would mean that there was a difference in both water levels and chemistry between these aquifers. The best manner of investigation to test these hypotheses was to insert piezometers.

The boreholes selected for the piezometers included lithologies of shale, calcrete and shale, and gravel, calcrete and lava. All the boreholes selected included Kalahari sands.

The following steps were taken to ensure complete accuracy from the piezometers:

- All the pipes used for the piezometers were cut longitudinally in 5mm x 100mm lengths.
- The piezometers were capped at their base to exclude the entry of fines.
- Gravel packs were inserted to a metre below the contact with the above lithology.
- A two-metre section of bentonite pellets were inserted on these gravel packs.
- This step was repeated for each lithological unit.
- The piezometer pipes were only slotted within their lithological unit, and remained intact in above units.
- Piezometers were installed for each lithological unit to test whether there is any discontinuance between these units.

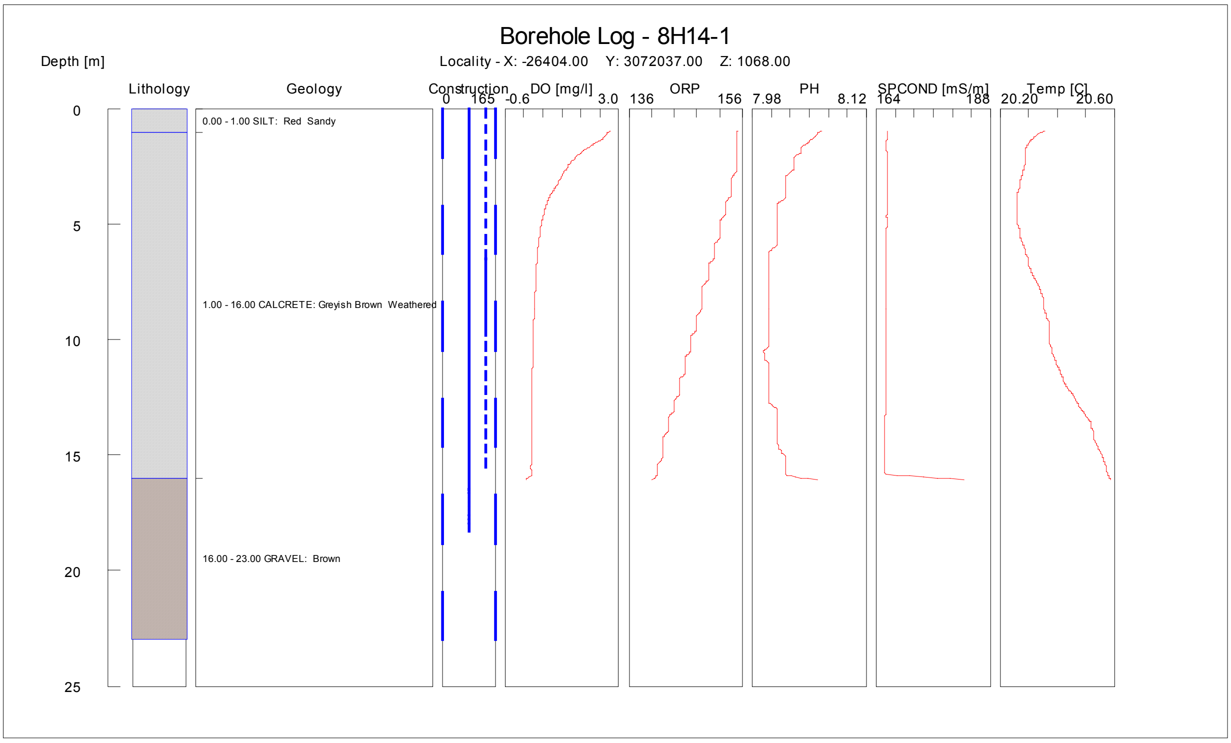


Figure 29: Borehole log for borehole 8h14-1 illustrating the two piezometers inserted into this borehole together with the borehole log and hydrochemical profile

Figure 29 illustrates the geological log for borehole 8H14-1 and the two piezometers inserted into this borehole. The piezometers used in this borehole were installed to test the continuity between the gravels and calcretes.

The results gained from measuring the water levels and chemistry in the piezometer-fitted boreholes indicates that there is no perched aquifer in the Vaalharts. The water levels measured in these piezometers had no variation from the other piezometers in that particular borehole. The hydrochemistry from the various piezometers also delivered similar results.

The aquifer in the Vaalharts therefore seems to be continuous.

4.2.5 INTEGRATED GEOLOGICAL MODEL

The geological logs gathered during the drilling phase of this project were entered into a geological visualisation program, Rockworks (Version 3.4.1.6, Rockware Incorporated). This program enabled us to model the geology in the Vaalharts based upon the drilling work that was undertaken during this project. The geological visualisation, however, could only be focussed on the Irrigation Scheme side of the Harts River, as this was the focus of the research.

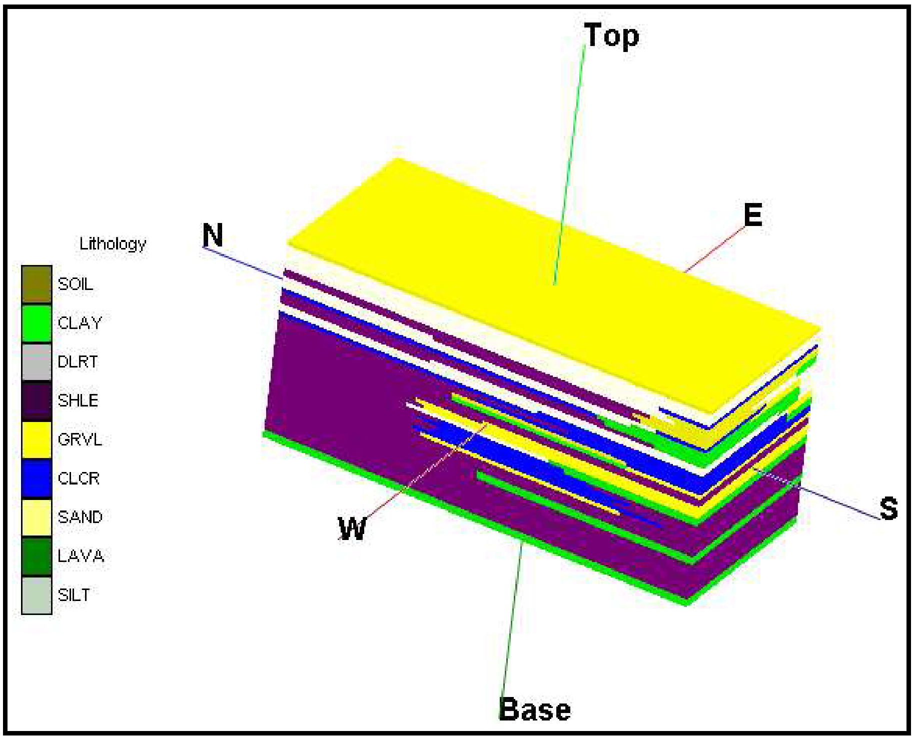


Figure 30: Diagram illustrating the modelled geology in the Vaalharts

In, Figure 30 above, a diagram illustrates the modelled geology on the eastern side of the Harts River. The lithology legend is provided to the left of the geology model. The geology model shows thicker shales to the northern side of the Vaalharts Irrigation Scheme, with thinner shales in the south of the scheme. In addition, while the model indicates calcretes throughout the scheme, the calcretes are more pronounced in the southern half of the scheme. The southern half of the scheme's geology is represented more by gravels and clays. This may be due to possible erosion and deposition as the Harts River meandered during the Vaalharts' geological history.

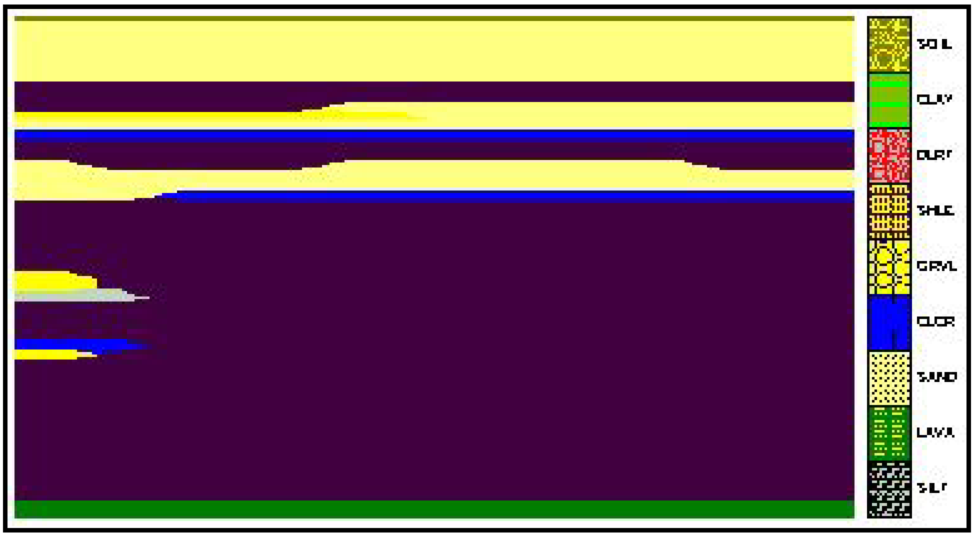


Figure 31: Diagram illustrating an east–west cross–section of the modelled Vaalharts geology in the north

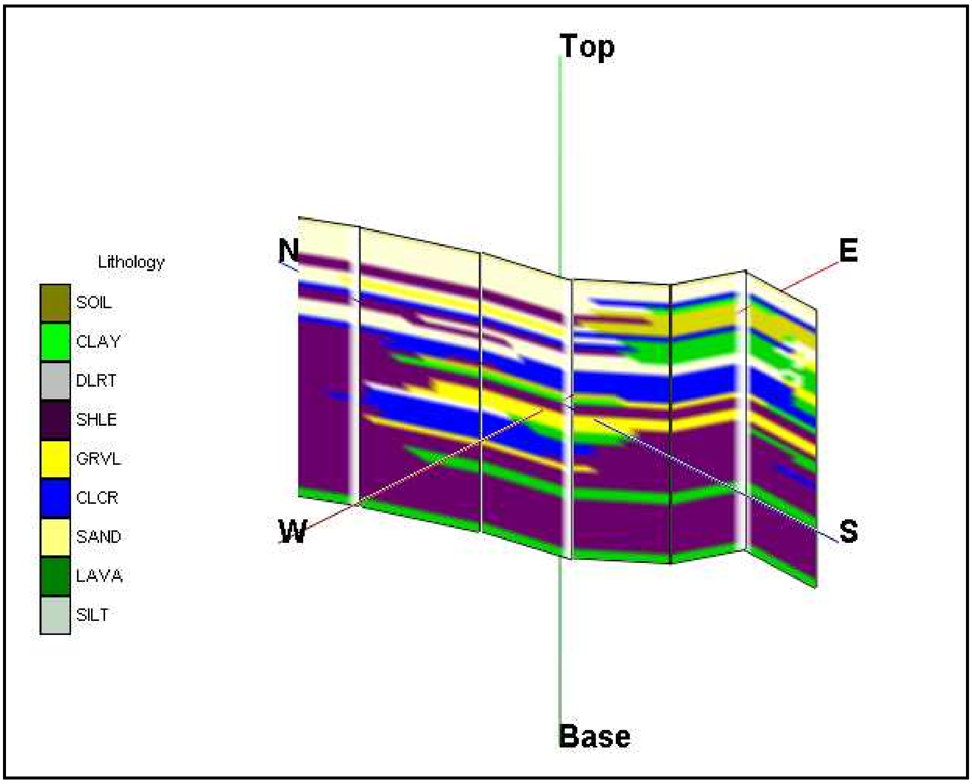


Figure 32: Diagram illustrating a fence diagram of the modelled Vaalharts geology from north to south

In the above two diagrams, Figure 31 illustrates an east - west cross - section of the modelled Vaalharts geology from boreholes in the north of the Scheme, while Figure 32 represents a fence diagram of the geology from north to south in the south of the Vaalharts Scheme. The difference between these two diagrams is the amount of clays, gravels and calcrete, with the southern half of the Vaalharts presenting a larger amount of clays, gravels and calcrete.

4.3 AQUIFER PARAMETER TESTS

Various aquifer parameter tests have been used during the fieldwork stage of this research in order to understand the aquifer mechanics occurring in the Vaalharts. The tests used include slug tests, multi rate pump tests, constant rate pump tests and tracer tests. All of these methods will be discussed further in this chapter.

Each of these tests has the ability to give either different information about the aquifer mechanics, or confirm information discovered in another type of aquifer parameter test.

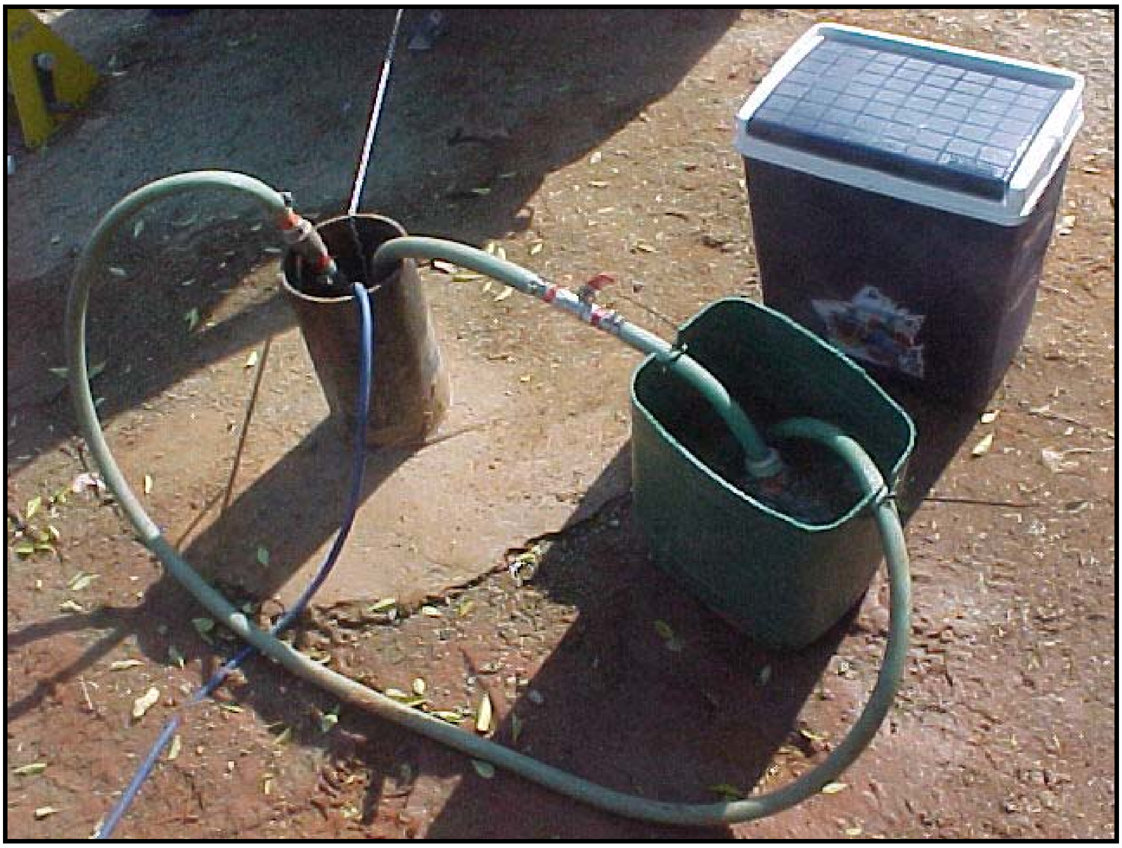


Figure 33: Photo illustrating the arrangement used to conduct the Tracer tests at the Vaalharts

4.3.1 TYPES OF TESTS

4.3.1.1 SLUG TESTS

A slug test is a method used to measure the hydraulic conductivity or transmissivity of a borehole. This is done by measuring the rate of recovery or recession in the borehole, following a sudden addition into the borehole or extraction of water from the borehole of a known volume. When a closed cylinder is inserted into a borehole, the static water level will rise, as the cylinder replaces its own volume in the borehole. This action will increase the pressure within the borehole. The equilibrium in the water level is altered, and the water level will then recover to its initial water level. By measuring the rate of recovery, or recession, the borehole's transmissivity or hydraulic conductivity can be measured. In order to gain an accurate result from a slug test, a recovery of at least 90% of its initial value is needed (Van Tonder *et al*, 2002).

A method was developed by Vivier *et al* (1995) to estimate the yield of a borehole. In order for this method to work, a borehole with 0.165m diameter is necessary. The water level also needs to recover to at least 90% of its original water level. The formula derived by Vivier *et al* (1995) is as follows:

$$y = 117155\,x^{-0.824}$$

Where: x=recession time in seconds

y=possible yield of the borehole in L/h

The determination of the hydraulic conductivity from a steady state slug test is mainly reliant on two equations. The Bouwer and Rice (1976) equations were based on the Thiem equation, below.

$$Q = 2\pi K L_e \frac{h_t}{\ln(r_e / r_w)}$$

Where

Q = well discharge in m^3/d
K = hydraulic conductivity of the aquifer around the borehole
L_e = effective length of the screened or open section of borehole
L_w =distance between the water table and bottom of the aquifer
H_0 = height of water table above the impermeable base of the aquifer
r_e = effective radial distance over which the head loss occurred
r_w = radial distance of disturbed zone from the borehole's centre
h_t head in the well at time $t > t_0$

The Thiem equation, above, led Bouwer and Rice to derive the following two equations for the hydraulic conductivity determination from a slug test:

$$\ln\frac{r_e}{r_w} = \left[\frac{1.1}{\ln\left(L_w / r_w\right)} + \frac{C}{L_e / r_w}\right]^{-1} \qquad (1)$$

The above equation (1) is valid for a fully penetrating borehole ($L_w = h_0$). The second Bouwer and Rice equation (2) is valid for $L_w < h_0$,

$$\ln\frac{r_e}{r_w} = \left[\frac{1.1}{\ln\left(L_w / r_w\right)} + \frac{A + B\ln\left\{\left(h_0 - L_w\right)/ r_w\right\}}{L_e / r_w}\right]^{-1} \qquad (2)$$

Where the dimensionless coefficients A, B and C are functions of L_e/r_w (Bouwer and Rice, 1976) (Rudulph *et al*, 1992).

In his thesis regarding variable head tests, Rudolph indicated 'the ability of slug tests to differentiate between different types of aquifers' and that 'slug tests could…be used to identify the nature of South African aquifers' (Rudolph *et al*, 1991).

4.3.1.2 MULTI-RATE TEST

A multi rate test is a single-well test performed to evaluate the productivity of a borehole (Van Tonder *et al*, 2002). The multi rate test also gives a good indication as to the rate at which a constant rate test can be performed. The results of a multi rate test will also be able to indicate whether a constant rate test is warranted. A multi rate test is conducted by pumping the borehole at increasing rates over time steps that are not necessarily equal. A step-drawdown test can also be used with decreasing pumping rates, but then the results should be analysed with the Birsoy-Summer's Method.

The Birsoy-Summers Method (1980) was presented for a "drawdown response in a confined aquifer that is pumped step-wise or intermittently at different discharge rates" (Krusemann and De Ridder, 1994). By applying the superposition to Jacob's approximation of the Theis equation:

$$s = \frac{2.30Q}{4\beta KD} \log \frac{2.25KDt}{r_2 S}$$

The following expression for the drawdown in the aquifer at time t during the nth pumping period of intermittent pumping

$$S_n = \frac{2.30Q_n}{4\Pi KD} \log \left\{ \left(\frac{2.25KD}{r_2 S} \right) \beta t(n)(t - t_n) \right\}$$

Where

$$\beta t(n) = \prod_{i=1}^{n-1} \left(\frac{t - t_i}{t - t'_i} \right)^{Q_i / Q_n}$$

$$= \left(\frac{t - t_i}{t - t'_i} \right)^{Q_1 / Q_2} x \left(\frac{t - t_2}{t - t'_2} \right)^{Q_2 / Q_n} x \ldots x \left(\frac{t - t_{n-1}}{t - t'_{n-1}} \right)^{Q_{n-1} / Q_n}$$

Where

t_i = time at which the I-th pumping period started

$t-t_i$ = time since the I- th pumping period started

t'_I = time at which the I - th pumping period ended

$t-t'_I$ = time since the I-th pumping period ended

Q_i = constant well discharge during the I-th pumping period

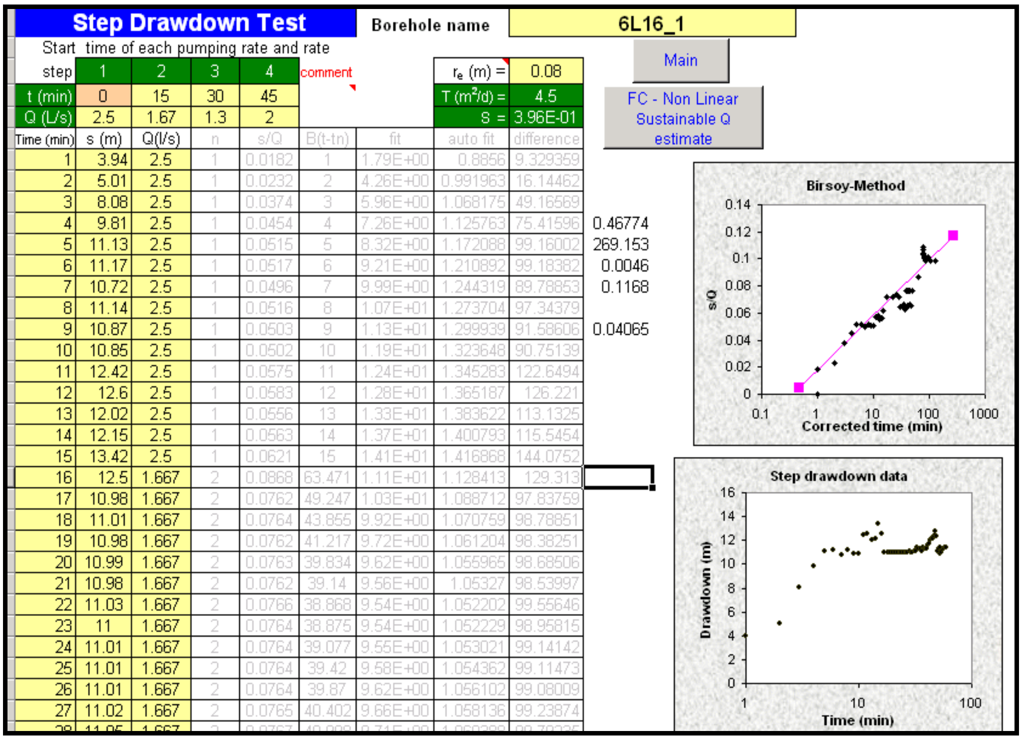
(Birsoy and Summers, 1980)

The Birsoy-Summers Method can be used if the following assumptions and conditions are satisfied (Krusemann and De Ridder, 1994):

- The aquifer is confined
- The aquifer has a seemingly infinite areal extent
- The aquifer is homogenous, isotropic, and of uniform thickness over the area influenced by the test
- Prior to pumping, the piezometric surface is horizontal over the area that will be influenced by the test
- The well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow
- The aquifer is pumped step-wise or intermittently at a variable discharge rate or is intermittently pumped at a constant discharge rate
- The flow to the well is in a steady state

These assumptions therefore allowed the Birsoy-Summers (1980) method of analysis to be applied to the multi rate pumps tests conducted in the Vaalharts Irrigation Scheme during this research. The assumptions agreed with the conceptual model constructed during this research from literature and from drilling experience in the Vaalharts Irrigation Scheme during this period.

The results gathered from a step-drawdown test could be used to determine the hydraulic conductivity of the area surrounding the borehole. These hydraulic conductivity values can then be used in the numerical models of groundwater flow for the Vaalharts area. It should be remembered however, that the storativity values attained from the step-drawdown test results analysis are inaccurate, and should be discarded in favour of s-values attained in constant rate tests (Krusemann and de Ridder, 1994)



Step Drawdown Test Borehole name: 6L16_1

Start time of each pumping rate and rate

step	1	2	3	4	comment
t (min)	0	15	30	45	
Q (L/s)	2.5	1.67	1.3	2	

r_e (m) = 0.08

T (m^2/d) = 4.5

S = 3.96E-01

0.46774
269.153
0.0046
0.1168
0.04065

Time (min)	s (m)	Q(l/s)	n	s/Q	B(t-tn)	fit	auto fit	difference
1	3.94	2.5	1	0.0182	1	1.79E+00	0.8856	9.329359
2	5.01	2.5	1	0.0232	2	4.26E+00	0.991963	16.14462
3	8.08	2.5	1	0.0374	3	5.96E+00	1.068175	49.16569
4	9.81	2.5	1	0.0454	4	7.26E+00	1.125763	75.41596
5	11.13	2.5	1	0.0515	5	8.32E+00	1.172088	99.16002
6	11.17	2.5	1	0.0517	6	9.21E+00	1.210892	99.18382
7	10.72	2.5	1	0.0496	7	9.99E+00	1.244319	89.78853
8	11.14	2.5	1	0.0516	8	1.07E+01	1.273704	97.34379
9	10.87	2.5	1	0.0503	9	1.13E+01	1.299939	91.58606
10	10.85	2.5	1	0.0502	10	1.19E+01	1.323648	90.75139
11	12.42	2.5	1	0.0575	11	1.24E+01	1.345283	122.6494
12	12.6	2.5	1	0.0583	12	1.28E+01	1.365187	126.221
13	12.02	2.5	1	0.0556	13	1.33E+01	1.383622	113.1325
14	12.15	2.5	1	0.0563	14	1.37E+01	1.400793	115.5454
15	13.42	2.5	1	0.0621	15	1.41E+01	1.416868	144.0752
16	12.5	1.667	2	0.0868	63.471	1.11E+01	1.128413	129.313
17	10.98	1.667	2	0.0762	49.247	1.03E+01	1.088712	97.83759
18	11.01	1.667	2	0.0764	43.855	9.92E+00	1.070759	98.78851
19	10.98	1.667	2	0.0762	41.217	9.72E+00	1.061204	98.38251
20	10.99	1.667	2	0.0763	39.834	9.62E+00	1.055965	98.68506
21	10.98	1.667	2	0.0762	39.14	9.56E+00	1.05327	98.53997
22	11.03	1.667	2	0.0766	38.868	9.54E+00	1.052202	99.55646
23	11	1.667	2	0.0764	38.875	9.54E+00	1.052229	98.95815
24	11.01	1.667	2	0.0764	39.077	9.55E+00	1.053021	99.14142
25	11.01	1.667	2	0.0764	39.42	9.58E+00	1.054362	99.11473
26	11.01	1.667	2	0.0764	39.87	9.62E+00	1.056102	99.08009
27	11.02	1.667	2	0.0765	40.402	9.66E+00	1.058136	99.23874

Figure 34: FC – Program step–drawdown analysis sheet from borehole 6L16_1 in the Vaalharts area used for the multi–rate analysis

The minimum time duration for a multi rate test is four steps of fifteen minutes, equating to a total test of one hour. This is a minimum, and the test can be run over a longer period. Pumping the borehole for a period of time until the drawdown stabilises runs the test. The pumping rate can then be increased until the drawdown once again stabilises. The drawdown in the borehole must be measured and recorded in accordance with a prescribed time schedule (Van Tonder *et al*, 2002).

The pump tests conducted in this project were analysed using the FC - Method (Flow Characteristic Method) (Van Tonder *et al*, 2002).

The FC software was developed by Van Tonder *et al* (2001) for the Department of Water Affairs and Forestry. It includes the following methods of analysis:

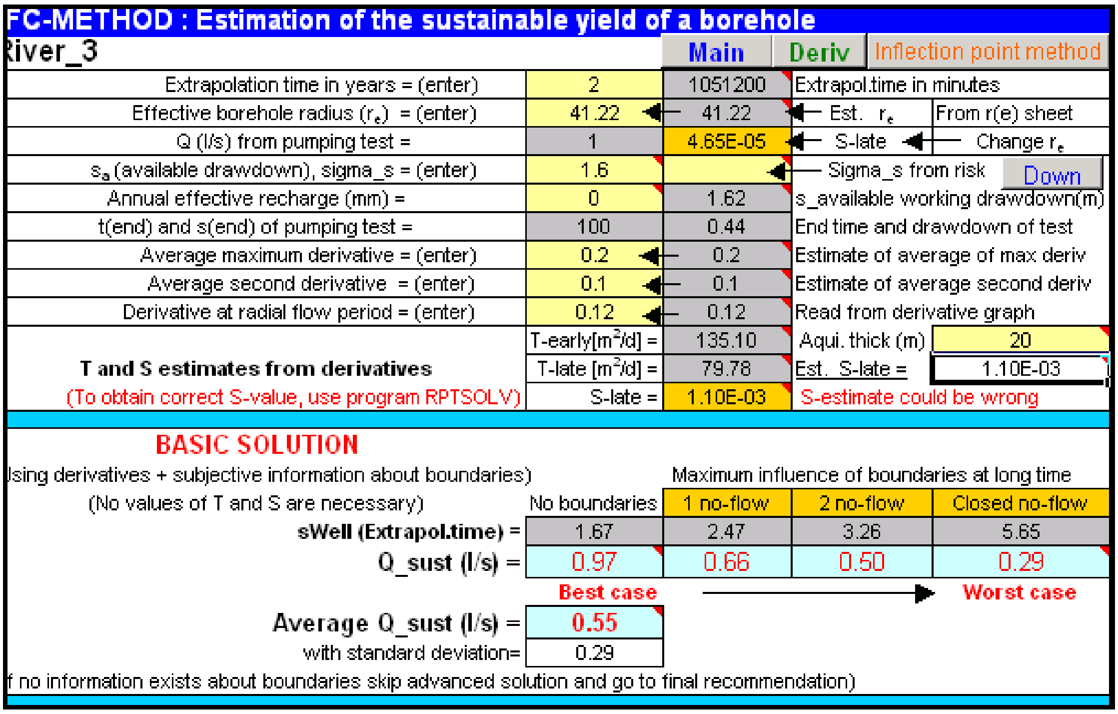
- Porous aquifer solutions (Theis, Cooper-Jacob I and II, Hantush methods and also a solution for water table aquifers)

- Step drawdown and multi rate analysis
- Fractal pumping test analysis (Barker's Generalized Radial Flow model)
- Slug test analysis (Bouwer and Rice method)
- Estimation of a risk-based sustainable yield of a borehole by using drawdown derivatives, boundary information and error analysis
- Testing the suitability of the water according to Classes used by DWAF
- Different diagnostic plots for flow regime identification (eg. Derivatives, second derivatives, LogLog (Theis)-plot, LinLog (Cooper-Jacob)-plot, square root of time plot, fourth root of time plot, spherical and recovery plot)
- Delineation of borehole protection zones in fractured aquifers
- Refer to Section 2.4.1

(Van Tonder *et al*, 2001)

4.3.1.3 CONSTANT RATE TEST

A constant rate test is "performed in order to assess the productivity of the aquifer according to its response to the abstraction of water" This response can be analysed to provide information with regard to the hydraulic properties of the groundwater system (Van Tonder *et al*, 2002). The information gained from a constant rate test enables the determination of the optimal sustainable yields of the borehole, for various time and drought scenarios.



FC-METHOD : Estimation of the sustainable yield of a borehole

iver_3

Extrapolation time in years = (enter)	2	1051200	Extrapol.time in minutes	
Effective borehole radius (r_e) = (enter)	41.22	41.22	Est. r_e	From r(e) sheet
Q (l/s) from pumping test =	1	4.65E-05	S-late	Change r_e
s_a (available drawdown), sigma_s = (enter)	1.6		Sigma_s from risk	Down
Annual effective recharge (mm) =	0	1.62	s_available working drawdown(m)	
t(end) and s(end) of pumping test =	100	0.44	End time and drawdown of test	
Average maximum derivative = (enter)	0.2	0.2	Estimate of average of max deriv	
Average second derivative = (enter)	0.1	0.1	Estimate of average second deriv	
Derivative at radial flow period = (enter)	0.12	0.12	Read from derivative graph	
	T-early[m^2/d] =	135.10	Aqui. thick (m)	20
T and S estimates from derivatives	T-late [m^2/d] =	79.78	Est. S-late =	1.10E-03
(To obtain correct S-value, use program RPTSOLV)	S-late =	1.10E-03	S-estimate could be wrong	

BASIC SOLUTION

Jsing derivatives + subjective information about boundaries)

(No values of T and S are necessary)

		Maximum influence of boundaries at long time		
	No boundaries	1 no-flow	2 no-flow	Closed no-flow
sWell (Extrapol.time) =	1.67	2.47	3.26	5.65
Q_sust (l/s) =	0.97	0.66	0.50	0.29
	Best case			**Worst case**
Average Q_sust (l/s) =	**0.55**			
with standard deviation=	0.29			

f no information exists about boundaries skip advanced solution and go to final recommendation)

Figure 35: Example of the sustainable yield analysis sheet used in the FC Method program

The duration of the constant rate test depends on the objectives of the test results. It is obviously important that the borehole be stressed sufficiently in order for the water level to reach the main water strike. Although an eight-hour test is usually recommended for the purpose of sustainable yield, a two-hour test is sufficient to gain parameters such as storativities and transmissivities if radial flow is measured, as in the case of the Vaalharts (Van Tonder *et al*, 2002).

In the majority of cases within the Vaalharts research, where step-rate tests were not performed, constant rate tests were conducted. In certain cases, where the slug test yielded hydraulic conductivities so low a yield that neither multi rate nor constant rate tests were feasible, the hydraulic conductivity gained from the slug test was used.

4.3.1.4 TRACER TESTS

4.3.1.4.1 TYPES OF TRACERS

There are two types of materials that can be used to conduct tracer tests, namely natural or artificial tracers. Natural tracers include isotopes such as O_{18}, whereas artificial tracers are tracers that have been introduced into the natural system. These include radioactive tracers, activatable tracers, chemical tracers and particulate tracers.

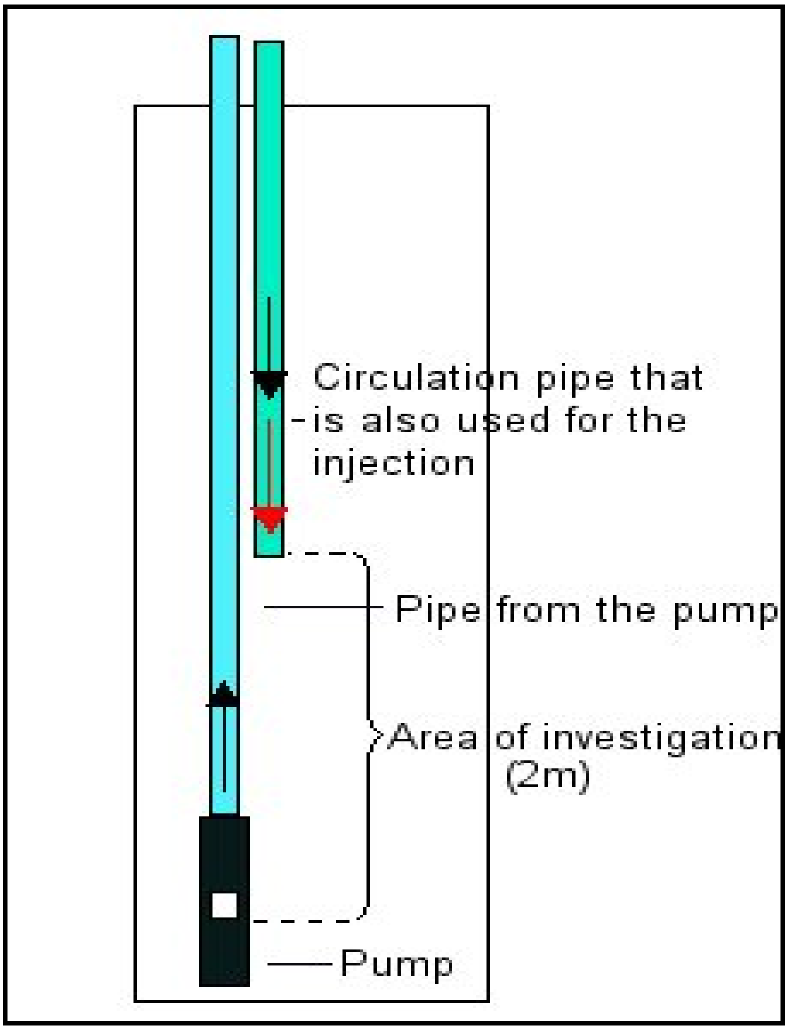


Figure 36: The method used for the preparation of an injection-withdrawal tracer test (Riemann, 2002)

4.3.1.5 DEFINITION

“Tracers are identifiable substances that, from the examination of their behaviour in a flowing medium, may be used to infer the general behaviour of the medium” (Riemann, 2002). Artificial tracers are used in the field of geohydrology in order to trace fluid movement and dispersion.

4.3.1.6 SELECTION

The ideal groundwater tracer needs to exhibit the following characteristics:

1. Conservative, and will follow the movement of the water without loss from the flow due to physical or chemical processes, for example adsorption on sediments or equipment
2. Non - toxic, can be applied with no administrative or legislative requirements
3. Detectable with a high sensitivity and can be measured accurately *in - situ* in the field
4. Does not contaminate the terrain of investigation and does not affect results of further tests
5. Inexpensive, and analysis costs are relatively low (Riemann, 2002).

4.3.1.7 TYPES OF TRACER TESTS

The type of tracer test that was used during the investigation into the quantification of the salts in the Vaalharts Irrigation Scheme was a single-well Injection Withdrawal test. Leap and Kaplan first described the single-well Injection Withdrawal Tracer test for the estimation of groundwater flow velocities in 1988.

The single-well Injection - Withdrawal tracer test is conducted by injecting a known volume of tracer solution into the test borehole, allowing the tracer to drift under the influence of the natural hydraulic gradient for a period, and then removing the tracer by pumping the test borehole to recover the tracer (Riemann, 2002).

During the Injection Withdrawal tracer tests conducted in the Vaalharts during this investigation, two types of artificial tracers were used. The tracers used were either NaCl (sodium chloride) or NaBr (sodium bromide). In some cases, both artificial tracers were used.

4.3.1.8 TEST RESULTS AND ANALYSES

4.3.1.8.1 SLUG TESTS

The slug tests provide two pertinent results. The results of major interest were firstly, and most importantly, values of hydraulic conductivity for the boreholes tested, and therefore the hydraulic conductivity of the area surrounding the borehole. The second result was an appropriate indication for a pumping rate for the constant rate and multi rate pumping tests. The slug tests were also able to give an approximate value for the hydraulic conductivity of the fractures present in the borehole.

The hydraulic conductivity results that were encountered from the slug tests covered a wide range of values. The slug tests conducted in the Vaalharts area delivered recoveries that were incomplete within a 30-minute period, whereas other boreholes recovered so quickly that accurate measurements were impossible. The hydraulic conductivities that *could* be measured ranged between 0.1m/d and 2.0m/d. These values give an average hydraulic conductivity for the full lithology in the particular borehole.

4.3.1.8.2 MULTI-RATE PUMP TESTS

The multi rate pump tests were performed on four of the seventeen boreholes drilled during this phase of the project. The complement of the boreholes were either tested using the above-mentioned slug tests or constant rate pump tests.

The multi - rate test results could be analysed for hydraulic conductivity, transmissivity and storativity. While the hydraulic conductivity and transmissivity of the boreholes are quite accurate, a certain degree of uncertainty exists when calculating the storativity with multi rate pump test results.

The transmissivities gained from the multi rate pumping tests range between the values of 4.2m^2/d for both boreholes 6L16-1 and 6L16-2and 43.3m^2/d for borehole 1G14-1. The final borehole tested by means of multi rate tests was borehole 1K10-1, which yielded a transmissivity of 31.6m^2/d. These boreholes yielded hydraulic conductivity values of between 0.1 m/d and 1.66 m/d.

As previously mentioned, the storage coefficients gained from the multi rate pump tests are not completely accurate, as no observation boreholes were present for these tests. Whereas the boreholes that were multi rate tested delivered storage coefficient values in the order of 10^{-01} .The boreholes that were tested by means of constant rate pump tests delivered storage coefficient values in the order of 10^{-03}. The storage coefficient values obtained from the multi rate pump tests should rather be ignored for accuracy reasons.

Table 3: Hydraulic conductivies and transmissivities of the boreholes that were multi rate pump tested

BOREHOLE	TRANSMISSIVITY	HYDRAULIC CONDUCTIVITY
1G14-1	43.3 m^2/d	1.66 m/d
1K10-1	31.6 m^2/d	0.3 m/d
6L16-1	4.2 m^2/d	0.1 m/d
6L16-2	4.2 m^2/d	0.11 m/d

4.3.1.8.3 CONSTANT RATE TESTS

The constant rate tests are generally more accurate than the multi rate tests in terms of their sustainable yields, transmissivities, hydraulic conductivities and storativities. It is however, recommended that, in order to gain a correct sustainable yield, the borehole be should pump tested for a minimum of eight hours, and that the main water strike should be reached during that test. It was, however, decided that the constant rate pump test should only be conducted for a two-hour period, because correct storage coefficient and transmissivity values could be gained from this time period. Sustainable yield determination was not the object of these tests.

