The hydrogeological relationship between recharge, abstraction and spring flow in the Zeerust dolomitic aquifer

MR Pyburn

21235430

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Supervisor: Prof I Dennis

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SUMMARY

Study area

The study area centres on the newly developed Vergenoegd well field (VWF) on the farm Vergenoegd 60 JO west of Zeerust in the North West Province. The area is underlain by dolomiteswhich are part of the Malmani Sub-Group in the Chuniespoort Group of the Transvaal Supergroup.

The majority of the dolomite is located in quaternary catchment A31C. It forms part of the Malmani River drainage, a part of the Marico catchment which drains northward to join the Limpopo River system. This catchment’s western boundary also forms the westernmost boundary of primary catchment “A”. West of this divide is the Molopo Catchment (primary catchment “D”). The Molopo Eye is also located on the same dolomite as the Malmani Eye (eight kilometres southwest), but drains towards the Atlantic Ocean via the Molopo drainage system whereas the Malmani Eye drains towards the Indian Ocean via the Malmani-Limpopo drainage system.

The study area forms part of the Crocodile West-Marico Water Management Area.

According to the hydrogeological map series of South Africa, the dolomite is described as a Karst Type aquifer. Dolomite is known as a rock type with significant groundwater potential due to the occurrence of groundwater in open cavities. Depending on the siting of production boreholes, dolomite aquifers can yield in excess of 20 L/s. Dolomite aquifers are classified as Major Aquifers according to the South African Aquifer Classification System. The development of the Rietpoort, Uitvalgrond and Vergenoegd well fields are testimony to the significant water potential of the Zeerust Dolomites (Botha, 1993).

Historical work

For more than a century the groundwater potential of the dolomites west of Zeerust has been known and investigated. The fluctuations in spring-flow emanating from the dolomite were the most readily observable effects of change in the aquifer recharge. As far back as pre-1906 there have been reports of spring-flow declining in the area, and states of low water levels. It was mostly attributed to below average rainfall.

In order to optimally exploit the potential of the dolomite aquifers on a sustainable basis (without compromising spring-flow), attempts have been made since the 1960’s to

quantify the volume of water available. This is done by quantifying the volume of water being added annually to the aquifer as a percentage of recharge.

As more farmers tapped into the groundwater potential of the dolomite aquifers, the government saw it necessary to protect the groundwater by means of declaring a Groundwater Control Area, effectively limiting and controlling abstraction to ensure sustainability.

In 1965 the first case of alleged over-abstraction was investigated. A farmer alleged that the '*extreme weakening of the flow from the spring at Vergenoegd No. 3*' was the direct result of excessive pumping of nearby boreholes. The report concluded that a cone of depression could be observed around the points of abstraction, but that this did not influence the spring-flow at that time. The weakening of the spring was due to a combination of below average natural recharge and increased abstraction. The Zeerust boreholes were subsequently decommissioned in 1967.

Data and interpretation

Existing data were obtained from the NGA (National Groundwater Archive), WARMS (Water Resource Management System) containing water use data, and HYDSTRA monitoring data. The HYDSTRA data proved the most valuable in terms of monitoring data.

New data were sourced from the hydrocensus and monitoring runs undertaken in 2012 and form part of this study. A fieldwork trip including a monitoring run of all identified boreholes was initiated in November 2012, while the monitoring data for the Vergenoegd monitoring boreholes were sourced.

Although the Vergenoegd and Tweefontein Dolomite Compartment Units (DCU) have been split by the Vergenoegd Dyke in previous literature, it was grouped together as the Paardevlei Groundwater Management Unit (GMU) in 2009. Since the VWF boreholes occur on both sides of the Vergenoegd Dyke, the new GMU is seen as the study area. Three springs occur here: the Vergenoegd Spring (eyes) and the Paardenvallei Springs. The Paardenvallei Springs' data were more complete and did not reveal any impact from the VWF. The fluctuations seem to be more controlled by climatic conditions, mainly rainfall recharge.

The monitoring data for the Vergenoegd Spring were insufficient to draw any significant conclusions, but the fact that farmers downstream complained about a reduction in their irrigation water from the spring, is indicative of a reduction in flow prior to the aquifer being recharged in 2011-12. Although the reduction in spring-flow was predicted during the numerical modelling of the borehole field, it was not identified during the EIA preceding the development as having a cumulative impact on the farmers irrigating from the canal.

Groundwater level monitoring data from various sources were used to assess the possible impact of the abstraction on the aquifer. The monitoring boreholes located in the Paardenvallei GMU did not reveal any adverse effect of the VWF on the water table in the long term. In fact, the water levels prior to the borehole field development were on par with what was measured in November of 2012. It must be noted that monitoring data were not available for the entire period covered since the inception of the field of boreholes, and therefore fluctuations on a shorter term is likely, as might have been the case in 2010 when irrigation farmers complained about a decline in the Vergenoegd Spring-flow.

The EIA Audit report submitted in 2011 (Masilo & Associates, 2011) indicated that no correlation exists between groundwater levels and the abstraction from the borehole field.

The calculations in this study contradict these findings. The EIA report however concluded that the abstraction volumes from some of the production boreholes of the VWF exceeded the recommended levels in 2010 indicating poor management of the borehole field. It also confirmed that monitoring data are lacking and concluded that the monitoring protocol was not fully in accordance with the 2005 modelling update and EMP recommendations.

Conclusions

Due to the lack of monitoring data for the area, short term fluctuations cannot be accurately be predicted. When the available monitoring data is examined, it be deduced that there is a seasonal fluctuation in water levels as well as spring-flows and that these two components are in relation. This fluctuation is due to the precipitation variations between wet and dry months that affect recharge.

From the recharge calculations and subsequent modelling undertaken during this study, it can be deduced that there is a high correlation between the recharge, abstraction and spring-flow factors in this area. It is also apparent that these factors influence one another greatly and that variance in one of the inputs will have an adverse effect on the rest and will change the system's response significantly, this is especially so when abstraction rates are increased as well as when drought conditions are simulated.

Based on the available monitoring data, including spring-flow and groundwater level data, it can be concluded that the VWF might show a long term impact on the aquifer.

It is likely that, the abstraction from the VWF reduces the spring-flow of the Vergenoegd Springs, which in turn has a cumulative impact on the irrigation farmers receiving water from the spring via a canal. This is especially so in the dry months when recharge is limited. This reduction was predicted during the modelling phase. The reduction in water levels then causes the secondary effect of sinkholes forming in the area due to weakened dolomite stability, especially in areas where there are contributing factors, such as pipeline leaks.

Recommendations

Monitoring of the spring-flow from the Vergenoegd Eyes must be reinstated as a matter of priority. The irrigation farmers downstream claim that the VWF leads to a reduction in their irrigation water from the spring, which in turn leads to loss of production, income loss and creation of sinkholes. Other than this study, there are no data to prove that the abstraction does not adversely affect the spring-flow from the Vergenoegd Eyes, and the farmers might be entitled to compensation due to loss of income. This issue must be investigated further on a legal basis.

Ngaka Modiri Molema District Municipality (NMMDM) as the Water Services Authority and DWA as the custodians of water resources in South Africa are mandated to ensure that proper monitoring are done. This includes monitoring of the abstraction volumes, groundwater levels and spring-flows from the affected compartment. To ensure the continuous monitoring of the borehole fields, the monitoring can be outsourced on a tender basis to external contractors. The monitoring reports must be audited annually.

The management of the VWF must be audited on a catchment and national level as per the 'dolomite guideline'. The lack of proper and continuous monitoring data being the most important factor hindering proper management, must be addressed.

The recommendations pertaining to the operation and maintenance of the well field made in the EIA and numerical modelling report must be adhered to (Sections 8.1.18 and 8.1.15). Similarly the findings and recommendations of the 2011 Audit report (Section 8.2) must be implemented. In essence these recommendations are the modelled sustainable yields (that were determined as being exceeded in the 2011 audit). The 2011 audit then goes on to recommend that the abstraction rates immediately be reduced to their modelled rates and that proper monitoring be instated.

Once monitoring data collection has been reinstated and a sufficient amount of time series data has once again been recorded, a similar study to this should be completed. A comprehensive hydrocensus should be conducted in which important data and observations should be made. Any changes to the area should be noted and recorded. It would be beneficial to conceptualise the system if changed and based thereupon, run another analytical model to determine if the correlation between recharge, abstraction and spring-flow has changed and if so, to what extent.

LIST OF ABBREVIATIONS

Abbreviation	Description
3D	Three Dimensional
BCC	Bogare Consultants Consortium
CDM	Central District Municipality
CRD	Cumulative Rainfall Departure
DACE	Department of Agriculture, Conservation and Environment
DCU	Dolomite Compartment Unit
DPEM	Direct Parameter Estimation Method
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
CSM	Conceptual Site Model
cumec	Cubic metres per second
cusec	Square meters per second
EIA	Environmental Impact Assessment
EMP	Environmental Management Plan
fasl	Feet above sea level
FWR	Far West Rand
GMA	Groundwater Management Area
GMU	Groundwater Management Unit
GPS	Global Positioning System
GRU	Groundwater Resource Unit
ha	Hectare
HYDSTRA	Monitoring database of DWA
IWRM	Integrated Water Resource Management
L/s	Litres per second
L/h	Litres per hour
m^3/a	Cubic metres per annum (year)
mamsl	Metres above mean sea level
mbgl	Metres below ground level
Mm^3	Cubic Millimetres
NGA	National Groundwater Archive
NMMDM	Ngaka Modiri Molema District Municipality
NWA	National Water Act
NWRS	National Water Resource Strategy
POI	points of interest
RoD	Record of Decision

ToR	Terms of Reference
SRTM	Spatial Radar Topography Mission
SVF	Saturated Volume Fluctuation
UWF	Uitvalgrond Well Field
WARMS	Water Resource Management System
WMA	Water Management Area
VWF	Vergenoegd Well Field
WBWSS	Welbedacht Bulk Water Supply Scheme
WRIMS	Water Resource Information Management System

Table of contents

List of Figures

List of Tables

1 INTRODUCTION

A study was conducted of the property on which the Vergenoegd Well Field (VWF) is located to investigate the potential impact of the bulk groundwater abstraction from the VWF as part of the Welbedacht Bulk Water Supply Scheme (WBWSS) in light of concern that the monitoring requirements as per the licensing conditions are not being adhered to, and that over-abstraction is possibly taking place.

1.1 Objectives and Methodology

1.1.1 Objectives

- To gather and evaluate all relevant data and information pertaining to the study area and to determine areas where data are lacking, with the aim of determining if the data can be used to predict short-term fluctuations in groundwater levels.
- To conceptualise the issues at hand and to gain a better understanding of the system and how all the various hydrogeological influences interact.
- Demonstrate the methodology using the VWF as a case study.
- Accurately predict the recharge percentage of the area by making use of various calculations.
- Create, calibrate and run an analytical model that predicts the influences of abstraction on spring-flow and that correlates to the current situation.
- To obtain an understanding of the relationship between recharge, abstraction and spring-flow in the Zeerust Aquifer.
- Determine whether the abstraction rates of the VWF will indeed have an impact on the spring-flow quantities of the area and if so, to what extent.

1.1.2 Approach

Research was conducted by means of national and international literature. This comprised of numerous academic publications, consultant reports and data that were obtained from various sources. Rainfall, spring-flow, climatic and borehole data was requested and obtained from various institutions.

An evaluation of all existing information and data was then conducted and interpreted. A field work phase was then undertaken to conduct a hydrogeological investigation and to investigate relevant areas and objects of interest. Methods such as cumulative rainfall departure (CRD), saturated volume fluctuation (SVF) were used to calculate recharge percentages.

1.1.3 Layout of dissertation

Chapter 1: Introduction

Here the aims and approach of the study are described. The aims are laid out and the approach is briefly discussed.

Chapter 2: Literature Review

The information sources used to reach the aims of the study are provided. The background study is described and presents research into different aspects of recharge, abstraction, spring-flow and how they tie together. Various publications, articles and case studies are investigated. Following this section all the available work done in this specific field with regards to the Zeerust area is summarised.

Chapter 3: Background

The regional background is described and the investigation undertaken in 2002 is expanded upon. The Uitvalgrond Well Field (UWF) and VWF backgrounds are explained and all relevant information relating to the study area is provided. This includes the geographic, topographic, geologic, hydrogeologic and climatic settings.

Chapter 4: Approach

The quantification of recharge is described and how it can be estimated using the SVF and CRD methods and how it was used in this study to reach the estimated recharge percentage by means of software calculations.

The existing borehole data are explained and data discrepancies are highlighted. Data includes NGA, WARMS, HYDSTRA and monitoring data.

A hydrocensus was undertaken in 2012 and the findings, methodology and techniques used to complete the census are described as well as the findings of all the cumulative hydrocensus data.

Based on these results is a data interpretation where all the relevant data are interpreted and described. This is broken-down into; affected compartments, spring-flow data, monitoring data, data availability and sinkhole subsections.

The design and construction of the Conceptual Site Model (CSM) is expanded upon and described. This section contains information about the study area, aquifer characteristics and recharge calculations.

A model is then developed and all relevant information is expanded upon here.

Chapter 5: Conclusions

Based on the results, conclusions can be drawn concerning the study as well as to what extent the relationship between recharge, abstraction and spring-flow is.

Chapter 6: Recommendations

Future research can be recommended to address potential short comings and possible mediation measures are given relating to lack of monitoring.

Chapter 7: References

All documents referred to in the dissertation are listed.

Chapter 8: Appendices

The appendices include rainfall data, a summary of groundwater resource management in South Africa, a summary of previous hydrological work conducted in the study area and lastly recharge calculations.

2 LITERATURE REVIEW

2.1 Historical Work

The relevant reports and evaluation thereof are attached as Appendix A. The investigation into the historical work is relevant to this study as it serves to determine to which extent previous studies were undertaken on the Zeerust aquifers. It also provides a historical overview of the period that the relationships between abstraction and spring-flow have been affecting the Zeerust area.

2.1.1 Summary of historical work

For more than a century the groundwater potential of the dolomites west of Zeerust has been known.

The fluctuations in spring-flow emanating from the dolomite were the most readily observable effects of change in the aquifer storage. Since before 1906 there have been reports of spring-flow declining in the area. The GH3357 (II) report (DWAF, 1999) mentions the drying up of the Rietpoort, Buffelshoek and Paardenvallei Springs (see Figure 2-1). Low water levels southeast of Zeerust in the early 1950's are attributed to below average rainfall in the area between 1949 and 1952. This undoubtedly also affected spring-flow.

In order to optimally exploit the potential of the dolomite aquifers on a sustainable basis (without compromising spring-flow), attempts have been made since the 1960's to quantify the volume of water available. This is done by quantifying the volume of water being added annually to the aquifer as a percentage of rainfall. Aquifer recharge was initially anticipated as 6 per cent of rainfall based on work on other dolomitic areas in South Africa. This figure was subsequently refined to 12 per cent (depending on rainfall volume and intensity) (Aquisim, 2005).

Abstraction figures are important to spring-flow measurements to quantify the effect of water losses on the aquifer (measured by water levels). In 1965 the first case of alleged over-abstraction was investigated. A farmer alleged that the '*extreme weakening of the flow from the spring at Vergenoegd Eye*' (Figure 2-1) was the direct result of excessive pumping of nearby boreholes to augment supply to Zeerust. The report concluded that a cone of depression could be observed around the points of abstraction, but that this did not influence the spring-flow at that time (Botha, 1993).

The weakening of the spring was due to a combination of below average natural recharge and increased abstraction. All springs downstream of the Rietpoort Spring saw a decline in flow ranging from 42 per cent to 100 per cent between 1959 and 1965. The Zeerust boreholes were subsequently decommissioned in 1967.

Water levels and spring-flow recovered to above normal conditions after the good rains experienced between 1974 and 1976. Also in 1974 the six production boreholes at the Rietpoort Well Field (RWF) were commissioned which caused the Rietpoort Spring to cease flowing ten years later during a period of low rainfall. See Figure 2-2 for the Rietpoort locality map. A '*serious drought*' is described between 1977 and 1988 during which the water levels and spring-flows were monitored. The monitoring data were used to calibrate the first groundwater model to simulate the Rietpoort Compartment and model abstraction scenarios in 1988. The model highlighted the importance of monitoring data, and additional monitoring infrastructure was developed throughout for this purpose.

In 2002 two pivotal studies commenced concerning the water potential from the Zeerust Dolomites: a consortium of companies were appointed to perform a regional study on the dolomite compartments, during which over 50 compartments were delineated using aeromagnetic geophysical surveys and numerous groundwater levels regionally.

After four production boreholes failed completely in September of 2005, urgent measures were implemented to re-evaluate the borehole field potential and look for alternative sources of augmentation. It's unknown which specific boreholes failed. Based on the regional compartment delineation of the 2002 consortium study, the Paardenvallei-Vergenoegd DCU was identified as a compartment unit able to augment supply by 40-45 L/s sustainably (Figure 2-3) (Africon, 2002).

During the same year a numerical model for the groundwater flow from the Uitvalgrond Compartment was completed, leading to the development of four production boreholes from this compartment (called the UWF) to supply 31 L/s to the Welbedacht area as seen in Figure 2-4. The well field was commissioned in April 2003 and was the first phase of what is now known as the Welbedacht Bulk Water Supply Scheme.

In 2005 the numerical model for the UWF was updated (Aquisim, 2005) with new data, and expanded to include the Paardenvallei-Vergenoegd DCU and the Klaarstroom South DCU as potential sources. A geohydrological study (Khulani, 2005) coincided with this model update and eight new production borehole sites were identified based on regional gravity surveys.

An EIA was recommended for the development of the abstraction borehole field. After completion and obtaining environmental authorisation the WVF was developed and commissioned and a water use licence was issued by DWAF in February of 2007.

In 2010 the irrigation farmers receiving spring water from the Vergenoegd Springs via a canal system started to complain about a decline in the volume of irrigation water received, triggering fears of the possible impact of the newly developed VWF on the environment.