In five of the six boreholes tested using the constant rate pump test method, the boreholes were first tracer tested, and were then constant rate pump tested. This combined the two tests and increased efficiency. The method used was as follows:

- Firstly, begin the circulation phase of the injection withdrawal tracer test
- Effort must be made to keep the waterlevel constant throughout the injection phase
- At the circulation / injection end time, the pipe exiting the borehole should be removed from the circulation bucket
- Water levels and tracer concentration must then be measured simultaneously for a period of no less than two hours
- The withdrawal phase has a three - fold purpose, which not only completes the pump - test portion of the test, and measures the tracer breakthrough curve, but also rids the borehole of any possible tracer that may cause damage to the chemistry within the borehole
- Once the required pumping time is complete, the recovery of the borehole's water level may begin as per usual

The results of these tracer tests can be seen in Section 4.3.1.8.4.

The boreholes tested by means of constant rate pump tests gave varying results, in transmissivity (a function of hydraulic conductivity and aquifer thickness) and storativity. The sustainable yields, as mentioned, were not relevant to the objectives of the research, but have been included for interest sake.

The transmissivities that have been analysed from the boreholes tested by means of constant rate pumping tests ranged between 0.21m^2/d in borehole 1D3-1 and that of 194.43m^2/d as tested in borehole 1D7-1. This illustrates the variance of the fractured rock aquifers present in the Vaalharts. The fractured rock aquifers refer to boreholes where matrix and fractures are encountered. A borehole indicating a matrix aquifer is devoid of any fractures and is completely dense, while a borehole indicating a fractured aquifer has geology that is fractured, and therefore has preferred pathways, and provides easier methods of movement for water and solutes. The average transmissivity tested by means of constant rate test is 75m^2/d, indicating the wide range of values encountered. This value is very similar to the average transmissivity measured by Gombar and Erasmus (1976) of 69m^2/d.

The unsteady-state (or Theis) Equation, which was derived from the analogy between the flow of groundwater and the conduction of heat (Krusemann and de Ridder, 1994), is written as:

$$s = \frac{Q}{4\pi KD}\int_u^{\alpha}\frac{e^{-y}dy}{y} = \frac{Q}{4\pi KD}W(u)$$

Where:

s = the drawdown in m measured in a piezometer at a distance r in m from the well

Q = the constant well discharge in m^3/d

KD = the transmissivity of the aquifer in m^2/d

u = $\frac{r^2 S}{4KDt}$ and consequently $S = \frac{4KDtu}{r^2}$

S = the dimensionless storativity of the aquifer

t = the time in days since pumping started

The Cooper - Jacob Method, also known as the Jacob Method, was developed in 1946 (Krusemann and De Ridder, 1994). It is based upon the Theis Method. The Cooper-Jacob equation is as follows:

$$s = \frac{2.30Q}{4\pi KD} \log \frac{2.25KDt}{r^2 S}$$

The Theis and the Cooper-Jacob equations were also used for the analysis of the constant rate pump tests. The Theis Method was developed in 1935 for unsteady-state flow that introduces the time factor and storativity (Krusemann and De Ridder, 1994). Theis noted that, when a well penetrating an extensive confined aquifer is pumped at a constant rate, the influence of the discharge extends outward with time. The rate of decline of the head, multiplied by the storativity and summed over the area of influence, equals the discharge (Krusemann and De Ridder, 1994).

The storage coefficients all range within the order of 10^{-03} or 10^{-04}. This shows relative homogeneity within the storage coefficient. The lowest storage coefficient was that of borehole 2J14_Riv-3 with a value of 9.90×10^{-04} while the highest storage coefficient value encountered was shared between boreholes 1D3-1 and 8H14-1 with a value of 1.10×10^{-03}. The storage coefficient values gained from the analysis of the constant rate pump tests were all pumped boreholes, and did not use observation boreholes for measurement. The storage coefficients are therefore not completely accurate. A combination of these values, and storage coefficient values from literature were used for application to the numerical models.

The hydraulic conductivity values are linked to the transmissivity values, as transmissivity is a product of the hydraulic conductivity and the aquifer thickness. The hydraulic conductivity ranges between 0.01m/d in borehole 1D3-1 and 9.72m/d in borehole 1D7-1, which intersected a fracture. The sustainable yields also varied, with borehole 1D3-1 having a sustainable yield of 0.01l/s while borehole 1D7-1 had a sustainable yield of 7.15l/s. The average sustainable yield for the boreholes tested was 2.67l/s. These varying yields illustrate the presence of the fractured rock aquifers in the Vaalharts.

Table 4: Storage coefficients, transmissivities and sustainable yields for the boreholes that were constant rate pump tested.

BOREHOLE	STORAGE COEFFICIENT	TRANSMISSIVITY	SUSTAINABLE YIELD
1D3-1	0.01	0.21m^2/d	0.01l/s
1D7-1	0.022	194 m^2/d	7.15l/s
2J14_RIV-3	0.009	58 m^2/d	0.37l/s
8H14-1	0.01	1.2m^2/d	0.07l/s
2J5-1	0.026	123m^2/d	5.75l/s

4.3.1.8.4 TRACER TEST RESULTS

The tracer tests conducted in the Vaalharts were conducted in order to obtain the velocity of natural gradient groundwater flow. Injection Withdrawal and Point Dilution tracer tests were used for flow velocity determinations. These flow velocities are referred to as Darcy velocity and seepage velocity.

Seepage velocity: $v = \frac{Q}{n_e A} = \frac{Ki}{n_e}$

Where:

Q = volume rate of flow

n_e = porosity

A = area

The seepage velocity refers to the average local velocity at a point. The Darcy velocity, however, refers to the average velocity of the groundwater in the area. It is noted with the equation:

Darcy velocity: $q = \frac{Q}{A} = Ki$

Where: q = Darcy velocity
Q = volume rate of flow
K =hydraulic conductivity
i =gradient
A =area

The results obtained in the Injection - Withdrawal and Point - Dilution tests yielded the following results:

Table 5: Seepage Velocity from Injection Withdrawal tracer tests

BOREHOLE NUMBER	SEEPAGE VELOCITY (INJECTION - WITHDRAWAL)
1B10-1	19m/d
1D3-1	2m/d
1D7-1	31m/d
2J5-1	21m/d
8H14-1	17.5m/d

Table 6: Darcy Velocity and Seepage velocity from Point Dilution tracer tests

BOREHOLE NUMBER	DARCY VELOCITY	SEEPAGE VELOCITY (POINT DILUTION)
1B10-1	2m/d	21m/d
1D3-1	1.5m/d	15m/d
1D7-1	3m/d	29m/d
2J5-1	1m/d	9m/d
8H14-1	22m/d	217m/d

The injection-withdrawal and point dilution tracer tests' results compare favourably with the results determined in the pumping tests conducted on these boreholes during the research. Borehole 8H14-1 however, was determined to have Darcy- and seepage velocities higher than those of the other boreholes that were tracer tested. It seems that the 2-metre section of the borehole used during the tracer test, had a fracture present. This explains the reason for the relatively high Darcy- and seepage velocities, even though the transmissivity measured for the borehole is only 5m^2/d. The effective porosity value of the lithologies tested in the Vaalharts Irrigation Scheme was obtained from the Tracer Tests conducted during this project. Values of 10% effective porosity were observed in the analysis of the tests conducted.

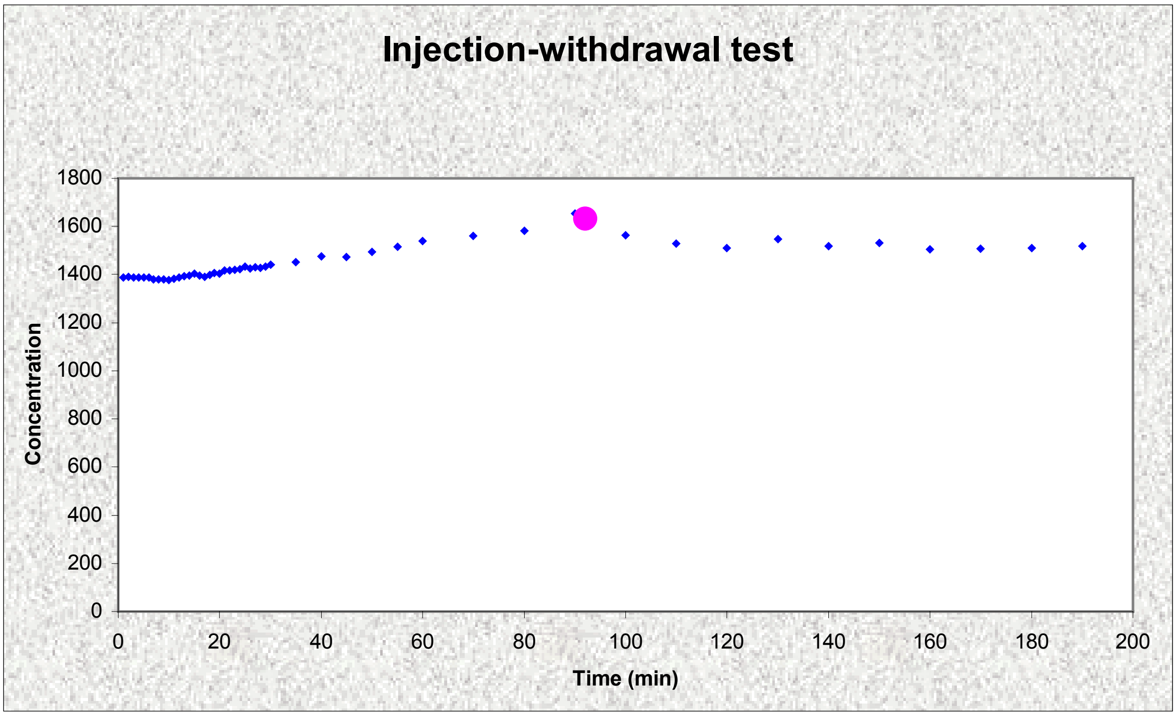


Figure 37: Example of a breakthrough curve from an Injection withdrawal tracer test conducted in the Vaalharts

4.4 WATER LEVELS

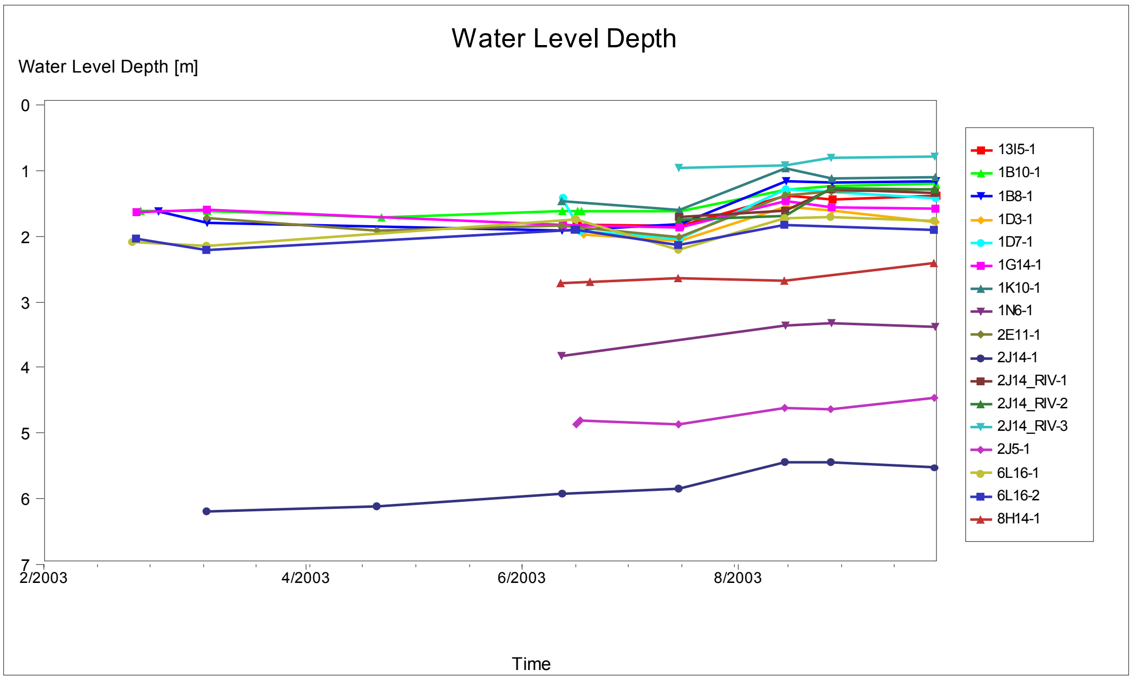


Figure 38: Water level data collected since the drilling phase of this project

In the above diagram, Figure 38, the water level data that has been collected from the boreholes drilled during the drilling phase of the project are illustrated. It is interesting to note that the majority of water level depths occur at approximately 2m below ground level. It is also important to note that these water levels have been taken during the winter months, when water levels are generally lower than during the summer months when the Vaalharts experiences its rainfall. The practice of irrigation must also be considered during this period.

In Figure 38, above, the water levels that have been taken from four boreholes, namely 2J14-1, 2J5-1, 1N6-1 and borehole 8H14-1 are generally lower than the other water levels. These can be explained by their positions relative to the topography present in their particular location. Borehole 2J5-1 is located just below the eastern plateau; borehole 1N6-1 is in the far north of the Irrigation Scheme, on the point where almost no other irrigation takes place; while boreholes 8H14-1 and 2J14-1 are located close to the Harts River, where a possibly steeper groundwater gradient seems to be occurring.

The piezometer water levels measured in the piezometers in boreholes 6L16-1, 8H14-1 and 1D7-1 were all the same as the other piezometers in their respective boreholes. The piezometers are referred to in Section 4.2.4.1.

The remaining boreholes have shown little fluctuation over this period of measurement. All the water levels have shown a slight rise following greater levels of irrigation during the early part of spring when crops are planted.

4.5 GROUNDWATER CHEMISTRY

The chemistry included in this section illustrates and discusses the present hydrochemistry: The chemistry has been collected during this project, and to a large degree, from the boreholes that have been drilled during this project.

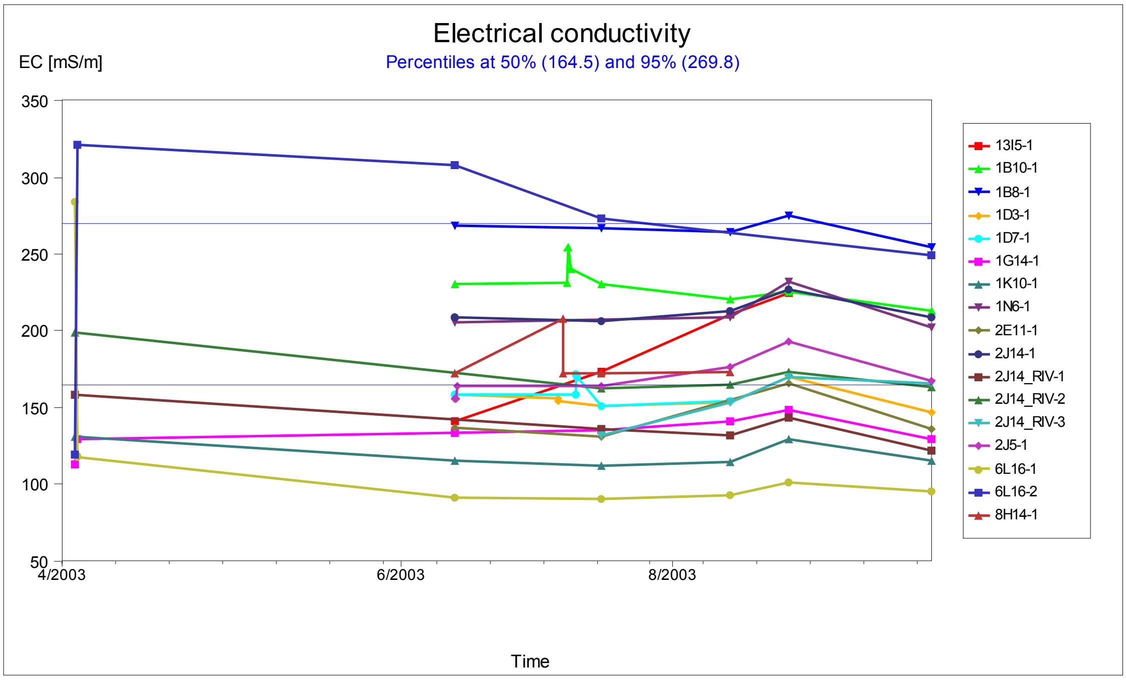


Figure 39: Electrical Conductivity values of the samples taken from the boreholes drilled during this project

In the above diagram, Figure 39, the electrical conductivity values of the samples from the boreholes drilled during this project are illustrated. The majority of the electrical conductivity values are between 100mS/m and 270mS/m, which is within the South African drinking water standards.

The two boreholes illustrating the highest and lowest electrical conductivities respectively, are interestingly enough both present on the same plot, and are within a 50m distance of each other. Borehole 6L16-1, illustrating the lowest conductivity of the samples illustrated, is drilled within 10m of a canal, which seems to be leaking water into the groundwater system via cracks in the concrete. Borehole 6L16-2 is however located within 10m of irrigated land, and seems to have a higher electrical conductivity due to the influence of the fertilizers being applied to the lands. An interpretation of the canal water and the groundwater sampled in borehole 6L16-1 is illustrated in Section 4.5.2.

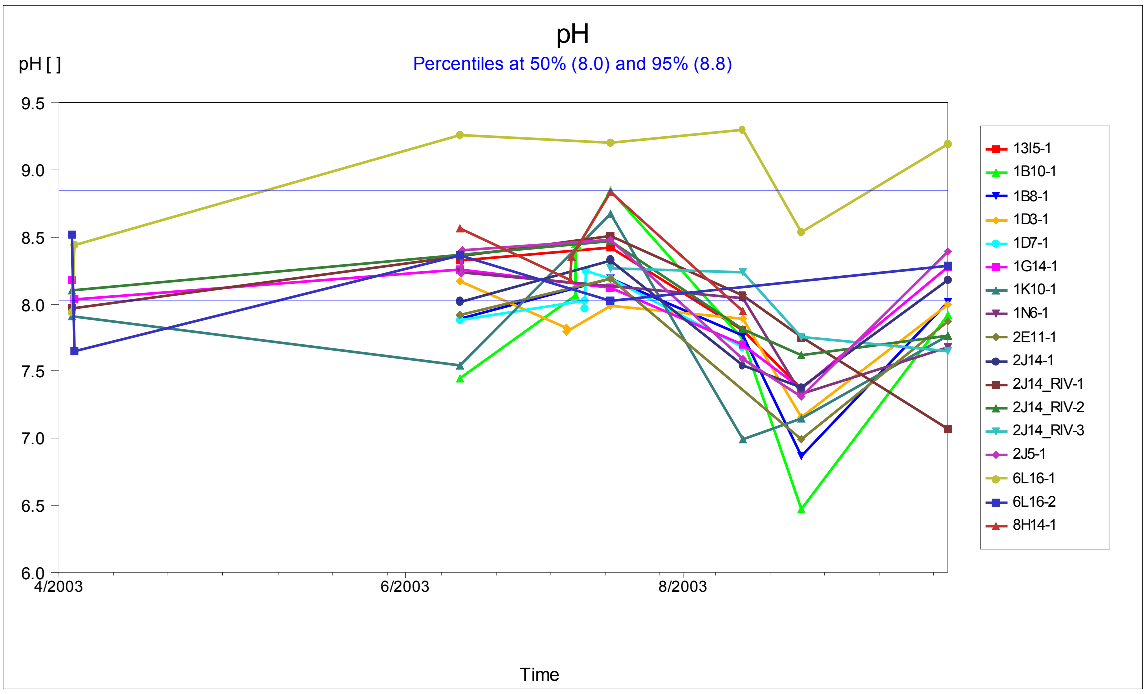


Figure 40: Time–series graph illustrating the pH values for groundwater samples collected in the Vaalharts

In the above time - series graph, the pH-values for groundwater samples collected in the Vaalharts are illustrated. As is evident from the above graph, the pH values are all within the present SA drinking water standards, with no pH-value above 9.5 pH-units. All of the pH-values seem to have shown a similar trend since late Winter/early Spring when increased irrigation began in the Vaalharts Irrigation Scheme. The pH of the groundwater fell to relatively neutral values at the beginning of the irrigation period, but seem to have returned to original level of approximately 8 pH-units.

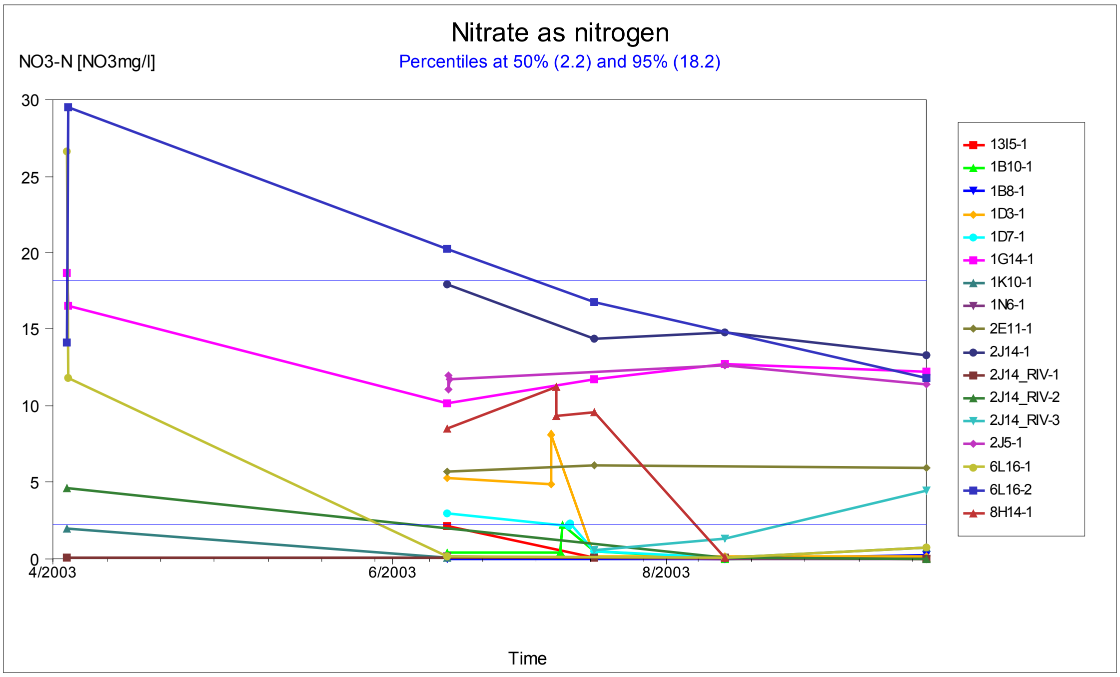


Figure 41: Time–series graph illustrating the nitrate values for groundwater samples collected in the Vaalharts

In the above time-series graph, nitrate values for groundwater samples collected from the seventeen boreholes drilled in the Vaalharts during this project are illustrated. As is evident from these data, certain of the groundwater samples are illustrating relatively high nitrate values. This may be due to a two-fold problem. Firstly, and possibly more probable, is the application of fertilizers to the irrigated lands in the Vaalharts. Secondly, and to a lesser degree, is the influence of shallow pit latrines (Hough and Rudolph, 2003).

The nitrate values in the Vaalharts seem to have all settled below a value of 15mg/l. This represents a potentially dangerous situation for people who use the groundwater for dinking purposes. The presence of nitrates in drinking water can have a toxic effect on infants, where methyglobinaemia, a form of anaemia, can occur. In this instance, the nitrogen combines with the haemoglobin. Methyglobinaemia is commonly known as ‘blue-baby syndrome.

In the article by Pulido-Bosch *et al* (1999), the natural nitrate values within geology can be as high as 20mg/l. It is difficult to separate the effect of natural nitrates from geology and man-introduced nitrates in the Vaalharts Irrigation Scheme.

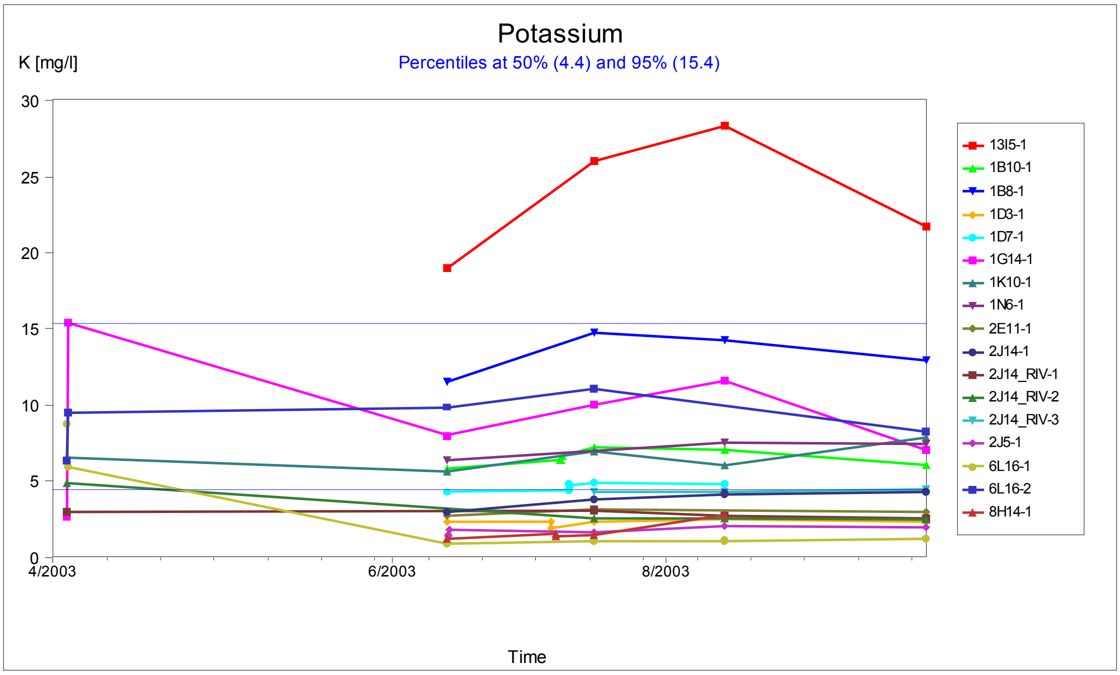


Figure 42: Time – series graph of the potassium values for groundwater in the Vaalharts

In Figure 42, potassium values for groundwater samples taken in the Vaalharts Irrigation area are illustrated. As can be seen here, there is no potassium sample having a value greater than 30mg/l, while 95% of the illustrated values fall under 15mg/l.

Potassium is one of the major elements used in the manufacture of fertilizers, the others being nitrogen and phosphate. The potassium levels in borehole 13I5-1 can be explained by possible fertilizer effects from irrigation in the nearby lands, located approximately 50m from the borehole. The potassium levels show an increase during late summer, when the wheat is usually planted, indicating that the fertilizers were probably applied simultaneously.

On the large scale, however, the potassium concentrations have remained relatively constant.

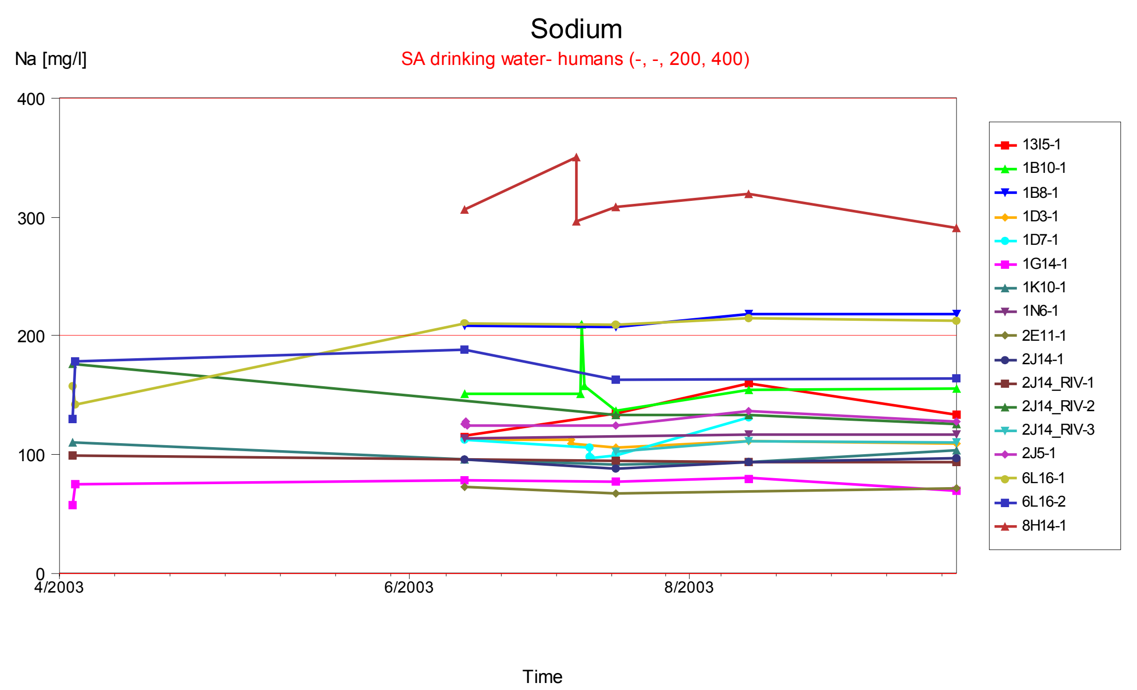


Figure 43: Time – series graph illustrating groundwater sodium values

In Figure 43, the sodium values for groundwater samples collected in the Vaalharts Irrigation area have been collected. As can be seen from this illustration, a trend of sodium values is present throughout the sampling period, and has remained relatively stable.

In borehole 8H14-1, the sodium concentration is relatively higher than in the other boreholes. The increased levels of sodium in this borehole have remained at approximately the 300mg/l mark. Borehole 8H14-1 is located on the edge of an irrigation land, and agricultural pesticides and fertilizers that have been added to this particular irrigation land may explain the sodium values.

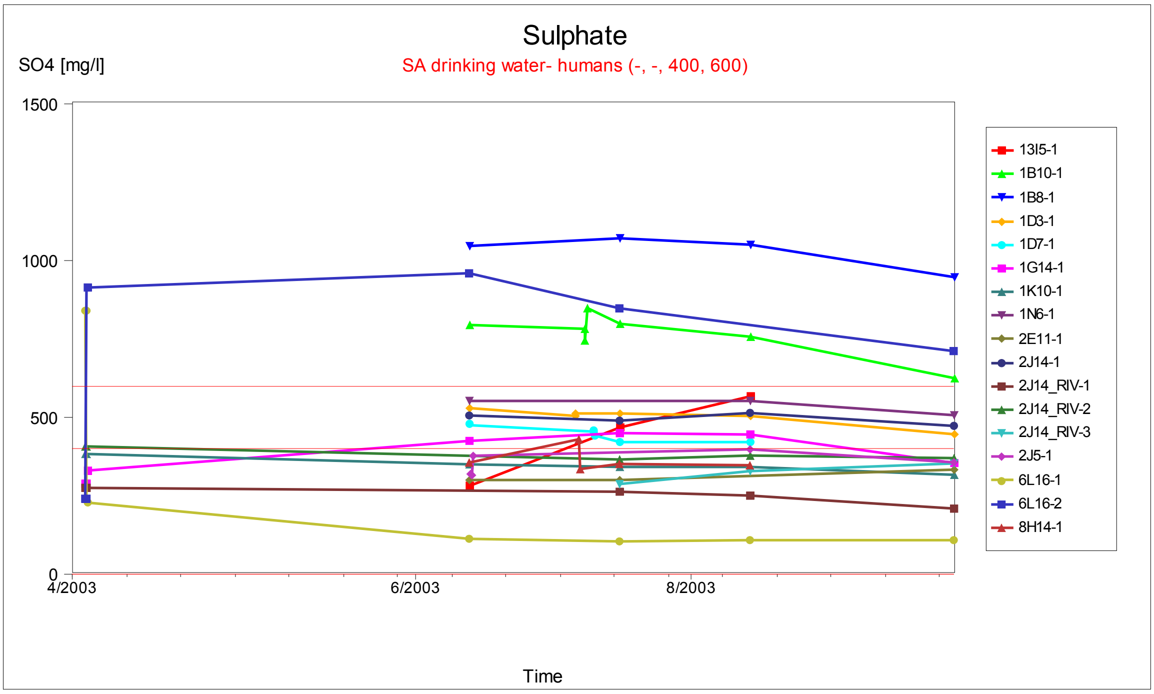


Figure 44: Time–series graph of the sulphate values from groundwater samples collected in the Vaalharts Irrigation area

In the above time-series graph, Figure 44, the sulphate values for groundwater samples collected in the Vaalharts Irrigation Scheme are shown. The sulphate values appear relatively high in concentration.

The sulphate levels illustrated in this time-series graph are possibly either associated with the incoming irrigation water from the Vaal River, from fertilizer addition or both. The annual average addition of fertilizers is 50000t, while the annual average addition of sulphates from irrigation water alone to the Vaalharts Irrigation Scheme over the past 13 years is 127300t.

4.5.1 COMPARITIVE CHEMISTRY

Geo-Hydro Technologies (GHT) conducted a sanitation protocol during 2003 in the Vaalharts Irrigation Scheme. The project was directed at the groundwater interaction with the numerous pit latrines throughout the Scheme. Due to the nature of the investigation, groundwater samples were taken from across the Vaalharts North Canal area to give an accurate representation (Hough and Rudolph, 2003). The location and groundwater chemistry sampled during this project is illustrated in the figures below.

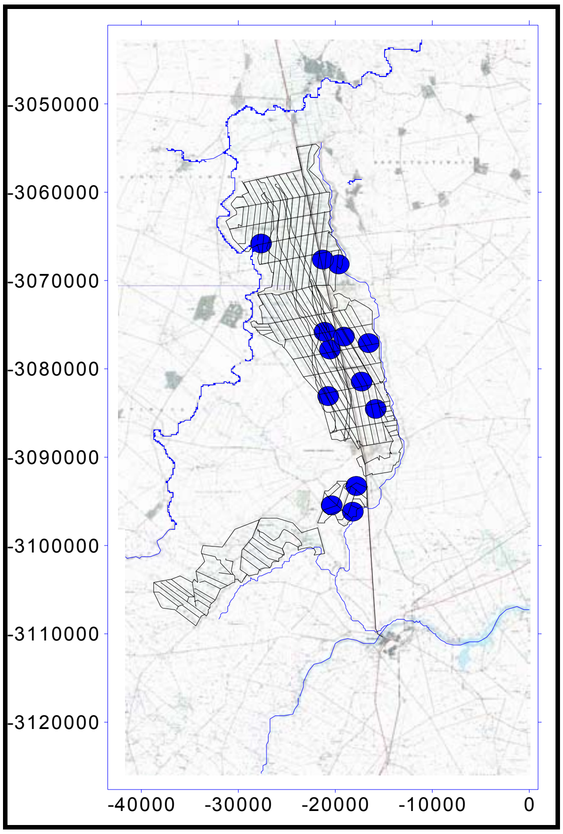


Figure 45: Diagram illustrating the Vaalharts investigation area and the boreholes sampled during the sanitation protocol in the North Canal area

In the above diagram, Figure 45, the relative location of the boreholes sampled during the sanitation protocol conducted by Geo-Hydro Technologies is illustrated.

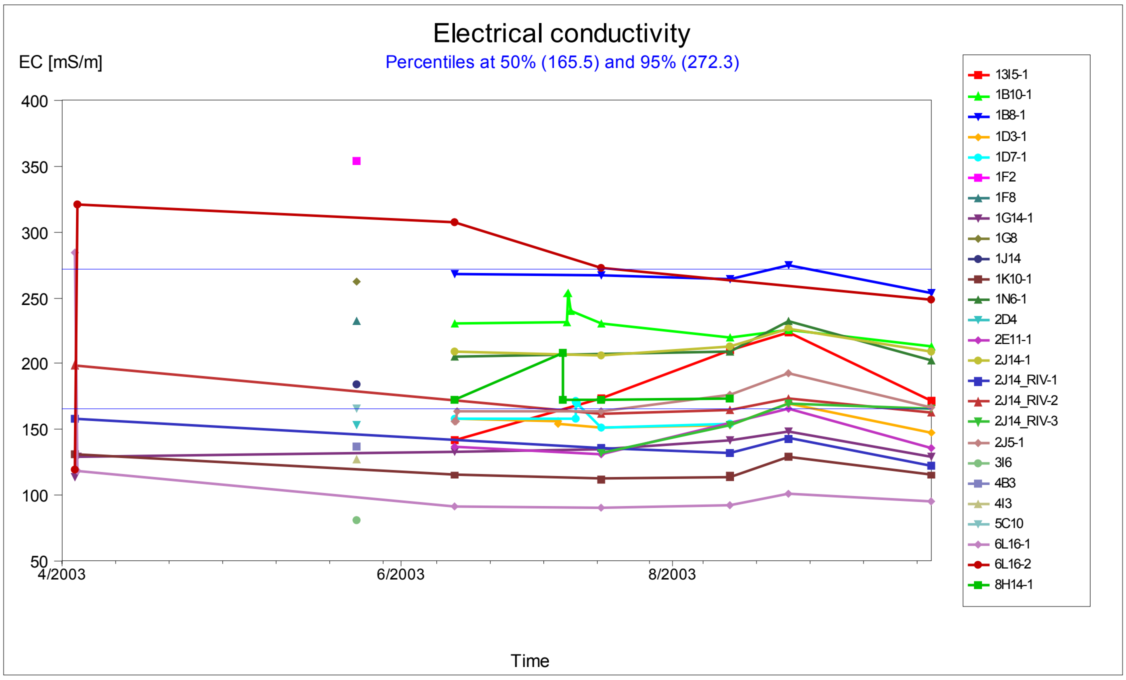


Figure 46: Time-series graph illustrating the electrical conductivity of the boreholes sampled during this project, compared to those sampled during the GHT sanitation protocol

In Figure 46 above, a time-series graph of the electrical conductivity of the groundwater samples taken during the sanitation protocol, as compared to the groundwater samples taken during this project are illustrated. As can be seen from the above time-series graph, the range of values complies with those values taken during this project. The sanitation protocol was conducted over a short-term, and therefore lacks conclusive time-series data with which to compare the chemistry results. The once off values gathered during that project do, however, give a range of values with which to compare well to the data sets collected during this research project.

4.5.2 HYDROCHEMICAL PROFILING

Hydrochemical profiling was conducted in the Vaalharts Irrigation Scheme to study the effects of the various lithologies on the chemistry, and to determine whether there was a perched aquifer or stratification present in the Vaalharts. The hydrochemical profiling would be able to support the information gathered by water levels in the piezometers, and therefore conclude whether or not a perched aquifer is present.

The hydrochemical profiling is conducted by inserting a depth-specific profiler down the borehole. The profiler measures dissolved oxygen, electrical conductivity, pH, REDOX potential and temperature at a frequency of every two seconds. The probe uses a pressure transducer to determine the depth. The probe is therefore able to measure depth-specific chemistry.

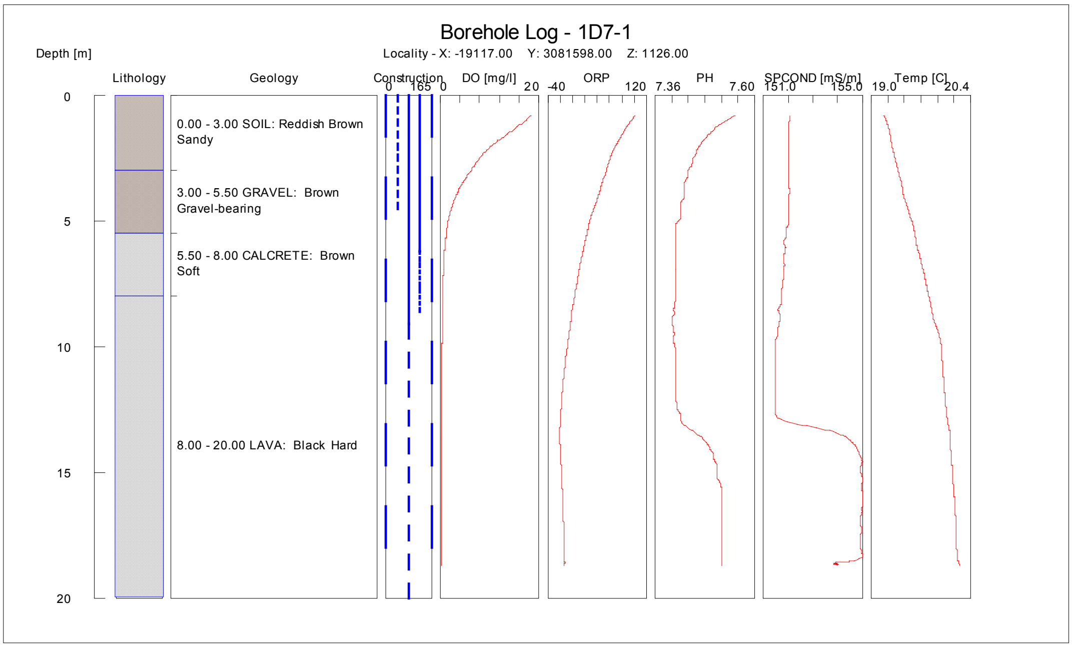


Figure 47: Borehole 1D7-1 geological log illustrating hydrochemical logging

In Figure 47, the hydrochemical log for borehole 1D7-1 is illustrated. The only differences that occur between the various lithologies are natural. There is a variation in pH and electrical conductivity within the lavas, although the pH is altered by only 0.1 pH-values, while the EC increases from 151mS/m to 155mS/m: a variation of only 4mS/m. This is possibly due to natural processes such as a fracture within the lavas.