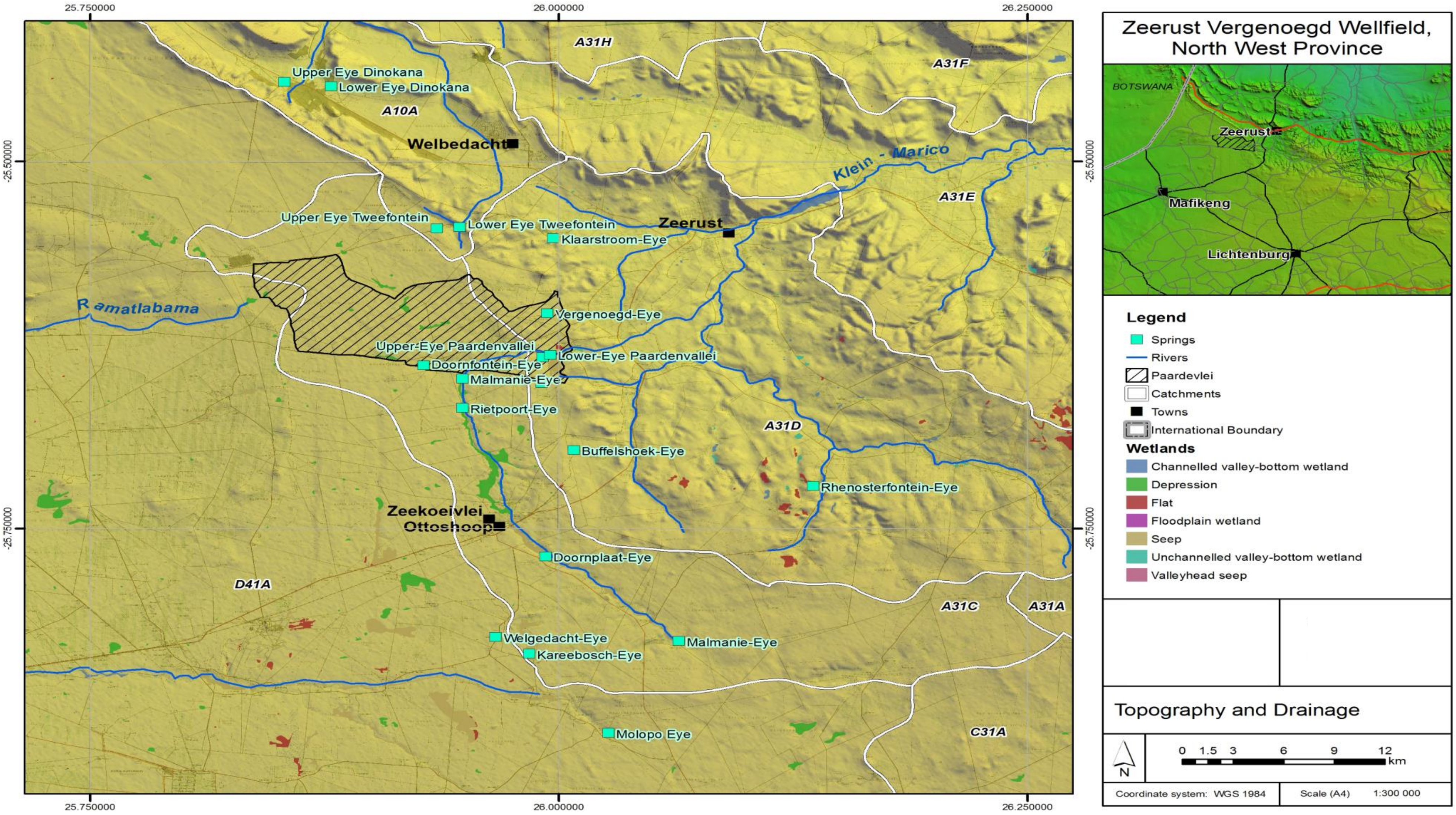


Figure 2-1: Springs, Topography and Drainage of the Zeerust Area

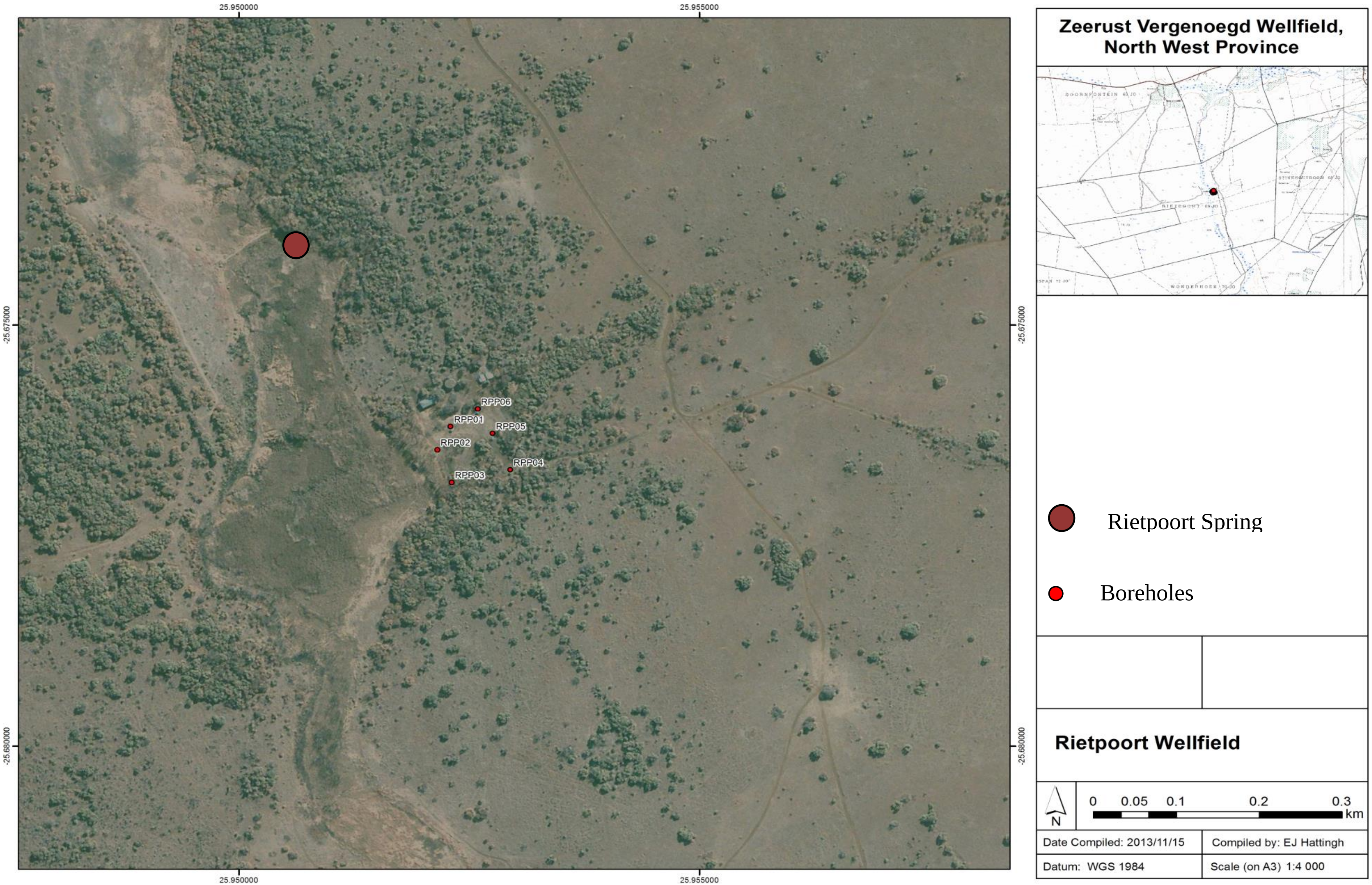


Figure 2-2: Rietpoort Wellfield

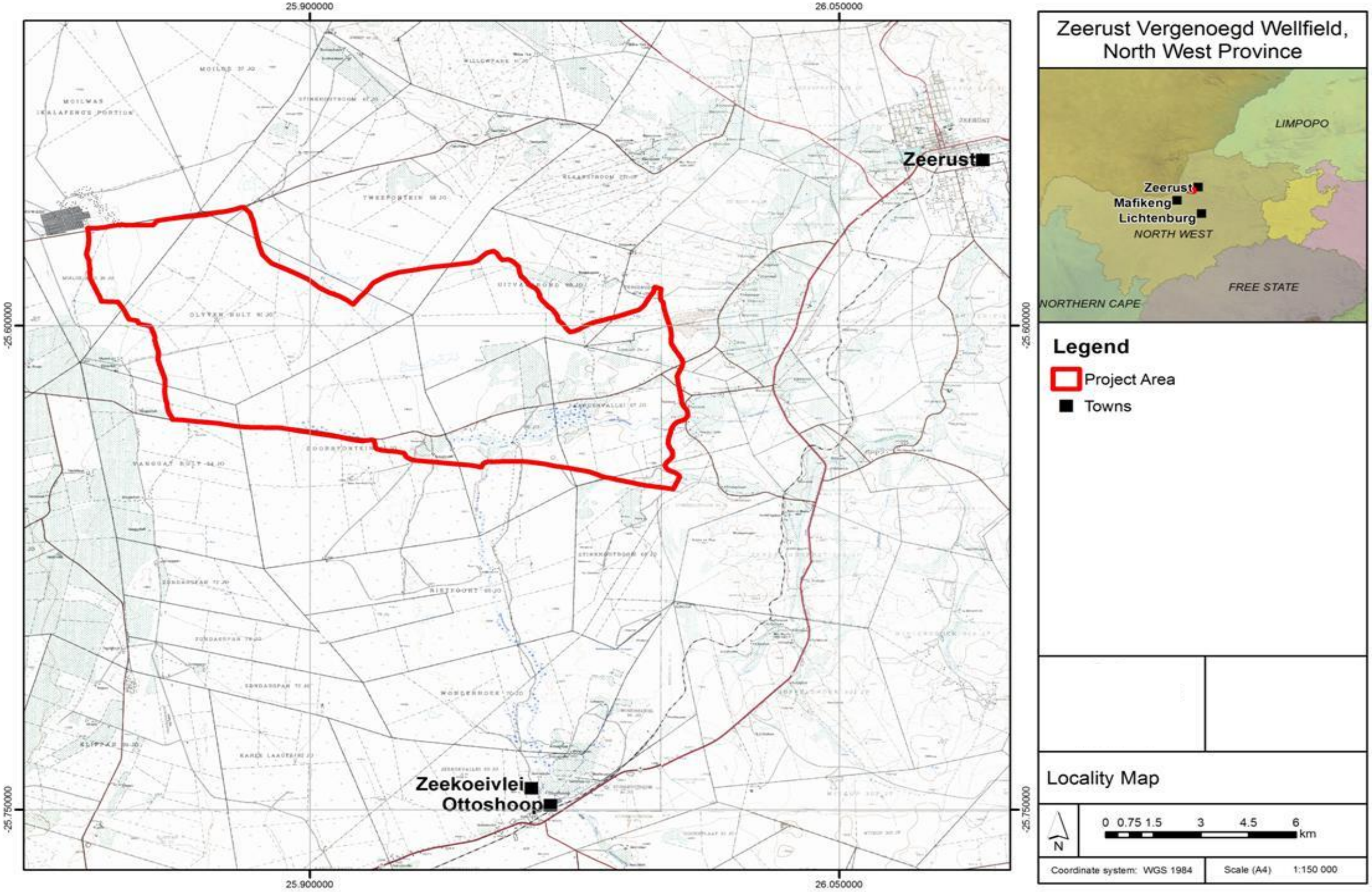


Figure 2-3: Locality map of the Paardevallei Groundwater Management Unit as study area

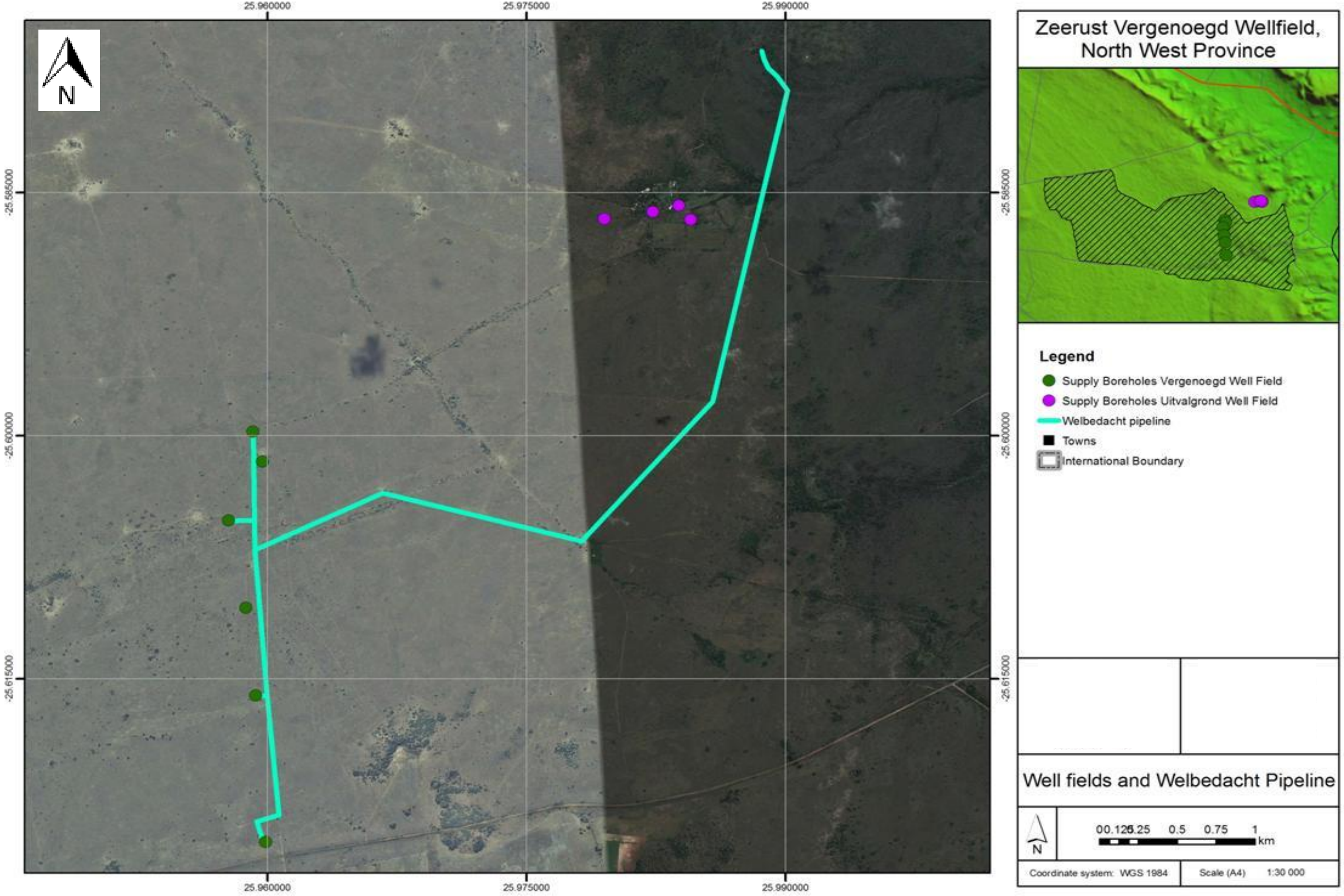


Figure 2-4: Welbedacht supply pipeline showing Uitvalgrond and Vergenoegd well fields

2.2 Background Study

In karst landscapes, the generally harmonious pattern of surficial drainage is broken up and closed depressions take over the landscape to varying degrees. Superficially, it lacks organisation and the drainage system is often found underground (Marshal and Norton, 2009). In fractured carbonate rocks, successful and unsuccessful boreholes can exist in close proximity, depending on the frequency of fractures or solution chambers intersected by the borehole (Buttrick and Van Schalkwyk, 1998). In situations where rapid direct recharge can occur, fracture enlargement by dissolution has great influence, causing local permeability to be almost infinite compared to other parts of the same formation (Freeze and Cherry, 1979). High baseflow values consisting of both groundwater and interflow are often present. Karst aquifers can represent highly anisotropic storativity and permeability conditions, e.g. with double or triple porosity (Bredenkamp and Vogel, 2007).

The major outflow points (known as *eyes*) from dolomitic aquifers in South Africa have represented reliable sources of water for the local communities for many years (Bredenkamp *et al,* 1995).

In Zeerust surface water is scarce throughout the area as most of the rivers are non-perennial. The absence of surface water over such an extensive area of dolomite is ascribed to the joints which occur within it (Clay, 1981). The duration of flow in the springs is likely to be highly variable and some may only last for a short period of time after major precipitation recharge events. Others may be semi-permanent. The patterns of spring-flow are expected to be closely linked to the patterns of recharge in the bomolopo area. Spring-flow will be subject to evaporation and evapotranspiration losses and in semi-arid areas may only contribute to sustaining static pools in the river channel rather than stream flow (Button, 1970).

Taylor and Greene (2008) set out several methodologies that could be followed to determine the effects and relationship between recharge and spring-flow. They are as follows:

Spring Discharge Hydrograph Analysis

A wide variety of graphical, time-series, and spectral analysis techniques have been applied to this method of investigation.

Interpretation and analysis of a spring hydrograph by using recession analysis it is possible to identify whether the overall basin flow characteristics are dominated by quick flow (conduit-dominated flow), slow flow (diffuse-dominated flow), or mixed flow, and to evaluate the timing and magnitude of changes in spring discharge that correspond to changes between these flow regimes. Although these methods are based on Darcian theories, the hydrograph analysis has been applied to large number of karst aquifers (Taylor and Greene, 2008).

Precipitation Response Analysis

Because of the inherently high transmissivity of karst aquifers, the spring-flow's quality and quantity are largely connected to recharge by means of precipitation. Depending on the magnitude of conduit-to-fracture ratio, spring hydrographs may show a flexible response to recharge events. If there is a high ratio conduit-to-fracture/matrix coupling, the spring will respond in a relatively short time (hours to weeks) to a recharge event, whereas if this ratio is low, the spring response may take many days or weeks. Knowing how the spring response is related to the recharge events is so important in karst hydrology that much research has been directed toward methods of simulating or predicting this response (Taylor and Greene, 2008).

Three approaches, linear systems analysis, lumped parameter (statistical modelling), and numerical deterministic modelling, commonly are used to simulate or predict the output function (spring discharge) of a karst system.

Linear systems analysis has been used in the hydrological sciences for many years to characterize rainfall-runoff relations (Dooge, 1973; Neuman and de Marsily, 1976) and has been used to describe rainfall (recharge)-spring discharge relations in karst systems (Dreiss, 1982; 1983; 1989). The use of a linear method to characterize a nonlinear system (karst groundwater flow) has been justified on a practical basis (Taylor &Greene, 2008).

In some karst basins, a linear response (kernel function) cannot adequately simulate the spring outflow. The purpose of lumped-parameter models is to simulate the temporal variations in discharge from springs. When the discharge rate varies continuously and depends on hydrologic input processes of precipitation, sinking streams, evapotranspiration, and infiltration, a model can be developed that produces the output based on some or all of the inputs (Zhang and Bai, 1996).

Water Tracing With Fluorescent Dyes

Dye-tracer testing is a versatile method that can be employed in a number of ways by using various combinations of field and laboratory techniques that can be tailored to fit the specific objectives, context, and scale of the investigation (Bredenkamp, 2010). The basic goal of any dye-tracer test is to create a detectable fluorescent signal in water that can be positively identified as originating from the injected tracer dye and that can be interpreted in a manner needed to achieve the planned objectives of the test (Taylor and Greene, 2008).

The hydrogeologic complexities presented by karst terrains often magnify the difficulties involved in identifying and measuring or estimating water fluxes. Conventional hydrogeologic methods such as aquifer tests and potentiometric mapping, though useful, are not completely effective in identifying the processes involved in the transfer of water fluxes in karst, or in characterising the hydrogeologic framework in which they occur, and may provide erroneous results if data are not collected and interpreted in the context of a karst conceptual model (Taylor and Greene, 2008).

Two more methods were used when a study was compiled when the total annual spring-flow of the San Pedro River at Charleston in south-eastern Arizona decreased by about 66 per cent from 1913 to 2002. The San Pedro River is one of the few remaining free-flowing perennial streams in the arid South-western United States, and the riparian forest along the river supports several endangered species and is an important habitat for migratory birds. The decreasing trend in spring-flow has led to concerns that riparian habitat may be damaged and that overall long-term water supply for a growing population may be threatened. Resource managers and the public had an interest in learning more about the trend and the possible causes of the trend (Thomas and Pool, 2006).

Thomas and Pool (2006) investigated the decreasing trends in spring-flow of the San Pedro River. Their study evaluated trends in seasonal spring-flows and trends in the relation between precipitation and spring-flow.

Two methods were used to partition the variation in spring-flow and to determine trends in the partitioned variation: (1) regression analysis between precipitation and spring-flow and statistical tests of time trends in regression residuals, and (2) development of regression equations between precipitation and spring-flow for three time periods (early, middle, and late parts of the record) and testing to determine if the three regression equations (rainfall-runoff relations) are significantly different.

Method 1 was applied to monthly values of total flow (average flow) and low flow (3-day low flow), and method 2 was applied to total flows. An important feature of the statistical analysis in the study is that it provides objective criteria for making decisions and interpretations about the data.

There were few significant trends in seasonal and annual precipitation or spring-flow for the regional study area. Precipitation and spring-flow records were analysed for 11 time periods ranging from 1930 to 2002; no significant trends were found in 92 per cent of the trend tests for precipitation, and no significant trends were found in 79 per cent of the trend tests for spring-flow. For the trends in precipitation that were significant, 90 per cent were positive and most of those positive trends were in records of winter, spring, or annual precipitation that started during the mid-century drought in 1945-60. For the trends in spring-flow that were significant, about half were positive and half were negative.

Trends in precipitation in the San Pedro River Basin were similar to regional precipitation trends for spring and autumn values and were different for summer and annual values.

The analyses were successful in explaining much of the variation in spring-flow.

Groundwater pumping in the upper San Pedro watershed in Mexico and the United States had a mixed influence on spring-flow trends at Charleston (Thomas and Pool, 2006). Statistical analyses indicate that seasonal pumping from boreholes near the river for irrigation in the spring and summer was a major factor in the decrease in low flow.

A long term case study was conducted by the hydrologic evaluation section in the USA to determine the effect of varying rainfall on aquifer discharge in Florida, USA. Hammett (1990) determined a statistically significant decline in annual mean discharge for the Peace River at Bartow, Zolfo Springs and the Arcadia gauging stations from the 1930s to 1984. Lewelling *et al* (1998) updated this work by including the subsequent 10-year period and found the same declining trend from the 1930s to 1994. Previous studies attribute this flow decline primarily to various factors, mainly loss of baseflow contribution due to groundwater abstraction (Hammett,1990;Lewelling *et al*,1998).

While there is little doubt that anthropogenic factors have contributed to flow reductions, the role of long-term, multi-decadal variation in rainfall toward spring-flow changes has received little attention until very recently (HES, 2003).

In the study it was determined that to maintain the Peace River as a perennial flow system, 30 to 35 inches of annual rainfall is required to provide sufficient discharge from springs. Statistical estimates of Peace River flow through regression of empirical data and surface-water model results indicated that a 5-inch per year decline in rainfall could result in spring-flow volume changes ranging from 22 to 35 per cent - expressed as a percentage of mean flow. About 90 per cent of observed spring-flow decline was attributed to a post-1970 rainfall departure of 5.7 inches per year. At a nearby station, also in the study area, about 75 per cent of the observed spring-flow decline can be related to long-term changes in rainfall (HES, 2003).

Another case study undertaken in Scotland evaluated the relationship between rainfall and spring-flow on the North Pentland Springs and revealed statistical linkages with precipitation accumulations over 1-7 months. Precipitation totals were found to be able to explain up to 54 per cent of the variability in monthly spring-flow values, leaving 46 per cent of the variability to be accounted for by other factors such as evaporation.

In the study it was determined that gradual decreases in spring-flows over the 80 years from 1904, for which local precipitation data were available, appear to be the result of decreases in annual precipitation totals. This applied to all three groups of measured spring-flows.

Yet another international case study relating to the relationship between spring-flow and rainfall was compiled by Stogner (2000) which describes trends in precipitation and trends in spring-flow in the Fountain Creek watershed and presents a qualitative assessment of changes in channel morphology of selected reaches of Fountain Creek downstream from Colorado Springs, Colorado, USA.

The relationship between precipitation and spring-flow was evaluated for years 1960 through 1997, the period when all four precipitation monitoring stations were active. Daily precipitation was summed and average daily precipitation calculated.

Average daily precipitation was cumulated and compared to the cumulative daily spring-flow. A seasonal evaluation of the relation between precipitation and spring-flow was conducted for the typically dry base-flow months of November through February and the wetter summer months of March through October to determine if the influence of summer thunderstorms were biasing the interpretation of the relation. Precipitation and spring-flow that coincided with dry and wetter periods were summed, averaged, and cumulated and compared.

The analysis indicated that changes in the relation between precipitation and spring-flow were nearly identical for the dry months of November through February as well as the wetter months of April through October. A very strong correlation between precipitation and spring-flow was established.

Similarly, a study was undertaken by Girish and Joshi (2004) in a small drainage catchment in the Himalayan mountains to study the correlation between spring discharge and rainfall patterns. Peak spring discharge coincided with peak rainfall in two springs, another spring's effects were delayed by a month due to geological factors. The spring that was affected by geological factors had a gradual decline in spring-flow when the rainfall declined whereas the springs not affected by geological factors had a rapid effect when rainfall subsided.

Rainfall and spring discharges were related closely to each other in all six springs that were included in the study. The peak discharge coincided with peak rainfall only in two springs, in others, the peak discharge occurred one month after peak rainfall. The springs were perennial in nature and yielded substantial water during the non-rainy season (Girish & Joshi, 2004). This is similar in response to springs in the Zeerust area according to the historical data whereby increases in spring-flows can be noted after heavy rainfall events.

The spring-flow quantities fluctuated largely between the rainy and non-rainy seasons. Spring-flow diminished to a great extent during the dry months. Thus, many of the water supply schemes in the region suffered due to this highly seasonal pattern of spring discharge.

In the springs where geological factors reduced transmissivity, the water yield was less fluctuating and the decline from peak discharge was only one-third, indicating that they were least dependant on the current season's rainfall (Girish & Joshi, 2004).

The region was experiencing water supply issues in the dry seasons due to the reduced spring discharge. Therefore, an understanding of the relationship between spring discharge and recharge area characteristics can be of enough applied value with regard to long-term water conservation strategies where people depend upon springs for fresh water.