No substantial variations in chemistry were recorded by means of hydrochemical profiling, supporting the results delivered by the piezometric water levels, that the Vaalharts aquifer is continuous, and that no perched aquifer exists in the Vaalharts.

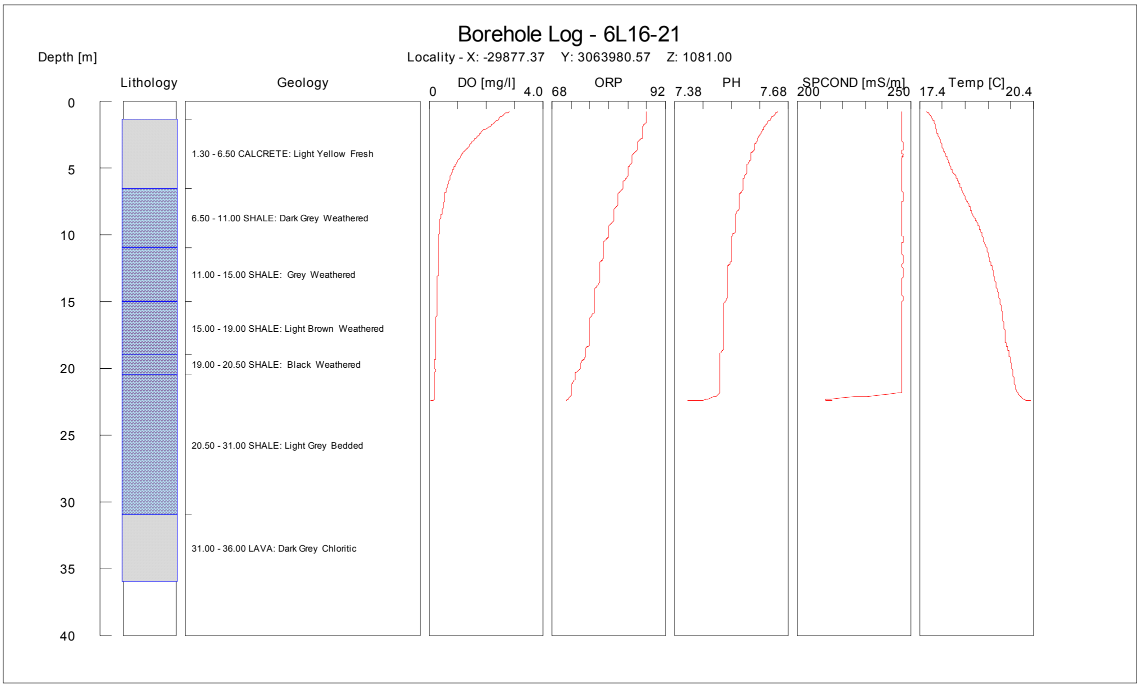


Figure 48: Borehole log for borehole 6L16-2, illustrating the deeper piezometer

The borehole log illustrated in Figure 48 shows a hydrochemical profile for the deeper piezometer in borehole 6L16-2. This piezometer is sectioned off to only measure the shale aquifer.

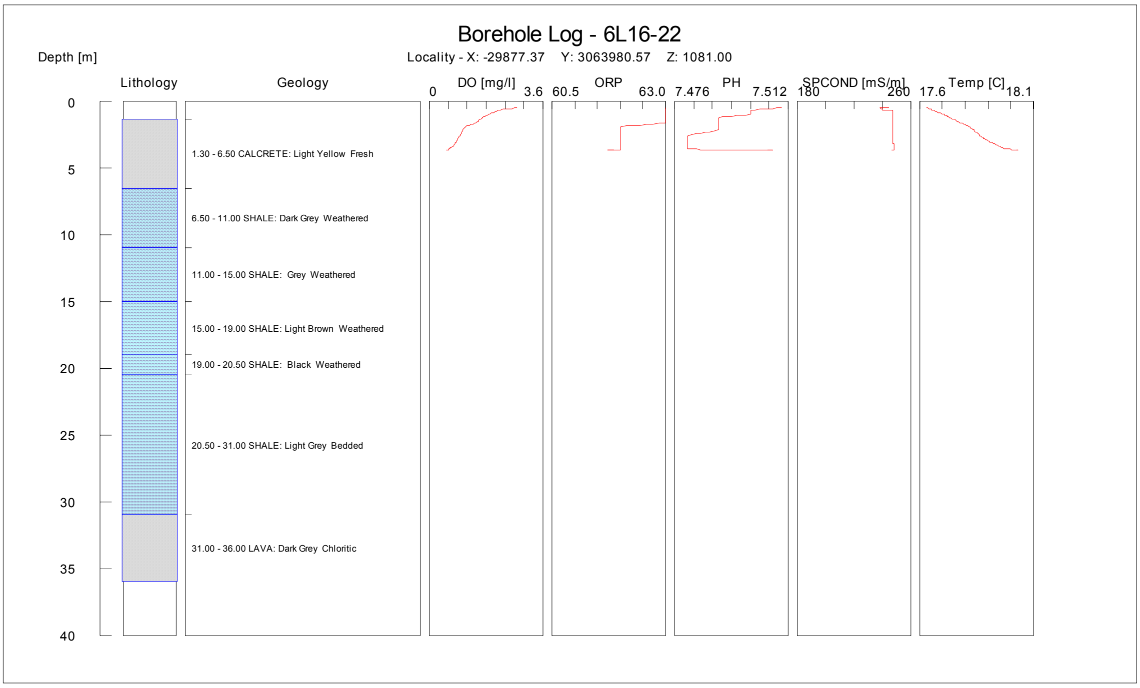


Figure 49: Borehole log for borehole 6L16-2, illustrating the shallower piezometer

Figure 49 illustrates a borehole log for borehole 6L16-2, showing the hydrochemical profile for the shallower piezometer. This piezometer is sectioned off to only measure the calcrete aquifer. The sudden sharp changes seen in the parameters illustrated occur as the probe reaches the bentonite seals. A comparison of the above two diagrams indicates no variation between the two piezometers' measurements.

4.5.3 GROUNDWATER CHEMISTRY INTERPRETATIVE DIAGRAMS

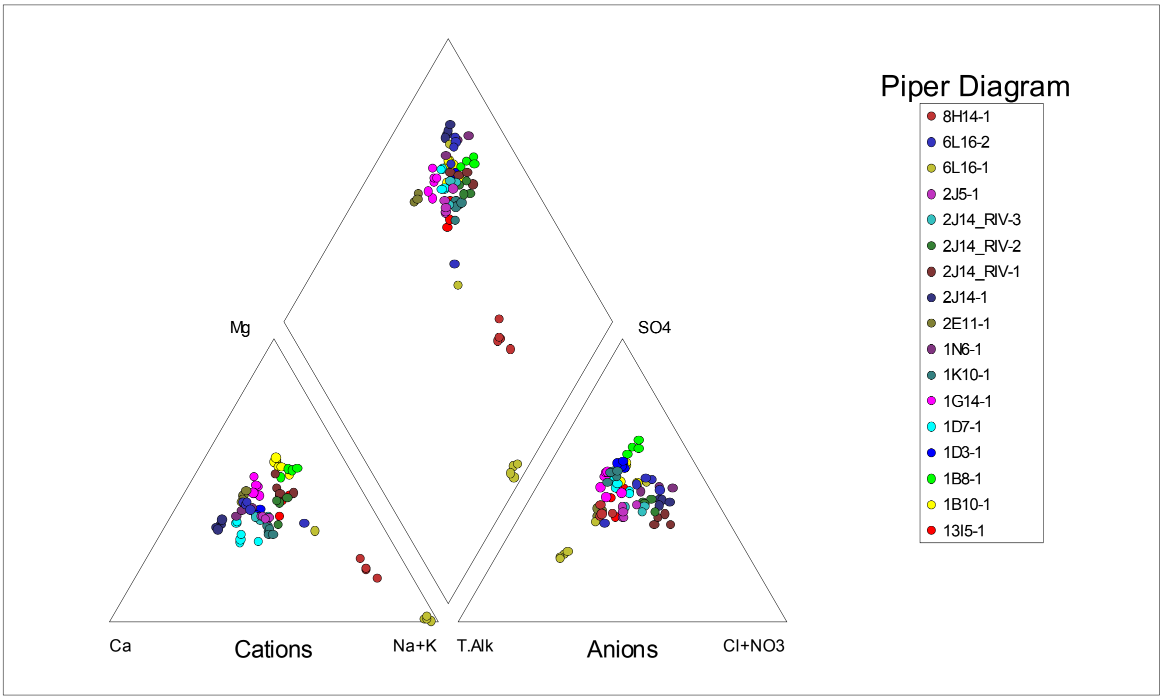


Figure 50: Piper Diagram for the groundwater samples collected from the Vaalharts

In the above diagram, Figure 50, a Piper Diagram has been illustrated for the groundwater samples collected in the Vaalharts Irrigation Scheme area. As can be seen from this diagram, there is no dominant anion or cation, although some of the cations do tend towards the Na+K field. This illustrates a possible mixing of many waters entering the Vaalharts Irrigation Scheme, and the geology.

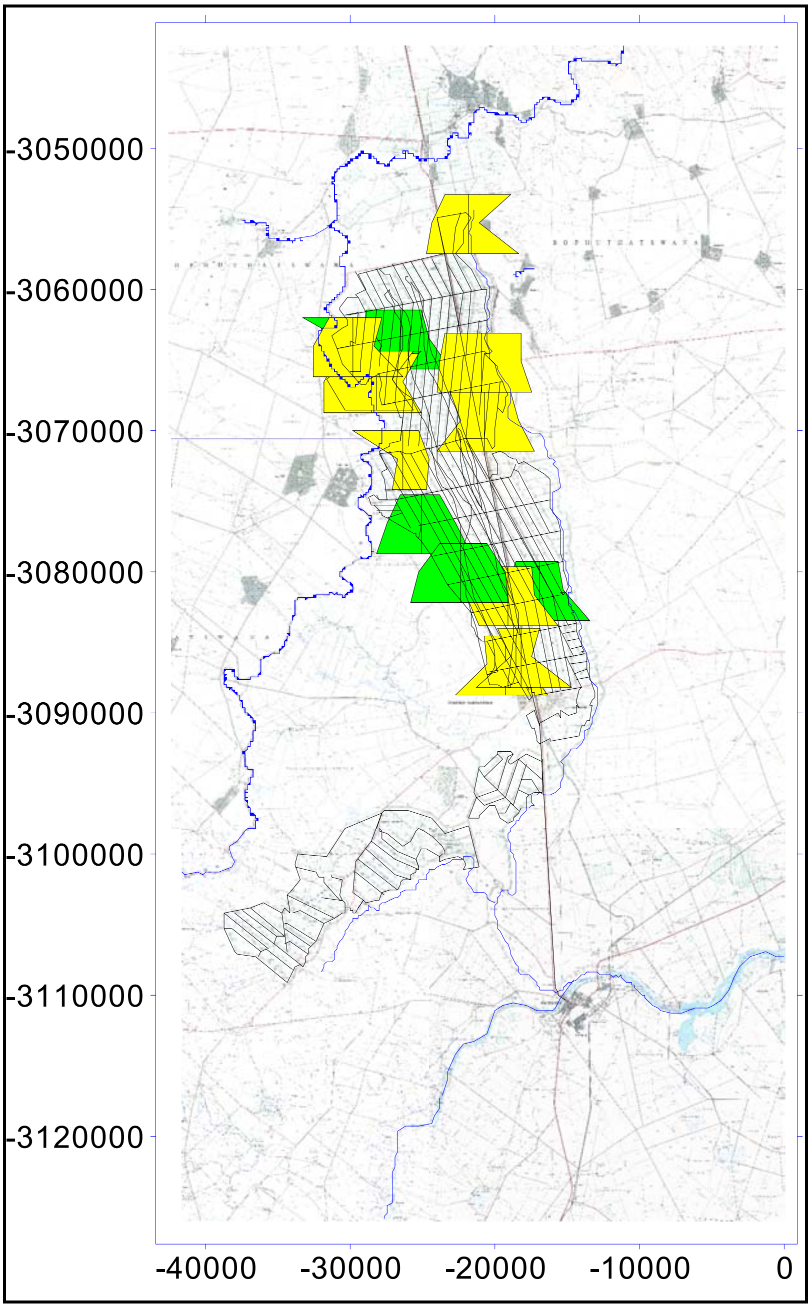


Figure 51: Map illustrating Stiff diagrams for the groundwater in the Vaalharts irrigation Scheme.

The above Stiff diagrams give a visual impact of the water type. This gives water with similar chemistry similar shapes, thereby aiding easy comparison.

The majority of the above Stiff diagrams illustrate relatively high sulphate, chloride and nitrate anions, and high magnesium cations. The high chlorides and magnesium values can possibly be explained by the geology, namely the regional distribution of shales or calcretes. The high level of sulphates in the groundwater seems to be entering the system from the Vaal River irrigation water. The origin of the chloride, magnesium and sulphate in the groundwater is further illustrated in the diagrams below:

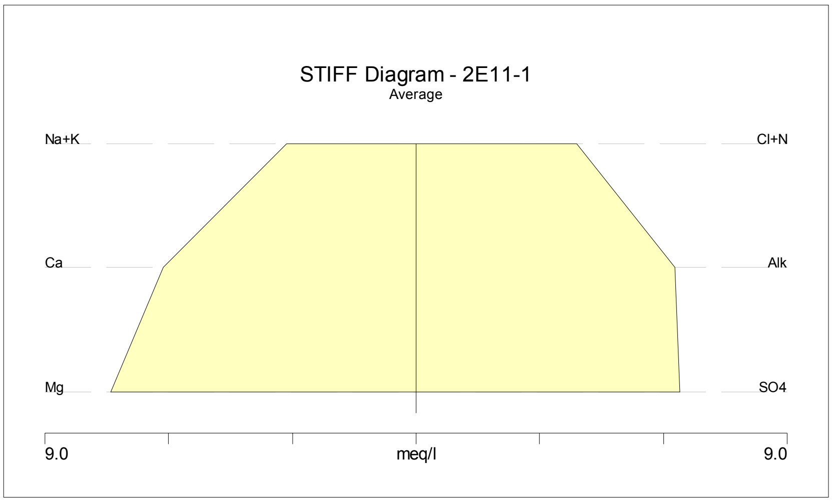


Figure 52: STIFF diagram for groundwater in borehole 2E11-1

Figure 52 illustrates a Stiff diagram for the groundwater sampled in borehole 2E11-1. Borehole 2E11-1 consists largely of highly mineralised Dwyka shales. This is a typical example of Stiff diagrams for groundwater found in shale-rich lithology.

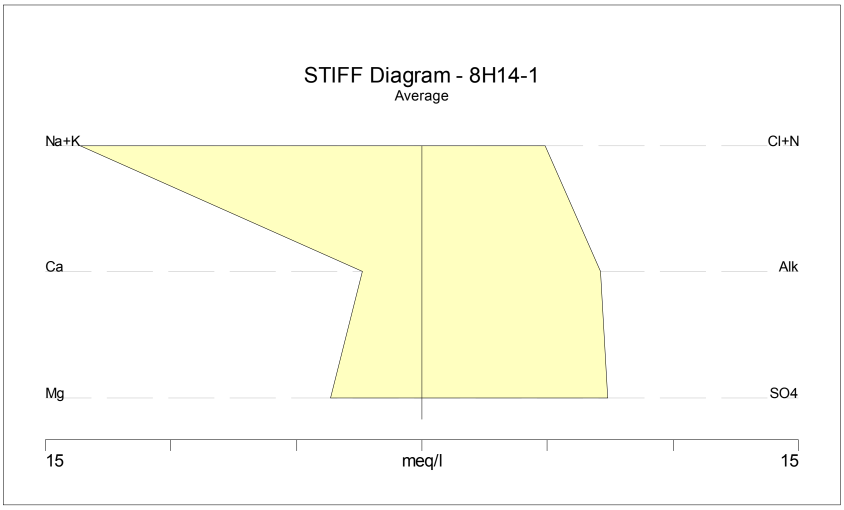


Figure 53: Stiff diagram for groundwater in borehole 8H14-1

Figure 53 is a Stiff diagram for groundwater sampled in borehole 8H14-1, a calcrete-rich borehole. In comparison to the groundwater found in shale-rich lithologies, the magnesium present in calcrete-rich boreholes are found in much smaller quantities.

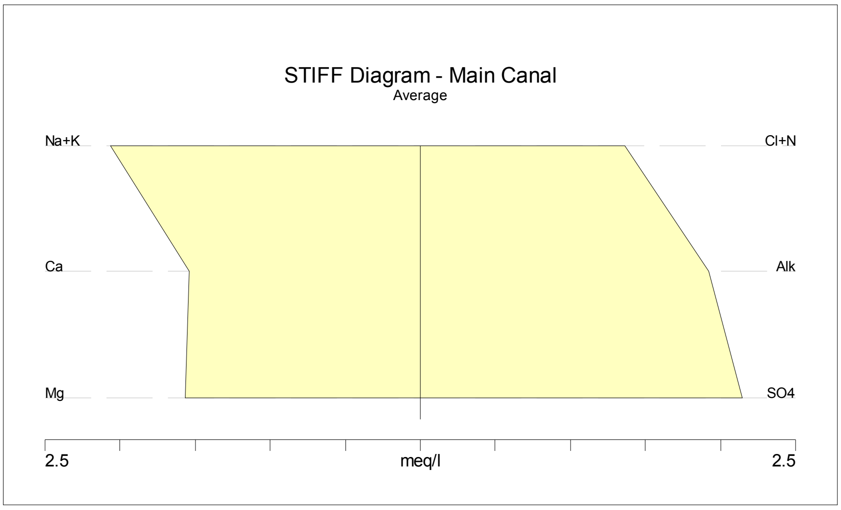


Figure 54: Stiff diagram for incoming irrigation water at Warrenton

In Figure 54, a Stiff diagram for water entering the Vaalharts Irrigation Scheme is illustrated. The water was sampled in the Main Canal, near Warrenton. It illustrates the manner in which sulphates are entering the Vaalharts Irrigation Scheme. The Stiff diagrams illustrated here link to the Salt Balance in Section6.2.

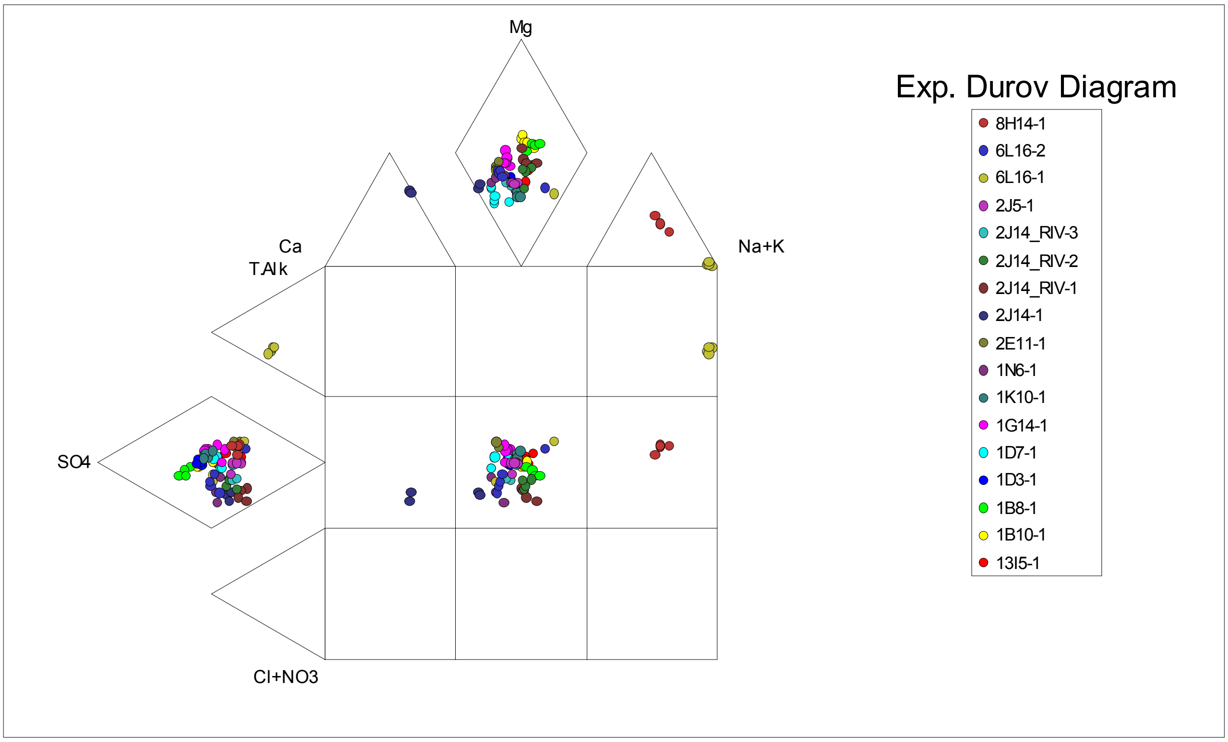


Figure 55: Expanded Durov Diagram for the groundwater in the Vaalharts Irrigation area

In the above diagram, Figure 55, an Expanded Durov Diagram is illustrated representing the groundwater samples taken in the Vaalharts Irrigation Scheme. As can be seen, there is a dominance of magnesium-sulphate waters some sodium-sulphate waters are also present.

As illustrated in the above Stiff diagrams, it seems that the magnesium in the groundwater is derived from the shales, while the sulphates are derived from the incoming Vaal irrigation water.

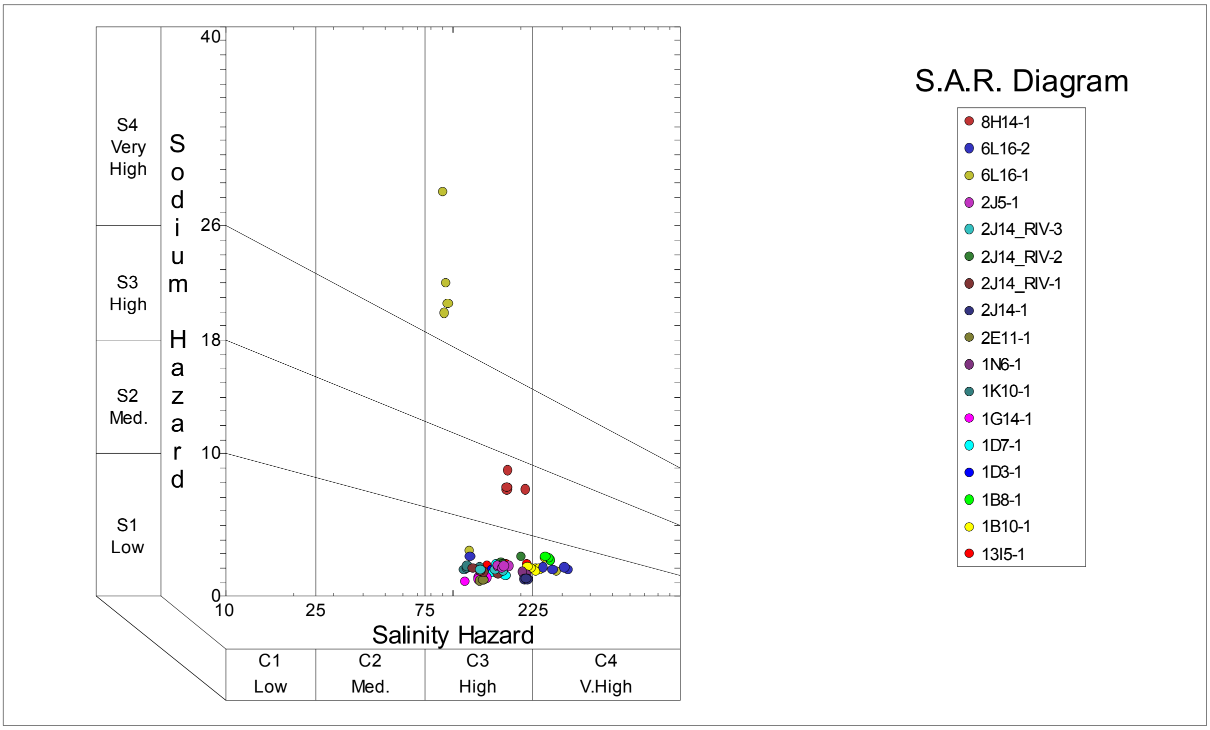


Figure 56: SAR Diagram for the groundwater samples collected in the Vaalharts Irrigation area

In the above diagram, Figure 56, a Sodium Adsorption Ratio Diagram is shown for the groundwater samples collected in the Vaalharts Irrigation Scheme. As can be seen in this diagram, the salinity hazard of the groundwater is high, while the sodium hazard low to medium, with only one groundwater sample, that of borehole 6L16-1 being high.

4.6 CONCLUSION

The water quality discussed in this section indicates that the Vaalharts' groundwater can be described as magnesium-sulphate enriched. It has been illustrated that the origin of these enriching minerals is firstly, in the case of the magnesium, a product of the predominantly shale environment, while secondly, in the case of the sulphates, a product of the Vaal River irrigation water entering the groundwater system.

The influence of the incoming irrigation water on the groundwater in the Vaalharts aquifer is discussed in the section dealing with the Vaalharts Irrigation Scheme Salt Balance (refer to Section 6.2).

5 NUMERICAL MODELS

5.1 PRESENT CONCEPTUAL MODEL OF PROCESSES

In order to understand the geohydrology of the Vaalharts system, a good idea of the geology, topography and climate needed to be gained. This understanding of the main factors was achieved during the literature review of the well-documented Vaalharts area. The geology, climate and topography are discussed in the following section.

5.1.1 TOPOGRAPHY

The Vaalharts Irrigation Scheme is relatively flat, although it slopes gently towards the Harts River. There are two kopjes on either side of the valley, leaving the Vaalharts area as a basin. The shape of the Vaalharts is a result of the glaciers that moved through the Vaalharts during the Dwyka period.

The Vaalharts valley and the vicinity are represented by four stages of erosion. These are discussed as follows:

- The pre-Karoo Harts-Dry Harts Valley surface, eroded in tilted Ventersdorp, Black Reef and dolomite formations, represented now as the sub-Dwyka conformity.
- The post-Karoo peneplane surface that is now represented by the dolomite and Ventersdorp plateaus on either side of the Harts-Dry Harts valley.
- The re-excavated Harts-Dry Harts Valley surface, probably of late-Tertiary age, eroded mainly during the Karoo. The Harts-Dry Harts pediments in the Dwyka and the higher hill slope elements in the Ventersdorp and the dolomite represent this surface.
- The surface of incision of the Harts River, probably since Pleistocene, into the lower parts of the former pediments, that consists of dolerite sills, Dwyka formations, calcretes and Kalahari sands (Temperley, 1967).

5.1.2 CLIMATE

The Vaalharts is a semi - arid area. The area is a summer rainfall region, with 80% of its rainfall occurring during these months. The annual rainfall for the Vaalharts area, as measured at the Jan Kempdorp and Hartswater stations is 430mm per annum. The Vaalharts area has an average January rainfall of 74mm for the period of 1940 to 2000, and an average July rainfall of 4.73mm for the same period (SA Weather Service).

The average maximum temperature for January is 32ºC while the average minimum January temperature is 18ºC. The average maximum June temperature is 16ºC with an average minimum June temperature of 1ºC (SA Weather Service).

The Vaalharts Irrigation Scheme lies within a valley with a maximum altitude of 1150masl and a minimum altitude of 1050masl.

5.1.3 BACKGROUND GEOLOGY

The geology in this area consists predominantly of Ventersdorp lavas and other volcanic intrusive rocks; Black Reef and dolomite series; Dwyka shales and tillites; calcretes and gravels; and Kalahari sands. Initially the Kalahari sands are found. These sands vary between a depth of 0m and 8.5m. In the region of the canal, these sands range from 12m to 13m (Gombar and Erasmus, 1976). In the region of the Harts River itself, the sands can reach a depth ranging from 20m to 25m. The gravel profile is a result of the development between the Kalahari sands and the lower geology. These gravels are generally quite thin, and are in the region of approximately 0.25m, although, they can range up to depths of between 2.0m and 2.5m. The calcretised sands and calcrete is irregular in the Vaalharts geology. The depths are found to be between 4m and 12m. They seem to have a local development.

Below the calcretes, the Dwyka shales and tillites are found. This geology is present because of the glaciers that moved through the area approximately 280Ma to 300Ma. The tillites are a sedimentary rock produced as a result of the compaction cementation of glacial till, while the shales are sedimentary rocks formed as a result of the compaction of silts, clays or sands that accumulate in deltas and on the edges of lakes. These rocks have generally low porosity and permeability.

Ventersdorp lavas and granites represent the basement geology in the Vaalharts area. These rocks are very dense, with low porosity, but may be permeable due to the possible fractures within them.

5.2 PRESENT CONCEPTUAL MODEL OF HYPOTHESES

5.2.1 INTRODUCTION

In order to construct a feasible plan for this research, hypotheses first needed to be constructed. These hypotheses were based upon the available literature that had been documented on the Vaalharts Irrigation Scheme and work conducted in the Vaalharts during this research. This included information regarding the geology, geohydrology, drainage systems, rainfall, surface water flows, soil-water balances, and hydrochemistry.

This information was sourced from the National Groundwater Database, various maps discussing work completed on Vaalharts, an academic thesis, electronic information, SA weather bureau, Department of water Affairs and Forestry, Water Research Commission reports and personal communications.

A large proportion of information was also gained from fieldwork conducted during this research. This fieldwork included an extensive network of monitoring boreholes across the Vaalharts Irrigation Scheme, groundwater monitoring, a hydrocensus and surface water monitoring. All this information provided continuing support for various hypotheses regarding the location of the salts and the mechanics of the Vaalharts' geohydrology.

5.2.2 HYPOTHESIS 1

The first hypothesis scenario investigated was based on the fact that due to dams and weirs having been built upstream of Vaalharts on the Harts River, sufficient 'flushing' of the system was not taking place.

In effect, what was investigated was the possibility that although sufficient salt quantities were not being encountered in the Harts River downstream of the Vaalharts Irrigation Scheme, salts were still possibly being transported towards the Harts River by groundwater, but were not being 'flushed' by the now reduced Harts River flow.

It was hypothesized that, if salts were entering the groundwater together with any added water, for example rainfall or irrigation, these salts would then flow, together with the groundwater, towards the Harts River.

Use was made of the numerical modelling package 'Processing MODFLOW for Windows' (Chiang and Kinzelbach, 1998) to test the hypothesis, using generalized parameters. In this model of the North Canal area using the topography and a general water level of 2.5mbgl, the groundwater would flow towards the Harts River (Refer to Figure 1). The fact that the groundwater would flow towards the Harts River was an anticipated result.

If this hypothesis were true, then the salts should have been following the groundwater to the Harts River, which, according to Herold and Bailey (1996), were not seen in the surface water chemistry results for the monitoring stations on the Harts River. This therefore meant that the salts were possibly being captured in the bank storage along the Harts River, and due to the reduced water flow in the Harts River and more infrequent flooding, were not being released from this bank storage into the surface water system. If such flooding had occurred, and released the salts from bank storage, then it was possible that during such a flooding event, the salts would not be measured at the monitoring stations on the Harts River.

In order for such a hypothesis to be proven, or disproven, certain tests would then have to be conducted. The most complete experiment to be used in such cases would need to give the exact groundwater levels, over a precise limited area, as near as possible to the Harts River. This would then not only give groundwater chemistry in the area of bank storage, but also be able to provide exact groundwater flow gradients on a micro-scale.

In order to test this hypothesis, three boreholes were drilled on the banks of the Harts River. To ensure accurate test results, these three boreholes were cased with Johnson screens (refer to Section 4.2.4). The results of this hypothesis indicated that the salts were not being stored in the banks of the Harts River, and were in fact reaching the river.

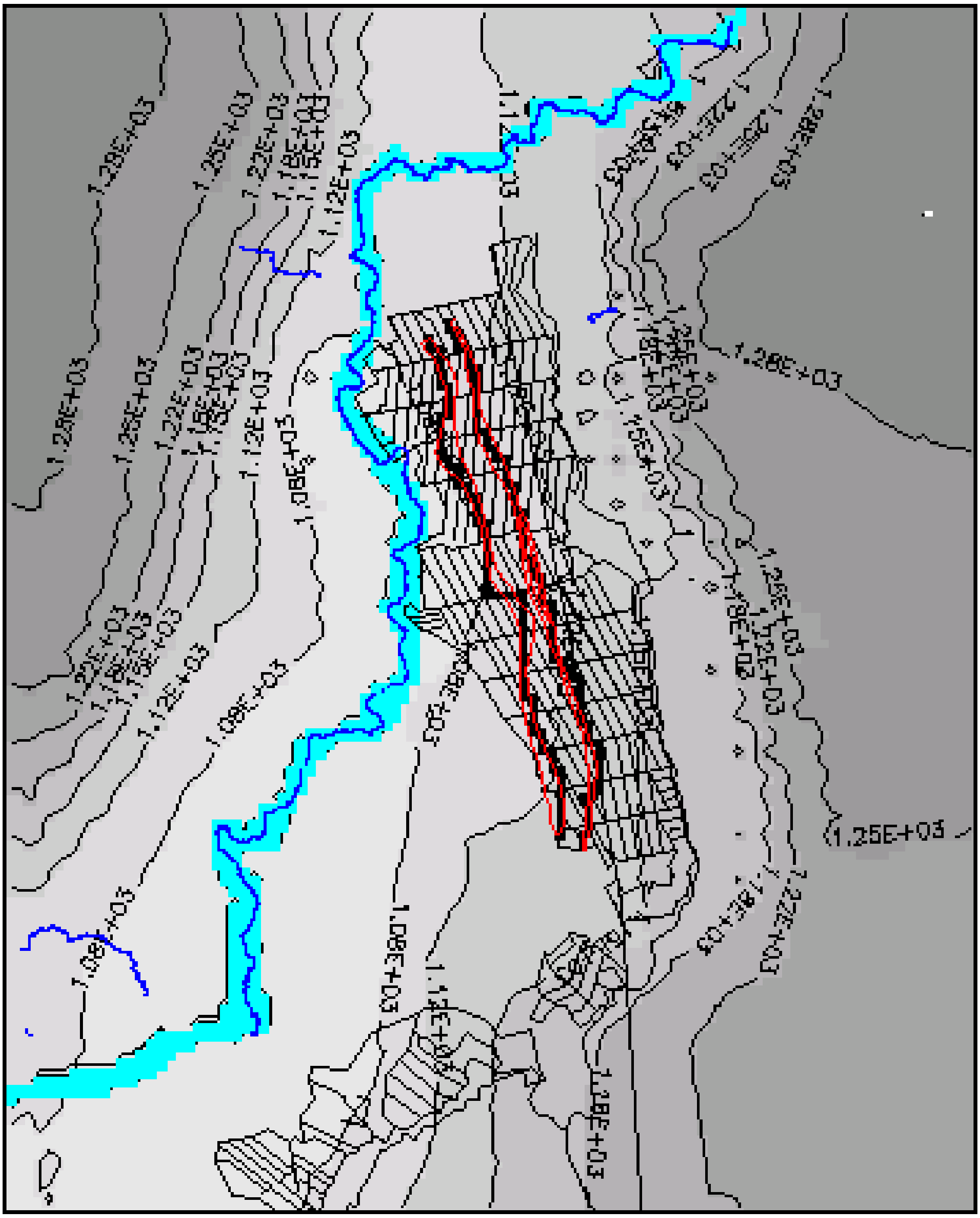


Figure 57:Diagram illustrating the modelled water level results for conceptual hypothesis 1.

The numerical model constructed to test this hypothesis used the measured water levels in the Irrigation Scheme to test whether the groundwater is flowing towards the Harts River. The numerical model indicated that groundwater is flowing towards the Harts River, thereby adding support to the data collected from the three boreholes on the banks of the Harts River. The fact that the groundwater flow is towards the Harts River, and not the Vaal River further to the south, indicates that salts should therefore be seen in the Harts River, and therefore too the three boreholes that were drilled alongside the Harts River, to the northern ends of the Scheme.

5.2.3 HYPOTHESIS 2

The second hypothesis was structured on the findings of the first hypothesis. In the first hypothesis, it was found that there is no bank storage, and that groundwater does in fact move towards the Harts River. Herold and Bailey (1996) had indicated that salts are not reaching the Harts River at the same rate at which they are entering the groundwater. This therefore led them to believe that a flow reversal of groundwater and salts was going to occur. The reason for this is that they were not measuring the degrees of salts that they expected in the Harts River.

The second hypothesis surrounded the idea that salts were moving towards the Harts River, but were undergoing a mixing from natural recharge between the Irrigation Scheme and the Harts River. This mixing from recharge created a reduction in concentration of the salts within the groundwater moving towards the Harts River.

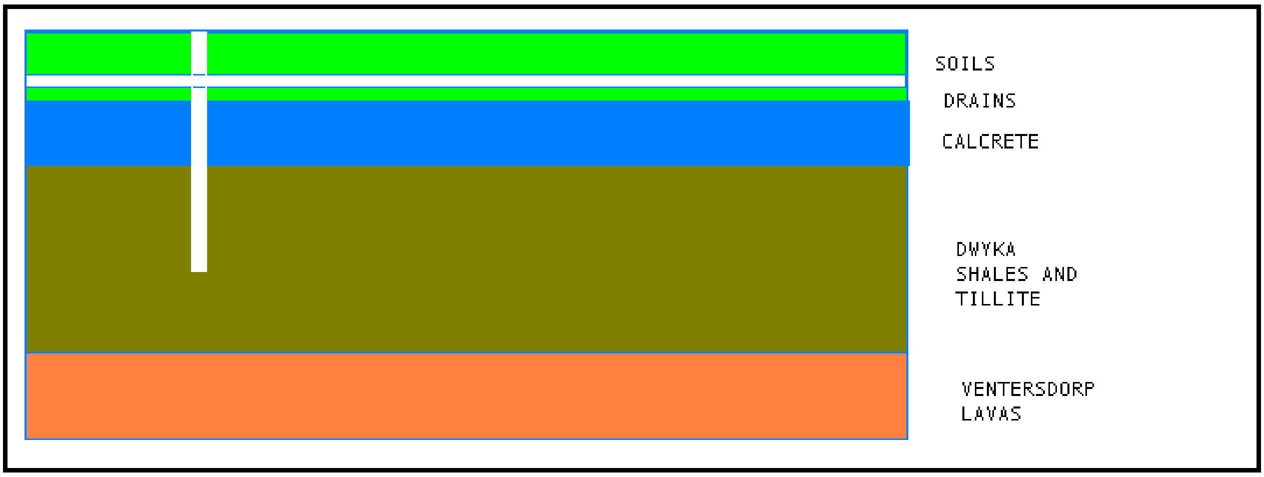


Figure 58: Present conceptual model of the geology present in the Vaalharts Basin

The main feature of the second hypothesis was that the salts would undertake concentration reduction and mixing on their path towards the Harts River, due to the influence of recharge, and upon reaching the river, would have such a reduced concentration that they would be for all intents and purposes, invisible.

The conceptual numerical model was based upon the presumption, that due to the relative density of the calcretes, only the upper sand aquifer would be used to model the simulation. This is not to say that the lower aquifers were inactive in reality, but that for the simulation, the sand aquifer would suffice.

The numerical model for the hypothesis was therefore constructed as follows. A one-kilometre stretch of land was introduced with a series of 20 blocks of 2500m^2 land, with a soil depth of 6m and a static water level of 2mbgl. The water level had a slight gradient, based on the values of Gombar and Erasmus (1976). The gradient of the groundwater across the one-kilometre stretch of land was 5x10^{-5}.

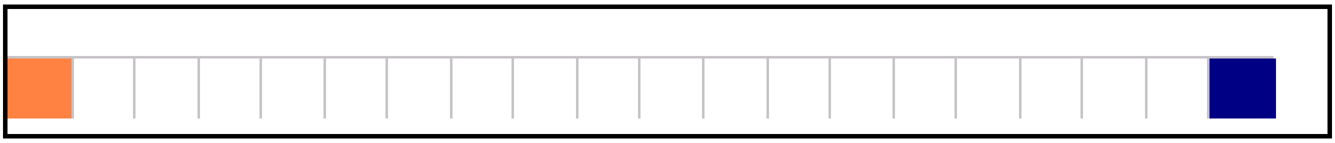


Figure 59: Grid outline for the prior conceptual model of hypothesis 2, illustrating the flow of water from the irrigated lands (orange) to the Harts River (blue).

A fixed head boundary was applied to the 'river cell' in order to take water out of the system, and generate a model of natural conditions to mimic the actions of the Harts River in reality. This means that, although water is flowing towards the Harts River, the final cell would keep a constant water level, simulating the removal of water from the system. This would essentially be the same as the natural conditions, in taking water out through the river. The concentration on the 'river cell' was not fixed.

The horizontal hydraulic conductivity of the sands used for the conceptual model of hypothesis 2 was in the same order as the hydraulic conductivity value provided by Van Wyk *et al*, (1993) in their report to the DWAF, namely 1m/d.

The storage coefficient used for this conceptual model was in line with the above-mentioned report by Van Wyk *et al.* (1993). The value used for the storage coefficient in the sands was 5.7×10^{-3}. Storage coefficient is defined as being 'the volume of water of a saturated aquifer that a unit volume of aquifer releases from storage under a unit decline in hydraulic head' (Krusemann and de Ridder, 1994).