While the international literature provides a large deal of background and all are equally applicable methods to quantify the relationship between rainfall, recharge and spring-flow, as well as the fact that all the methods can be used to a degree of certainty, there is a method that was developed in South Africa that will be used in this study due to its suitability whereby recharge can be calculated with a reasonable level of confidence as well as the fact that it was developed locally.

Suitable Methods To Use For This Study

Bredenkamp *et al* (1995) set out to evaluate the correlation between precipitation and spring-flows in the Rietpoort aquifer of the Zeerust area, South Africa.

The purpose of the study was to determine if this compartment would be adequate for groundwater supply to communities in the area in the wake of numerous springs ceasing to exude.

The Rietpoort compartment is part of the Malmani dolomites and is bounded by dolerite dykes.

The methodology followed by Bredenkamp *et al* (1995) was to firstly gather all rainfall and water-level data as well as all available abstraction data. The recently developed Cumulative Rainfall Departure (CRD) method was used in which a recharge value could be calculated using the available data.

The Wondergat sinkhole in the vicinity proved to be a valuable information source. Water levels could be observed visually and measured within the hole. This served as a useful tool to assess the accuracy of the CRD method that made use of sparse borehole monitoring data within the Rietpoort aquifer.

Water levels from the sinkhole as well as boreholes were compared to rainfall data and a correlation was observed - succeeding rainfall events, water levels rose in proportion to the quantity of rainfall received and on average 3 weeks after the rainfall event took place. When the water levels rose to a certain height, referred to as “the magical number“ (Bredenkamp *et al,* 1995), springs started to discharge once again.

The CRD method also allows for abstraction data to be added which has a marked effect on water levels. When this data was added it was noted that due to the lower than average rainfall received during that time period in combination with the abstraction of water for supply, water levels dropped to a level which caused the springs to cease flowing. From the calculations it was determined that for the springs to start flowing once again, either the recharge should increase in the compartment (mainly in the form of rainfall), or the abstraction rates should be lowered, especially in the southern parts of the compartment.

The calculations that were made using the CRD method closely mimicked the actual fluctuations that were observed in the Wondergat. This reaffirmed the CRD method as a valid means to calculate aquifer recharge even when the monitoring data is fairly sparse.

Description Of The Cumulative Rainfall Departure (CRD) and Saturated Volume Fluctuation (SVF) Method

The CRD method conforms to the concept that equilibrium conditions develop in an aquifer over time until the average rate of losses equals the average recharge of the system (Bredenkamp *et al,* 1995).

The rationale behind the departure method is that in any area, despite large annual variations in precipitation, an equilibrium is established between the average annual precipitation and the hydrological responses such as runoff, recharge and losses from the system. Similarly the vegetation type and density have adapted to the prevailing climate and rainfall characteristics (Bredenkamp *et al,* 1995).

The CRD method, based on the water-balance principle, is often used for mimicking of water level fluctuations. Because of its simplicity and minimal requirement of spatial data, the CRD method has been applied widely for estimating either effective recharge or aquifer storativity, and consequently gained a focus in South Africa (Van Tonder and Xu, 2001).

The CRD and SVF (see Section 4.4.4) methods can both be used to predict aquifer characteristics such as recharge, even when there is a lack of spatial data. When rainfall and water level data are available, the data can be compared to estimate recharge. A limited amount of data are needed to mimic water level fluctuations, this process then provides a method to determine the relationship between rainfall, spring-flow and abstraction. Bredekamp *et al* (1995) applied the CRD method to dolomitic aquifers and attained satisfactory results.

Bredenkamp *et al* (1995) clearly showed that natural groundwater level fluctuation is related to that of the departure of rainfall from the mean rainfall of the preceding time. If the departure is positive, the water level will rise and vice-versa. However, it was demonstrated that as long as there was surplus of recharge over discharge of an aquifer, even though the departure is negative, the natural water level may have continued to rise (Van Tonder and Xu, 2001).

Van Tonder and Xu (2001) improved upon the formula defined by Bredenkamp *et al* (1995) to make use of a shorter series of rainfall data that could not be accurately reflected in the original equation.

Van Tonder and Xu's (2001) equation is as follows:

Firstly with regards to the water balance equation. Assuming an aquifer area of (A) receiving recharge from rainfall (Q_R) with production boreholes (Q_P) tapping the aquifer and with natural outflow (Q_{OUT}), a simple water balance equation for a given time interval *i* can be written as follows:

$$Q_{Ri} = Q_{pi} + Q_{outi} + \Delta h_i AS \quad (i = 1, 2, 3 \ldots N) \qquad (1)$$

where Δh_i is water level change and S aquifer storativity. If Q_{Ri} is averaged over such a time interval where Δh_i is zero, the system may be treated as in equilibrium. This is, however, seldom the case in reality.

If Q_{Pi} is a constant rate, aquifer storage ($\Delta h_i AS$) adjusts to accommodate for net balance between Q_{Ri} and $Q_{outi.}$ This adjustment of the storage would be reflected in piezometeric surface or water level changes in boreholes. The cause-effect relationship between rainfall oscillation and water-level fluctuation is effectively represented by the correlation between the CRD and water level fluctuation.

Bredenkamp *et al.* (1995) defined CRD as follows:

$${}_{av}^{1}CRD_i = \sum_{n=1}^{i} R_n - \kappa \sum_{n=1}^{i} R_{av} \quad (i = 0, 1, 2, 3, \ldots N) \qquad (2)$$

Where R is rainfall amount with subscript "$_I$" indicating the i-th month "$_{av}$" the average and k=1+(Q_P + Q_{out})/(AR_{av}). K=1 indicates that pumping does not occur and k>1 if pumping and/or natural outflow takes place. It is assumed that a CRD has a linear relationship with a monthly water level change. Bredenkamp *et al* (1995) derived:

$$\Delta h_i = (r / S) \cdot ({}_{av}^{1}CRD_i) \; (i = 0, 1, 2, 3, \ldots \mathrm{N}) \qquad (3)$$

where r is a percentage of the CRD which results in recharge from rainfall.

Equation (3) may be used to estimate the ratio of recharge to aquifer storativity through simple regression between CRD_i and Δh_i (Bredenkamp *et al.,* 1995).

The improved formula created by Van Tonder & Xu (2001) is as follows:

$$
{}^{1}_{t}CRD_i = \sum_{n=1}^{i} R_n - \left(2 - \frac{1}{R_{av} i} \sum_{n=1}^{i} R_n \right) \sum_{n=1}^{i} R_t \qquad (4)
$$

$$
(i = 1, 2, 3, \ldots N)
$$

where $R_{t,}$ a threshold value representing aquifer boundary conditions, is determined during the simulation process. It may range from 0 to R_{av} with 0 indicating an aquifer being closed and R_{av} implying that the aquifer system is open, perhaps being regulated by spring-flow. Note that Equation (4) reduces Equation (2) if rainfall events R_i do not show a trend ($R_t = R_{av}$). In this case, cumulative rainfall average would conform to R_{av}. It is assumed that CRD is the driving force behind a monthly water level change if the other stresses are relatively constant. The groundwater level will rise if the cumulative departure is positive and it will decline if the cumulative departure is negative.

Since CRD $\propto$ ($\Delta h + (Q_p + Q_{out})/(AS)$), then rCRD = $S(\Delta h + (Q_p + Q_{out})/(AS))$. After rearrangement, one obtains the following:

$$
\Delta h_i = (r/S) \cdot \left({}^{1}_{t}CRD_i\right) - \left(Q_{pi} + Q_{outi}\right)/(AS) \qquad (5)
$$

$$
(i = 0, 1, 2, 3, \ldots N)
$$

Term $(Q_{pi} + Q_{outi})/(AS)$ in Equation (5) is necessary only if a pumping borehole has influence over the study area where water levels were collected. Equation (5) may be used to estimate the ratio of recharge to aquifer storativity through minimising the difference between calculated and measured Δh_i series (Van Tonder & Xu, 2001).

3 BACKGROUND

For ease of reference, the background to the abstraction borehole field development and problems related with the bulk abstraction will be given in the subsections below.

3.1 Regional investigation

- A detailed regional study of the Zeerust Dolomite Compartments was undertaken by a consortium of companies prior to and during 2002. This study included the detailed delineation of over 50 compartments, including the Dinokana, Doornfontein and Rietpoort abstraction borehole fields. A comprehensive 3D numerical model was compiled, the objective was to identify groundwater resources to augment the larger Zeerust area's supply with 231 L/s. One of the outcomes was the identification of the Vergenoegd Compartment where between 40-45 L/s could be developed sustainably (keeping the water table within a five metre drawdown on the long term) (Khulani, 2006). See Figure 2-3 for locality map.

3.2 Uitvalgrond Well Field (UWF)

- Botshelo Water (a bulk water service provider serving district and local municipalities) appointed Africon to develop an abstraction borehole field on the farm Uitvalgrond 60 JO (also known as Wolvekoppies) (Phumelela, 2008).

- Aquisim Consulting (2002) was appointed by Africon to evaluate the aquifer potential through aquifer testing and numerical modelling of several production boreholes on the farm Uitvalgrond 60 JO. The investigation concluded that a total of 30 L/s can be developed from four boreholes (Aquisim, 2002). The boreholes were suitably equipped and production commissioned in April 2003. The project is known as the Welbedacht Bulk Water Supply (Phumelela, 2008).

  The UWF failed the following year (2004), necessitating a re-evaluation of the aquifer potential. Additional water was also sought by the NMMDM further to the south. This project was called Welbedacht Bulk Water Supply Augmentation, or Phase II (Phumulela, 2008). This investigation made use of the geohydrological services of Khulani GeoEnviro Consultants (Khulani, 2008).

This phase of the investigation involved a detailed review of previous work done on Uitvalgrond 60 JO and a gravity survey over an area of 45 km^2 with the aim of refining the dolomite compartments and drilling production and monitoring boreholes (Khulani, 2008). Khulani recommended inter alia:

- That the abstraction from the Uitvalgrond boreholes must be reduced to 6 L/s (based on the spring-flow of Wolvekoppies Spring of 8 L/s) and monitored.
- The drilling of five monitoring boreholes, sited within the gravity survey area for additional data.
- Update of the existing 3D numerical model with the new data.
- An EIA as per regulations, and
- The drilling of eight new production boreholes to satisfy the demand of 40 L/s (Khulani, 2008).

3.3 Vergenoegd Well Field (VWF)

- The above recommendations by Khulani (2008) were implemented as follows:
  - The production from the UWF was reduced to 6 L/s and monitoring was implemented.
  - Five new monitoring boreholes were drilled.
  - Aquisim Consulting (2002) was again contracted to update and re-calibrate the 3D numerical model with new data.
  - With the new refined compartment information, and based on the numerical model, Aquisim (2002) confirmed the feasibility of abstracting the required volume (40 L/s) spread out over three compartments as follows:

Wolvekoppies/Uitvalgrond	6 L/s
Tweefontein South	10 L/s
Paardenvallei/Vergenoegd	30 L/s

    - DWA approved the investigation report and numerical model, and issued an abstraction license for the new augmentation scheme.
    - An EIA was also conducted and approved by the DACE in the form of a RoD.

- Subsequently seven new production boreholes were developed (drilled and tested) following "*protracted negotiations with landowners and communities*" (Khulani, 2008).

- According to the land owners, neighbours who have water rights for irrigation purposes from the canal fed by the Vergenoegd Springs complained in 2010 about a decline in the volume of water from the springs affecting their irrigation supply. There is therefore suspicion that the abstraction from the VWF negatively impacts on the underlying aquifer resulting in a decline in the spring-flow (AGES, 2010).

- According to the licensing conditions and EIA requirements, NMMDM (as the Water Services Authority), is required to monitor the water levels and abstraction volumes and submit these monitoring results on a quarterly basis to both DWA and the land owners. This is supposed to be performed by Botshelo Water (the Water Services Provider). The land owners claim that they have never received such reports creating doubt as to whether monitoring is being implemented (AGES, 2010).

- AGES was appointed by the land owners to independently investigate the apparent negative impact on the aquifer. A status quo assessment was done in 2010 during which no conclusive evidence of negative impacts on the aquifer could be found in the light of absence of historical and monitoring data (AGES, 2010).

- Meanwhile in 2010 Masilo and Associates were appointed to conduct an audit EIA to assess the compliance of the abstraction to the environmental obligations (Masilo and Associates, 2011).

3.4 Study area

3.4.1 Geographic setting

The study area centres on the newly developed VWF on the farms Kafferskraal 66 JO and Uitvalgrond 60 JO west of Zeerust in the North West Province. The hydrgeological influence of the abstraction is expected to be limited to the groundwater compartment in which the abstraction borehole field is located, and therefore this compartment will be used as a boundary to the study area. The investigation was however not limited to this area, and included background information and data acquisition from a more regional area (see Figure 2-3).

3.4.2 Topographic setting

Topographic data were obtained from the SRTM's database (90m grid resolution) and colour-scaled to aid visualisation on a regional scale. The dolomite outcrops form a regionally flat topography, although on a more local scale undulations and incised river valleys are present. The regional topography is characterised by the prominent hills and valleys towards Zeerust (see Figure 3-1).

3.4.3 Geologic setting

The dolomite referred to forms part of the Malmani Sub-Group in the Chuniespoort Group of the Transvaal Supergroup. The name Malmani was derived from the Malmani Spring having its origin on the dolomites and giving rise to the Malmani River. The Malmani Sub-group is underlain by the Black Reef Formation, a clastic sedimentary series of quartzite, conglomerate and shale. This formation forms the base of the Transvaal Supergroup and is characterized by a positive relief, smooth texture and light tone on aerial photographs (Button ,1970). The Black Reef Formation is stratigraphically defined as the sedimentary succession between the basal unconformable contact with older Achaean rocks and the base of the lowermost dolomite bed (Coetzee, 1996).

Within the dolomite series overlying the Black Reef Formation, different formations exist with varying compositions. At the base, the Oaktree Formation consists of a dark chert-poor dolomite with some shale. This formation is characterised by large stromatolitic domes, shale marker beds, the Convulate Chert Marker and a tuffite marker.

The formation has a uniform dark colour, a low relief and no distinctive geomorphic expression. The contact between the Oaktree and overlying Monte Christo Formation is gradual and taken at the change from a dark brown to a light grey dolomite and a corresponding increase in chert content (Obbes, 1995).

The overlying Monte Christo Formation is a chert-rich dolomite, containing interbedded banded and oolitic chert. The formation has a streaky appearance, moderate relief, a course texture and well-defined bedding traces on aerial and orthophotographs. In some areas this formation has been intruded by a series of Precambrian dolerite dykes striking east-west and north-south. Preferential dissolution and erosion along structurally controlled lineaments has occurred to produce a karst topography, associated with sinkhole formation (SACS, 1980).

Overlying the Monte Christo Formation is the Lyttelton Formation; another chert-poor dolomite unit with a chocolate brown colour (Figure 3-2).

The lower part of the succession contains more chert than the central portion. Megadomal stromatolites are fairly common in the Lyttleton Formation. Chertified columnar stromatolites and cross-bedded dolarenite beds also occur. The unit is characterised by a dark tone, a relatively subdues topography and poorly defined bedding traces on aerial photographs. The contact with the overlying Eccles formation is gradational and is taken at the change of colour from dark brown to grey and an increased chert content (Clay, 1981).

The Eccles Formation which overlies the Lyttleton formation contains light grey interbedded dolomite and chert bands which weather to produce the typical “bread and butter” appearance. The Eccles formation is characterized by excellent bedding traces on aerial photographs. A chert-shale breccia occurs near the top of the Eccles formation The chert poor dolomite directly above the chert-shale breccia has a dark brown colour. The Eccles formation is capped by a silicified chert breccia which constitutes a reliable marker unit (Obbes, 1995).

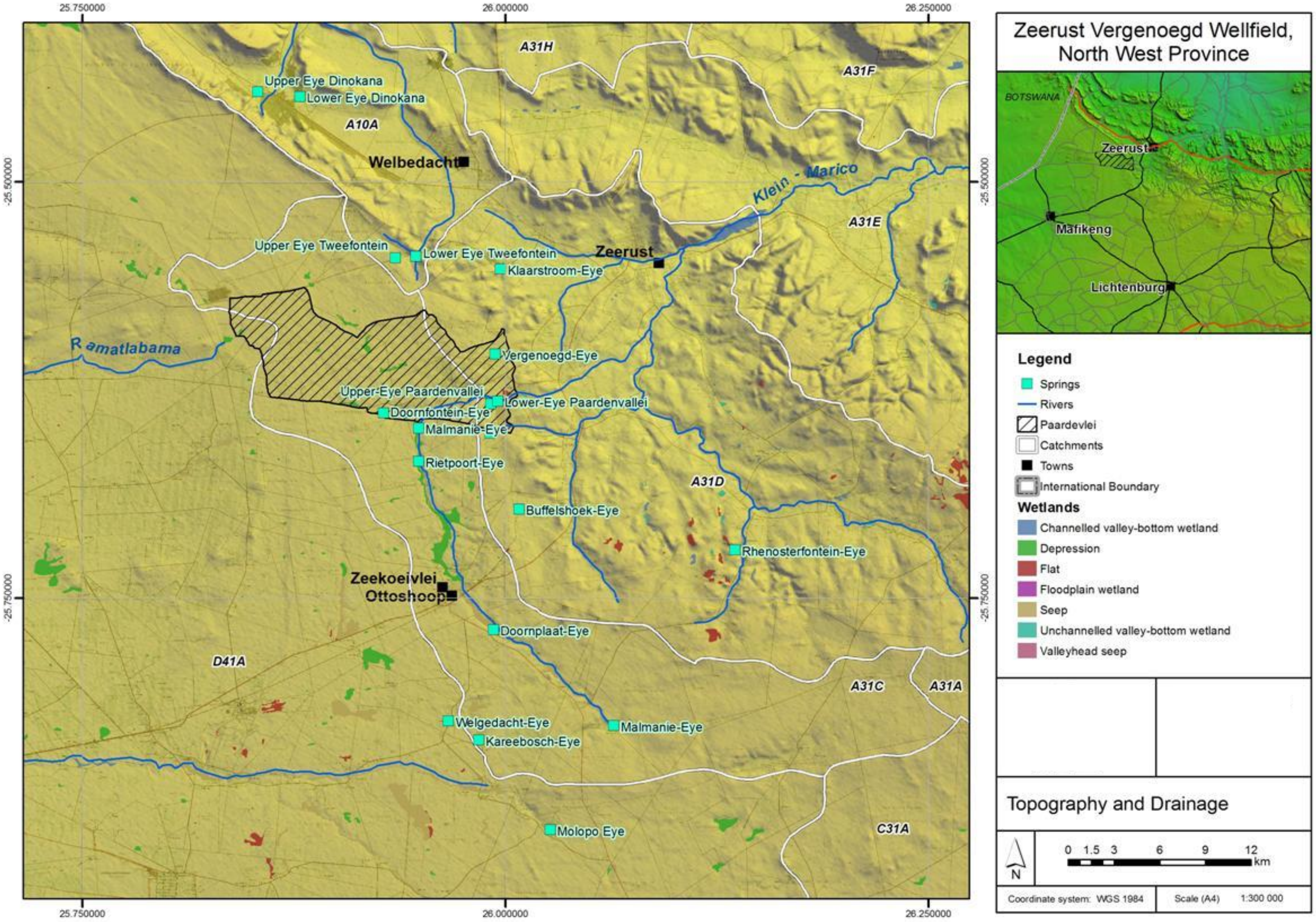


Figure 3-1 Topography around the study area

The stretch of dolomite west of Zeerust strikes in a northerly direction, with a shallow dip towards Zeerust (the east). The basal Oak Tree Formation therefore outcrops on the western side of the dolomite series, and the Eccles and Frisco Formations to the east (Figure 3-3).

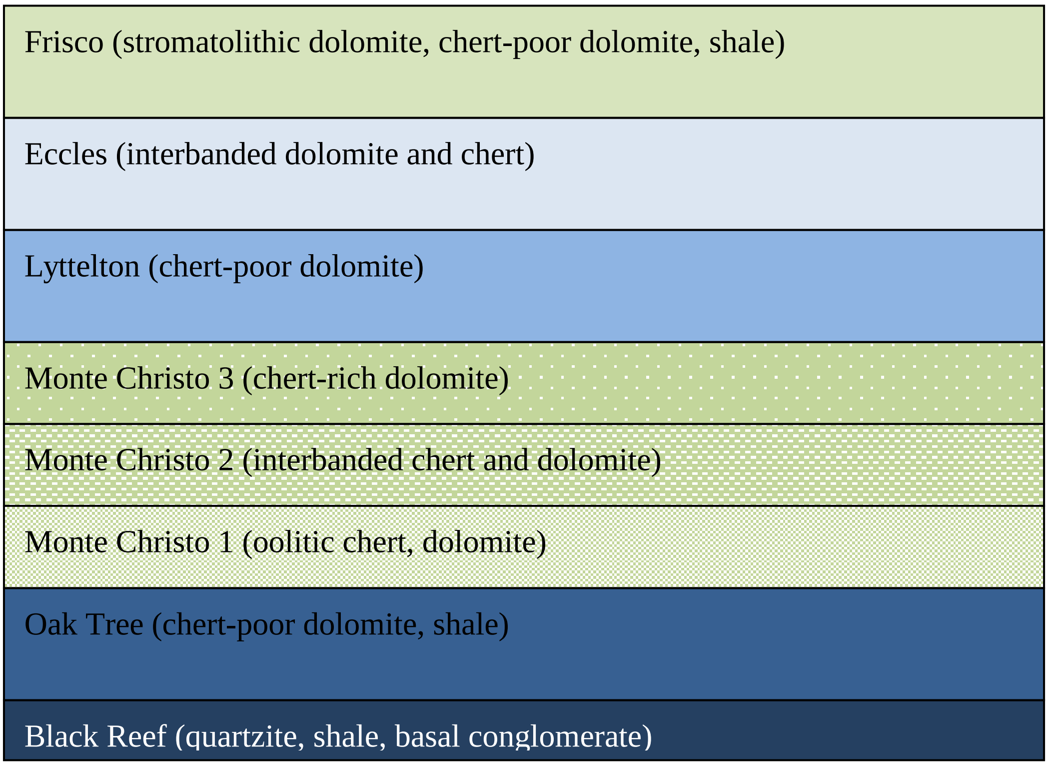


Figure 3-2 Stratigraphic sequence of Malmani dolomites west of Zeerust (colours correspond to the 1:250000 geological map