The effective porosity used for this conceptual model was in standing with sands of this type, and with Krusemann and De Ridder (1994), namely 10%.

The recharge that was applied to the cells was based upon a 3% recharge value of the 430mm/a that the Vaalharts area receives, as supplied by the South African Weather service. This value amounted to a daily recharge of 3.43×10^{-5}mm/d. The 5% recharge value is the same as that used for the area between the Vaalharts Irrigation Scheme and the Harts River in the main Vaalharts numerical model.

The following step in constructing this initial conceptual model for the second hypothesis was applying a concentration to the cells. It was decided that a fixed concentration of 1350mg/l, based on TDS measurements taken during this research, would be applied to the cell furthest from the river in the irrigation area, and that no concentration would be applied to cells between this cell and the river. This would be in keeping with natural conditions of the area where there exists a minimum distance of approximately one kilometre between the irrigation plots and the Harts River.

Table 7: Table illustrating the water levels and concentrations of the hypothesis 2 numerical model simulation

BLOCK NUMBER	WATER LEVEL (mamsll	SALT CONCENTRATION (TDS)
1 (IRRIGATED LAND)	1079.75	1350
2	1079	1310
3	1078.25	1275
4	1077.5	1220
5	1076.75	1160
6	1076	1090
7	1075.25	1035
8	1074.5	975
9	1073.75	900
10	1073	830
11	1072.25	750
12	1071.5	660
13	1070.75	580
14	1070	505
15	1069.25	430
16	1068.5	370
17	1067.75	320
18	1067	270
19	1066.25	230
20 (HARTS RIVER)	1065.5	200

The above table, Table 7, illustrates the various concentrations, and water levels in metres above mean sea level, for the initial conceptual numerical model. The values are shown together with their corresponding cell number. Cell 1 is the initial concentration cell where the initial TDS of 1350mg/l was applied, while Cell 20 is the final cell in the series, also known as the 'river cell'. The final TDS load that reaches the 'river', according to this model, is 200mg/l, or approximately 26mS/cm electrical conductivity.

These values indicate that there is a reduction in concentration from each cell onto the following cell. This trend can be seen continuing as the water dilutes the concentration in the form of recharge in this case, and mixing.

The values used for these models were based on initial conceptual values gained from literature.

Measured results from the three boreholes drilled on the banks of the Harts River, and the borehole drilled directly upgradient of these them in the irrigation area are illustrated below.

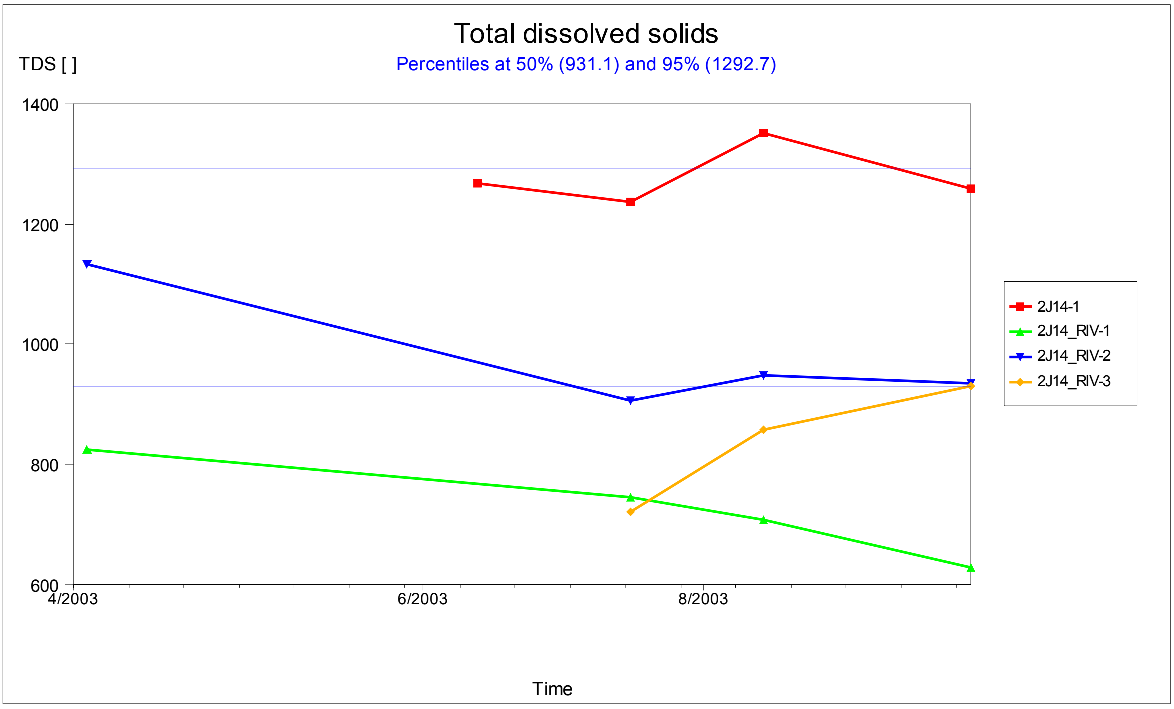


Figure 60: Diagram comparing TDS values of three boreholes drilled on banks of Harts River and borehole in adjacent irrigation area

Figure 60 illustrates the comparison of TDS values between the three boreholes drilled on the banks of the Harts River and a borehole drilled adjacently in the irrigation area. The borehole situated in the irrigation area is illustrated in red, namely borehole 2J14-1, while the three river boreholes are illustrated in blue, yellow and green. Borehole 2J14-1's TDS concentration is between 400mg/l and 500mg/l higher than the boreholes located along the Harts River. The distance between the borehole in the irrigation area and the three boreholes on the riverbank is approximately 350m. The results from the numerical model indicates a decrease of TDS concentration from 1350mg/l to 975mg/l, decrease of 375mg/l, while an average TDS of the borehole in the irrigation area, namely 2J14-1 less the average of the TDS values measured in the riverbank boreholes indicates a decrease of 395mg/l. The results therefore obtained in the numerical model are very similar to those obtained in reality.

5.2.4 PRESENT CONCEPTUAL MODEL

The present conceptual model of the Vaalharts' aquifer and the processes that have an effect on this aquifer is based upon the information gathered during the course of this research. This information includes work completed before the initiation of this research and work that that has been conducted as part of this thesis.

The processes discussed here refer to the Vaalharts Irrigation Scheme and the area between itself and the Harts River; the processes having an affect on the irrigation scheme and the processes that the Vaalharts is having an immediate effect on, namely the Harts River.

The Vaalharts irrigation Scheme receives a pre-determined volume of water from the Vaal River. The water entering the Vaalharts from the Vaal River at Warrenton is received via an extensive canal system destined primarily for irrigation. The majority of this water is transferred to dams within the farms, while a percentage of this water, that is not used, passes directly through the canal system as tailends into the Harts River to the west of the Irrigation Scheme.

Once the water has been delivered to the farm dams, it is distributed to the crops. As the water leaves the farm dams, fertilizers can be added to this water. The water is applied to the crops by various forms of irrigation, such as pivot, drip and flood irrigation.

As the water is applied to the crops, a number of processes take place. The crops accept a certain proportion of the water, and salts, as evapotranspiration. Evapotranspiration includes water that is used for daily functions of the crops, and water that is accepted by the crops and released to the atmosphere as transpiration. Evapotranspiration also includes water that is lost to the atmosphere as evaporation.

Water that passes the root zone is either collected by the subsurface drains, or passes through to the groundwater as recharge. The subsurface drains were installed in the Vaalharts predominantly in the 1970's and 1980's, although the installation of these drains still takes place on a small scale. The subsurface drains were estimated by Streutker (1977) to collect approximately 7.3% of the water entering the Vaalharts irrigation area via the canal system. Although the subsurface drainage has been increased since 1977, this has not been significant.

The recharge in the Vaalharts Irrigation area was determined by means of recharge maps for the area (Vegter, 1995). The chloride method for determining the recharge in the Vaalharts delivered unlikely results, as the highly mineralised shales influenced the chloride in the groundwater. The recharge determined from Vegter's maps (1995) indicated an average recharge of 4.65% for that area.

The upper lithology is comprised of Kalahari sands. A large proportion of this lithology has been tested by the Vaalharts Agricultural Research Station to determine the hydraulic conductivities in this upper zone that is of particular importance to agriculture in the area. The hydraulic conductivities determined by the Agricultural Station vary between 4m/d and 24m/d, depending on the location within the North Canal area. These hydraulic conductivities can be associated to the geology encountered during the fieldwork phase of this research.

The geology in the Vaalharts varies from north to south. The areas in the north of the North Canal area consist predominantly of sands and shales, with calcretes and gravels occurring more infrequently. The geology further south in the North Canal area consists more of sands, clays, calcretes, gravels and shales. This variation, due to alluvial processes in the Harts River valley, accounts for many of the differences seen in the hydrogeology within the area. It seems that as the Harts River meandered through the Harts River valley over time, the River deposited most of the fine materials further downstream, from what is the present day lower half of the Vaalharts Irrigation Scheme.

The shales throughout the Vaalharts generally possess a double porosity with some boreholes illustrating hydraulic conductivities in the range of 0.1m/d, while others have hydraulic conductivities in the range of 19m/d. The shales seemed well fractured with a number of hydraulic conductivities measured above 10m/d.

Toward the south, within the irrigation scheme a larger proportion of clays, calcretes and gravels exist. The dense clays and calcretes are likely to inhibit the flow of groundwater as compared to further north, with hydraulic conductivities in the range of 4m/d in the upper Kalahari sands, and hydraulic conductivities in the range of between 0.1m/d and 1.5m/d. Where encountered, the gravels indicated relatively high conductivities though, in the range of between 2m/d and 6m/d.

The vertical hydraulic conductivity determines the rate at which leakance occurs between the various lithologies. The Kalahari sands are believed to have a relatively high leakance as a result of the relatively high porosity. It is therefore believed that any water passing the subsurface drains should reach the lithology below the Kalahari sands.

This theory is supported by the results of the piezometers installed in the Vaalharts Irrigation Scheme during this research, and the results of the hydrochemical profiling. The water levels measured in the piezometers showed no variance between the various lithologies, disproving the possibility of a perched aquifer. The hydrochemical profiling also indicated relatively little chemical variation with depth. Neither the piezometers nor the hydrochemical profiling gave any indication of a perched aquifer.

The natural groundwater gradient was determined to be 0.0059 towards the Harts River. This illustrated that the groundwater was moving towards the Harts River. Using the determined transmissivities of the aquifer in the Vaalharts area, the groundwater gradient, the knowledge that the groundwater is moving towards the Harts River, and the length of investigation along the Harts River, the groundwater flux towards the river was empirically determined as being approximately 11.3Mm^3/annum.

A further step in understanding the movement of the groundwater, and the salts that were entering the Vaalharts aquifer via irrigation, was to understand the influence of natural recharge on these salts. A numerical model (see Section 5.2.3) was established to simulate the processes occurring between the Irrigation Scheme and the Harts River. It is believed that natural recharge has a mixing effect on the salts in the aquifer, and therefore a reduction in concentration that is seen in the Harts River. The numerical model gave a further indication of this process, where the amount of mixing from natural recharge reduced the concentration of the salts in the aquifer from 1350mg/l (average TDS measured during this research) to a TDS of 200mg/l over a distance of 1km. Field measurements also supported the hypothesis of mixing with natural recharge and subsequent concentration reduction.

A summary of the conceptual model of the Vaalharts area is therefore as follows:

- Irrigation water, together with salts are entering the system from the Vaal River.
- Before this water is applied to the crops, fertilizers are added.
- Plants extract a proportion of this water and salts, while a further proportion is either collected by the subsurface drains, or is leached into the groundwater system.
- The fractured rock aquifer underlying the Vaalharts then provides a pathway for this water and salts to the Harts River. The rate of groundwater flow is relatively quicker in the northern parts of the Vaalharts, where shale lithology

is dominant, while in the southern half, the rate is relatively slower as a result of the clays and calcretes' lower hydraulic conductivities.

- The groundwater moves towards the Harts River at a rate of approximately 11.3Mm^3/annum.
- The natural recharge from rainfall has a mixing effect on these salts, and therefore a reduction in concentration of these salts occurs before the salt-bearing groundwater reaches the Harts River.

5.2.5 ANALYTICAL MODEL FOR SALT LOAD DETERMINATION

The salt load entering the Harts River system was calculated analytically. The program used for this determination, namely GW Reserve, was developed by Van Tonder *et al* (2002) in order to gain a rapid assessment of the groundwater reserve component in an area. The salt load estimation in the GW reserve program uses the Ogata equation (from Freeze and Cherry, 1998):

$$\frac{C}{C_{0_0}} = \frac{1}{2}\left[erfc\left(\frac{1-v}{2\sqrt{D_1 t}} \right) + \exp\left(\frac{vl}{D_t} \right) erfc\left(\frac{1+vt}{2\sqrt{D_i t}} \right) \right]$$

Where:

l = distance along the flow path

v = the average linear water velocity

t = time

C = concentration at time t

C_0 = initial concentration

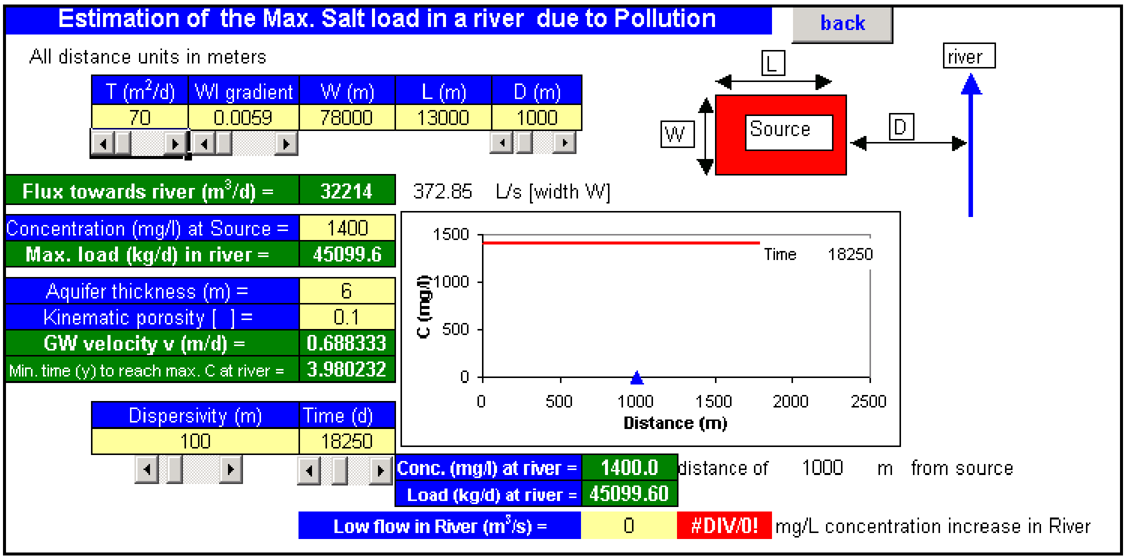
D = the coefficient of molecular diffusion, for the solute in the porous medium

An estimation of the maximum salt load entering the river system for the Vaalharts area was calculated, based upon general parameters collected during the work that has been completed to date. This analytical calculation doesn't take into account the recharge entering the groundwater system.

In order to calculate the salt load using this program, certain values for parameters in the Vaalharts needed to be known. These included the general size parameters of the Vaalharts, namely the length and width of the Scheme, together with the distance between the Scheme and the Harts River. These values were measured to give a general approximation for the entire Scheme. The width of the Scheme used was 78000m, a length from the eastern plateau to the Harts River of 10000m, and a distance between the Irrigation Scheme and the Harts River of 1500m. A water level gradient of 0.0059 was calculated and used between the water levels in the irrigation area and the water levels alongside the river. An average transmissivity of 70m^2/d was used for the area, based on aquifer parameter tests conducted in the area during this thesis, and on literature (Gombar and Erasmus, 1976).

A concentration of Total Dissolved Solids in the groundwater was necessary. The initial concentration used was 1350mg/l: an average of the measured groundwater TDS during this research. This equates to a maximum salt load of 45000kg/d at the Harts River system. The maximum salt load per day equates to 16500t/annum salts entering the Harts River system from groundwater. The salt load entering the Harts River system, as calculated during the Salt Balance of this thesis (Section 6.2), is

15850t/annum, which considering the above mentioned concentration reduction and mixing, compares favourably to the 16500t/annum derived from this analytical model.



Estimation of the Max. Salt load in a river due to Pollution

All distance units in meters

T (m^2/d)	Wl gradient	W (m)	L (m)	D (m)
70	0.0059	78000	13000	1000

Flux towards river (m^3/d) = 32214 372.85 L/s [width W]

Concentration (mg/l) at Source = 1400

Max. load (kg/d) in river = 45099.6

Aquifer thickness (m) = 6

Kinematic porosity [ ] = 0.1

GW velocity v (m/d) = 0.688333

Min. time (y) to reach max. C at river = 3.980232

Dispersivity (m)	Time (d)
100	18250

Conc. (mg/l) at river = 1400.0 distance of 1000 m from source

Load (kg/d) at river = 45099.60

Low flow in River (m^3/s) = 0 #DIV/0! mg/L concentration increase in River

Figure 61: Salt load estimation sheet in GW Reserve used to determine the salt load being added to the Harts River relative to the Vaalharts

5.3 NUMERICAL MODEL

The use of numerical groundwater models is becoming widespread in the environmental sciences. It enables the investigation into geohydrological conditions and the prediction of groundwater flow and contamination transport. Groundwater numerical models can be used for remediation design, feasibility studies, development of performance monitoring networks, or risk assessment (Harbaugh and McDonald, 1996).

In order to investigate an aquifer system in a changing time or space, a numerical groundwater model can be extremely useful. The numerical model used to simulate the aquifer system in the Vaalharts irrigation area was Modflow. Modflow is a modular two- or three-dimensional finite difference groundwater flow model that was developed by McDonald and Harbaugh of the United States Geological Survey (Havenga, 2002) for the purpose of computation of hydraulic heads in saturated porous medium with uniform water temperature and density (Harbaugh and McDonald, 1996).

The Modflow transport program used during the Vaalharts transport modelling was MT3D. MT3D simulates transport by using the pre-calculated flow fields generated in Modflow (Chiang and Kinzelbach, 1999). The original version of Modflow-88 is able to simulate the effects of wells, drains, head-dependent boundaries, recharge and evapotranspiration (Havenga, 2002). Since the development of Modflow, however, a number of various codes have been developed in conjunction with Modflow. The codes, or packages, are integrated into Modflow, and deal with specific features of the hydrological system. A package communicates with Modflow through data files (Havenga, 2002).

With respect to the Vaalharts system, a numerical model was imperative. It was important to understand the pattern of flow in the Vaalharts region, as this would impact the transport of the salts, whether towards the Harts River or Vaal River. It would not only indicate the direction of movement of the applied salts, but also the rate of movement with which the salts in the Vaalharts Scheme would reach their destination. It enabled an understanding of the various processes measured during the course of this project, and their impact on each other. Furthermore, it allowed various scenarios to be tested and the results thereof to be studied.

5.4 RELEVANCE OF MODFLOW

Modflow is an internationally accepted numerical modelling software package. The U.S. Geological Survey developed Modflow in the United States during the 1970's and early 1980's. PMWIN, a graphically designed user interface for Modflow is equipped with supported model packages and several other modelling tools. Chiang and Kinzelbach developed the PMWIN package in 1998. PMWIN is able to handle up to and including 1000 stress periods, 80 layers and 250000 cells per model layer (Chiang and Kinzelbach, 1998). Some reasons for using Modflow as the modelling package, and more specifically PMWIN as the user-interface for the Vaalharts project are listed below.

- It is accepted by a number of international justice systems
- Modflow can simulate steady- and transient-state flow in an irregularly shaped flow system in which the aquifer layers can be either confined, unconfined, or both confined and unconfined
- External stress simulations such as recharge, wells, drains, evapotranspiration and flow through river beds is possible
- Hydraulic conductivities and transmissivities can be assigned to various layers and differ both spatially and anisotropically
- The storage co-efficient can be heterogeneous
- Internationally Modflow is currently the most widely-used finite difference model for flow and transport simulations
- The mass transport package, MT3D, runs in conjunction with Modflow, and can be used for the simulation of solute transfer (Havenga, 2002)

5.5 INADEQUACIES OF MODFLOW

The Modflow program makes use of finite difference solution to calculate numerically. The result is that the model consists of rows and columns, thereby making it difficult to simulate the flow through an irregular or angled boundary, such as the bends within the Harts River.

PMWIN has the ability to only import a maximum of 2000 points into the 'field interpolator' in order to simulate contours into the model area. This therefore creates slight inaccuracies with regard to imported topographic heights or hydraulic heads.

Natural systems are often geometrically and hydraulically complex and are unable to be accurately numerically modeled, which therefore means that a numerical model is a tool, and not an answer.

5.6 BACKGROUND INFORMATION ON THE CONSTRUCTION AND CALIBRATION OF A CONCEPTUAL NUMERICAL MODEL

The object of a model is to simulate, as far as possible, naturally observed conditions. In order for this to happen, a large amount of quality data is necessary for a conceptual model to be constructed. A conceptual model means the design and construction of simplified conditions of the natural scenario. Once the conceptual model has been constructed, this can then be applied to a numerical model, to be solved using existing program codes. This is a crucial step in the process of groundwater modelling. Processes necessary for the development of a numerical model are as follows:

- Known geological and geohydrological parameters for the study area
- Static water levels for the study area
- The interaction of the geohydrology on the boundaries of the study area
- An understanding and application of this understanding of the processes taking place within the study area that may have an influence on water movement within the study area
- Simplifying assumptions necessary for the development of a numerical model and selection of the suitable numerical code (Havenga, 2002)

It should be remembered that a groundwater numerical model approximates the events taking place within the natural environment, and the accuracy of the simulated processes depends greatly on the quality of the naturally measured data. The implication of this statement is that there will always be a level of inaccuracy within a groundwater numerical model as compared to the natural conditions. A groundwater numerical model is a tool. The manner in which this tool is used is decisive in terms of results. A groundwater numerical model is a tool that can be used to make decisions, if sufficiently accuracy standards have been met. It should not be used as a predictive tool, but rather as an evaluation tool of the processes taking place within the study area, making use of changing parameters (Havenga, 2002).

5.7 ASSUMPTIONS AND LIMITATIONS

The Vaalharts numerical groundwater model is, as are all groundwater models, a representation of the naturally occurring conditions. Certain assumptions therefore had to be made, while certain limitations also persisted in representing natural conditions. The following assumptions were made:

- The rivers in the area were treated as fixed heads
- As there is no significant groundwater extraction in reality due to the water allocation from the Vaal River, no discharge was included
- As there are large volumes of water being applied by irrigation. In the irrigation areas, a higher volume for recharge was applied
- Rainfall values were accepted from the South African Weather Bureau
- Recharge results from US laboratories were still being awaited at the time of project completion; literature-derived recharge values were therefore assigned to the model based upon the known geology. These recharge

values are based upon isotope data that was collected by Geo-Hydro Technologies (Bloemfontein)

- Geological structures (eg. dykes) were unclear in the geology of the Vaalharts area and were therefore disregarded
- The basic lavas in the stratigraphy were accepted as being the lower boundary within the stratigraphy due to their relatively impermeable nature

5.8 MODEL INPUT PARAMETERS

5.8.1 STEADY-STATE PARAMETERS

The quality of a groundwater numerical model output depends largely on the quality of the data used for input into the model. The initial groundwater model of the Vaalharts area was based largely on related reports from sources such as Department of Mines and Department of Water Affairs and Forestry, and data generated during the course of this project within the Vaalharts area.

The model calibration was based on the natural conditions observed in the area and changing values of model input parameters in attempting to match these field conditions within certain criteria. Steady-state flow is defined as ‘a characteristic of groundwater or vadose zone flow system where the magnitude and direction of specific discharge at any point in space are constant in time’ (Department of Environmental Quality, State of Michigan, 1994). The model used a steady-state condition to run the initial scenario based upon the input data, followed by a transient-state condition where certain scenarios can be run over time. The transient-state condition runs the scenarios over a user-specified period. The transient-state condition, in addition to steady-state condition input requirements, needs the storage of the relative aquifers to be specified.

5.8.1.1 Discretisation

In the Modflow program, an aquifer system is replaced by discretised domain consisting of an array of nodes and associated cells (‘blocks’ for calculating finite difference). At each of these cells, the hydraulic head is calculated. This nodal grid forms the platform for the groundwater numerical model. One or more layers within the numerical model can represent the varying geohydrological layers’ areas. The thickness, in turn, of each layer represents the natural condition of each geohydrological unit, and may vary according to the natural conditions. The location of these cells are described as columns, rows and layers.

The mesh size (rows and columns) can also be refined. This may take place if a greater understanding of a smaller area is required, thereby gaining a possibly greater understanding of that area.

The model was assigned 320 rows and 152 columns with a cell size of 250m x 250m. This equates to a model area of 3040km^2. The model area’s co-ordinates are -3120000, -2000 (lower right corner) to -3040000, -40000 (upper left corner).

5.8.1.2 Layers

The Vaalharts model constructed during this project made use of a two-layer model. Confined conditions were applied to these layers.

5.8.1.3 Layer Construction

The contoured surface was interpolated onto the model area, and was calculated and interpolated for the base and top of the various layers. The layer depths were based upon geology encountered during literature reviews of Vaalharts specific data and drilling that took place during the course of this project.

The upper layer was assigned values for the sands, according to geological logs drilled during this and other projects, averaged at approximately 6m. The lower layer was assigned average values for the calcretes, clays, gravels and shales due to their relatively similar range of depths, and depths of the geological strata from borehole logs. The lower layer was applied a depth of 30m, based upon averages in the Irrigation Area from geological logs. The basic lavas were assumed impermeable, thereby concentrating the aquifer parameters on the sands and clay, calcrete, gravel and shale unit. The aquifer parameters for these geological units were found to be in the same order, although spatial variations did occur according to the borehole logs in a north-south section. Zones of varying parameters were applied to accommodate these variations.

5.8.1.4 Boundary Conditions

One of the most important steps in constructing a groundwater model is deciding upon the model area, and the boundaries of that particular area. The boundary condition expresses the manner in which the investigation area reacts with the rest of the immediate environment. Once these boundaries have been specified, and the model area decided upon, the boundary condition has to be decided.

The boundary determination in this project took much consideration, as too small an area would not include the Vaal River and would therefore affect the flow of groundwater within the model area. The same was true if too large an area were considered. It was therefore decided to include the Vaal River in the area of Warrenton, but not extending as far south as Delportshoop, or as far north as Schweizer-Reneke. Eastern and western boundaries were decided to include the Ghaap Range to the west, and the basic lavas to the east, as these would act as groundwater flow boundaries

Fixed head boundaries were applied to the Harts River and Vaal River. A fixed head boundary will prevent the water level from rising or falling in the rivers, as is generally representative of these two rivers.

5.8.1.5 Initial Hydraulic Heads

The initial hydraulic heads for the model simulation used the actual water levels measured in the area combined with Bayesian Interpolation and applied to the model area using the Field Interpolator function in PMWIN. It would have been ideal to have had measured water levels for each of the cells in the groundwater numerical model, but this was obviously impossible.

Two methods can be used to simulate water levels for each cell within the model area:

- Using measured water levels as existing data; interpolation can be used to apply piezometric water levels to each cell within the model area. The interpolation technique being referred to in this case is Bayesian interpolation. Bayesian interpolation is used where sampling data are available for much of the area, and where there is a better than 80% correlation between these water levels and the topographic height at this point. See Figure 62 for an example of a Bayesian interpolation graph).
- Where measured water levels are available, but not in close proximity to one another, PMWIN as user-interface for Modflow can be used to calculate per-cell water levels. The water levels in such case will therefore correlate closely to surface levels.

The first option illustrated above was used for the numerical model, as a 98% correlation between the topography and water levels were calculated.

The initial hydraulic heads are, once interpolated, used to simulate initial groundwater flow conditions in the model area.

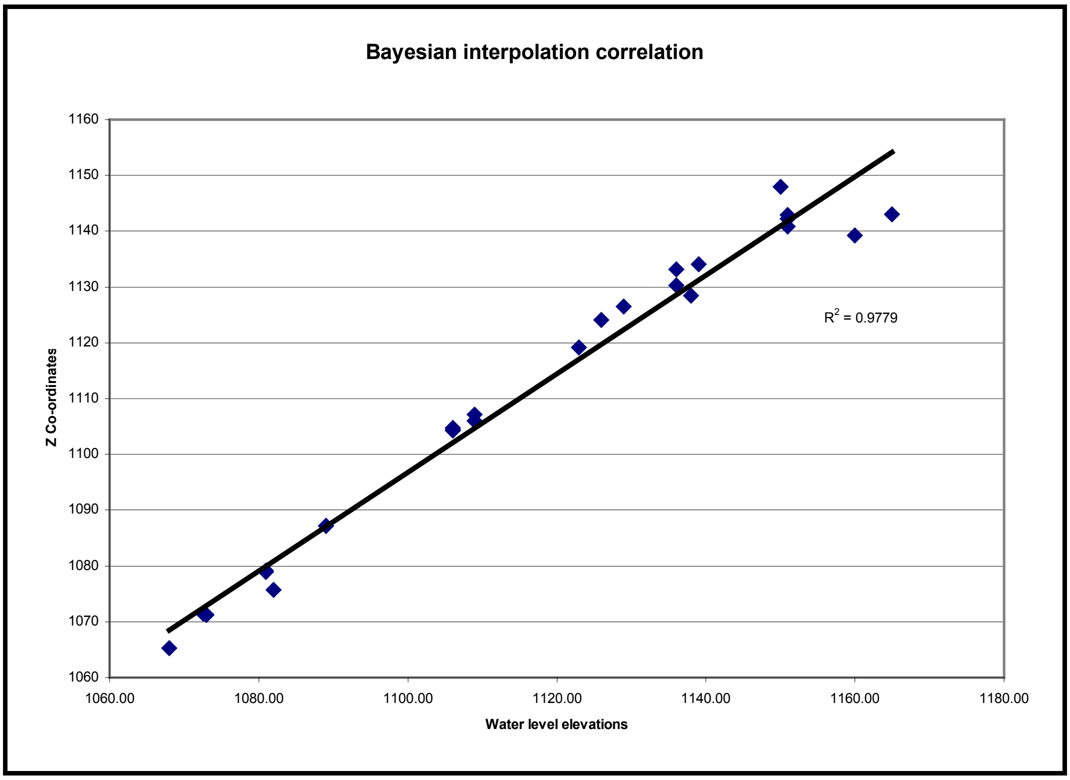


Figure 62: Correlation between water levels and topographic elevations

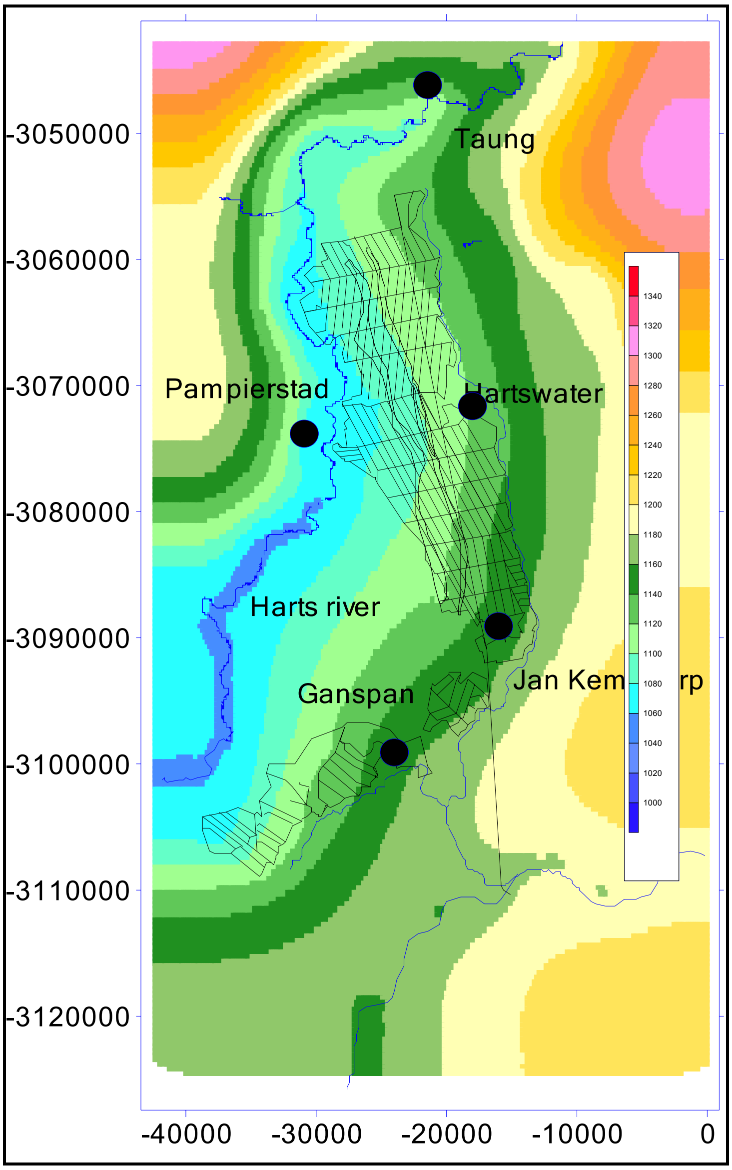


Figure 63: Initial water levels used in the Vaalharts numerical model

5.8.1.6 Horizontal Hydraulic Conductivity and Transmissivity

The majority of aquifers are heterogeneous in terms of their hydraulic properties (Havenga, 2002). This statement was found to be also true in the case of the Vaalharts Irrigation area. Although the hydraulic conductivities encountered during our studies within the Vaalharts area remained within the same order of values, the heterogeneity in the hydraulic properties throughout the aquifers was evident. This can largely be explained by the presence of a fractured rock aquifer, with the presence of matrix and fractures, and geological variation.

The transmissivity was calculated by PMWIN by using the product of the horizontal hydraulic conductivity and the aquifer thickness.

As mentioned, two layers were used for the Vaalharts model, although there was spatial variation in a north-south section of the area. This spatial variation can be seen in Section 4.2.4. The various pre-determined areas therefore each had separate hydraulic conductivities applied to them, based upon knowledge of the geology and tested aquifer parameters. For instance, areas with a higher degree of gravels were assigned a higher hydraulic conductivity for that area. In other areas, where fractures with significant yields were encountered, an increased hydraulic conductivity was assigned.

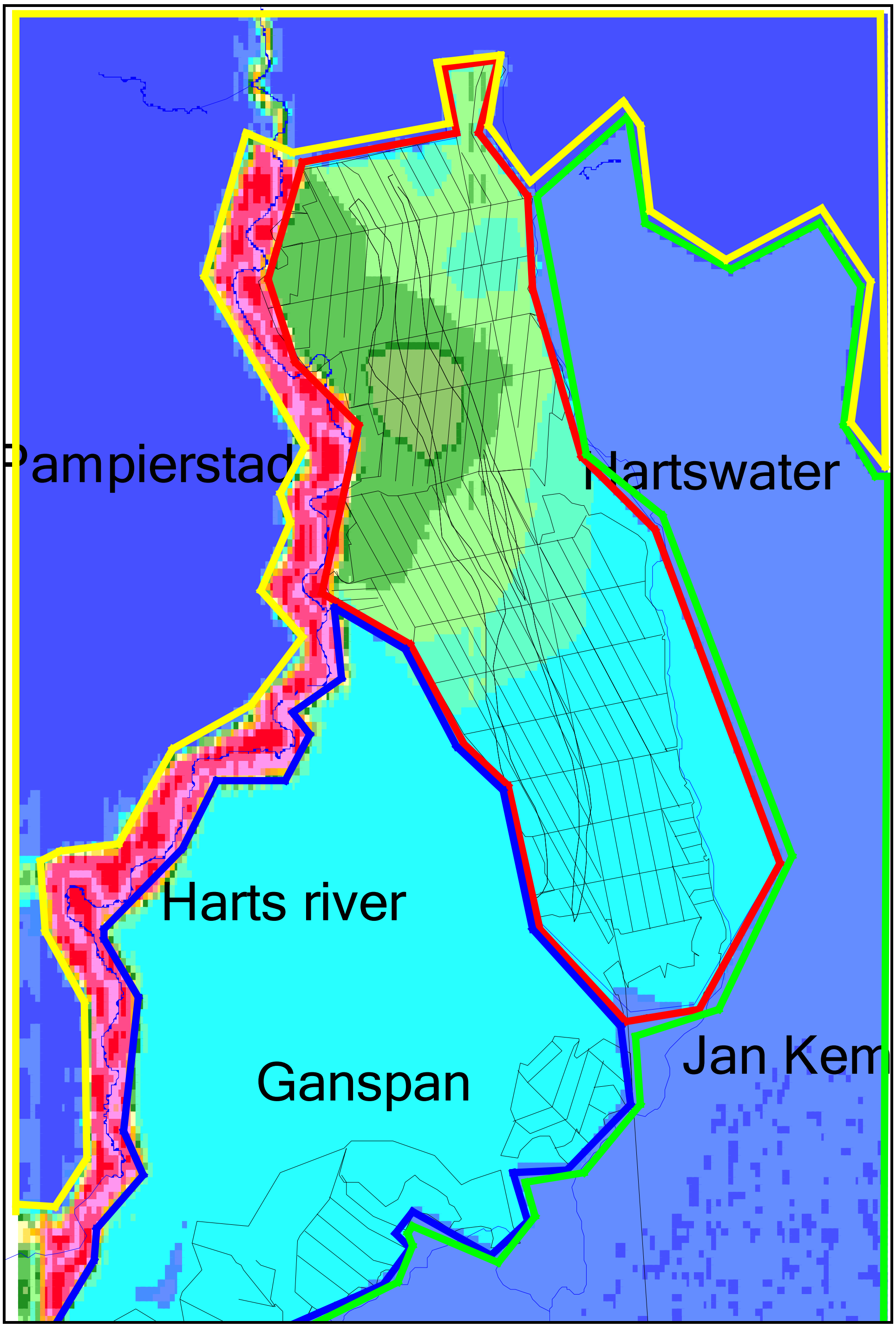


Figure 64: Diagram illustrating the horizontal conductivities used in Layer 1 of the numerical model

Table 8: Hydraulic conductivity values used in Layer 1 of the Vaalharts numerical model

ZONE	HYDRAULIC CONDUCTIVITY RANGE	INFORMATION SOURCE
1 (RED)	7m/d - 18m/d	Badenhorst (2003), Ellington (Section 4.3, 2003)
2 (BLUE)	7m/d	Vermaak *et al* (2002)
3 (GREEN	2m/d - 2.3m/d	NGDB (2002), Kent *et al* (1980)
4 (YELLOW)	0.17m/d	NGDB (2003), Kent et al (1980)

In Table 8 the hydraulic conductivities used for Layer 1 of the Vaalharts numerical model have been illustrated. The zones have been illustrated in Figure 64 by encircling the area in colour. The North Canal area (Zone 1) used values supplied by Badenhorst (2003) were derived from slug-tests performed in the upper 2 m of soil profile, and were determined during the course of this research, as illustrated in Figure 65 as initial values. The values used in Zone 2 were based on geology encountered by Vermaak *et al* (2002) for the West Canal area and extrapolated between the North Canal area and the West Canal area. The values used in Zones 3 and 4 were collectively gained from the NGDB (2002) and Kent *et al* (1980). The values that have been illustrated in Table 8 represent the final calibrated values used in the numerical model.

In Layer 1 of the Vaalharts model, various hydraulic conductivities were assigned, based upon the criteria described above. As can be seen in Figure 65, the model area, of which this diagram represents only a portion, was divided into areas of hydraulic conductivity as described by Badenhorst (2003).

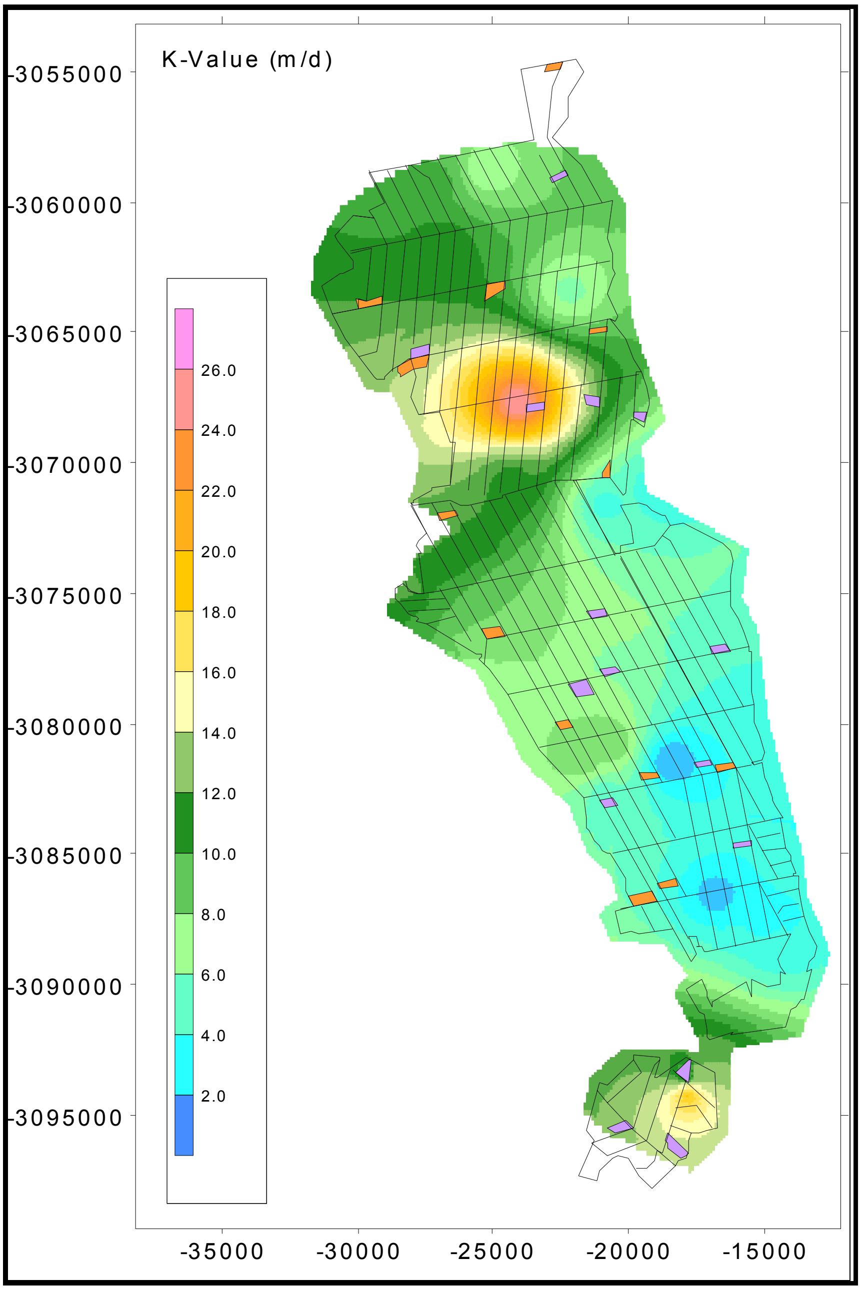


Figure 65: Diagram illustrating hydraulic conductivities measured by Vaalharts Agricultural Station

In Figure 65, the horizontal hydraulic conductivity values measured by Badenhorst of the Vaalharts Agricultural Station are illustrated. The values illustrated above were gained from tests conducted in the upper 2m of the sand aquifer. Relatively lower hydraulic conductivities in the southern parts of the North Canal area are indicated with relatively higher hydraulic conductivities in the northern half of the area. These values were used when assigning horizontal hydraulic conductivities to the upper layer of the Vaalharts numerical model. These observations coincide with aquifer parameter tests undertaken in the Vaalharts area during the course of this project. Furthermore, it also coincides with the geological logs indicating a larger amount of clays being present in the southern portions of the Vaalharts. The hydraulic conductivities assigned to these zones vary between 0.17m/d and 18m/d.

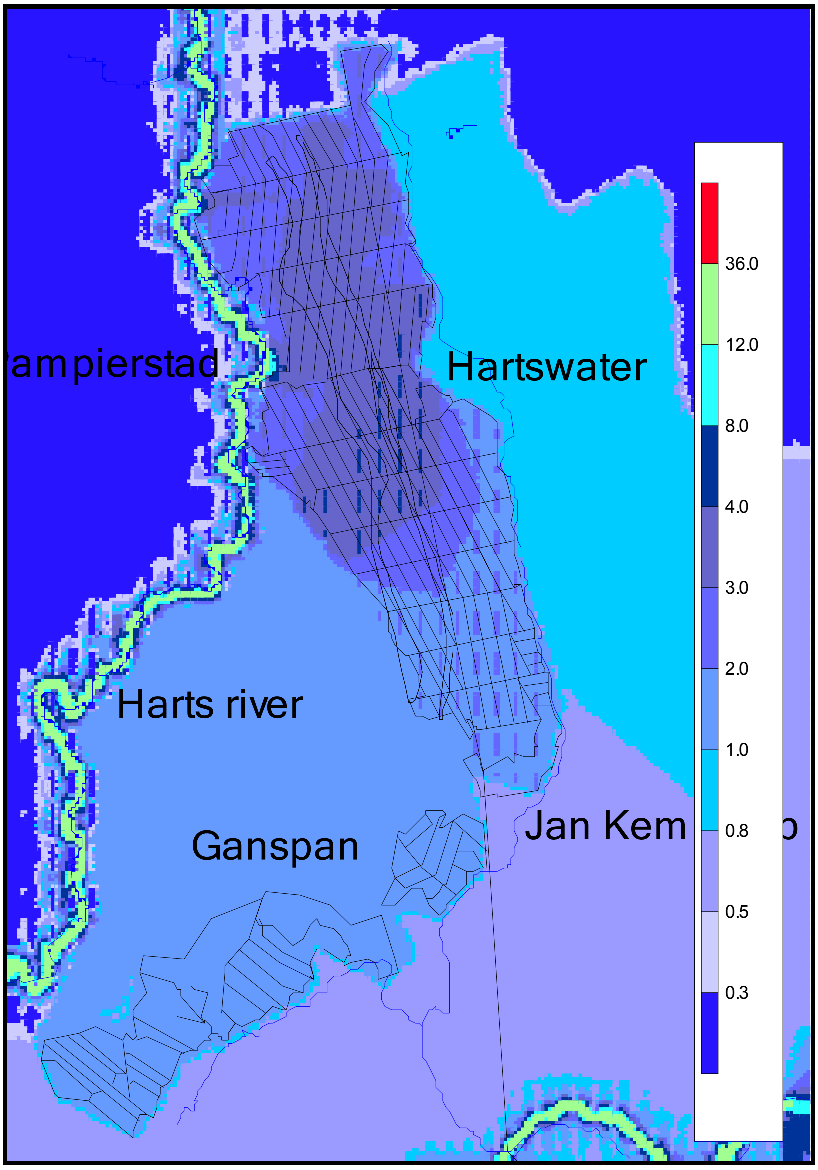


Figure 66: Diagram illustrating the horizontal conductivities used in Layer 2

In Figure 66, the various zones of hydraulic conductivity in layer 2 are illustrated. These zones coincide closely with the zones illustrated in Figure 66 above. As can be seen, in both Layers 1 and 2 zones of high hydraulic conductivity were applied to the Harts and Vaal Rivers, in order to simulate natural conditions. In the remaining areas, relatively high hydraulic conductivities were assigned to the zones in order to simulate the geometric mean of the fractured rock aquifers that were encountered during testing. In the second layer, where clay, calcrete and shale were roughly grouped together, and then separated within the model by zones, relatively similar hydraulic conductivities were assigned. This was due to the small variation in results between these three geological units in the Vaalharts model area. Relatively high hydraulic conductivities were assigned to this layer (between 0.1m/d and 4m/d). These high hydraulic conductivities are a product of the geological processes in the area, and the generic mean calculated from aquifer tests conducted during this thesis. The values can be explained by weathering, fracturing and geological properties within the Vaalharts area.

5.8.1.7 Drains

The drain package works as follows: When the hydraulic head in a drain cell is greater than the elevation of the drain, the water flows into the drain and is removed by the numerical model (Chiang and Kinzelbach, 1998)

The drain package was applied to the North Canal and West Canal areas during the simulations. The drains were applied to the east-west lying streets, even though drainage lies north-south between the streets, as these drains would collect a representative amount of the water in the sand aquifer. The drains applied in the model accurately represent the processes occurring naturally in the Vaalharts system. A drain conductance of 20000m^2/d was applied per drain cell. This depicts the drainage processes taking place within the Vaalharts. In PMWIN, the drain function removes the water from the model, as do the subsurface drains in the Vaalharts Irrigation Scheme. The high conductance was applied to drains as the drains were only positioned where the canals are in reality, and where the drainage water moves. It was believed that if a higher conductance were applied to these cells, it would accurately simulate the vast subsurface drainage.

The subsurface drains were positioned 2mbgl to simulate natural conditions.

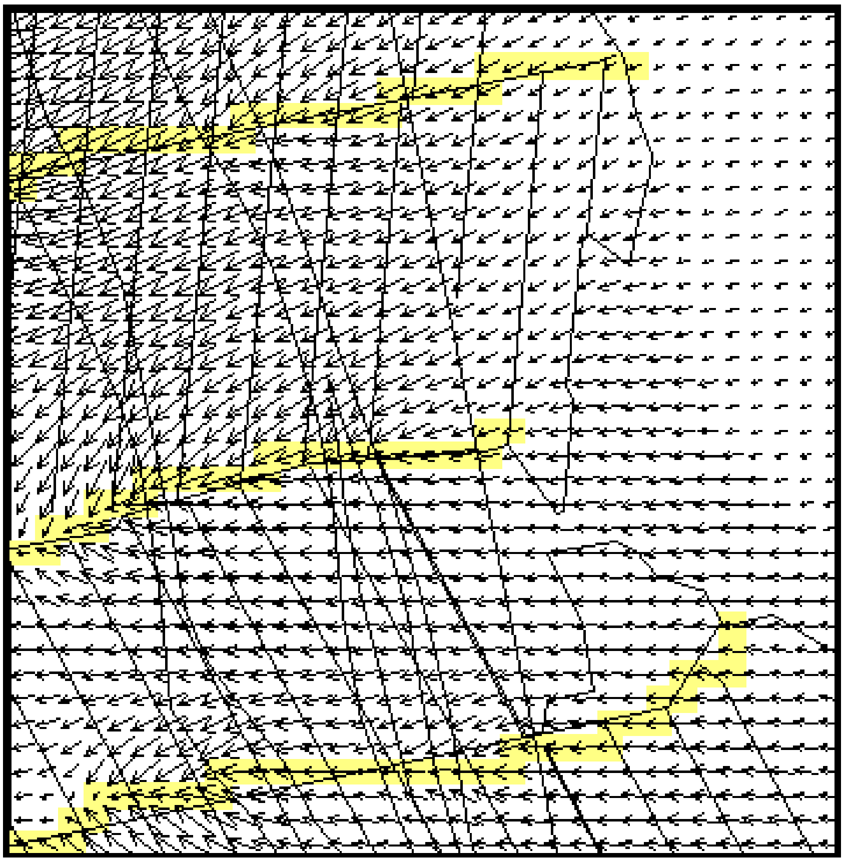


Figure 67: Diagram illustrating groundwater flow towards subsurface drains in the irrigation area

5.8.1.8 Recharge

The recharge package in Modflow is designed to simulate naturally occurring recharge to the groundwater. The recharge was only applied to the upper layer, allowing the vertical hydraulic conductivity to determine the amount of water flowing from the upper to the lower layer.

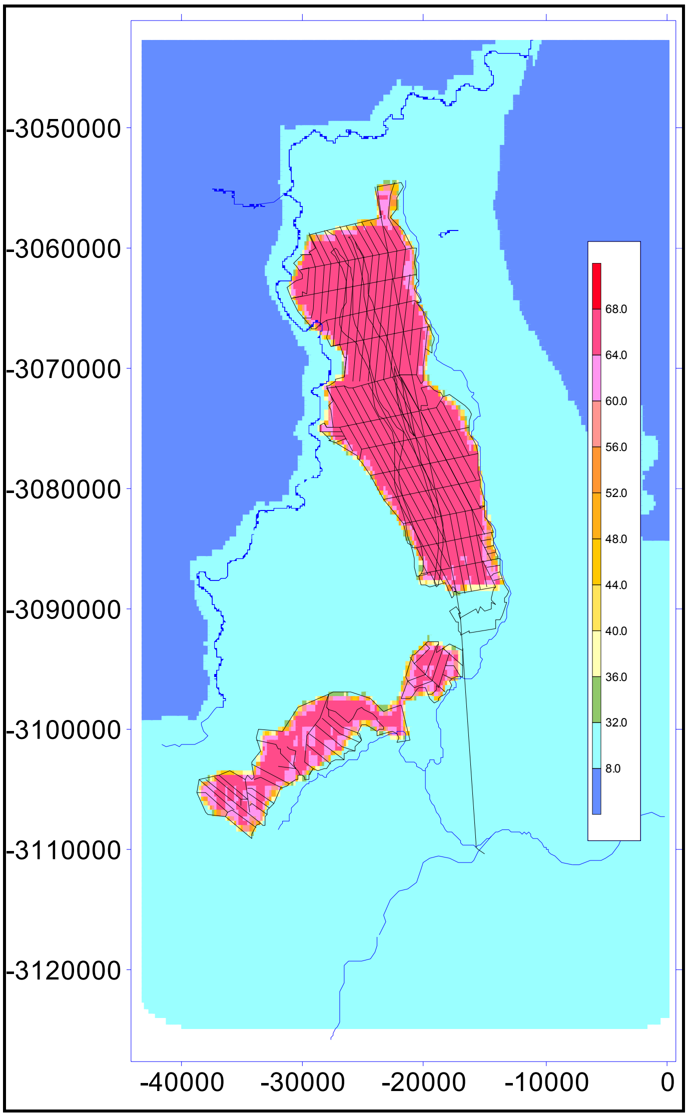


Figure 68: Areas of different recharge (mm/annum)

A higher recharge was applied to the irrigation areas of the West Canal and North Canal in order to simulate artificial recharge from irrigation. A recharge of 5% of annual rainfall and irrigation water was applied to the irrigation areas, while a recharge of 3% of annual rainfall was applied to the non-irrigated areas with shale, calcrete, gravel geology, while the dolomitic and igneous geologies received a 1% recharge (Vegter, 1995). The average annual rainfall in the Vaalharts area is 430mm/a. The various recharge values were based upon geology encountered during the investigation into the Vaalharts area, either during literature investigations or actual drilling work in the area.

5.8.2 TRANSIENT-STATE PARAMETERS

5.8.2.1 Storage Coefficient

The storage coefficient is a parameter that is only applied to the model during transient conditions. Krusemann and De Ridder (1994) describe storage "of a saturated confined aquifer as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head". The storage coefficient is the product of the specific storage value and the depth of the layer. As can be seen in Figure 69 below, only two storage coefficient values were used.

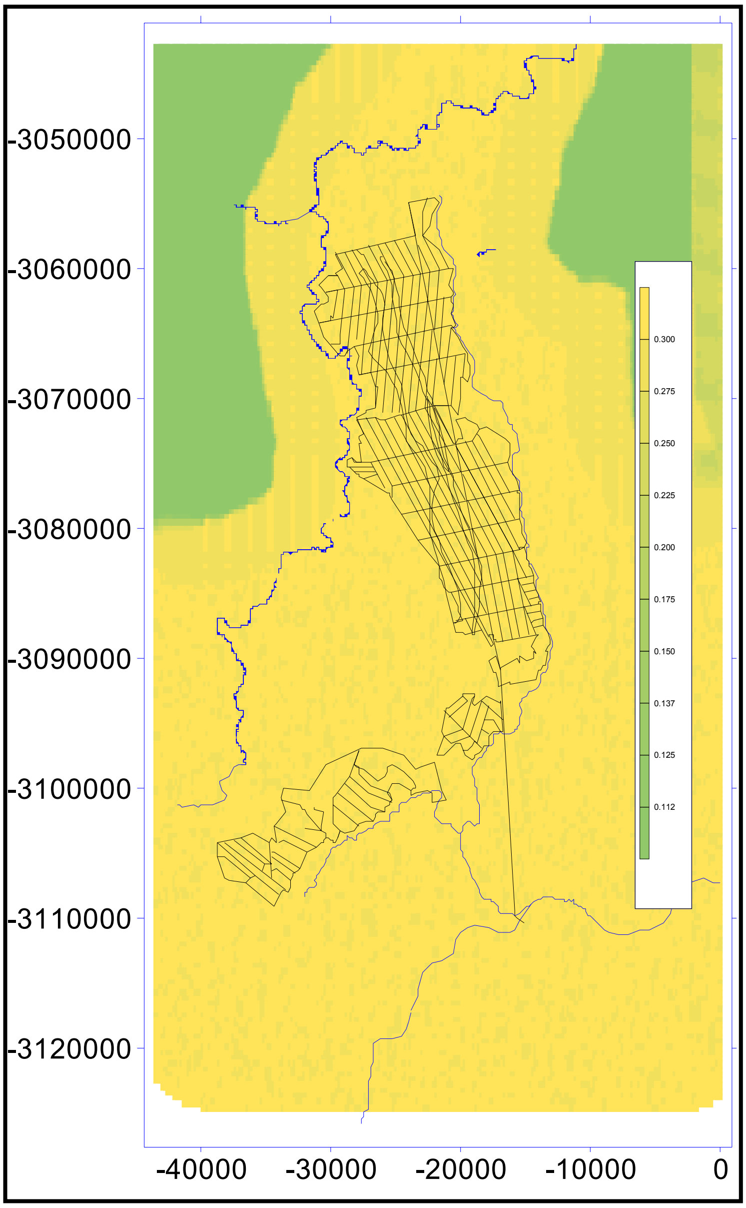


Figure 69: Diagram illustrating the zones and values of storage coefficient used

The storage coefficients used in the model assumed that the area seen in yellow in Figure 69 consisted predominantly of shales, and could therefore be assigned a singular value. The areas in green in Figure 69 assume the lavas and dolomites have similar storage coefficients due to their generally impermeable nature. Values used for these storage coefficients were supplied by Krusemann and De Ridder (1994) and Van Tonder (personal communication, 2003).

5.9 WATER BUDGET FROM NUMERICAL MODEL

The Water Budget function in PMWIN calculates the amount of water flowing into and out of the designated area. Within the Water Budget function, it is possible to assign particular zones within the model area. This can be done either by assigning a zonal value to a particular cell and copy this cell value throughout the desired area by using the ‘cell-by-cell’ function or by applying a zone to the designated area and assigning a particular value to the entire zone. These zones can be applied to investigate scenarios at particular areas, such the measurement of the volume of water entering the Harts River from across the Vaalharts Irrigation Scheme for example.

The more pertinent results gained from the Water Budget have been displayed in Section 6.2, namely the Salt Balance, although the results for the entire model domain have been illustrated in Table 9, below.

Table 9: Water Budget information for the Vaalharts model area (m^3/d)

FLOW TERM	IN	OUT	DIFFERENCE
STORAGE	0.02	0.001	0.02
CONSTANT HEAD	11300	66100	54000
DRAINS	0	63500	63500
RECHARGE	118000	0	118000
SUM	129600	129600	0.002

The Constant Head flow term indicates the volume of water being gathered by the Harts and Vaal Rivers per day, namely 11000m^3 entering the Vaalharts system per day from the rivers, 66000m^3 being taken from the system per day, with a nett loss of 55000m^3 of water per day.

The Drain flow term represents the subsurface drains present in the Vaalharts, namely in the North and West Canal areas. It illustrates that the cumulative loss to the drains is 63500m^3 per day, or 23Mm^3/annum.

The recharge flow term has been calculated as 5% in the irrigation areas, and as 3% in Karoo geology, while it is only 1% in the igneous geology. The amount of water assigned to the Karoo and igneous areas, outside of the irrigation area, is the average annual rainfall of 430mm/annum. In the irrigation area, however, the amount of water assigned to this area was representative of the irrigation water application. This is more representative of natural conditions for the Vaalharts.

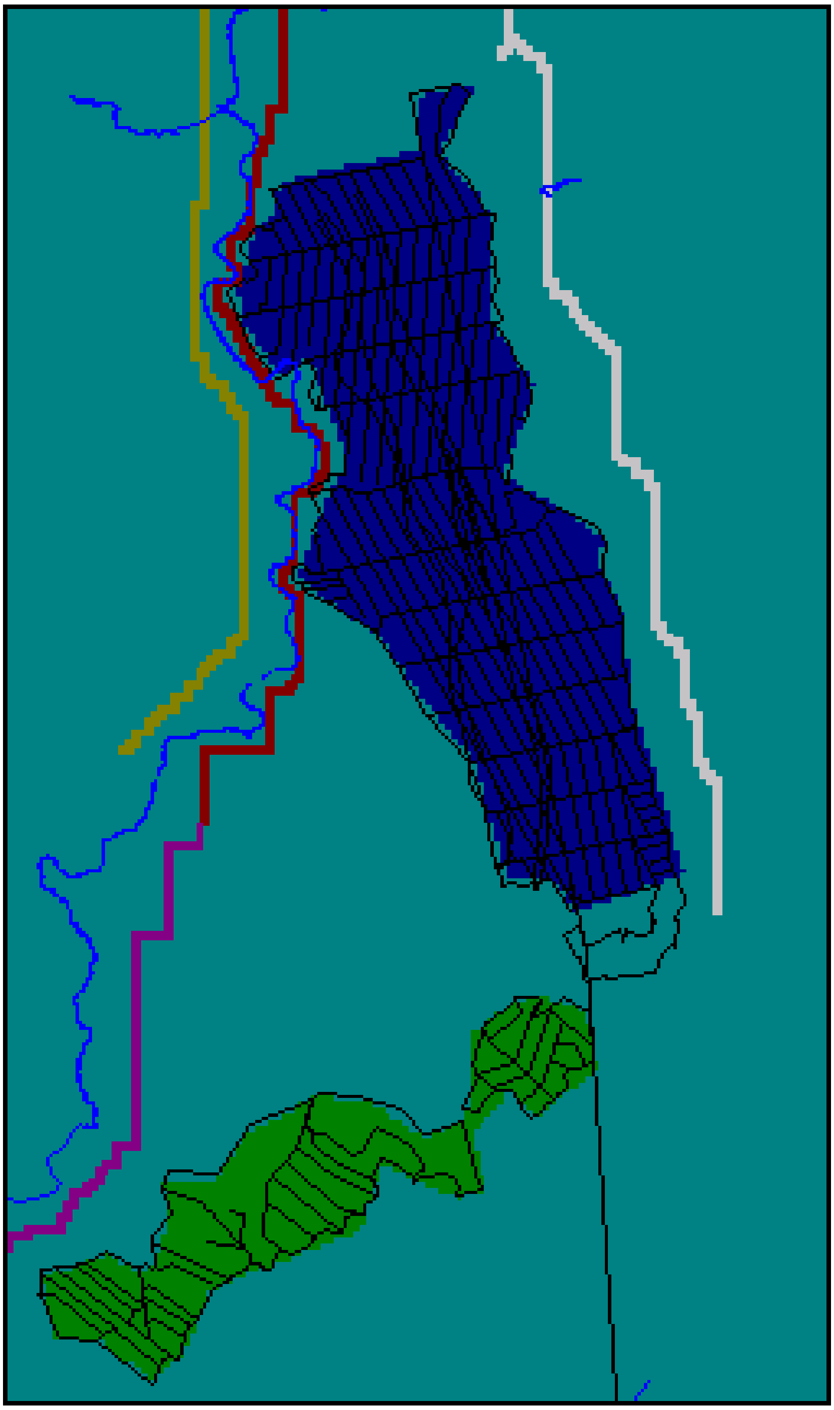


Figure 70: Diagram illustrating the various zones used for the water budget

The zones indicated in Figure 70 have been used to determine the volumes of water entering or leaving an area. Of particular interest are the volumes of water entering and leaving the irrigation areas. The volume of water leaving the irrigation areas is the main contributor to the groundwater flux being seen in the Harts River. There is however, recharge being added to the groundwater flux, although the groundwater flux from the irrigation areas consists of most of this water.

The zones which have been used in Figure 70 have delineated the North Canal area (Dark blue), West Canal area (green), groundwater entering the North Canal area from the hills to the east (white line), groundwater entering the Harts River from the North Canal area (red), groundwater entering the Harts River from the West Canal area (pink line) and the groundwater entering the Harts River area the western side of the Harts River (yellow line).

Although the water budget for the entire model area has been shown (see Table 9), of possibly greater significance is the water budget for the specific zones, as illustrated in Figure 70. These zones were determined in the numerical model to illustrate the volumes of water entering and leaving specific areas.

Of particular interest are the volumes of water being recharged onto the North Canal and West Canal divisions of the Vaalharts Irrigation Scheme. These volumes, together, with the water entering the Harts River from the side of the Vaalharts Irrigation Scheme play a major role in the water balance (Section 6.1) for this thesis.

Table 10: Zonal model water balance (m^3/d)

	GROUNDWATER FLUX ENTERING	GROUNDWATER FLUX LEAVING	RECHARGE	DRAINS
NORTH CANAL	17069	19482	48300	45945
WEST CANAL	10925	13543	16622	14039
HARTS RIVER	39283	-	-	-

The zonal water budget volumes for the North canal, West Canal and Harts River are illustrated in Table 10. The volumes illustrated in the above table are depicted as m^3/d. As can be seen, the North Canal has a total of 17069m^3/day entering the area, while 19482m^3/d leave the North Canal area as groundwater flux towards the Harts River. These values equate to 6.2Mm^3/annum entering the North Canal, while 7.1Mm^3/annum leave the North Canal. The recharge entering the aquifer underlying the North Canal irrigation area is 17.6Mm^3/annum, while the subsurface drains collect 16.7Mm^3/annum.

The West Canal sees a total of 3.98Mm^3/annum entering the aquifer underlying the irrigation area, with a total of 4.94Mm^3/annum leaving this aquifer. 6.06Mm^3/annum are entering the aquifer as recharge, while 5.1Mm^3/annum leave the area as drainage.

The Harts River sees a total of 14.3Mm3/annum entering the river system from the eastern, Vaalharts Irrigation Scheme side of the river.

5.10 MASS TRANSPORT MODEL

The MT3D Mass Transport package that accompanies the PMWIN modelling program is designed to simulate certain transport mechanisms, namely:

- Advection (pollutant moves with the groundwater flow)
- Molecular diffusion (movement of pollutant caused by concentration gradient)
- Dispersion (Spreading of pollutant caused by micro- and macroscopic) heterogeneity of aquifer
- Decay

- Sorption (Adsorption: Adhesion of molecules or ions to the grain surface)

  (Desorption: Release from adsorbed solid phase to solute phase)
- Chemical and biochemical reaction

(Chiang and Kinzelbach, 1998)

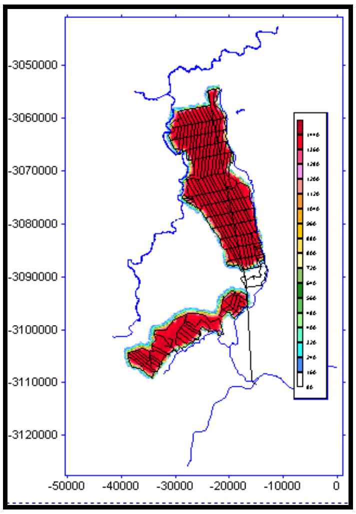
The MT3D mass transport package is therefore able to simulate the movement of a pollutant source, whether it is a continuous- or a point source. In the Vaalharts numerical model it was used to simulate the continuous application of fertilizers and irrigation water onto the irrigation areas of the North- and West Canals over a period of 50 years.

In structuring the mass transport model, it was imperative to simulate natural conditions in the Vaalharts. The dispersion was decided upon by using the longitudinal transverse, vertical transverse and horizontal transverse dispersivities. The result of the horizontal transverse, and the vertical transverse dispersivities divided into the longitudinal transverse dispersivity is a 10% ratio. This allowed us to gain the dispersivity of the model domain by combining the ratio of these dispersivities and the length of the area between the irrigation area and the Harts River, where the plume would be traveling. It was decided to use an average of this distance, and therefore use the dispersivity value of 150.

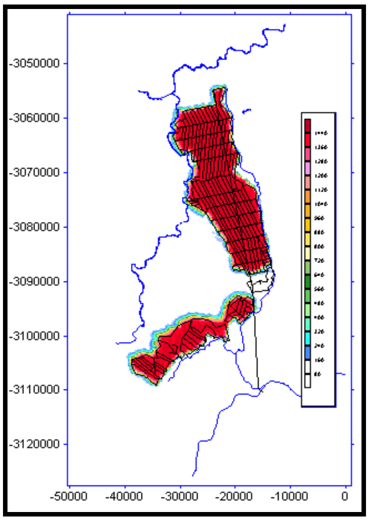
An effective porosity of 10% was used in the numerical model. The effective porosity refers to the total number of voids available for field transmission to the total volume of porous medium.

The initial concentration of the model domain needed to simulate the natural conditions, and therefore used the TDS concentration of the groundwater in these areas. The groundwater was assigned an initial TDS concentration from before irrigation began in the Vaalharts area. The initial TDS concentration used throughout the model was 500mg/l, thereby simulating natural conditions.

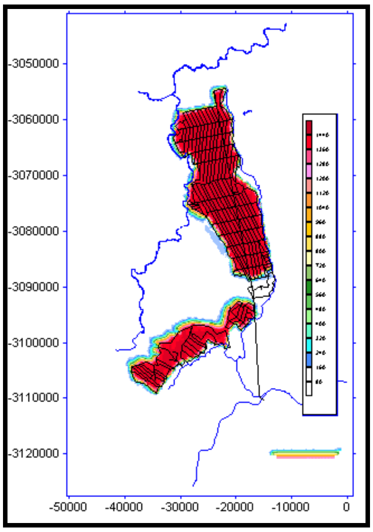
The recharge was applied in an effort to simulate natural conditions. The recharge applied to the model took into account both natural and artificial recharge. The concentrations were applied to the model domain by means of recharge, which is believed to be as near to the natural conditions as possible. A concentration TDS of 30mg/l was applied to the model domain *outside* the irrigation area, in order to simulate the TDS concentration of the rainfall in the area (Van Tonder, personal communication, 2003). The TDS concentration of the recharge *inside* the irrigation area was assigned a value of 3500mg/l, which reproduces the TDS concentration of the leaching/recharge as indicated in Section 6.2. The results of the mass transport model are indicated in the figures below:



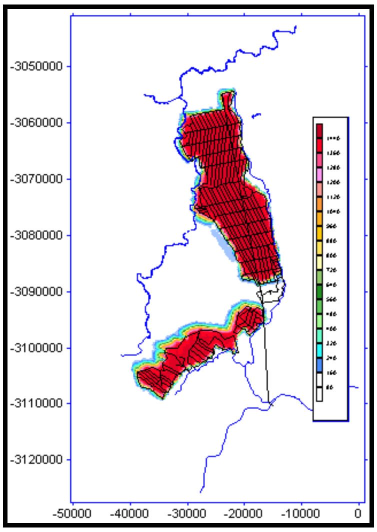
10 years



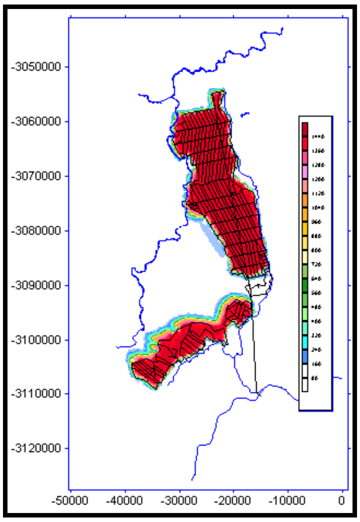
20 years



30 years



40 years



50 years

Figure 71: Plume developments from Mass Transport model

In the above diagrams, the development of the contaminant plume is illustrated over a 50-year period. It is important to note that the plume does not seem to reach the Harts River in the southern half of the North Canal area and the north-eastern portion of the West Canal area. This is caused by the reduction of contamination concentration in these areas as the plume moves towards the river, with the result that the level of concentration of the contaminants is the same as the surrounding *non-irrigated area*. The movement of the plume can therefore not be seen without removing the natural simulation of the initial concentration value of 500mg/l.

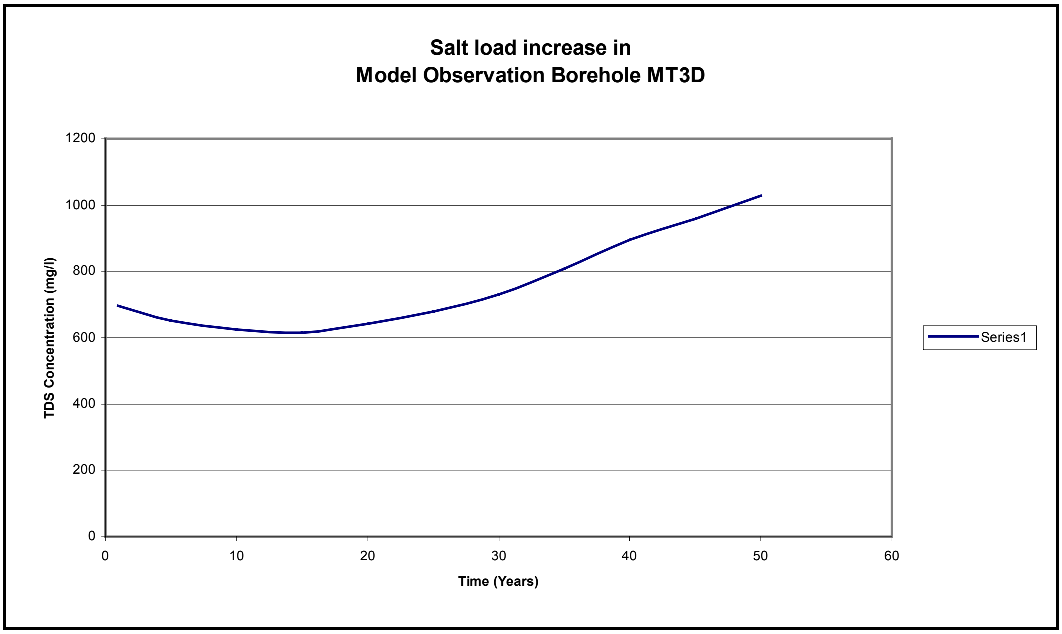


Figure 72: Diagram illustrating movement and increase of plume TDS between North Canal area and Harts River

In Figure 72, the increasing TDS concentration, as the contaminant plume moves towards the Harts River, is illustrated. This model-generated observation borehole is located between the North Canal irrigation area and the Harts River. It illustrates how the contamination levels firstly decrease as dilution of the rainfall takes effect, and the concentration falls from 700mg/l to 600mg/l in a period of 10 years. Once the contamination plume reaches the observation borehole, after 15 years at this point, there is a steady increase to 1000mg/l. Although the input recharge has a concentration level of 3500mg/l, the dilution effect has decreased the concentration to only 1000mg/l: less than a third of the original concentration.

The MT3D Observation borehole is significant to the concentration measurements that are taken from the modelled results. There is no actual borehole that is positioned at this point between the North Canal area and the Harts River, and the MT3D observation borehole is able to extrapolate the measurements and movements of salts from the North Canal area into the Harts River.

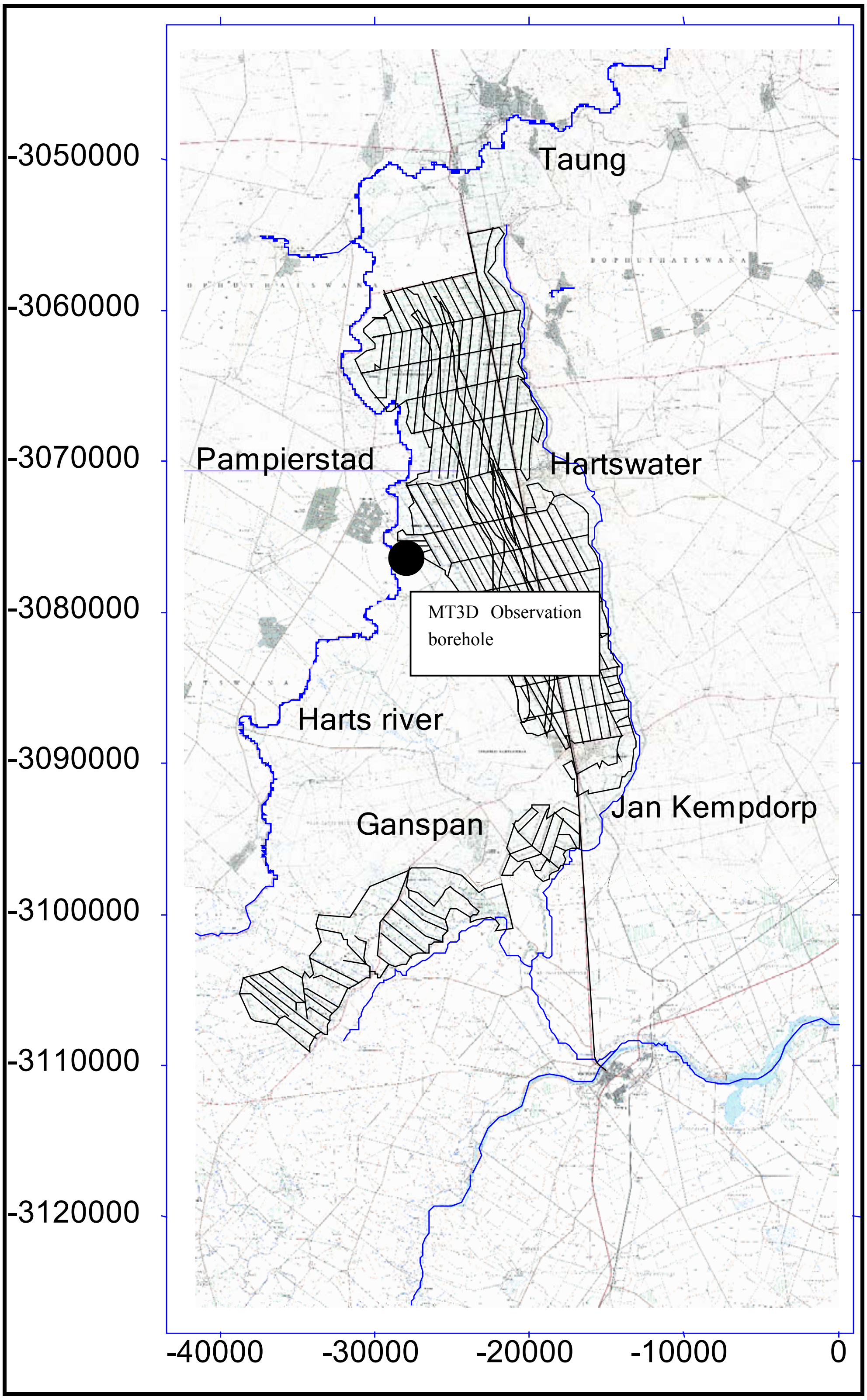


Figure 73: Location of Model Observation borehole for MT3D

5.11 VAALHARTS NUMERICAL MODEL CONCLUSIONS

An important consideration when constructing this model was to determine whether salts from the Vaalharts irrigation area were moving towards the Vaal River, south of Vaalharts. This hypothesis would have had an impact on the two previous hypotheses in that there would have been less groundwater travelling towards the Harts River, and therefore possibly less salts seen in the Harts River. The groundwater flow contours therefore gained by the groundwater model completion were paramount to the understanding of the hydraulic system underlying the Vaalharts Irrigation area. The Vaal River was however found to have a minor effect on the processes occurring in the Vaalharts.

The greatest effect on the Vaalharts system was seen to come from irrigation in the area. The groundwater recharge coming from the irrigation practices had the greatest effect on the groundwater levels in the area, and were seen to rise the level of the water table in the irrigation areas and its immediate surroundings.

The subsurface drains simulated in the model proved able to remove 7.5% of the total amount of water entering the system from the canals, excluding any losses to evapotranspiration, canal leakance.

The groundwater flow was moving towards the Harts River within the Harts River valley. This indicates that all salts entering the groundwater system should, under natural groundwater flow gradient, move towards the Harts River system.

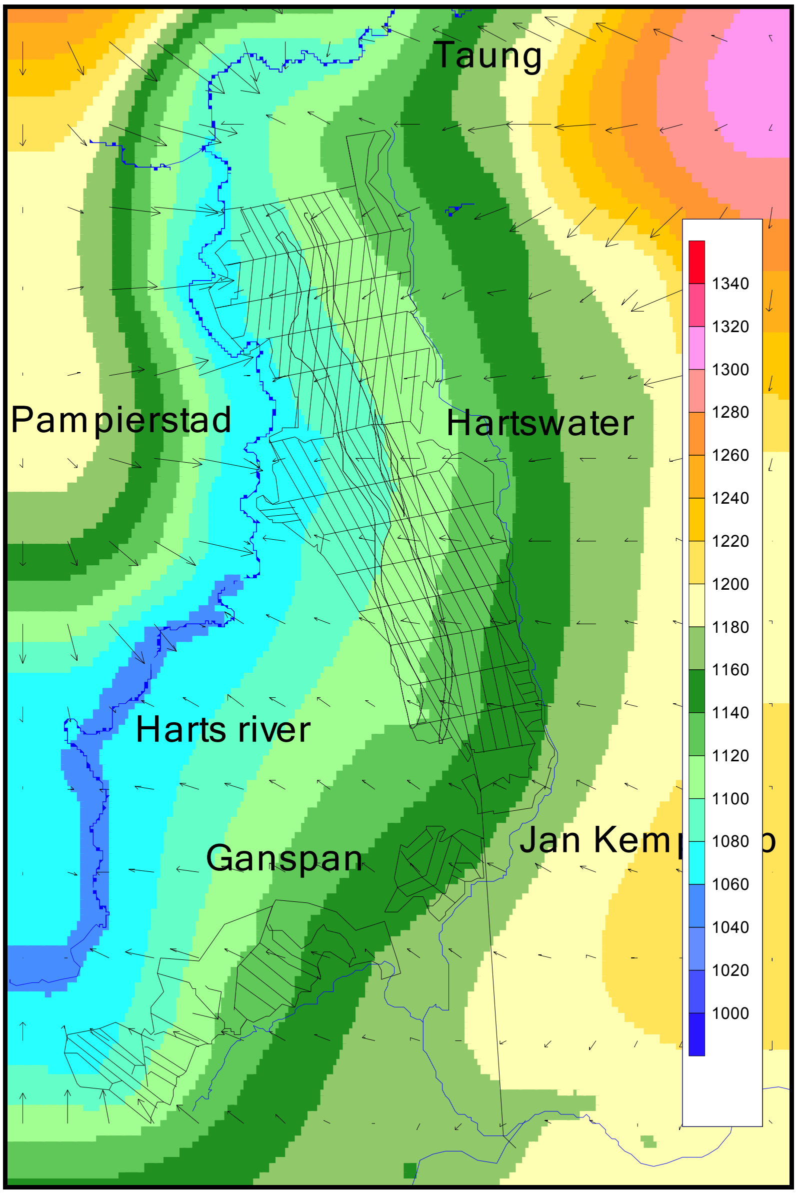


Figure 74: Diagram illustrating direction of groundwater flow in the model domain

The movement of contaminants towards the Harts River system was made evident in the mass transport simulation. In the mass transport simulation, a contaminant was applied to the irrigation areas simulating the natural processes of recharge and leaching from fertilizer application in the agricultural processes within the Vaalharts. The path of this contamination was clearly towards the Harts River, although clear indication of this movement *into* the Harts River was hidden by the fact that the contamination plume concentration became reduced by the effect of the recharge by rainfall. The contamination plume eventually assumed a similar concentration as the groundwater in the *non-irrigated* areas between the irrigation areas and the Harts River.