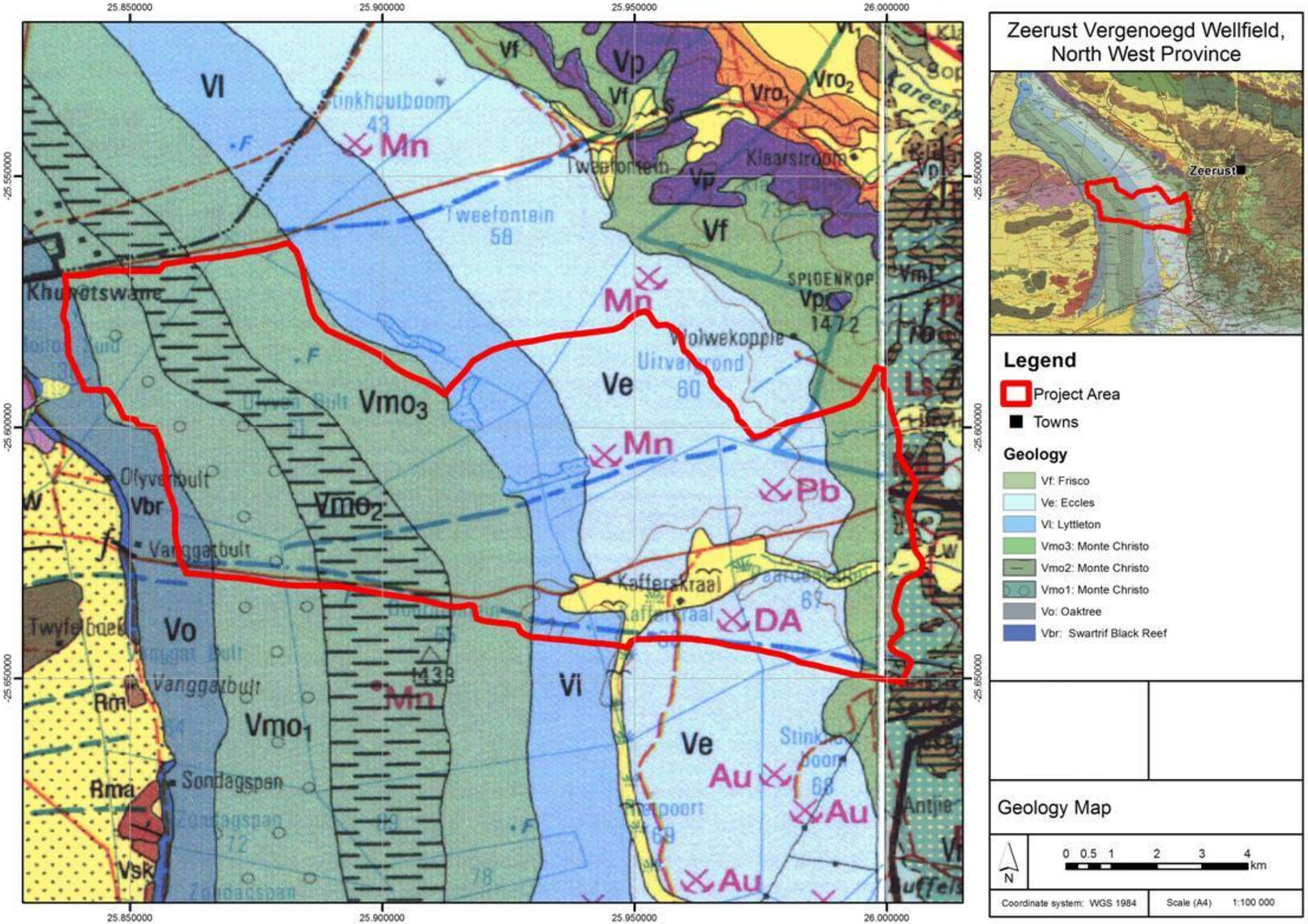


Figure 3-3: Geological map of the study area

3.4.4 Hydrogeologic setting

Aquifer description

According to the hydrogeological map series of South Africa (DWA, 2001), the dolomite is described as a Karst Type aquifer. This is due to the occurrence of groundwater in dissolved cavities in the dolomite. Dolomite consists of calcium-magnesium carbonate and is readily dissolved in acid (Bredenkamp, 2009). Acidic groundwater in the geological past has dissolved cavities underground that are connected through fissures and fractures to form a vast interconnected system of underground reservoirs. Cavities that are not hydraulically connected, or are separated by impermeable dykes that penetrated the dolomite form individual compartments with independent hydraulic properties (Figure 3-4). The area is situated within the Paardevallei and Klaarstroom GMA’s.

Quaternary catchments

The majority of the dolomite is located in quaternary catchment A31C as shown in Figure 3-4. It forms part of the Malmani River drainage, a part of the Marico catchment which drains northward to join the Limpopo River system. This catchment’s western boundary also forms the westernmost boundary of primary catchment “A”. West of this divide is the Molopo Catchment (primary catchment “D”). The Molopo Eye is also located on the same dolomite as the Malmani Eye (eight kilometres southwest). East of catchment A31C is A31D which also overlies the eastern portion of the dolomites. The UWF boreholes are located in this catchment.

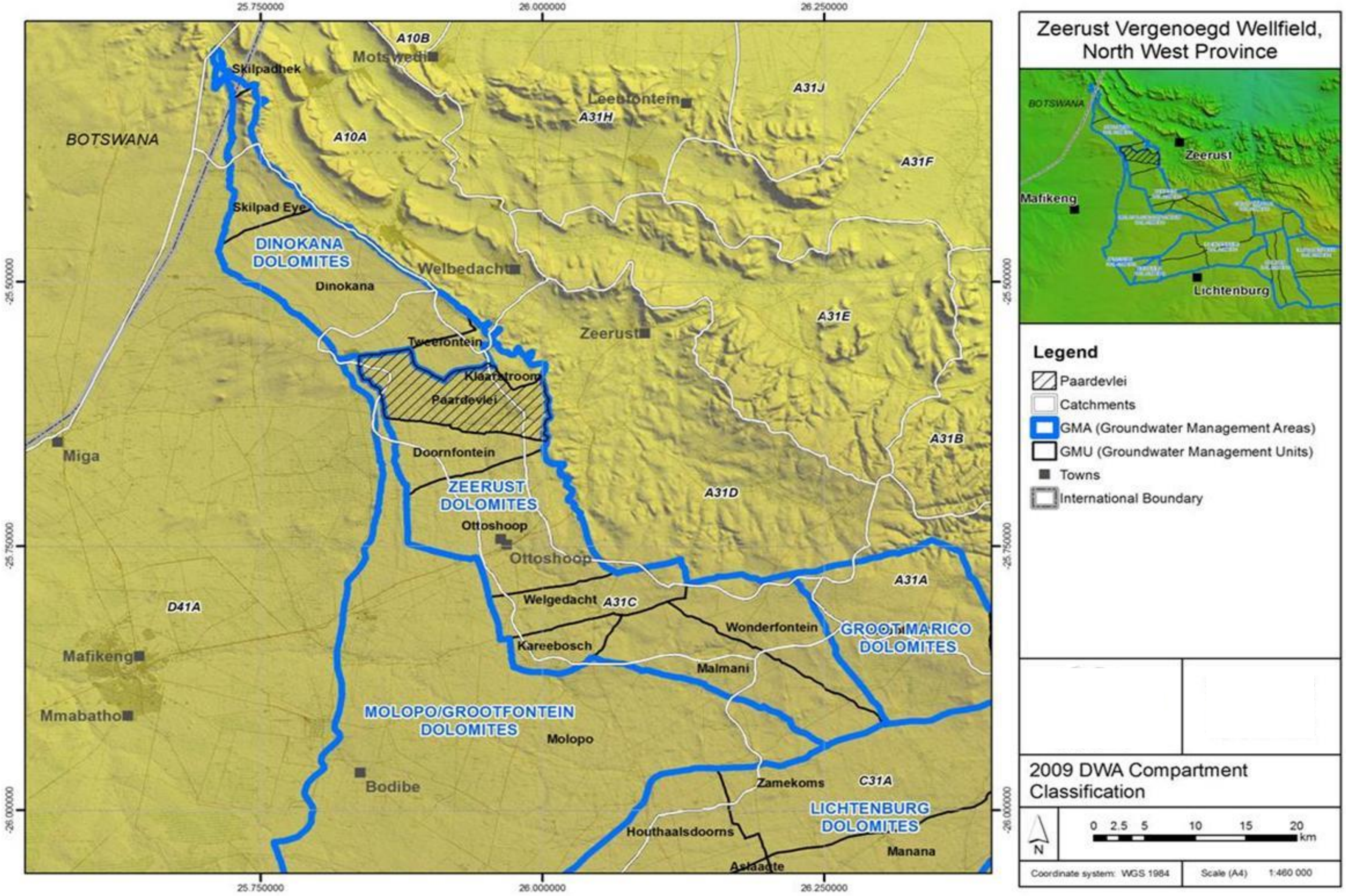


Figure 3-4: Hydrogeologic setting of the study area

Aquifer parameters

The key hydraulic parameters that require quantification to enable the viability of abstraction schemes to be determined in transmissivity (T) and storage (S). Much work has been carried out to try and determine a) methodologies and b) to assign values to these parameters (Bredenkemp *et al*, 1991). One of the key problems in this regard is the heterogeneity of the dolomite so that applying average figures across compartments is largely meaningless (DWA, 2006).

The highly transmissive nature of the dolomite results in the original water table being very flat, with a very low gradient from one end of a compartment to the other. Solution cavities and fissures are likely to be enlarged with time by continuous circulation of water from the surface into possible cavities caused by abstraction cycles, thus possibly increasing transmissivity and storage (DWA, 2006).

As with transmissivity (T=Kd where d is the saturated thickness) and storage, hydraulic conductivity (K-value) is highly variable due to the heterogeneous nature of the dolomites. Bredenkamp (1991) suggests an average storage value ranging from 1 to 5 for dolomitic aquifers in this specific areas.

From historical pump test data, Aquisim (2002) concluded that the aquifer transmissivity value is large (thousands of m^2/day) and that the storativity value is in the order of 0.0095 to 0.0821. It is difficult to accurately predict aquifer parameters in dolomites due to their variance in weathering and secondary permeability. These are typical values, which are often obtained for the karstified portions of dolomite formations in Southern Africa.

Aquifer yields

Dolomite is known as a rock type with significant groundwater potential due to the occurrence of groundwater in open cavities. Depending on the siting of production boreholes, dolomite aquifers can yield in excess of 20 L/s. Dolomite aquifers are classified as Major Aquifers according to the South African Aquifer Classification System (DWA, 2011). The development of the Rietpoort, Uitvalgrond and Vergenoegd abstraction borehole fields are testimony to the significant water potential of the Zeerust Dolomites.

3.4.5 Climatic setting

The area is located in the summer rainfall area of South Africa. Rainfall is characterised by short intense thundershowers during summer months (October-March). The average annual rainfall of the area is 547 mm, this was calculated from all available historical data reviewed for numerous rainfall stations in the vicinity.

Rainfall data forms an important part of the relationship between recharge, abstraction and spring-flow and is necessary to calculate the recharge factor affecting this relationship. Rainfall data were obtained from Agromet in Potchefstroom and from the Water Resource Information Management System (WRIMS). The Mmabatho Airport (16936) and a station at Marico (17557) were sourced from Agromet, while several stations were sourced from WRIMS: 050849, 0508649, 0508721, 0508825, 0509035, and 0509042. These stations were plotted to indicate their relative positions around the area of investigation as shown in Figure 3-5.