The relation of these model conditions compared to natural conditions is discussed in Section 5.2.3.

6 WATER AND SALT BALANCE

6.1 WATER BALANCE

The water balance for the Vaalharts Irrigation Area and surrounding region is an integral portion of this project. The Vaalharts system has been suspected of acting as a salt sink, thereby subtracting a large portion of the salts from the system. It was assumed by Herold and Bailey in their 1996 report to the WRC that approximately 100000t/annum of salts are missing. It was further assumed that these salts were moving towards the aquifer, and would force a flow reversal of the salts into the Harts River.

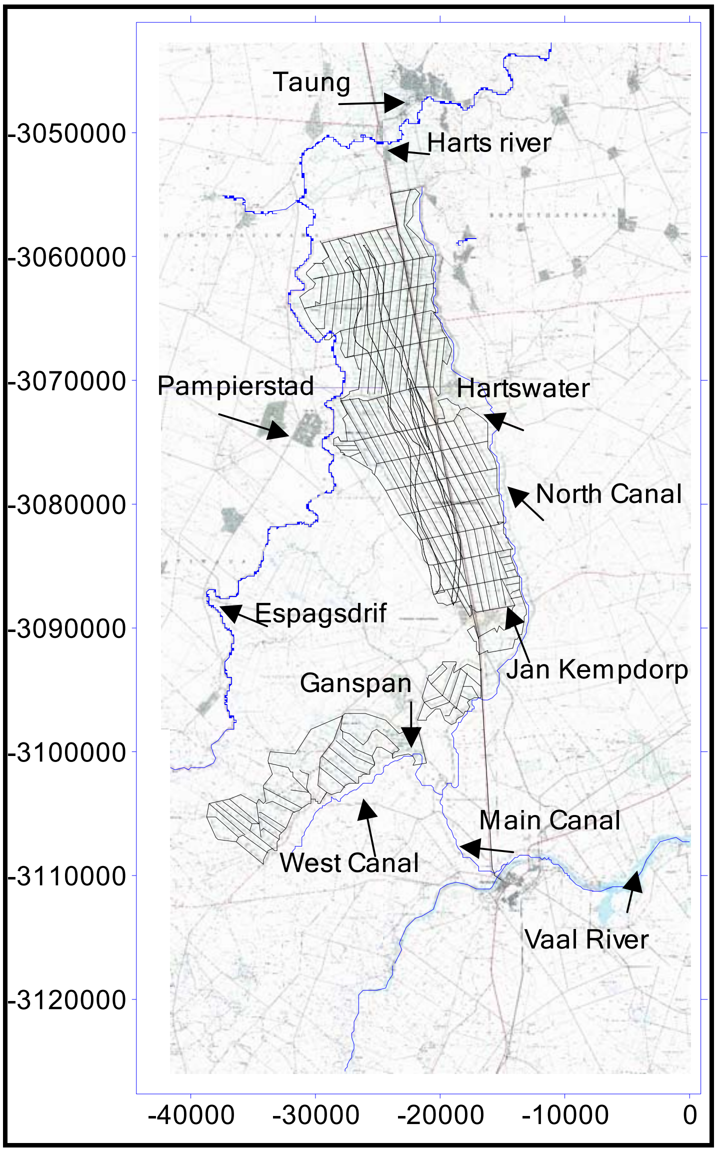


Figure 75: Map of the Vaalharts region illustrating areas used to calculate the water balance

When conducting the water balance for the Vaalharts region, it is important to divide the balance into two components, namely incoming and outgoing water. The water termed incoming, is water from the irrigation canals and rainfall into the area. As the initial question surrounding this project was whether the Vaalharts *is* acting as a salt sink, and at the same time not allowing water and salts to flow through to the Harts River, it was necessary to view the area holistically. The rainfall and recharge being added to the system therefore had to include the entire area from the irrigation scheme to the Harts River.

The incoming water for this equation was inclusive of irrigation water, namely the water entering the system from the North Canal and West Canal. This is irrigation water to be used in the North Canal and West Canal areas. As this combined water enters the 'Vaalharts system', it was combined when calculating the water balance. Rainfall being added to the area was calculated using the average rainfall for the Hartswater and Jan Kempdorp rainfall stations. Hartswater has an average rainfall of 416mm/annum over the past 67 years, while Jan Kempdorp has an average rainfall of 445mm/annum over the past 67 years. An average of these two rainfall values, namely 430mm/annum was used to calculate the average amount of rainfall being added to the Vaalharts region per year over the holistic 72000ha area.

The recharge portion of this equation was calculated as 5% (five percent) of both the incoming irrigation water and rainfall (Vegter, 1995). Recharge in this equation is seen as water applied to the surface and has passed the subsurface drains in the irrigation scheme. The recharge portion of this equation has therefore been added to the aquifer. Certain of the values calculated empirically were re-checked using the water budget function of PMWIN. The value of 5% used for the recharge determination was based on the properties of the Kalahari sands in the irrigation area. A 3% recharge value was used for the areas devoid of these deep Kalahari sands outside the irrigation area that had greater amounts of clay.

The water leaving the system included over-allocated tailend water from irrigation input, drainage water that had been accumulated by the subsurface drains in the Vaalharts, runoff from rainfall, groundwater moving into the river, and evapotranspiration.

Runoff was calculated from figures obtained by the WR90 series of reports at 5.7mm per annum. As ground that is water saturated has a generally higher runoff than unsaturated ground, the Vaalharts area, with its shallow water table, may be assumed to have a generally higher runoff than those areas not directly in the irrigation area (Midgley *et al,* 1994).

The groundwater moving towards the river was calculated using Darcy's Law, and the equation:

$$Q = TiL$$

Where Q = Darcy Flux towards the river
T = Transmissivity
i = Gradient of the groundwater
And L = Length of investigated area.

The transmissivity used for the calculation was an average gained from pump tests conducted for the entire area during this project. The boreholes used for this pump test analysis were drilled by DWAF in the North Canal area of Vaalharts, while pump-test analyses completed by Vermaak *et al* (2002) were used for the West Canal area of the Vaalharts. These boreholes included an array of both fractured, matrix and double-porosity aquifers. A transmissivity value of 70m^2/d was used for this calculation. The gradient was calculated using an average water level gradient across the area, namely 0.0059. The length of the river in the Vaalharts region was used for the determination of L, namely 78000m. This included the length of the river from south of Taung, north of the North Canal area, to the south of Espagsdrif, and just north of the Ganspan agricultural area. This gave a Darcy Flux of 11.76Mm^3/annum, or 32000m^3/d towards the Harts River. This equation is the same used to calculate the salt load reaching the Harts River from the Ogata-Banks Equation.

The term evapotranspiration in this model applied to any water that either went to crop requirements or evaporation. Evapotranspiration is that portion of the water being added to the system and being used by the crops for basic functions, or being released into the atmosphere as transpiration.

Table 11: Empirical values calculated for the Vaalharts Water Balance (Mm^3/annum)

Name	Incoming water (M m3/a)	Outgoing water (Mm3/a)
North Canal	272.01	
West Canal	42.97	
Rainfall	309.60	
Groundwater going to river		11.76
Canal Tailends		23.35
Recharge		28.38
Drainage		23.63
Runoff		4.10
Evapotranspiration		533.37
Totals	624.58	624.58
Difference (Inflow - Outflow)	0.000	

In Table 11, the various volumes of water flowing into, and exiting the Vaalharts system are illustrated. The volumes have been illustrated in units of million cubic metres per annum. The values for the North Canal, West Canal and Tailends' volumes were received from The Department of Water Affairs and Forestry at Jan Kempdorp. The groundwater flux towards the Harts River was calculated by means of Darcy's Law and checked by means of the water budget function in PMWIN. Runoff was calculated from WR90 data, while evapotranspiration and recharge were calculated empirically. Table 11 used empirical values for these calculations.

Evaporation in these water balance equations is assumed to be all water leaving the Vaalharts Irrigation Scheme that is not tailends, drainage, recharge, runoff or groundwater flux. The same evapotranspiration value used in the empirical determination is used in Table 12.

Table 12: Values used for Vaalharts Water Balance using empirical values, and model values where possible

Name	Incoming water (M m3/a)	Outgoing water (Mm3/a)
North Canal	272.01	
West Canal	42.97	
Rainfall	309.60	
Groundwater going to river		14.34
Canal Tailends		23.35
Recharge		28.38
Drainage		23.63
Runoff		4.10
Evapotranspiration		533.365
Totals	624.578	627.158
Difference (Inflow - Outflow)	-2.580	

In Table 12, a combination of empirical and model-generated values was used to account for this balance. The model-generated values that could be used were those of recharge, drainage and groundwater flux towards the river. These values differed as compared to the empirical values on the whole. The variation between these values is as follows:

Table 13: Comparison of empirical and model-generated values used for the water balance

	Empirical	Model-generated
Recharge	28.38	27.93
Drainage	23.35	24.68
Groundwater flux	11.76	14.34

In Table 12, above, using the different model-generated values as seen again in Table 13, a difference of 2.58Mm^3/annum can be seen. This forms a difference of 0.51% as compared to the total incoming water into the system. This difference is still at such a small proportion that it could be attributed to loss in seepage from canals and dams, and the numerical errors that averages induce.

6.2 SALT BALANCE

In the Vaalharts Salt Balance, quantities of water obtained in the Water Balance were combined with water quality measurements taken for each component. The water quality measurements were, in the most cases converted to Total Dissolved Solids (TDS) by the summation of the various macro-elements, in the analyses. Calculating a conversion factor for converting the Electrical Conductivity to TDS was done to check these TDS values. Plotting the various values, drawing a correlation of these values, and calculating the mean variance provided a conversion factor of 7.62. Figure 76 illustrates the mean variance and conversion factor calculated from the TDS values.

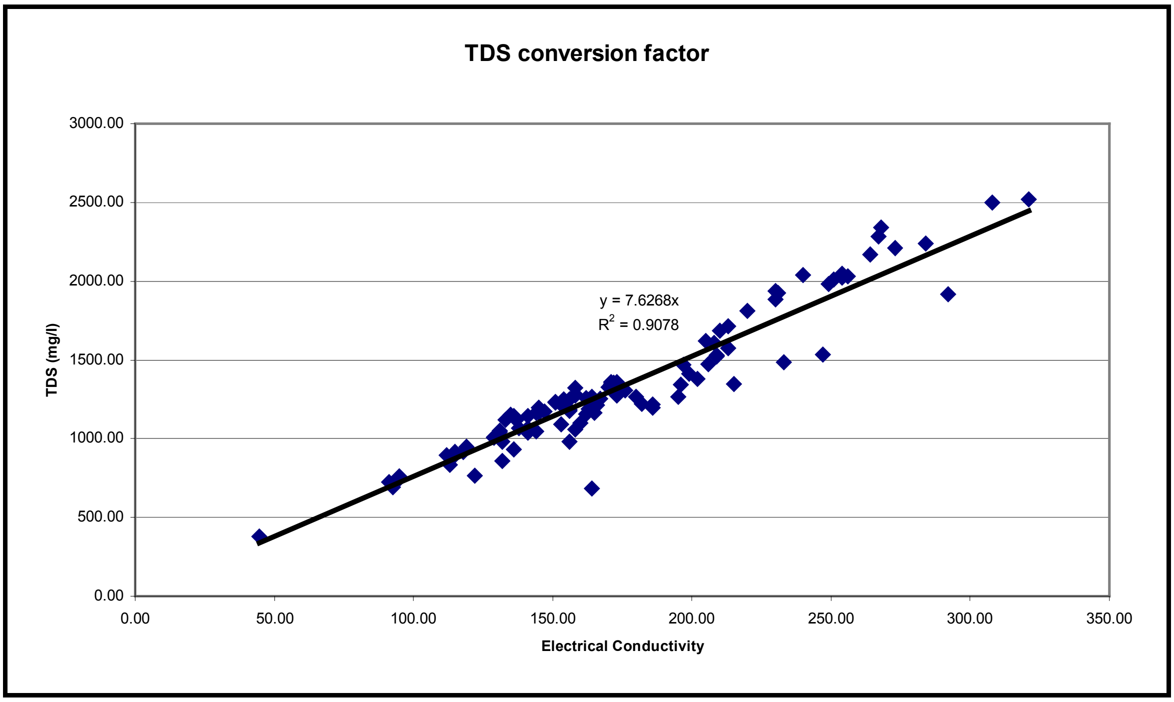


Figure 76: Plotted TDS values, their mean variance, and the conversion factor gained from this exercise

The values used for the water entering the Vaalharts canal system, namely the Main Canal, West Canal, Klipdam-Barkly and North Canal were assigned the value obtained from measurements taken in the Vaal River at Warrenton, Station C9R001. This was done as all the water entering the system comes from the Vaal River at this point. Another TDS used for this calculation was derived from Du Preez *et al* (2000). In their calculations, they used a long-term average for the incoming TDS, which was 356mg/l. The TDS that was used for a comparison of ranges, gained from the afore-mentioned Vaal River Station was 415mg/l.

The rainfall was assigned a TDS of 30mg/l (Van Tonder, verbal communication, 2003). It may be thought negligible, although the rainfall, with an average annual volume of 309Mm^3 still has an average TDS load of 9300 tons of salt load addition to the Vaalharts system. The rainfall has an interesting role to play in the Vaalharts. While adding a salt load of 9300t/annumannum, it still has a diluting effect on the system as it adds 309Mm^3 per annum of water.

Further to the surface water portion of the Vaalharts salt balance are the tailend subtractions and the drainage water subtractions. The tailends are a measured entity, measured by the Water Control office of the Jan Kempdorp Department of Water Affairs and Forestry. There is a measured average of 23.3Mm^3/annum of water being over-applied to the Vaalharts system. This water then passes through the system and joins the Harts River via the canals, which in turn rejoins the Vaal River. This water has the same TDS as the water travelling through the canals. The short-term average TDS value for this water is 415mg/l, while the long-term average is 355mg/l.

The drainage water applies to the water being used in the irrigation area by the farmers, passing the root system of the crops, and being taken out of the system by the subsurface drainage system. This water has been measured in the drainage canals, as having a TDS of approximately 770mg/l during the course of this research. This is however not a true representation of the TDS concentration of the drainage water, as it would have mixed with the tailends' water by this stage and have had its concentration diluted. The volume of the drainage water was calculated both empirically and by means of the numerical model. These values have been addressed in the previous section, namely 'Water Balance'. They are 23.3Mm^3/annum, calculated empirically, and 21.9Mm^3/annum obtained from the 'Water Budget' function from the numerical model. Either of these two values would therefore denote a TDS load of 18200t/annum from the empirical calculation, or 19000t/annum from the model derived value, taking into account the inaccuracy of the TDS measurement.

The TDS of the groundwater was obtained from measurements taken during this project. It is an average of the measurements taken across the spectrum in the North Canal and West Canal areas. The TDS calculated for the groundwater was derived from the product of the TDS conversion factor and the average of the electrical conductivity values. The average electrical conductivity was 176mS/m, which gave a TDS of 1350mg/l for the groundwater TDS load calculation. This TDS concentration of 1350mg/l equates to a salt load of 15800t/annum of salts leaving the Vaalharts system from groundwater to the Harts River in the empirical calculation, or 19400t/annum in the model-derived calculation.

Simultaneously, an average TDS load can be calculated for the groundwater present in the Vaalharts aquifer, comprising of the North Canal, West Canal and areas between these irrigation areas and the Harts River. This can be calculated by assuming an average depth of aquifer (from surface to lavas) of 50m; an effective porosity of 10%, the area being calculated as 72000ha; and a pre-calculated TDS concentration of 1350mg/l. This calculation implies a volume of 3600Mm^3 as the groundwater reserve in the Vaalharts system. This volume, together with the TDS concentration of 1350mg/l, implies an average salt mass of 9720000t present in the aquifer. In Table 14, the values used for the aquifer volume and TDS load calculations are illustrated:

Table 14: Parameters for aquifer TDS load calculation

Parameters	**Values**
Area (ha)	72000
Area (m^2)	720000000
Aquifer depth(m)	50
Effective porosity	0.1
TDS concentration (mg/l)	1350
Aquifer volume (Mm^3)	3600
Aquifer salt mass (tons)	9720000

In applying values gained from the 'Effect of Water Quality on Irrigation Farming along the Lower Vaal River: The Influence on Soils and Crops' (Du Preez *et al*, 2000) where they used agricultural models to gain values for certain components of the salt balance in the Vaalharts, a greater understanding of the Vaalharts agricultural processes can be made. In this report, the authors made use of the Soil-Water Balance (SWB) model to quantify values of salt load addition in the Vaalharts agricultural scheme. Simultaneously, the Aragues model was used in order to compare values. The Aragues model takes into account the number of years during which agriculture has been practised on a large-scale within the Vaalharts Scheme, the salt load in the soil, the salt load addition, and the salt load removal, be it by means of crops or leaching. From the Aragues model, an estimated 101000t of salts have accumulated in the soils over the past 53 years, indicating an annual increase of 1900t of salts in the soils.

Furthermore, the Aragues model also indicates a modelled irrigation salt load addition of 5472000t over the 53 years of irrigation, or 103000t/annum in the Vaalharts. The Aragues model adds to this the fertilisation addition salt load, where 2560000t of fertilizers have been added over the 53 years of the Scheme's existence, or an annual increase of 48000t in the Vaalharts Irrigation Scheme. The Aragues model conducted by Du Preez *et al* (2000) addresses the salt removal in the Vaalharts. As mentioned previously, the salt removal has been sub-divided into salts removed by crops and by leaching. The salt removed by crops equates to a modelled 43tons/ha over the 53 years or 26000t/annum removal by crops from the Vaalharts Scheme. The removal of salts by leaching is 205t/ha/53 years. This equates to a leaching removal of 124000t/annum.

Table 15: Summary of Aragues model results

Parameter	Addition (t/annum)	Removal (t/annum)
Irrigation salts	103000	
Fertilizer	48000	
Crops		26000
Leaching		124000
Total	151000	150000
Difference (%)	0.66%	

In the SWB model conducted by Du Preez *et al* (2000), the components estimated also span a 53-year period for the Vaalharts Irrigation Scheme. Two values are given for each component listed namely a field capacity treatment and a 30% leaching treatment. The SWB model gives cumulative results, unlike the Aragues model, which was able to divide the respective results. The SWB model, is however able to supply a larger degree of components. In terms of salt addition, the SWB model gave the field capacity treatment (FCT) and 30% leaching treatment (LT) as 146590kg/ha and 190250kg/ha respectively. This equates to an addition of 88500t/annum FCT and 115000t/annum LT. The percentage of salt leaching, as illustrated by Du Preez *et al* (2000), is 95.2% for FCT and 97% for LT. This equates to values of 84000t/annum for FCT and 112000t/annum for LT. These values relate closely to those values supplied from the Aragues model, and have been used to supply ranges for recharge salt load addition to the Vaalharts aquifer. The SWB model was also able to supply values for the salts arrested in the soils. These values equate to 2700t/annum salt load addition for the FCT and 1500t/annum for the LT. These values fall into the same range as the values supplied by the Aragues model, and as such, have been used to further supply ranges for the salt load addition to the soils in the Vaalharts.

Table 16: Summary of SWB results

Parameter	Addition (FCT) (t/annum)	Addition (30% leaching) (t/annum)	Removal (t/annum) (FCT)	Removal (t/annum) (30% leaching)
Irrigation salts	88500	115000		
Fertilizer				
Leaching			84000	112000
Soils			2700	1500
Crops			1855	1860
Total	88500	115000	88555	115360
Difference (%)	-0.06%	-0.31%		

The calculation of the salt balance used the following equation:

$$IRRIGATION + FERTILIZERS = SOILS + RECHARGE / LEACHING + TAILENDS + DRAINAGE + CROPS + GROUNDWATER$$

The above equation represents the basic macro salt balance for the Vaalharts. The values that will be assigned to these parameters will be able to give ranges within which the salt balance can operate. A number of options are shown in Table 17, to illustrate these ranges.

Table 17: Table illustrating options used for Vaalharts salt balance

North Canal	112884	112884	112884	112884
West Canal	17832	17832	17832	17832
Groundwater going to river	15873	19356	15873	15873
Canal Tailends	17977	17977	17977	17977
Drainage	17979	17979	16859	17979
Recharge	84287	84287	84287	111758
Salts taken up by crops	25962	25962	25962	25962
Fertilizer addition	48302	48302	48302	48302
Salts in soils	1900	1900	2700	1500
Incoming salts	179018	179018	179018	179018
Outgoing salts	163979	167462	163658	191050
Incoming less outgoing	15039	11556	15359	-12032
Percentage difference	8.401%	6.455%	8.580%	-6.721%

In Table 17 the various options used for the Vaalharts salt balance determination have been illustrated. Of the components, the North Canal, West Canal, Fertilizer addition, Canal Tailends, and Salts taken up by crops have remained constant throughout the various options. The other components have changed singularly through the options.

Option 1:

- Used the empirically derived value for the volume of groundwater moving towards the Harts River, which with a TDS concentration of 1350mg/l, equates to a TDS load of 15873t/annum.
- Drainage also made use of the empirically derived value, namely 21600t/annum. The recharge component has made use of the FCT value of 84200t/annum as derived from the SWB model.

Option 1 is the basic option using empirical values for the salt balance determination. The salt balance for Option 1 indicates that there are 20500t/annum of salts being added to Vaalharts system, which at this stage is unaccounted for. These salts lie in the uncertainties encountered with using average values, and unmeasured volumes of water, such as drainage, for example. The practice of extrapolation accounts for much of the differences in these options' results.

Option 2:

- Same parameters as Option 1, except groundwater flux has changed.
- The empirically derived volume of groundwater moving towards the Harts River is replaced by the 'Water Budget' function derived groundwater flux. The TDS load is therefore the product of the TDS concentration and 14.3Mm^3/annum instead of 11.7Mm^3/annum of groundwater flux.
- This equates to a larger TDS load entering the Harts River, namely 19356t/annum in place of 15873t/annum.

Option 3:

- The drainage volume has changed from the empirically derived volume of 23.3Mm^3/annum to the model derived volume of 21.9Mm^3/annum.
- This has had the effect on changing the annual TDS load from 18000t to 17000t. This does, however, not represent a large difference in Incoming less Outgoing TDS values in the Vaalharts system.

Option 4:

- Values from SWB model from Du Preez *et al* (2000).
- In the first three options, the lesser leaching amount derived from the FCT calculation, namely 84300t/annum was used, while in Option 4, the larger amount of leaching, representing a 30% leaching treatment has been used, equating to an annual salt load addition of 112000t.
- This option indicates that there are 3000 more tons of salts leaving the Vaalharts system than are entering the system, which is impossible while using the available values. There will however be different values obtainable, with lesser result differences if lesser degrees of leaching treatments were used.

In the above Option 1, a salt balance difference of 15000t/annum can be seen. This difference can be attributed to any of the components of the salt balance. The 15000t/annum salt difference represents an 8% portion of the total Incoming salt load. Option 2 has a difference of 11500t/annum, or 6.5%. Option 3 represents a difference of 15400t/annum, or 8.5%. Option 4 has a difference of 12000t/annum, or 6.7%. These options are illustrated to indicate ranges of values.

In the 1976 report entitled “Vaalharts Ontwateringsprojek” by Gombar and Erasmus, chemistry was collected for a number of boreholes throughout the North Canal area. The Total Dissolved Solids of these boreholes’ samples averages at 1005mg/l, as indicated in Section 2.8. Furthermore, if one uses the present TDS average of the groundwater in the Vaalharts, namely 1350mg/l, there is an overall TDS increase of 350mg/l, or an average annual TDS increase of 13mg/l. Simultaneously, if the above calculated volume of the Vaalharts reserve is used, together with the average leaching addition of 98000t/annum, there is an average addition of 13.6mg/l to the Vaalharts aquifer over the past 27 years. The values used to calculate this addition of salts can be seen in Table 18 below.

Table 18: Values used to calculate TDS concentration increase with average leaching values

Parameter	Value
Volume (m^3)	7200000000
Annual leaching addition (t/annum)	98000
Present concentration in aquifer (mg/l)	1350
Conversion (m^3 to mg/l)	0.00000135
Aquifer salt (t)	9720000
Annual salt concentration increase (mg/l)	13.6

The SWB modelled average leaching amount of 98000t/annum therefore ties in closely with the measured results in the Vaalharts over the past 27 years. It must however be remembered that the salts are moving towards the Harts River, while still undergoing a dilution effect, and therefore a reduction in concentration, from the rainfall across the greater Vaalharts area.

In the table below the values used for the TDS concentrations indicated by Du Preez *et al* (2000) have been used to illustrate a possible range in which the salt loads can occur. Furthermore, it illustrates the importance of the salt load entering the system with the Vaal River water, and the effect it has on the salt load within the Vaalharts system.

Table 19: Values from Du Preez *et al* (2000) used for comparison (t/annum)

Components	Du Preez et al (2000) Option 1	Du Preez et al (2000) Option 2	Option 3	Option 4
North Canal	95203	95203	112884	112884
West Canal	15039	15039	17832	17832
Groundwater going to river	6861	6861	6785	6785
Canal Tailends	17977	17977	17977	17977
Drainage	21856	21856	16859	17979
Recharge / leaching	84287	111758	84287	111758
Salts taken up by crops	25962	25962	25962	25962
Fertilizer addition	48302	48302	48302	48302
Salts in soils	1900	1900	2700	1500
Incoming salts	158544	158544	179018	179018
Outgoing salts	158844	186315	154570	181962
Incoming less outgoing	-299	-27771	24447	-2944

In the table above, ranges of salt loads have been illustrated. These ranges are based upon values assigned by Du Preez *et al* (2000) for incoming Vaal Water concentrations. In Table 17, the TDS concentration used was 415mg/l, a recent average for the incoming Vaal River water, while in Table 19, the values used for the incoming Vaal River water was 350mg/l-a long-term average. As is evident in the comparison of these two tables, the total incoming salt load has decreased by 20500t/annum. The discrepancy of 300t/annum equates to a variance of 0.18% of the total incoming salt load.

In Option 2 of Table 19, the discrepancy of 28800t/annum equates to a variance of 18% of the incoming salt load. It is safe to assume that with the greater amount of salts entering the system, there will be a higher salt load leaching through to the groundwater. The lower leaching value evident in Option 1 of Table 19 would therefore be more relevant to the lower incoming salt load of 350mg/l used in this table.

7 CONCLUSION

The Vaalharts Irrigation Scheme was initiated approximately 55 years ago. It is the largest irrigation scheme in South Africa at approximately 32000ha. Vaal River water is furrowed via an extensive canal system from Warrenton into two subsequent canals, namely the North Canal and West Canal. The Vaalharts Irrigation Scheme receives an excess of 300Mm^3/annum from this canal system. Such pressure on the environment cannot perpetually remain without consequences. These consequences have been seen in the form of rising water levels and salinisation.

Research has been conducted in the Vaalharts since the 1960's addressing increasing water levels and salinisation within the irrigation area. Most recent was a report by Herold and Bailey (1996) discussing the long-term salt balance for the Vaalharts Irrigation Scheme. This report stated an annual loss of 100000t of salts to groundwater, and predicted that, as these salts were not being measured in the Harts River, that they would be seen in the form of a sudden salt reversal to the Harts River, thereby adding a massive strain to an already stressed river system.

This thesis was designed to address the impact of irrigation on the Vaalharts Irrigation Scheme. Steps necessary for this to be achieved was the description of the Vaalharts aquifer and the determination of this aquifer's characteristics, and the subsequent construction of a suitable conceptual model.

7.1 GEOHYDROLOGICAL INVESTIGATION

The achievement of these goals was obtained by:

- Conducting a literature review of Vaalharts-specific information that had pertinence to this research.
- This enabled an initial understanding of the processes affecting the Vaalharts Irrigation Scheme, such as geology and irrigation.
- Construction of hypotheses:
  - Investigate possible bank storage at the Harts River
  - Investigate possible mixing of the groundwater salts with natural recharge between the irrigation area and the Harts River.
  - Such mixing would cause a reduction in concentration of the salts.

7.2 FINDINGS

7.2.1 GROUNDWATER HYDROCENSUS:

- There were a number of boreholes drilled in past decades for geological surveys in the Vaalharts, and it was hoped that access could be gained to the groundwater through these boreholes.
- All these boreholes were, however, either blocked or destroyed.
- Domestic boreholes were found to negate depth-specific hydrochemical profiling, sampling and collection of water levels.
- These findings increased the need to drill a network of boreholes across the Vaalharts Irrigation Scheme.

7.2.2 DRILLING PROCEDURES:

- Began in February 2003 and was completed in May 2003.
- A network of 17 boreholes was drilled across the North Canal area.
- Three of these boreholes were positioned on the banks of the Harts River to test the hypothesis of bank storage.
- All boreholes were logged for their specific geology.
- An integrated geological model was then applied to these geological borehole logs to gain a 3-dimensional understanding of the Vaalharts' geology.

7.2.3 GEOLOGY:

- The geological logs determined from these boreholes indicated that the basement geology in the Vaalharts to be basic lavas.
- Above the lavas is a lithology of Dwyka shales.
- The shales vary in depth, and are more prominent to the north of the irrigation area.
- In the south, where the shales are less prominent, there is a greater proportion of clays, calcretes and gravels.
- The clays, calcretes and gravels are present to the north, but are less prominent.
- There are Kalahari sands lying above these lithologies throughout the Vaalharts Irrigation Scheme.

7.2.4 AQUIFER PARAMETER TESTS:

- Followed the completion of the borehole network.
- These aquifer parameter tests included slug tests, multi rate pump tests, constant rate pump tests and tracer tests.
- These tests are believed to have consolidated a firm understanding of the aquifer parameters in the Vaalharts as related to the geology.
- The aquifer parameter tests were conducted to determine the hydraulic conductivities, transmissivities, Darcy velocities and seepage velocities.
- The hydraulic conductivities varied between 0.1m/d and 19m/d.
- Transmissivities varied between 20m^2/d and 200m^2/d.
- The determined information indicated a fractured rock aquifer.
- The hydraulic conductivities are related to the fractured rock aquifer, and the geology variance throughout the aquifer.

7.2.5 THE TRACER TESTS:

- Darcy velocities in the range of 1m/d and 22m/d
- Seepage velocities encountered a range between 2m/d and 220m/d.

7.2.6 CONCEPTUAL MODEL:

- Further enhanced with the geological logs and the aquifer parameters determined from these tests.
- The conceptual model of the Vaalharts revolved primarily around the aquifer.

- Water was seen to enter the aquifer from both irrigation recharge and rainfall recharge.
- Water either collected by the subsurface drains and exported from the system via the extensive canal system, or moves past these drains to the groundwater table.
- The water entering the system moves relatively swiftly through the Kalahari sands [hydraulic conductivities measured between 4m/d and 22m/d (Badenhorst, 2003)].
- The groundwater table lies at approximately 2mbgl.
- This shallow groundwater table is kept relatively constant by the presence of the subsurface drains.
- Water that passes the drains, and enters the aquifer, moves towards the Harts River.
- The mixing of the groundwater and the related salts with the natural recharge creates a reduction in concentration of the groundwater.
- Average incoming water flows were calculated and applied to the conceptual model.
- These values were also assigned to the water and salt balances.
- The flow volumes were used to calculate the salt loads by applying measured Total Dissolved Salt (TDS) concentrations to these volumes.

7.2.7 NUMERICAL MODEL:

- The model domain was from Taung in the north, to south of Warrenton, and from the Ghaap Plateau in the west to the lava kopjes in the east.
- A two-layer model was used.
    - The first layer represented the Kalahari sands
    - Second layer represented the clays, calcretes, gravels and shales according to the geological borehole logs and aquifer parameter tests completed in the area.
- The integrated geological model was also used, together with literature, to understand and construct this 3-dimensional model.
- The numerical model indicated that all groundwater was moving towards the Harts River.
- Drains were applied to the irrigation areas, and represented the natural conditions by subtracting water from the system.
- The water budget function in PMWIN allowed values of flow to be measured, and correlated with measured and calculated values for the system.
- A mass transport model was simulated for the Vaalharts, and indicated movement of the salts towards the Harts River.
- These salts, on their path to the Harts River however saw a salt concentration reduction as the natural recharge had a mixing effect on the groundwater.

7.2.8 OBSERVATIONS:

- The drains had a larger effect on the groundwater flow than previously expected, and were seen to be keeping the water levels at their present levels.
- In order to keep the water levels constantly at or below the subsurface drains, even in periods of greater irrigation, the drains need to be cleaned on a regular basis.
- The fluctuating water levels create a crust of manganese to be distributed around the subsurface drains, thereby inhibiting their efficiency.
- Although the drains already keep the water levels at approximately 2mbgl, certain crops are sensitive to fluctuations, thereby increasing the need for the efficiency of the subsurface drains in the Vaalharts.

7.2.9 WATER AND SALT BALANCE:

- The balances were structured simply as incoming less outgoing water and salts.
- Water balance:
  - The North Canal and West Canal irrigation water, together with rainfall was termed incoming.
  - Outgoing water is divided into groundwater moving towards the Harts River, canal tailends, recharge, drainage runoff and evapotranspiration.
  - The water balance indicated an average of 300Mm^3/annum entering the North Canal and West Canal areas from the irrigation canals alone.
  - Rainfall had an addition of over 300Mm^3/annum to the entire Vaalharts investigation area.
  - The largest volume of outgoing water was assigned to evapotranspiration, with approximately 550Mm^3/annum leaving the system in this manner.
  - Values derived from the numerical model were used to apply ranges for the balance figures.
- Salt balance:
  - Salt concentrations, as average TDS values, were applied to the water volumes to calculate salt loads.
  - Incoming salts were termed as either irrigation salts or fertilizers, with Vaal River irrigation water adding approximately 130000t/annum to the Vaalharts Irrigation Scheme, while fertilizers only added 50000t/annum.
  - This indicates that the main addition of salts in the Vaalharts is from Vaal River irrigation water.
  - Although the average TDS is 356mg/l over the past 30 years, this still equates to an average of 130000t/annum. Increases in salt load in the

Vaal River between 1990 and 1995 saw this increase to an average of 145000t/annum during this period.

- The canal tailends and the drainage water dominated the mass of outgoing salts into the Harts River, with the tailends contributing approximately 18000t/annum and the drainage water contributing approximately 22000t/annum.
- The largest mass of salts leaving the system was the leaching, or recharge. These salts accounted for approximately 82000t/annum of the outgoing salts.
- Annual addition of approximately 1500t to the soils in the Vaalharts.
- Indicates an overall addition of salts to soils of approximately 83000t since the inception of the Vaalharts irrigation scheme.

7.2.10 ASSESSING PREVIOUS HYPOTHESES:

Herold and Bailey (1996):

- Predicted a possible flow reversal of salts from the Vaalharts aquifer to the Harts River.
- The data that were collected during this research indicates that this is unlikely.
- Although salts are moving to the Harts River at a rate of approximately only 7000t/annum, they are still moving towards the Harts River.
- Indicated presence of a two-aquifer system
  - Perched aquifer
  - Deeper underlying aquifer
  - This was tested during this research with both the installation of piezometers (refer to Section 4.2.4.1) and hydrochemical profiling (refer to Section 4.5.2).
  - Both these tests indicated that only one aquifer is present in the Vaalharts.

Gombar and Erasmus, 1976:

- Measured the average groundwater TDS concentration as 1005mg/l.
- At present the average groundwater TDS concentration is 1350mg/l.
- This groundwater TDS concentration increase equates to an average annual TDS increase of 13mg/l.
- These values of TDS increase can be associated with the salt balance of the Vaalharts, where the annual addition of approximately 100000t of leached salts into the groundwater, combined with the approximate volume of the Vaalharts aquifer, equates to the TDS increase.

7.2.11 CONCLUSION:

- The main aim of this project was to study the impact of irrigation on the Vaalharts aquifer.
- It was important to assess the damage that the irrigation was doing to the aquifer, and the possible impact that the aquifer could in-turn have on the

Harts River following a possible flow reversal and accompanying mass return of salts to the Harts River system, and therefore too the irrigation schemes downstream of this point on the Vaal River.

- The increase of the TDS concentration in the groundwater has already been discussed, together with the reasons for this increase.
- It is therefore necessary to discuss means by which this increase in the TDS concentration can be inhibited.

7.3 MANAGEMENT OPTIONS:

7.3.1 OPTION 1:

- A consideration to ensure cleaner water moving through the system is to duplicate the evaporation basins as mentioned in the 'Basinman' report (Wu *et al*, 1998).
- In the Murray-Darling basin in Australia, subsurface drainage water is pumped into evaporation basins.
- The water is then evaporated from these basins, leaving the salts.
- If this were practiced in the Vaalharts Irrigation Scheme, the drainage water, containing a high salt load would not re-enter the river system.
- The concept requires subsurface drainage, as in the Vaalharts Irrigation Scheme, which then transports collected excess water (drainage water) and pumps it into evaporation basins.
- These evaporation basins allow the open evaporation of the drainage water, and thereby leave the salts as residue in the basins.
- The positive result of such a practice would mean that lower-salinity water would enter the Harts River, meaning lower-salinity water for irrigation Schemes downstream of the Vaalharts Irrigation Scheme.
- If such structures were implemented in all of the irrigation schemes within South Africa, the complete cycle would benefit our agriculture.
- The practicality of instituting such a system into South African agriculture would however need to be carefully considered.
- The practice of installing evaporation dams would leave large tonnages of salts as residue, with little future use.
- This would also remove large volumes of water from the Harts River, having an effect on downstream irrigation schemes.

7.3.2 OPTION 2:

- It was mentioned that the major source of the salts in the Vaalharts Irrigation Scheme is the incoming Vaal River water.
- Short of addressing the upstream Vaal River practices and means by which to ensure cleaner water entering the Vaalharts system, the Vaalharts itself needs to be addressed.
- The logical approach to ensure lower salinity water enters the groundwater in the Vaalharts system is to make use of less water.

“Since agriculture accounts for nearly 70% of all water withdrawn from rivers, lakes, and underground aquifers for human use, the greatest potential for conservation lies with increasing irrigation efficiencies” (Clarke, 1991).

- What is needed in the Vaalharts is a more efficient manner of irrigation, where less water is applied per unit area, and therefore fewer salts enter the groundwater via leaching.
- A more efficient means of irrigating would be drip irrigation, that has a field application efficiency of 95%, which is 40% to 60% more efficient than gravity systems (Postel, 1993, 1997).
- The installation of drip irrigation in the Vaalharts would increase the efficiency of irrigation in the Scheme, thereby reducing the volumes of water needed.
- This would simultaneously decrease the volume of salts being applied to the Vaalharts Irrigation Scheme, and reduce the volume of salts going to groundwater and eventually entering the Harts River.

The Vaalharts Agricultural Scheme is a system encountering a steady increase in salinisation, both of soils and of groundwater. The effect of these processes is seen in the Harts River adjacent to the Scheme, and the irrigation schemes downstream of the Vaalharts Irrigation Scheme also see an effect. The problems occurring within the Vaalharts have to be seen in a holistic manner in order for agriculture to benefit. It is not only the outgoing water and salts that need to be addressed, but also the incoming. This means that all industry, mining and agriculture along our rivers need the same consistency in observation.

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8.1 DEFINITIONS OF KEYWORDS

The following terms have been defined in order to avoid any possible misunderstandings.

Confined aquifer - A confined aquifer is bounded above and below by an aquiclude. In a confined aquifer, the pressure of the water within the aquifer is usually higher than that of the atmosphere, so that, if a well taps the aquifer, the water in it stands above the top of the aquifer, or even above the ground surface. It is then known as a free flowing, or artesian well.

Unconfined aquifer - An unconfined aquifer is also known as a water table aquifer. It is bounded by an aquiclude, but not restricted by any confining layer above it. It has its upper boundary as the water table that is free to rise or fall. Water in a well penetrating an unconfined aquifer is at atmospheric pressure and does not rise above the water table.

Leaky aquifer - A leaky aquifer is also known as a semi-confined aquifer. It is an aquifer that has either both upper and lower boundaries as aquitards, or one boundary is an aquitard and the other an aquiclude. Water is free to move vertically through the aquitard, either upwards or downwards. The water level may stand either above or below the water table, depending on the recharge and discharge conditions present.

Irrigation Return Flow - That portion of the irrigation supplies water and direct rainfall that has not been used by the crops and that has the potential to enter the Harts River. This water would be comprised of surface water run-off and the water that has been collected by the subsurface drains. It excludes the portion of the percolation to the groundwater that contributes to a possible net increase in the long-term groundwater storage.

Total Potential Return Flow - The sum of the irrigation return flow and deep percolation to groundwater.

9 APPENDIX

9.1 WATER BUDGET

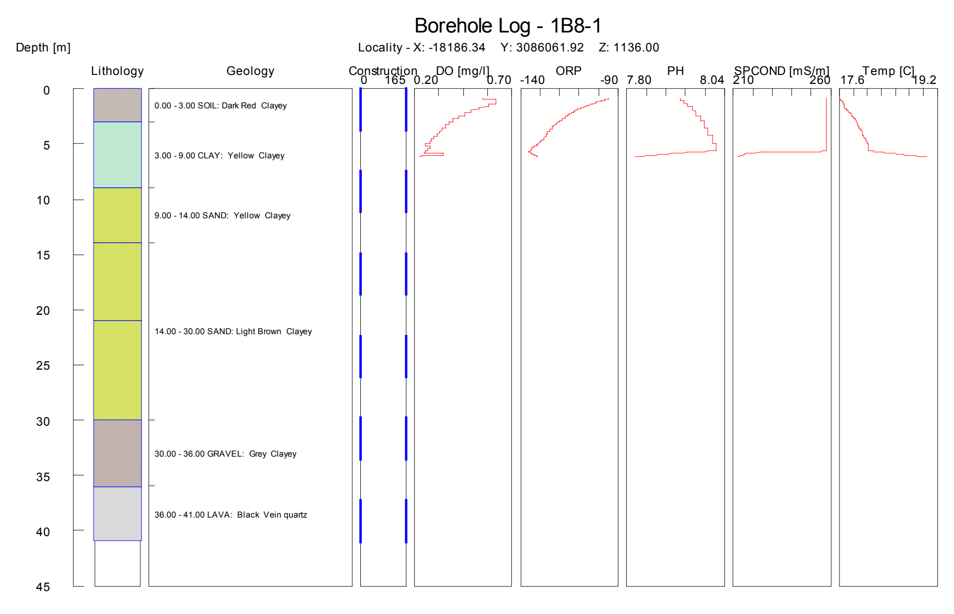
Appendix table 1: Table illustrating the water budget information for the irrigation areas

ZONE 1, LAYER 1			
FLOW TERM	**IN**	**OUT**	**IN-OUT**
STORAGE	0	7	-7
HORIZONTAL EXCHANGE	10551	10583	-32
DRAINS	0	50238	-50238
RECHARGE	48338	0	48338
SUM OF THE LAYER OF THE LAYER	89166	89235	-69
ZONE 1, LAYER 2			
FLOW TERM	**IN**	**OUT**	**IN-OUT**
STORAGE	0	33	-33
HORIZONTAL EXCHANGE	10464	8560	1904
SUM OF THE LAYER OF THE LAYER	38871	38870	1
ZONE 2, LAYER 1			
FLOW TERM	**IN**	**OUT**	**IN-OUT**
STORAGE	0	3	-3
HORIZONTAL EXCHANGE	6142	6135	7
DRAINS	0	17390	-17390
RECHARGE	16752	0	16752
SUM OF THE LAYER OF THE LAYER	31332	31369	-37
ZONE 2, LAYER 2			
FLOW TERM	**IN**	**OUT**	**IN-OUT**
STORAGE	0	15	-15
HORIZONTAL EXCHANGE	7148	6535	613
SUM OF THE LAYER	14989	14988	1
ZONE 3, LAYER 1			
FLOW TERM	**IN**	**OUT**	**IN-OUT**
HORIZONTAL EXCHANGE	5864	6183	-319
RECHARGE	420	0	420
SUM OF THE LAYER	6419	6419	0
ZONE 3, LAYER 2			
FLOW TERM	**IN**	**OUT**	**IN-OUT**
STORAGE	0	15	-15
HORIZONTAL EXCHANGE	7201	7284	-83
SUM OF THE LAYER	7435	7435	0
ZONE 4, LAYER 1			
FLOW TERM	**IN**	**OUT**	**IN-OUT**
STORAGE	0	3	-3
HORIZONTAL EXCHANGE	3333	3502	-169
RECHARGE	440	0	440
SUM OF THE LAYER	3773	3773	0
ZONE 4, LAYER 2			
FLOW TERM	**IN**	**OUT**	**IN-OUT**
STORAGE	0	15	-15
HORIZONTAL EXCHANGE	4999	5253	-253
SUM OF THE LAYER	5267	5267	0
ZONE 5, LAYER 1			
FLOW TERM	**IN**	**OUT**	**IN-OUT**
HORIZONTAL EXCHANGE	34560	35999	-1439
SUM OF THE LAYER	36328	36328	0
ZONE 5, LAYER 2			
FLOW TERM	**IN**	**OUT**	**IN-OUT**
STORAGE	0	1	-1
HORIZONTAL EXCHANGE	3974	3284	690
SUM OF THE LAYER	4303	4303	0

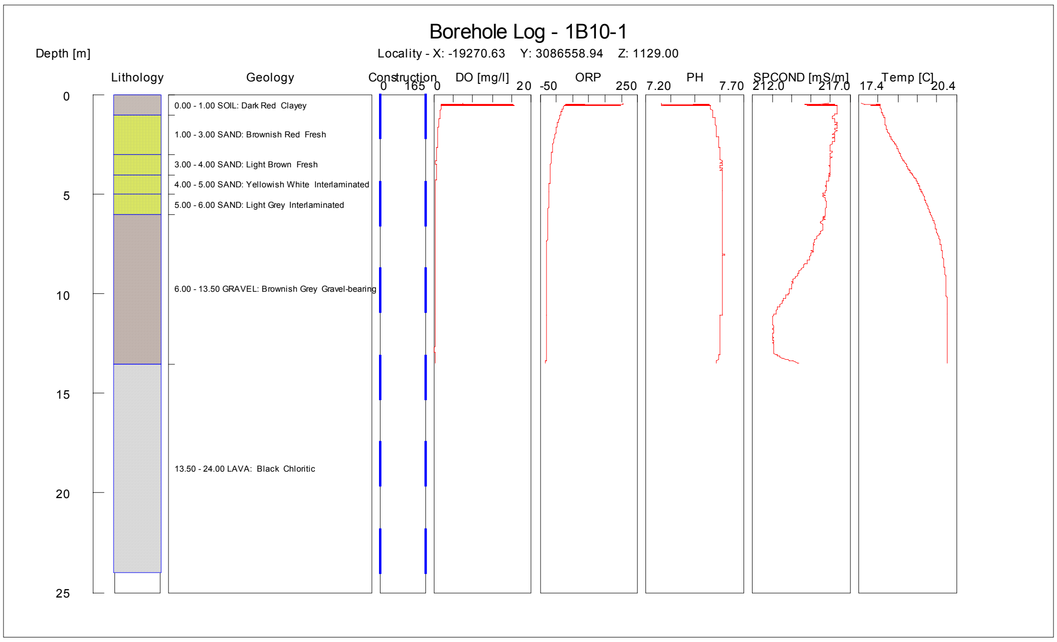
Appendix table 2: Description of Appendix table 1

ZONE	DESCRIPTION
ZONE 1	NORTH CANAL IRRIGATION AREA
ZONE 2	WEST CANAL IRRIGATION AREA
ZONE 3	NORTH CANAL, INCOMING GROUNDWATER
ZONE 4	WEST CANAL, INCOMING GROUNDWATER
ZONE 5	GROUNDWATER TO HARTS RIVER

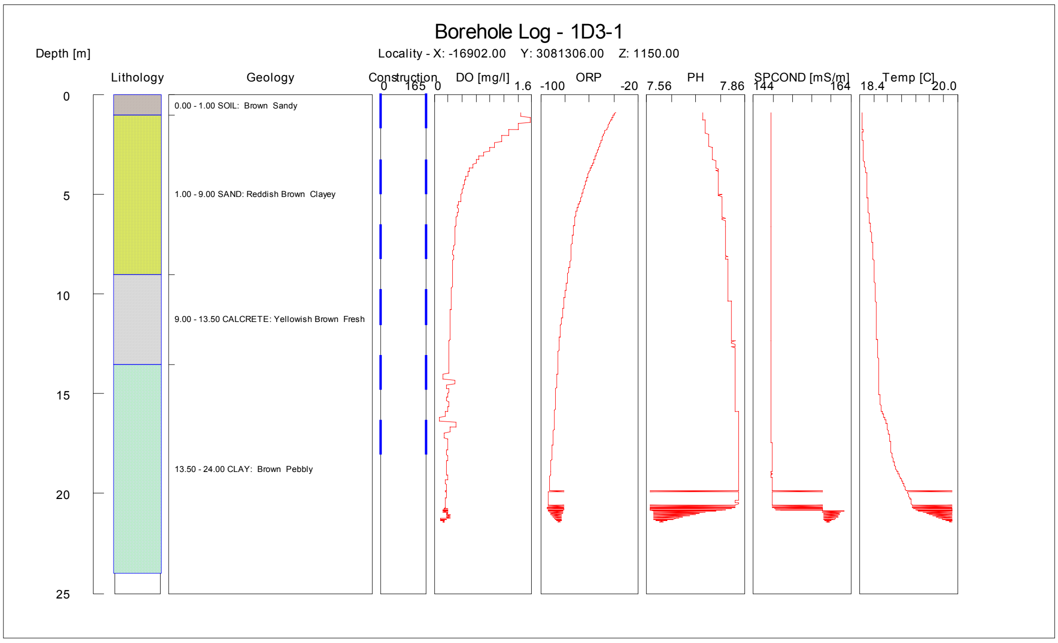
9.2 BOREHOLE LOGS AND DOWN-THE-HOLE CHEMICAL LOGS



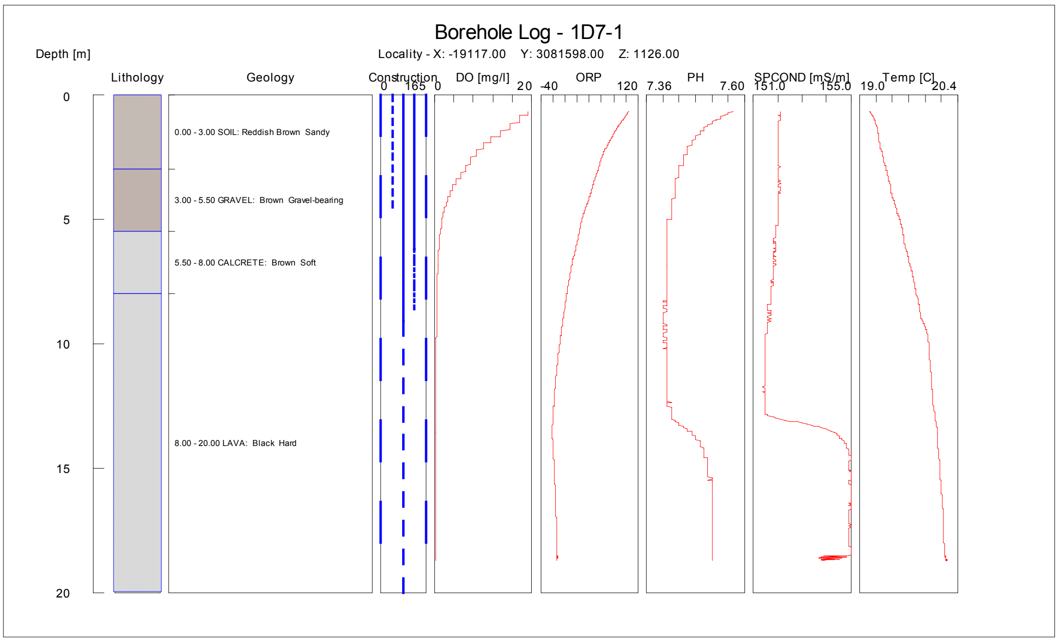
Appendix figure 1: Borehole log for borehole 1B8-1



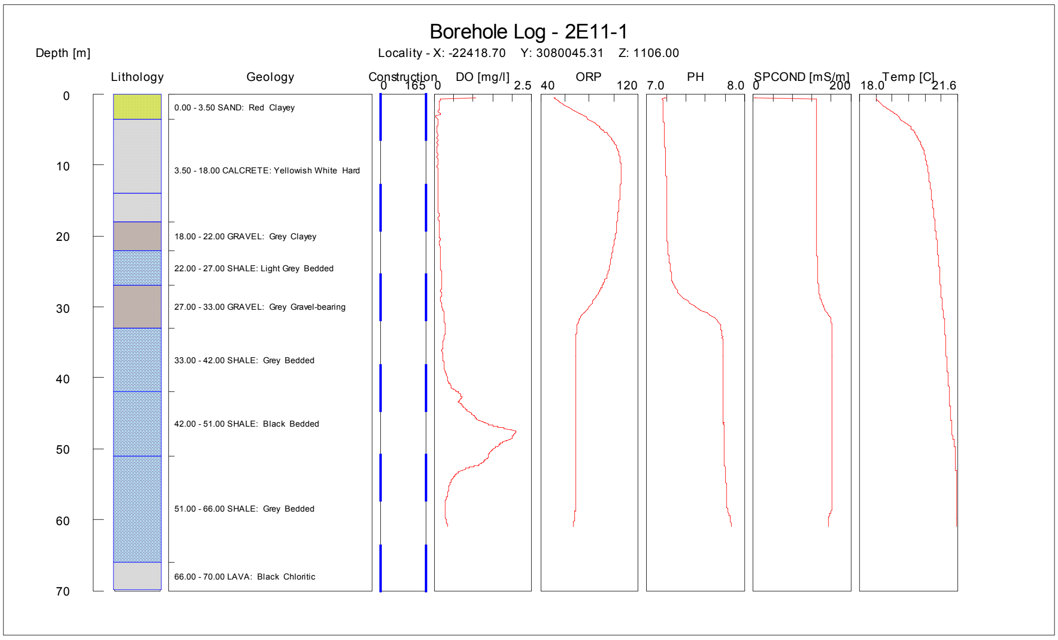
Appendix figure 2: Borehole log for borehole 1B10-1



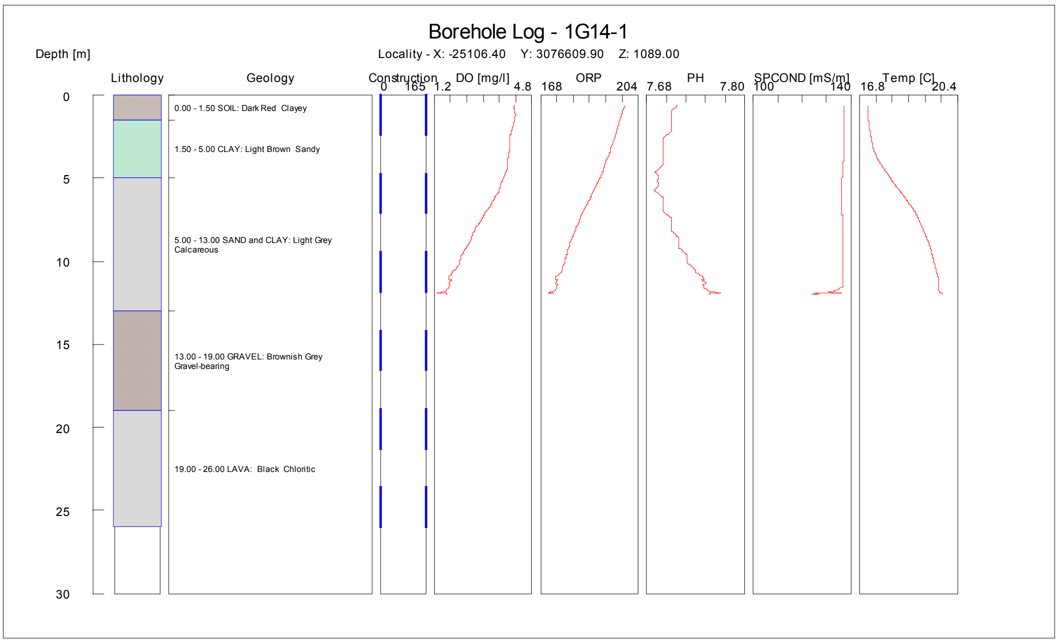
Appendix figure 3: Borehole log for borehole 1D3-1



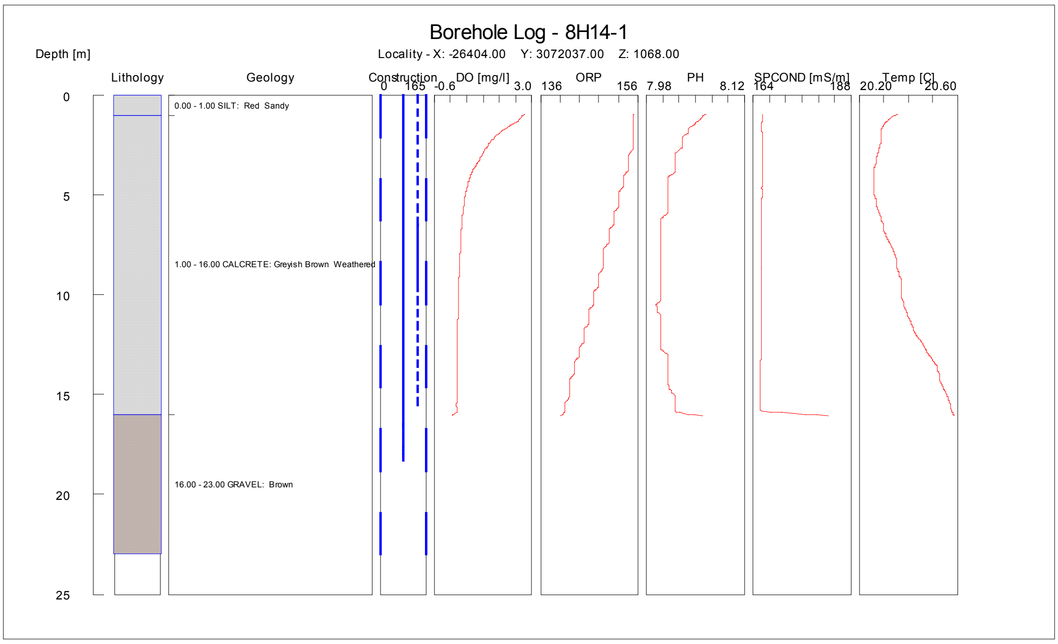
Appendix figure 4: Borehole log for borehole 1D7-1 at Tadcaster



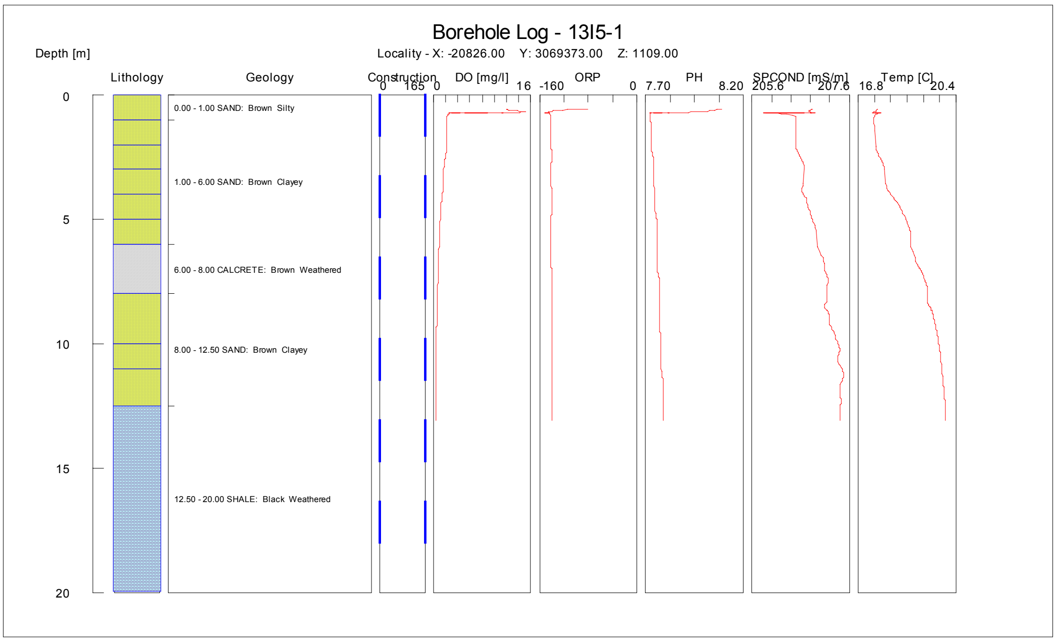
Appendix figure 5: Borehole log for borehole 2E11-1



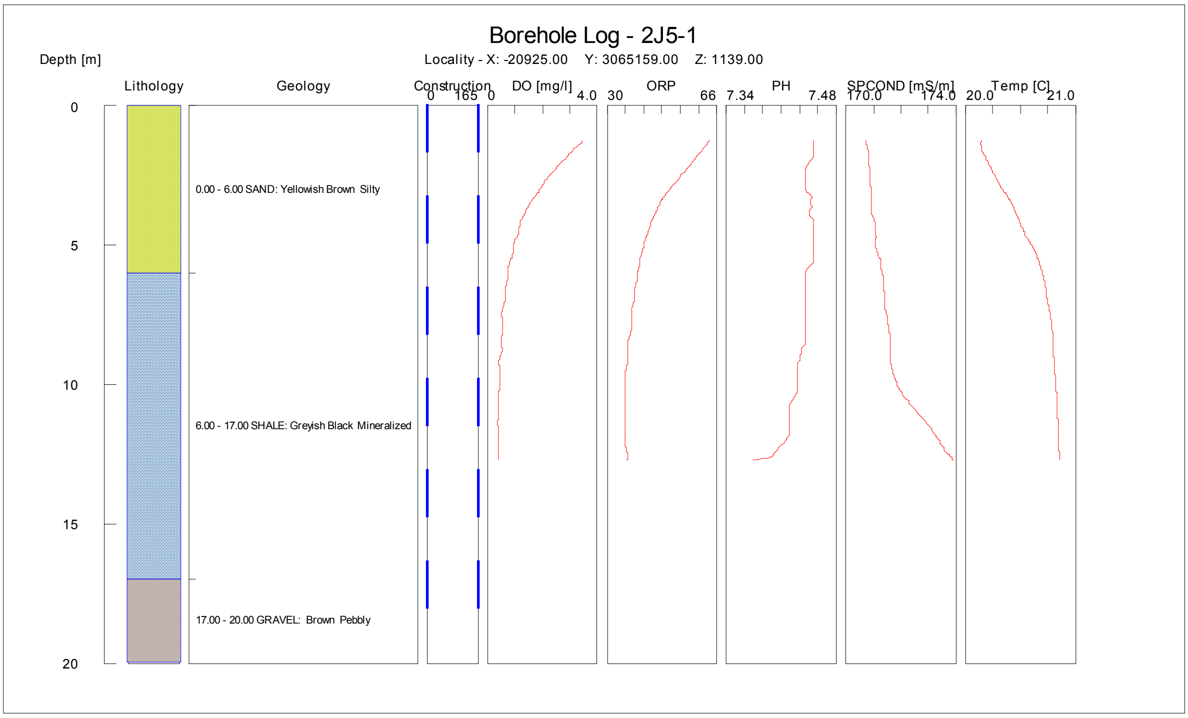
Appendix figure 6: Borehole log for borehole 1G14-1



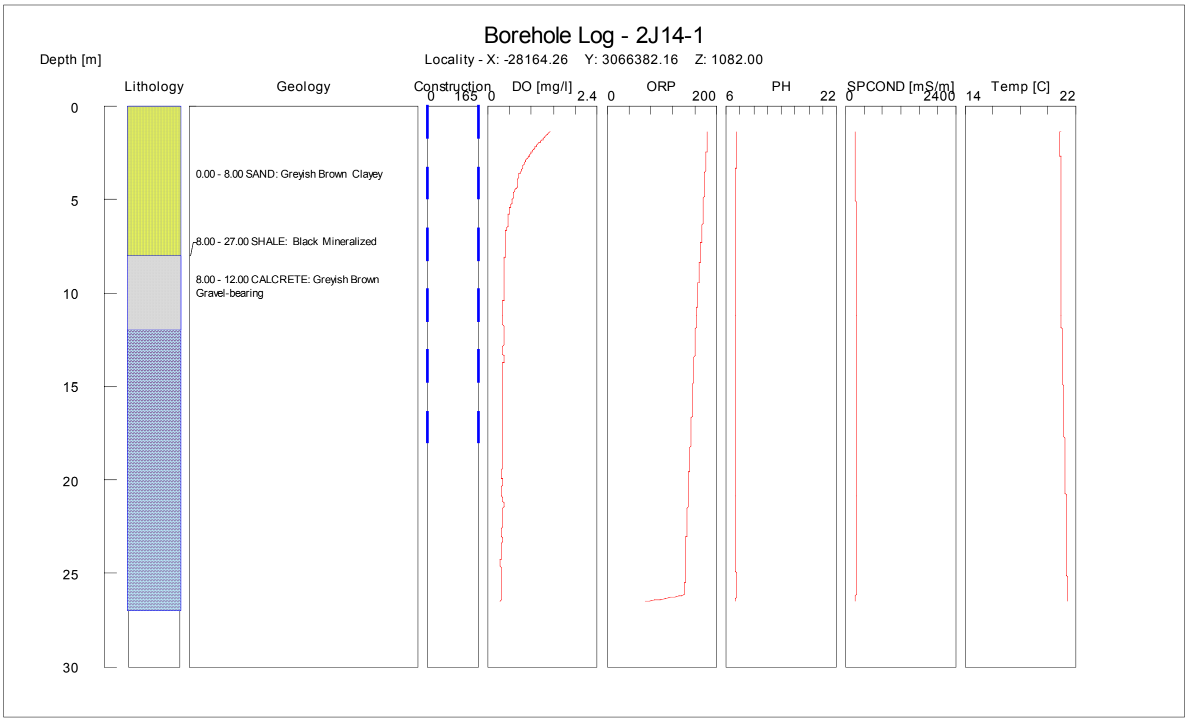
Appendix figure 7: Borehole log for borehole 8H14-1



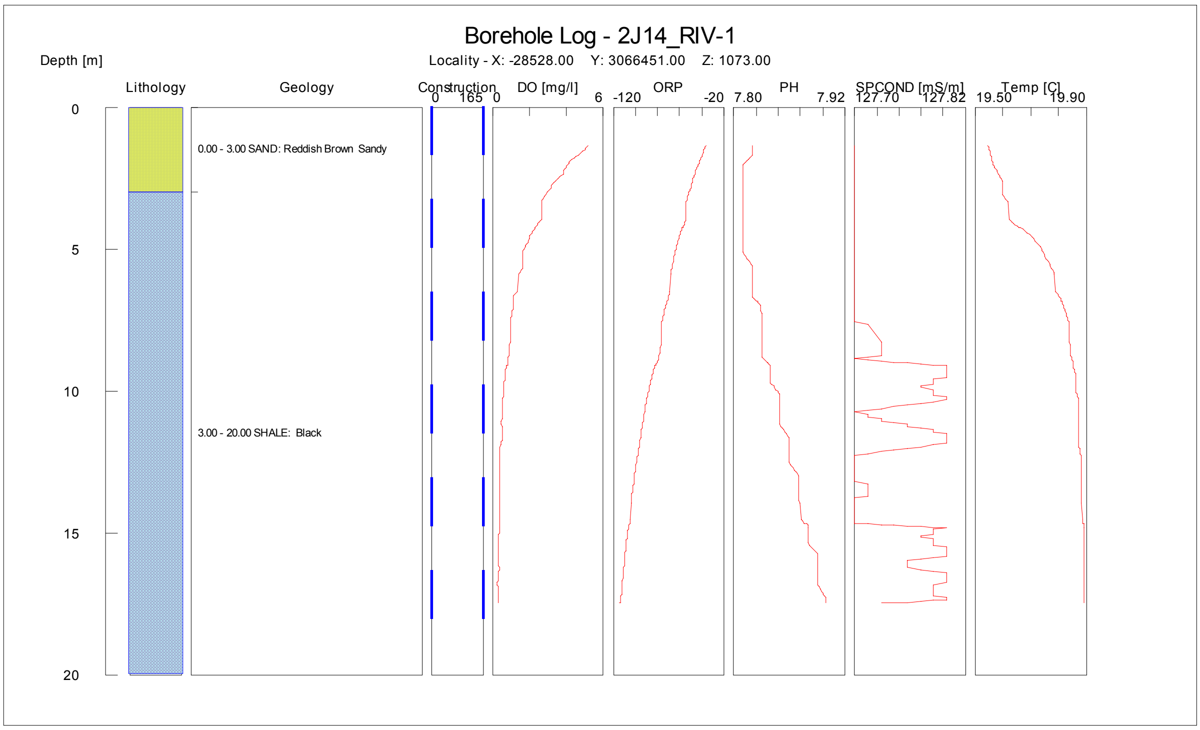
Appendix figure 8: Borehole log of borehole 13I5-1



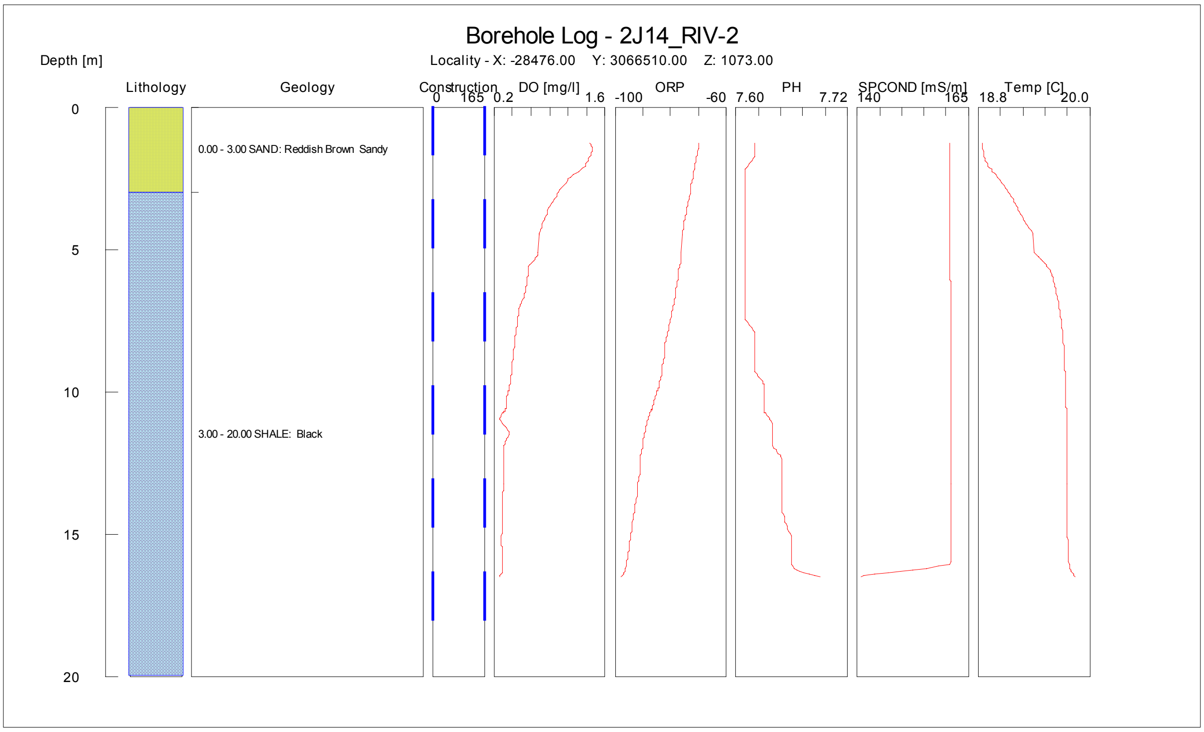
Appendix figure 9: Borehole log for borehole 2J5-1



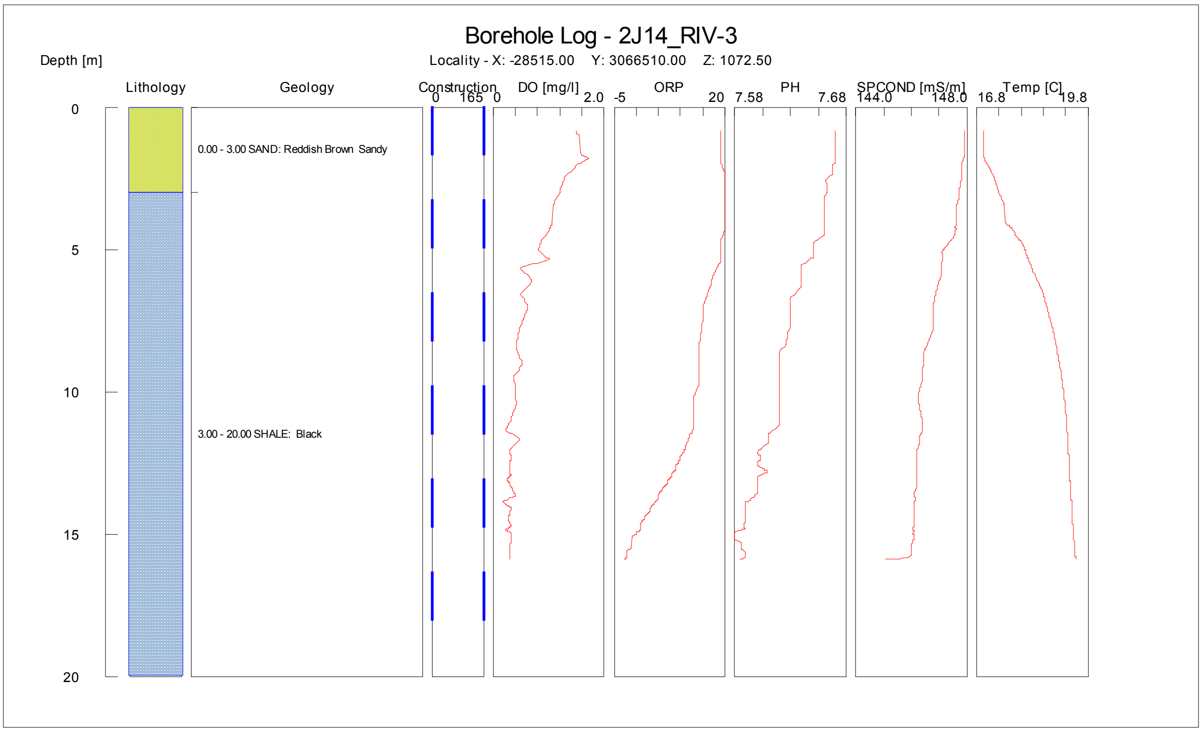
Appendix figure 10: Borehole log for borehole 2J14-1



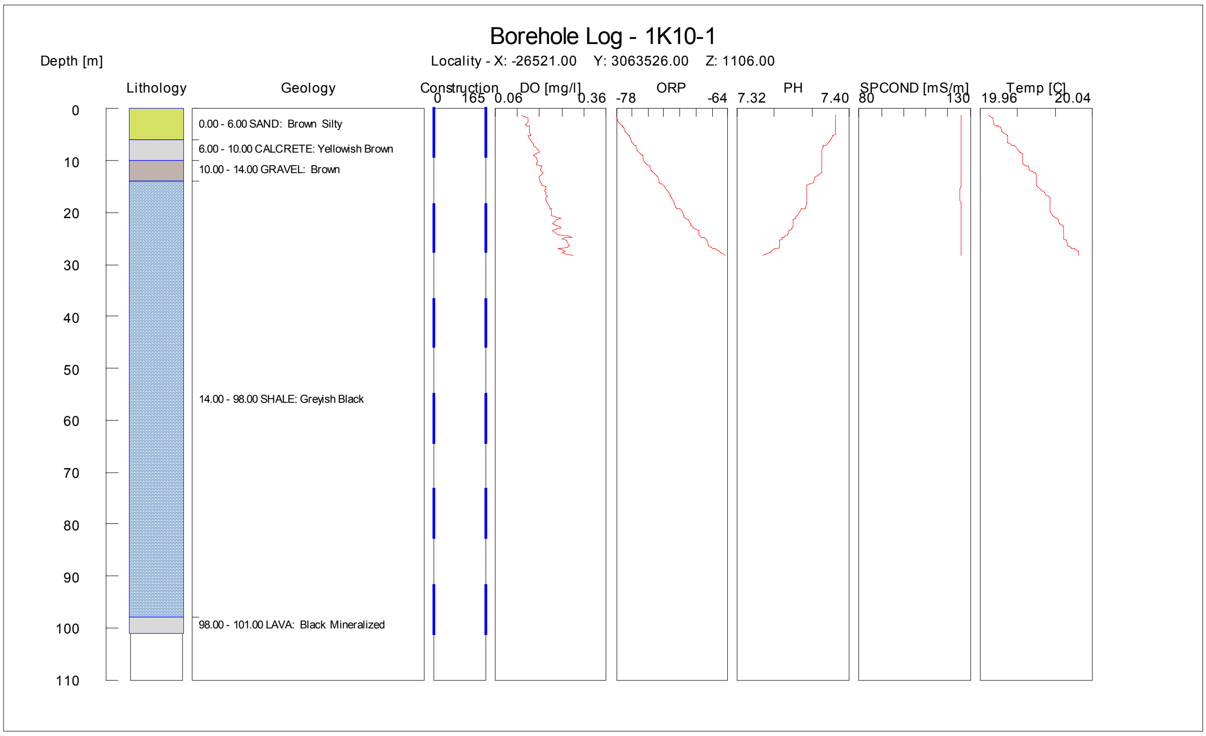
Appendix figure 11: Borehole log for borehole 2J14_RIVER-1



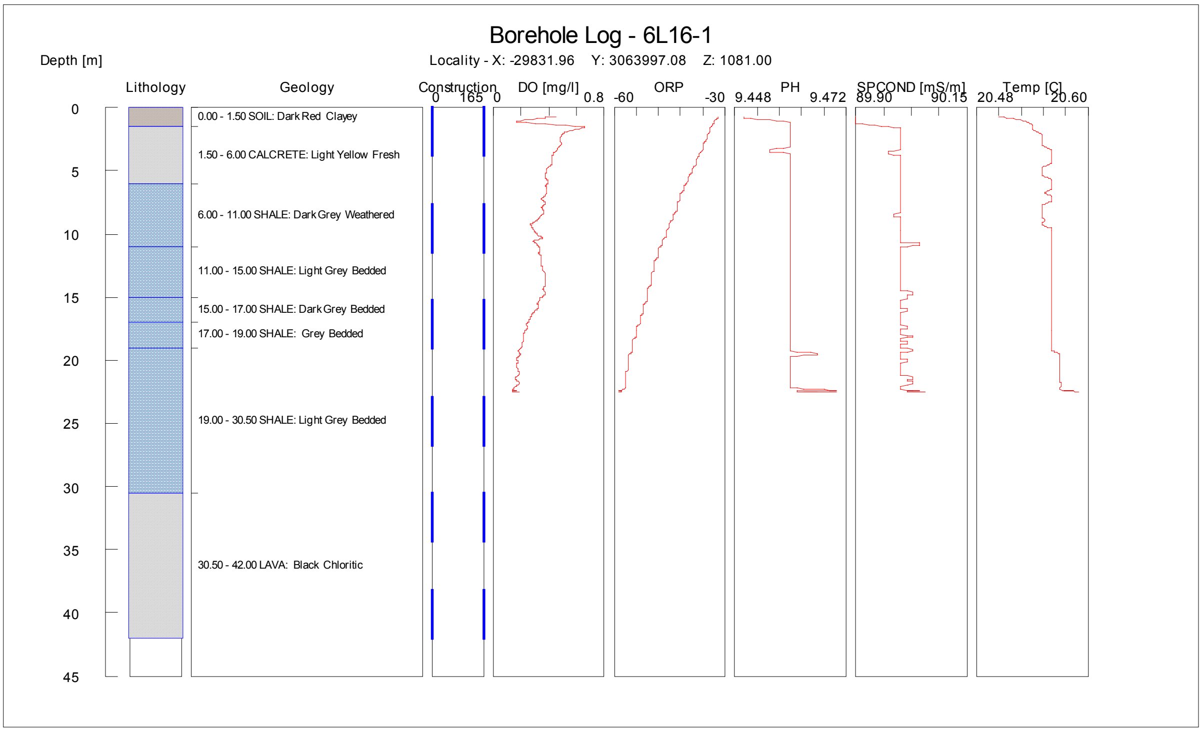
Appendix figure 12: borehole log for borehole 2J14_RIVER-2



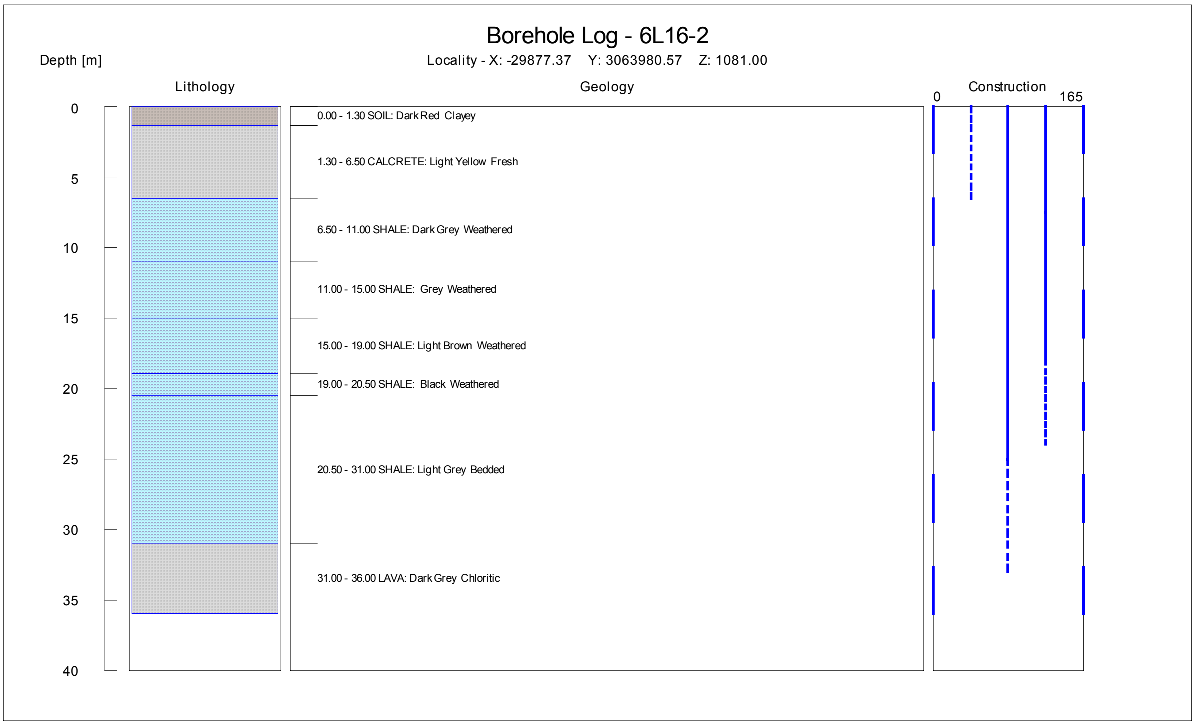
Appendix figure 13: Borehole log for borehole 2J14_RIVER-3



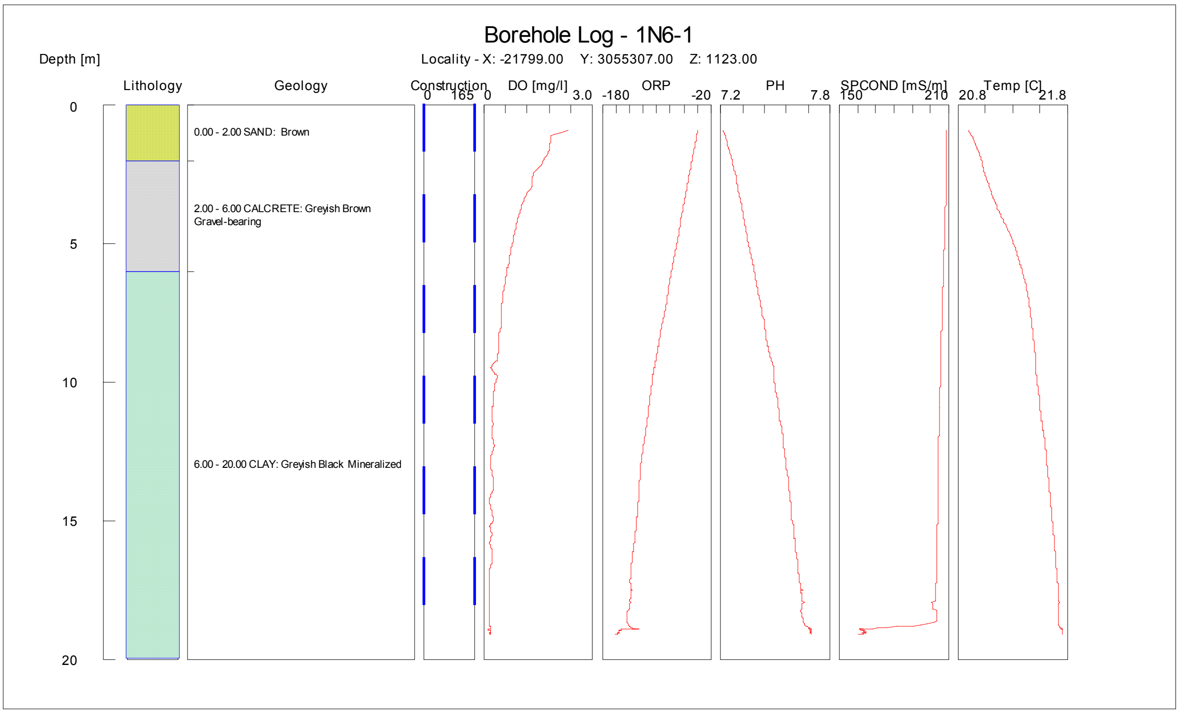
Appendix figure 14: Borehole log for borehole 1K10-1



Appendix figure 15: Borehole log for borehole 6L16-1

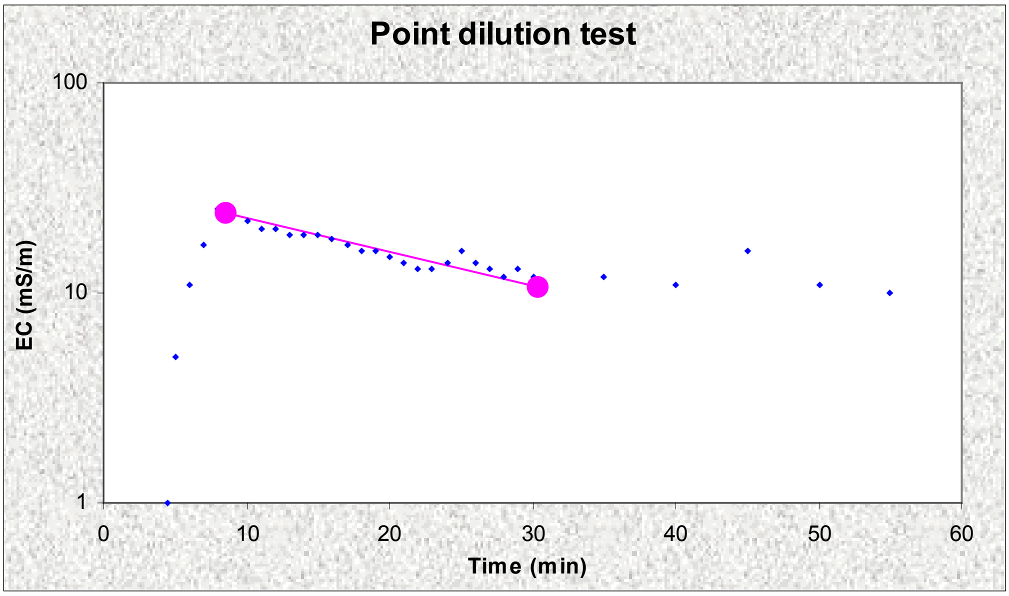


Appendix figure 16: Borehole log for borehole 6L16-2

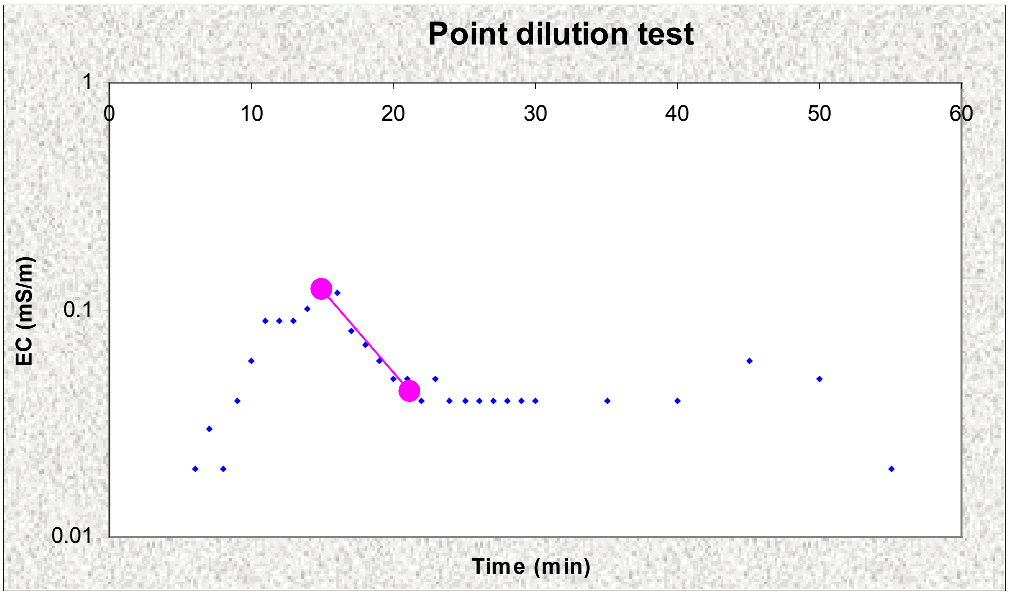


Appendix figure 17: Borehole log for borehole 1N6-1

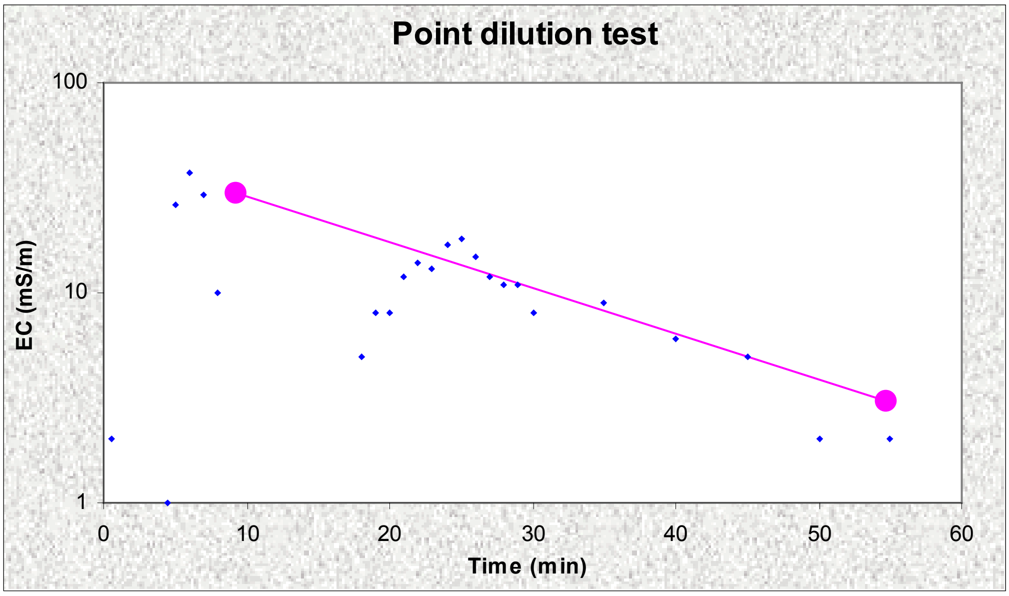
9.3 TRACER TEST GRAPHS



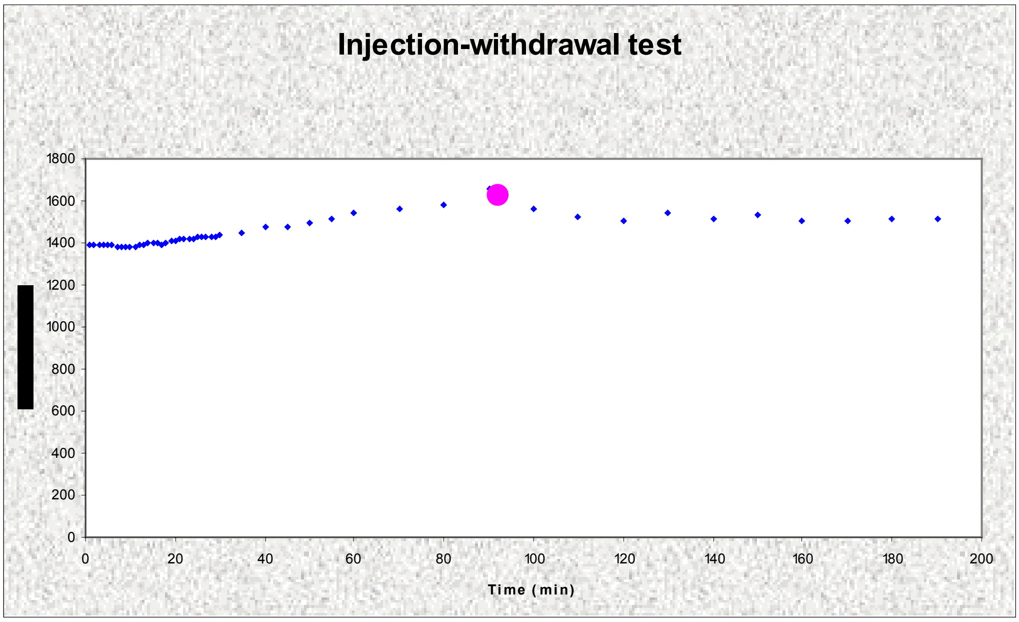
Appendix figure 18: Breakthrough curve for point-dilution test on borehole 1B10-1



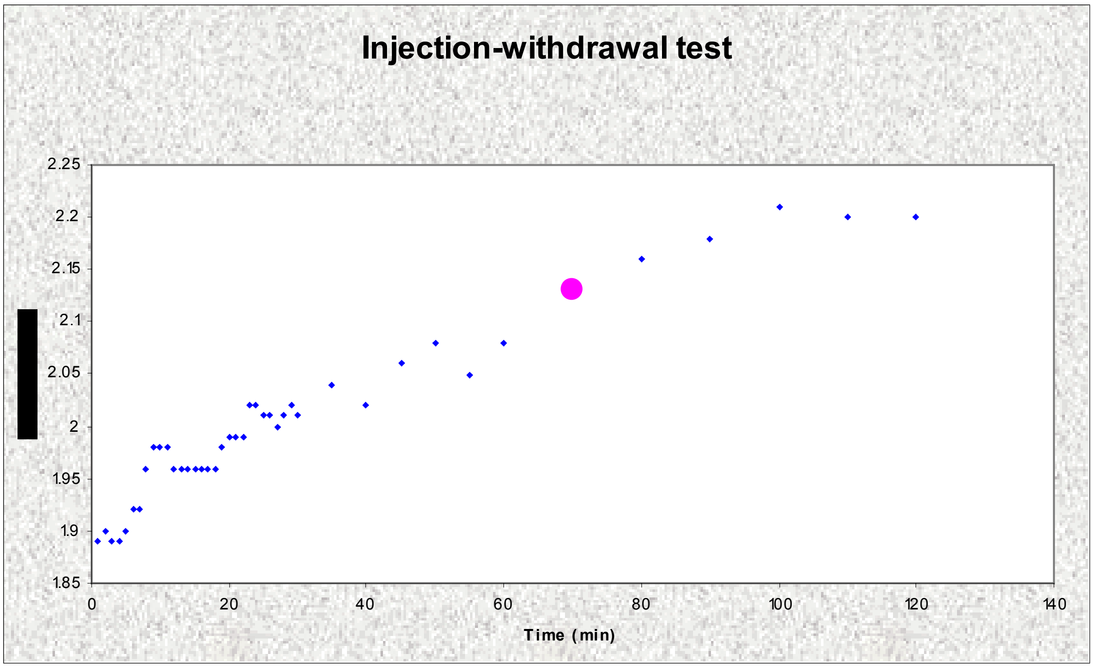
Appendix figure 19: Breakthrough curve for point-dilution test of borehole 1D3-1



Appendix figure 20: Breakthrough curve for borehole 1D7-1's point-dilution tracer test



Appendix figure 21: Breakthrough curve for borehole 2J5-1's injection-withdrawal tracer test



Appendix figure 22: Breakthrough curve for borehole 8H14-1's injection withdrawal tracer test

9.4 TABLE OF CHEMISTRY

SiteName	DateTimeMeas	pH	EC mS/m	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	PALK mg/l	MALK mg/l	Cl mg/l	SO4 mg/l	N NO3mg/l
Ground Canal	2003/09/10 00:00	8.13	105.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
Main Canal	2003/03/17 12:00	7.77	54.40	30.84	19.07	43.16	7.19	0.00	96.00	48.10	103.00	0.07
P'Stad_Harts River	2002/08/22 00:00	8.39	110.00	59.50	47.80	102.00	8.37	3.00	172.00	107.00	265.00	3.49
P'Stad_Harts River	2003/03/17 12:00	8.41	123.00	66.05	51.82	108.19	7.61	5.00	196.00	135.20	243.00	4.82
P'Stad_Harts River	2003/06/27 00:00	8.46	105.00	65.00	51.90	99.70	8.13	5.00	168.00	109.00	242.00	3.14
P'Stad_Harts River	2003/09/10 00:00	8.03	121.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH Riv 1.1	2003/03/17 12:00	8.43	100.90	59.07	41.42	85.87	7.96	1.00	125.00	109.70	212.00	4.99
VH Riv 1.3	2003/03/17 12:00	8.14	83.70	46.60	32.28	66.28	7.39	0.00	143.00	81.80	154.00	1.86
VH Riv 3.1	2003/03/17 12:00	8.18	97.80	57.78	41.26	82.02	7.49	0.00	168.00	94.65	202.00	2.77
VH1	2002/06/20 12:00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH10	2002/06/29 12:00	7.34	156.00	116.52	62.90	101.70	7.65	-1.00	214.00	97.00	321.00	12.31
VH11	2002/06/30 12:00	7.59	247.00	191.43	113.64	94.54	5.20	-1.00	294.00	224.00	542.00	4.95
VH12	2002/07/01 12:00	7.85	186.00	142.16	87.40	97.27	6.54	-1.00	250.00	118.00	427.00	13.87
VH13	2002/07/02 12:00	7.91	186.00	95.75	72.72	183.10	3.98	-1.00	323.00	133.00	326.00	6.88
VH14	2002/07/03 12:00	8.20	233.00	175.83	99.32	112.17	4.82	-1.00	299.00	228.00	487.00	12.10
VH15	2002/07/04 12:00	8.14	44.50	36.88	17.61	35.07	6.15	-1.00	142.00	29.00	65.43	13.33
VH16	2002/07/05 12:00	7.78	292.00	199.48	102.47	200.51	13.07	-1.00	402.00	243.00	662.00	4.41
VH17	2002/07/06 12:00	8.19	215.00	162.21	72.90	156.82	4.09	-1.00	266.00	271.00	356.00	0.08
VH19	2002/07/07 12:00	8.28	196.00	40.86	79.76	255.81	7.91	-1.00	476.00	139.00	234.00	6.82
VH2	2002/06/21 12:00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH20	2002/07/08 12:00	8.62	160.00	49.49	121.47	88.66	2.36	-1.00	400.00	116.00	222.00	9.57
VH21	2002/07/09 12:00	8.62	180.00	132.86	80.08	110.20	5.14	-1.00	374.00	105.00	371.00	5.69
VH22	2002/07/10 12:00	8.42	141.00	98.30	75.25	86.08	4.27	-1.00	293.00	99.00	314.00	2.59
VH24/1	2002/07/11 12:00	7.74	94.90	50.42	70.91	64.89	2.60	-1.00	262.00	81.00	173.00	0.18
VH3	2002/06/22 12:00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH4	2002/06/23 12:00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH5	2002/06/24 12:00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH6	2002/06/25 12:00	7.96	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH7	2002/06/26 12:00	7.84	197.00	74.04	135.70	153.68	3.06	-1.00	635.00	155.00	173.83	0.18
VH8	2002/06/27 12:00	7.68	182.00	104.49	88.63	137.72	4.78	-1.00	280.00	157.00	381.00	3.84
VH9	2002/06/28 12:00	8.16	195.00	98.71	80.25	153.65	10.32	-1.00	334.00	231.00	278.00	5.99

SiteName	DateTimeMeas	pH	EC mS/m	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	PALK mg/l	MALK mg/l	Cl mg/l	SO4 mg/l	N NO3mg/l
13I5-1	2003/10/12 00:00	8.25	171.00	89.55	106.00	133.25	21.70	0.00	325.00	181.00	432.00	0.07
13I5-1	2003/06/27 00:00	8.33	141.00	97.70	74.60	115.00	18.90	1.00	264.00	158.00	278.00	2.14
13I5-1	2003/07/30 00:00	8.42	173.00	108.29	107.16	133.85	25.96	1.00	266.00	196.00	464.00	0.04
13I5-1	2003/08/28 00:00	7.80	210.00	135.00	140.67	160.00	28.30	-1.00	352.00	228.00	563.00	0.00
13I5-1	2003/09/10 00:00	7.37	224.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
1B10-1	2003/06/27 00:00	7.45	230.00	125.00	202.00	151.00	5.78	0.00	332.00	257.00	790.00	0.35
1B10-1	2003/07/22 08:00	8.06	231.00	126.00	209.00	151.00	6.37	0.00	331.00	250.00	777.00	0.40
1B10-1	2003/07/22 10:00	8.45	254.00	123.00	201.00	209.00	6.33	0.00	330.00	339.00	740.00	0.37
1B10-1	2003/07/23 00:00	8.43	240.00	138.00	217.00	157.00	6.61	0.00	336.00	264.00	843.00	2.23
1B10-1	2003/07/30 00:00	8.85	230.00	114.87	197.57	136.04	7.20	15.00	319.00	245.00	794.00	0.44
1B10-1	2003/08/28 00:00	7.74	220.00	123.00	191.00	154.00	7.00	-1.00	289.00	231.00	751.00	0.00
1B10-1	2003/09/10 00:00	6.47	225.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
1B10-1	2003/10/12 00:00	7.92	213.00	111.00	181.50	155.25	6.05	0.00	338.00	230.00	619.00	0.09
1B8-1	2003/06/27 00:00	7.89	268.00	157.00	216.00	208.00	11.50	0.00	344.00	287.00	1040.00	0.02
1B8-1	2003/07/30 00:00	8.19	267.00	128.61	224.87	207.78	14.71	0.00	292.00	286.00	1067.00	-1.00
1B8-1	2003/08/28 00:00	7.77	264.00	121.00	221.33	218.00	14.20	-1.00	222.00	278.00	1048.00	0.00
1B8-1	2003/09/10 00:00	6.87	275.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
1B8-1	2003/10/12 00:00	8.02	254.00	103.00	213.17	218.50	12.85	0.00	229.00	279.00	941.00	0.21
1D3-1	2003/06/27 00:00	8.17	158.00	134.00	85.40	112.00	2.25	0.00	216.00	146.00	525.00	5.26
1D3-1	2003/07/20 08:00	7.82	156.00	131.00	88.50	112.00	2.26	0.00	214.00	148.90	500.00	4.86
1D3-1	2003/07/20 11:00	7.79	154.00	137.00	84.80	109.00	1.92	0.00	219.00	134.00	508.00	8.13
1D3-1	2003/07/30 00:00	7.99	151.00	121.59	85.20	105.59	2.31	0.00	222.00	139.00	507.00	0.17
1D3-1	2003/08/28 00:00	7.89	153.00	136.00	85.37	111.00	2.44	-1.00	197.00	143.00	499.00	0.12
1D3-1	2003/09/10 00:00	7.16	170.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
1D3-1	2003/10/12 00:00	8.00	147.00	130.50	80.30	109.00	2.27	0.00	224.00	135.00	441.00	0.13
1D7-1	2003/06/27 00:00	7.88	158.00	180.00	65.70	112.00	4.24	0.00	274.00	151.00	473.00	2.97
1D7-1	2003/07/24 08:00	8.03	158.00	170.00	65.10	106.00	4.36	0.00	266.00	159.00	451.00	2.15
1D7-1	2003/07/24 10:00	7.97	171.00	182.00	86.50	98.20	4.81	0.00	256.00	208.00	454.00	2.24
1D7-1	2003/07/24 12:00	8.25	170.00	179.00	87.00	97.10	4.68	0.00	255.00	207.00	438.00	2.27
1D7-1	2003/07/30 00:00	8.19	151.00	160.34	67.14	99.61	4.84	0.00	264.00	159.00	417.00	0.46
1D7-1	2003/08/28 00:00	7.68	154.00	151.00	63.57	131.00	4.75	-1.00	241.00	152.00	415.00	0.06

SiteName	DateTimeMeas	pH	EC mS/m	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	PALK mg/l	MALK mg/l	Cl mg/l	SO4 mg/l	N NO3mg/l
1D7-1D	2003/09/10 00:00	7.25	161.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
1D7-1D	2003/10/12 00:00	7.87	145.00	155.50	61.17	110.25	4.08	0.00	277.00	156.00	372.00	0.00
1D7-1M	2003/09/10 00:00	7.21	163.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
1D7-1M	2003/10/12 00:00	7.84	145.00	151.50	57.75	113.00	4.19	0.00	266.00	150.00	365.00	0.10
1D7-1S	2003/09/10 00:00	7.15	162.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
1D7-1S	2003/10/12 00:00	7.97	144.00	151.00	57.55	107.25	4.17	0.00	267.00	149.00	368.00	0.68
1G14-1	2003/04/03 00:00	8.18	113.00	84.77	86.13	57.44	2.60	0.00	181.00	79.00	286.00	18.71
1G14-1	2003/04/03 08:00	8.04	129.00	98.67	82.62	74.80	15.37	0.00	254.00	85.00	325.00	16.56
1G14-1	2003/06/27 00:00	8.26	133.00	105.00	97.00	77.50	7.97	0.00	254.00	90.00	420.00	10.19
1G14-1	2003/07/30 00:00	8.12	135.00	110.46	103.21	77.11	10.04	0.00	253.00	87.00	444.00	11.72
1G14-1	2003/08/28 00:00	7.70	141.00	118.00	97.30	79.80	11.60	-1.00	243.00	86.00	440.00	12.69
1G14-1	2003/09/10 00:00	7.37	148.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
1G14-1	2003/10/12 00:00	8.28	129.00	100.20	82.25	68.70	7.03	0.00	254.00	77.00	350.00	12.20
1K10-1	2003/04/03 00:00	7.91	131.00	111.46	64.89	110.19	6.50	0.00	203.00	120.00	380.00	1.93
1K10-1	2003/06/27 00:00	7.54	115.00	93.50	50.80	95.70	5.62	0.00	178.00	100.00	348.00	0.09
1K10-1	2003/07/30 00:00	8.67	112.00	90.30	51.33	91.82	6.92	11.00	182.00	95.00	337.00	-1.00
1K10-1	2003/08/28 00:00	6.99	114.00	91.50	46.97	93.10	6.06	-1.00	165.00	103.00	338.00	0.05
1K10-1	2003/09/10 00:00	7.15	129.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
1K10-1	2003/10/12 00:00	7.77	115.00	95.15	50.82	103.40	7.81	0.00	200.00	98.00	315.00	0.72
1N6-1	2003/06/27 00:00	8.24	205.00	218.00	114.00	113.00	6.32	0.00	266.00	290.00	551.00	0.13
1N6-1	2003/08/28 00:00	8.05	209.00	203.00	120.33	117.00	7.51	-1.00	179.00	318.00	548.00	0.00
1N6-1	2003/09/10 00:00	7.33	232.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
1N6-1	2003/10/12 00:00	7.68	202.00	164.00	110.00	117.00	7.46	0.00	122.00	330.00	503.00	0.00
2E11-1	2003/06/27 00:00	7.92	137.00	128.00	92.70	72.00	2.73	0.00	326.00	125.00	296.00	5.68
2E11-1	2003/07/30 00:00	8.19	131.00	114.17	90.65	66.86	3.12	0.00	288.00	122.00	296.00	6.13
2E11-1	2003/09/10 00:00	6.99	166.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
2E11-1	2003/10/12 00:00	7.87	136.00	126.50	86.57	71.75	2.97	0.00	326.00	122.00	331.00	5.94
2E11-deep	2003/08/28 00:00	8.01	173.00	58.40	37.83	295.00	4.14	-1.00	216.00	146.00	471.00	5.61
2E11-shallow	2003/08/28 00:00	7.52	138.00	122.00	93.50	73.50	3.45	-1.00	279.00	117.00	310.00	6.48
2J14_RIV-1	2003/04/03 00:00	7.97	158.00	84.34	113.05	98.59	2.93	0.00	192.00	252.00	273.00	0.07
2J14_RIV-1	2003/07/30 00:00	8.51	136.00	77.49	87.10	94.29	3.08	6.00	154.00	222.00	261.00	0.03
2J14_RIV-1	2003/08/28 00:00	8.06	132.00	71.80	77.10	93.90	2.73	-1.00	122.00	214.00	249.00	0.04

SiteName	DateTimeMeas	pH	EC mS/m	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	PALK mg/l	MALK mg/l	Cl mg/l	SO4 mg/l	N NO3mg/l
2J14_RIV-2	2003/04/03 00:00	8.10	199.00	143.83	94.24	176.09	4.83	0.00	227.00	305.00	406.00	4.59
2J14_RIV-2	2003/07/30 00:00	8.47	162.00	86.93	95.80	133.32	2.51	5.00	204.00	227.00	362.00	-1.00
2J14_RIV-2	2003/08/28 00:00	7.81	165.00	103.00	95.83	133.00	2.55	-1.00	176.00	239.00	375.00	0.05
2J14_RIV-2	2003/09/10 00:00	7.62	173.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
2J14_RIV-2	2003/10/12 00:00	7.77	163.00	105.00	97.50	126.00	2.43	0.00	207.00	237.00	368.00	0.00
2J14_RIV-3	2003/07/30 00:00	8.27	132.00	101.08	68.60	102.28	4.25	0.00	214.00	159.00	285.00	0.56
2J14_RIV-3	2003/08/28 00:00	8.24	153.00	128.00	77.23	111.00	4.28	-1.00	190.00	211.00	325.00	1.27
2J14_RIV-3	2003/09/10 00:00	7.75	170.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
2J14_RIV-3	2003/10/12 00:00	7.65	166.00	141.00	84.75	110.50	4.43	0.00	231.00	235.00	351.00	4.45
2J14-1	2003/06/27 00:00	8.02	209.00	248.00	105.00	95.70	2.94	0.00	207.00	296.00	502.00	17.96
2J14-1	2003/07/30 00:00	8.33	206.00	230.06	105.40	88.45	3.81	1.00	193.00	307.00	489.00	14.36
2J14-1	2003/08/28 00:00	7.54	213.00	265.00	105.00	93.20	4.16	-1.00	183.00	355.00	514.00	14.82
2J14-1	2003/09/10 00:00	7.38	227.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
2J14-1	2003/10/12 00:00	8.18	209.00	261.50	101.25	97.28	4.29	0.00	219.00	313.00	470.00	13.33
2J5-1	2003/06/27 06:00	8.39	156.00	124.00	81.10	126.00	1.48	1.00	286.00	173.00	318.00	11.94
2J5-1	2003/06/27 08:00	8.23	156.00	123.00	83.00	128.00	1.35	0.00	279.00	177.00	314.00	11.09
2J5-1	2003/06/27 17:00	8.40	164.00	139.00	88.50	124.00	1.81	1.00	287.00	176.00	374.00	11.71
2J5-1	2003/07/30 00:00	8.48	164.00	126.32	90.52	124.20	1.66	8.00	279.00	-1.00	-1.00	-1.00
2J5-1	2003/08/28 00:00	7.59	176.00	150.00	96.27	137.00	2.08	-1.00	250.00	207.00	396.00	12.62
2J5-1	2003/09/10 00:00	7.31	193.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
2J5-1	2003/10/12 00:00	8.39	167.00	131.50	83.72	128.25	1.96	5.00	294.00	183.00	356.00	11.44
6L16-1	2003/04/03 00:00	7.94	284.00	283.53	187.97	157.98	8.77	0.00	319.00	345.00	841.00	26.62
6L16-1	2003/04/03 08:00	8.44	118.00	58.45	52.29	141.51	5.96	5.50	272.00	86.00	227.00	11.84
6L16-1	2003/06/27 00:00	9.26	91.30	7.25	0.77	211.00	0.90	31.00	267.00	70.00	109.00	0.14
6L16-1	2003/07/30 00:00	9.20	90.00	4.12	0.00	209.60	1.03	26.00	267.00	65.00	102.00	-1.00
6L16-1	2003/08/28 00:00	9.30	92.70	5.41	1.10	215.00	1.09	29.00	243.00	67.00	107.00	0.04
6L16-1	2003/09/10 00:00	8.54	101.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
6L16-1	2003/10/12 00:00	9.19	94.90	4.65	2.08	212.50	1.18	29.00	286.00	68.00	105.00	0.74
6L16-2	2003/04/03 00:00	8.52	119.00	64.82	58.05	129.58	6.36	10.00	273.00	104.00	240.00	14.11
6L16-2	2003/04/03 08:00	7.65	321.00	309.70	207.96	178.81	9.48	0.00	315.00	487.00	914.00	29.49
6L16-2	2003/06/27 00:00	8.36	308.00	307.00	202.00	188.00	9.87	1.00	314.00	429.00	958.00	20.29
6L16-2	2003/07/30 00:00	8.03	273.00	262.43	181.34	163.29	11.11	0.00	306.00	352.00	848.00	16.81

SiteName	DateTimeMeas	pH	EC mS/m	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	PALK mg/l	MALK mg/l	Cl mg/l	SO4 mg/l	N NO3mg/l
6L16-2D	2003/08/28 00:00	7.63	256.00	244.00	155.67	162.00	9.49	-1.00	283.00	288.00	809.00	17.88
6L16-2D	2003/09/10 00:00	7.56	268.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
6L16-2S	2003/08/28 00:00	7.58	251.00	242.00	153.00	160.00	9.38	-1.00	292.00	275.00	803.00	10.42
6L16-2S	2003/09/10 00:00	7.65	269.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
8H14-1	2003/06/27 00:00	8.57	172.00	49.40	43.10	306.00	1.24	10.00	361.00	150.00	355.00	8.50
8H14-1	2003/07/21 08:00	8.18	208.00	59.20	63.70	351.00	1.57	0.00	398.00	204.00	430.00	11.21
8H14-1	2003/07/21 13:00	8.35	172.00	47.60	43.20	297.00	1.36	0.00	360.00	141.00	336.00	9.37
8H14-1	2003/07/30 00:00	8.84	172.00	49.30	44.91	308.18	1.49	13.00	356.00	144.00	349.00	9.58
8H14-1	2003/08/28 00:00	7.95	173.00	40.80	35.10	320.00	2.76	-1.00	317.00	143.00	347.00	0.04
8H14-1D	2003/09/10 00:00	7.78	177.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
8H14-1D	2003/10/12 00:00	8.45	162.00	32.55	34.35	299.75	1.68	5.00	336.00	148.00	325.00	5.69
8H14-1S	2003/09/10 00:00	7.91	174.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
8H14-1S	2003/10/12 00:00	8.53	163.00	36.25	35.70	291.25	1.66	8.00	342.00	144.00	310.00	8.49
8H14-1	2003/10/12 00:00	8.53	163.00	36.25	35.70	291.25	1.66	8.00	342.00	144.00	310.00	8.49
VH1	2002/06/20 12:00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH10	2002/06/29 12:00	7.34	156.00	116.52	62.90	101.70	7.65	-1.00	214.00	97.00	321.00	12.31
VH11	2002/06/30 12:00	7.59	247.00	191.43	113.64	94.54	5.20	-1.00	294.00	224.00	542.00	4.95
VH12	2002/07/01 12:00	7.85	186.00	142.16	87.40	97.27	6.54	-1.00	250.00	118.00	427.00	13.87
VH13	2002/07/02 12:00	7.91	186.00	95.75	72.72	183.10	3.98	-1.00	323.00	133.00	326.00	6.88
VH14	2002/07/03 12:00	8.20	233.00	175.83	99.32	112.17	4.82	-1.00	299.00	228.00	487.00	12.10
VH15	2002/07/04 12:00	8.14	44.50	36.88	17.61	35.07	6.15	-1.00	142.00	29.00	65.43	13.33
VH16	2002/07/05 12:00	7.78	292.00	199.48	102.47	200.51	13.07	-1.00	402.00	243.00	662.00	4.41
VH17	2002/07/06 12:00	8.19	215.00	162.21	72.90	156.82	4.09	-1.00	266.00	271.00	356.00	0.08
VH19	2002/07/07 12:00	8.28	196.00	40.86	79.76	255.81	7.91	-1.00	476.00	139.00	234.00	6.82
VH2	2002/06/21 12:00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH20	2002/07/08 12:00	8.62	160.00	49.49	121.47	88.66	2.36	-1.00	400.00	116.00	222.00	9.57
VH21	2002/07/09 12:00	8.62	180.00	132.86	80.08	110.20	5.14	-1.00	374.00	105.00	371.00	5.69
VH22	2002/07/10 12:00	8.42	141.00	98.30	75.25	86.08	4.27	-1.00	293.00	99.00	314.00	2.59
VH24/1	2002/07/11 12:00	7.74	94.90	50.42	70.91	64.89	2.60	-1.00	262.00	81.00	173.00	0.18
VH3	2002/06/22 12:00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH4	2002/06/23 12:00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH5	2002/06/24 12:00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH6	2002/06/25 12:00	7.96	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
VH7	2002/06/26 12:00	7.84	197.00	74.04	135.70	153.68	3.06	-1.00	635.00	155.00	173.83	0.18
VH8	2002/06/27 12:00	7.68	182.00	104.49	88.63	137.72	4.78	-1.00	280.00	157.00	381.00	3.84
VH9	2002/06/28 12:00	8.16	195.00	98.71	80.25	153.65	10.32	-1.00	334.00	231.00	278.00	5.99

SiteName	DateTimeMeas	pH	EC mS/m	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	PALK mg/l	MALK mg/l	Cl mg/l	SO4 mg/l	N NO3mg/l
G26733	1974/10/21 00:00	8.70	-1.00	34.00	46.00	-1.00	-1.00	-1.00	-1.00	169.00	293.00	-1.00
G26733	1974/10/21 00:00	8.30	-1.00	34.00	49.00	-1.00	-1.00	-1.00	-1.00	161.00	291.00	-1.00
G28330	1974/06/05 00:00	8.40	-1.00	26.00	39.00	-1.00	-1.00	-1.00	-1.00	52.00	72.00	-1.00
G28330	1974/06/18 00:00	8.10	-1.00	32.00	49.00	-1.00	-1.00	-1.00	-1.00	66.00	86.00	-1.00
G28330	1974/06/21 00:00	8.20	-1.00	24.00	49.00	-1.00	-1.00	-1.00	-1.00	67.00	82.00	-1.00
G30483	1975/04/17 00:00	7.90	-1.00	28.00	23.00	-1.00	-1.00	-1.00	-1.00	128.00	154.00	-1.00
G30483	1975/04/19 00:00	8.00	-1.00	28.00	28.00	-1.00	-1.00	-1.00	-1.00	131.00	158.00	-1.00
G30483	1975/04/21 00:00	8.20	-1.00	28.00	29.00	-1.00	-1.00	-1.00	-1.00	124.00	173.00	-1.00
5K5	1974/10/02 00:00	8.20	-1.00	59.00	49.00	-1.00	-1.00	-1.00	-1.00	57.00	138.00	-1.00
5K5	1974/10/07 00:00	8.10	-1.00	54.00	52.00	-1.00	-1.00	-1.00	-1.00	64.00	155.00	-1.00
G26720	1974/11/28 00:00	8.00	-1.00	64.00	39.00	-1.00	-1.00	-1.00	-1.00	106.00	127.00	-1.00
G26739	1974/11/20 00:00	8.10	-1.00	62.00	50.00	-1.00	-1.00	-1.00	-1.00	89.00	168.00	-1.00
G30455	1975/01/14 00:00	8.00	-1.00	30.00	62.00	-1.00	-1.00	-1.00	-1.00	136.00	80.00	-1.00
8H14	1975/02/14 00:00	7.70	-1.00	30.00	30.00	-1.00	-1.00	-1.00	-1.00	121.00	178.00	-1.00
4B3	2003/06/05 00:00	8.06	137.00	66.16	51.13	175.11	2.53	0.00	313.00	1.65	148.00	-0.01
5C10	2003/06/05 00:00	7.87	166.00	75.22	115.24	129.01	5.08	0.00	280.00	3.09	257.00	-0.01
2D4	2003/06/05 00:00	7.50	153.00	126.73	87.17	110.90	3.66	0.00	237.00	0.87	148.00	-0.01
6E10	2003/06/05 00:00	7.70	197.00	163.78	136.09	114.27	3.77	0.00	311.00	0.65	157.00	-0.01
1F2	2003/06/05 00:00	7.64	354.00	227.07	177.57	405.45	1.54	0.00	484.00	2.48	378.00	-0.01
1F8	2003/06/05 00:00	7.98	232.00	178.73	167.91	141.60	3.95	0.00	327.00	1.04	296.00	-0.01
1G8	2003/06/05 00:00	8.34	262.00	170.33	151.43	256.34	9.34	1.00	329.00	1.63	225.00	-0.01
3I6	2003/06/05 00:00	7.76	81.00	74.26	37.63	54.06	4.72	0.00	210.00	0.24	58.00	-0.01
4I3	2003/06/05 00:00	8.29	127.00	59.90	50.86	156.10	3.89	0.00	240.00	1.63	98.00	-0.01
1J14	2003/06/05 00:00	8.22	184.00	174.44	78.93	140.89	4.38	0.00	243.00	0.08	242.00	-0.01
9M5	2003/06/05 00:00	7.93	231.00	196.80	104.42	182.43	5.73	0.00	210.00	0.21	345.00	-0.01
2QI	2003/06/05 00:00	8.21	110.00	93.07	62.09	46.72	2.26	0.00	108.00	0.07	110.00	-0.01
11QI	2003/06/05 00:00	8.18	162.00	70.47	92.35	176.39	0.63	0.00	396.00	0.31	170.00	-0.01
2R4	2003/06/05 00:00	8.37	126.00	93.55	72.58	87.51	1.49	2.00	237.00	0.11	107.00	-0.01