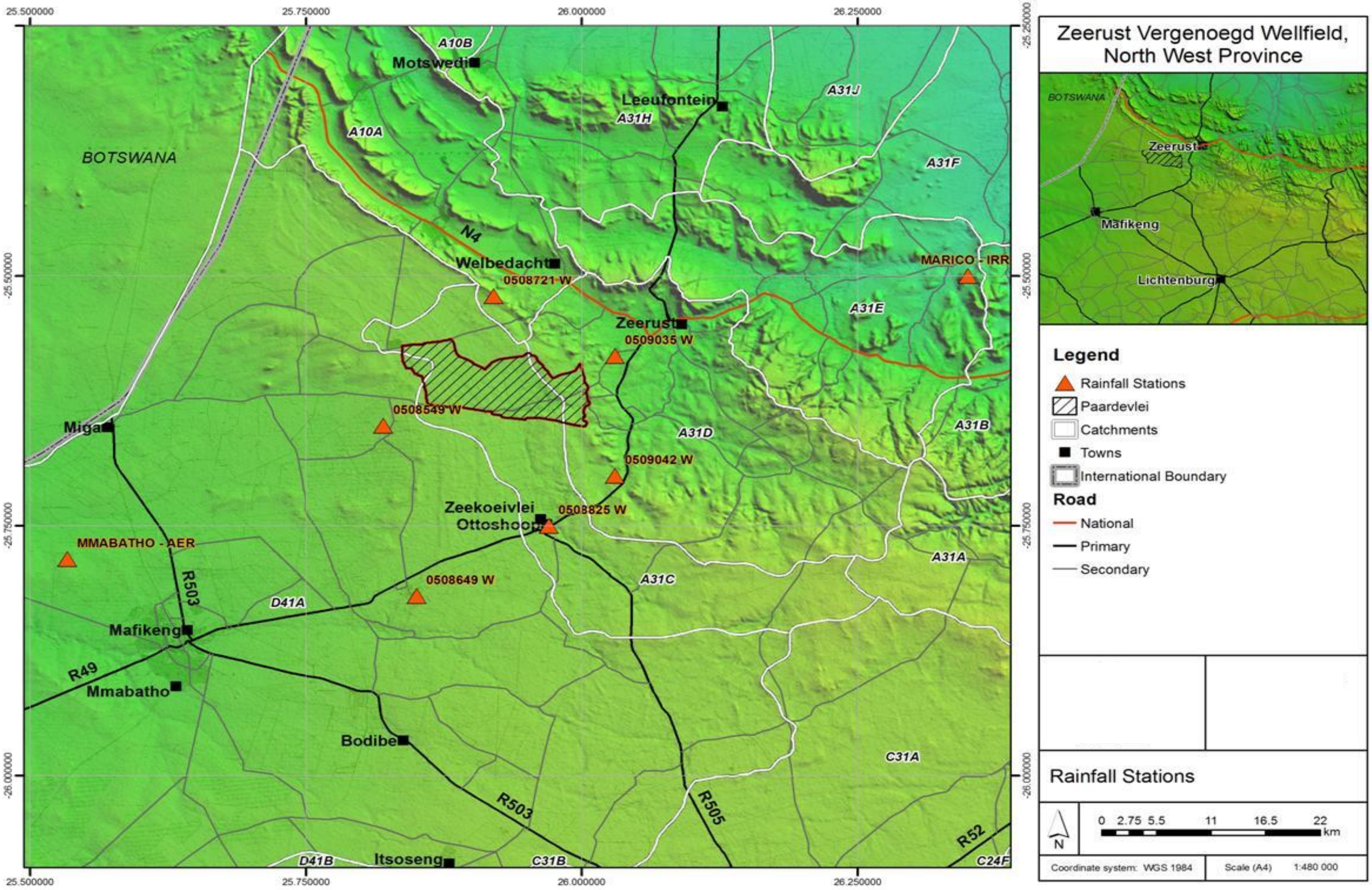


Figure 3-5: Weather stations used around the study area

Agromet data were incomplete and therefore did not reflect true annual rainfall figures.

The Marico station had uninterrupted data for 30 years between 1959 and 1989. Data needed to be patched for seven months in 1990, for four months each in 1992 and 1995 and one month each in 1998 and 2003. The year 2004 only had data up to April, thus the rest of the year was also patched as shown in Figure 3-6.

Data used for patching of the missing Agromet data stemmed from the WRIMS data where monthly precipitation data was present and *vice versa*.

Both the Agromet as well as the WRIMS' missing monthly data was patched using Oracle's Crystal Ball programme which is a Microsoft Excel based risk-assessment and simple simulation programme.

Probability distribution was used to gain a suitable value for the few months with missing data. Rainfall data are processed by the program whereby it automatically matches the data against the continuous and/or discrete probability distributions. The program then performs a mathematical fit to determine the set of parameters for each distribution that best describes the characteristics of your data which in turn provides a patched value (Figure 3-6).

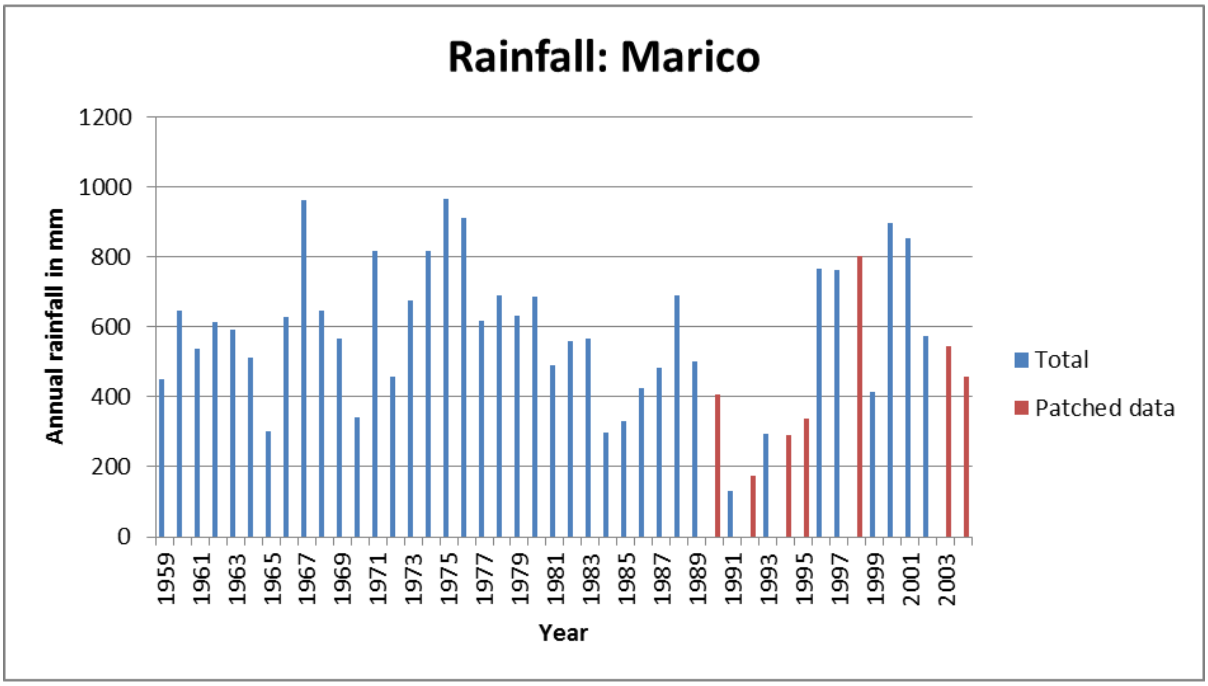


Figure 3-6: Patched precipitation data at Marico

At Mmabatho Airport the first four months of 1984 and the last four months of 2001 also needed to be patched. Three months in 1989, 1994 and 1995 needed patching, two in 1988 and 1999 and only one in 1991, which is an anomalous year in terms of the data. The patched data is illustrated in Figure 3-7.

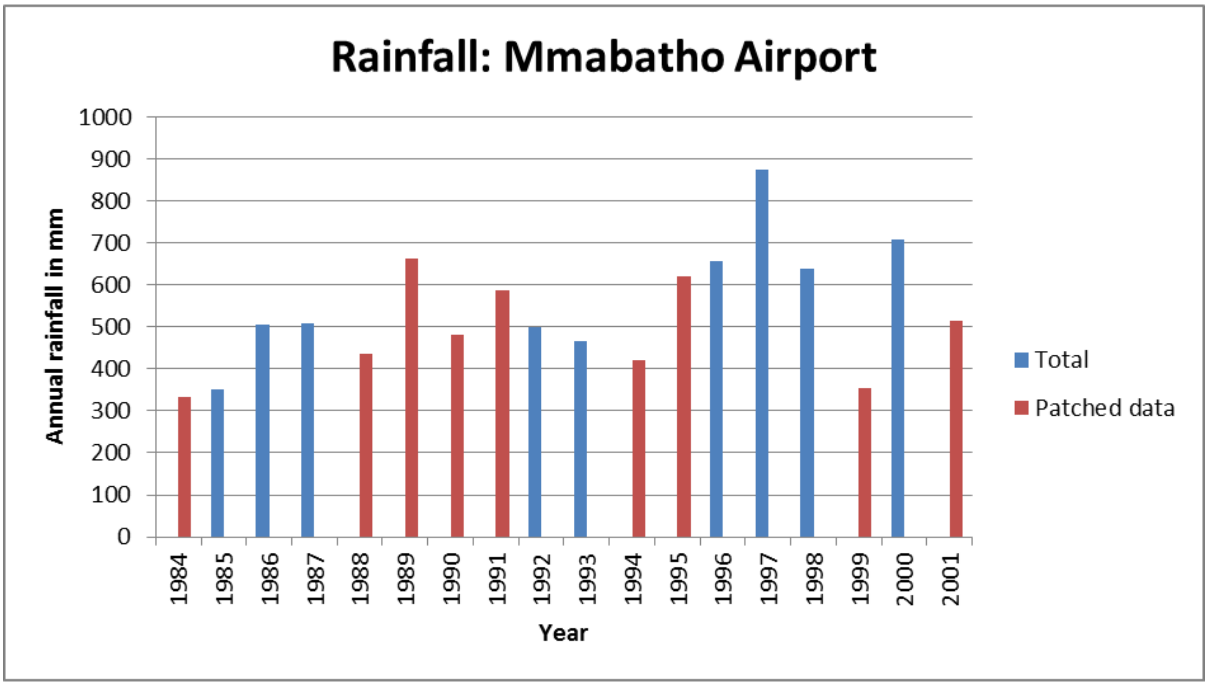


Figure 3-7: Patched precipitation data at Mmabatho

At Mmabatho 588 mm of rain was measured (the data was patched for July in the dry season) while Marico only realised 130 mm with no data missing. This pattern is repeated in the following four years although the discrepancy between the two stations reduces annually. Between 1989 and 1995 Mmabatho consistently measured more rainfall than at Marico (see Figure 3-8).

From the combined bar chart it can be seen that the rainfall is very erratic and differs substantially from year to year.

The reliability of the WRIMS data is also unknown. No data manipulation was done and graphs were drawn from the data as-is. The data for the individual stations were plotted individually, and combined in Figure 3-9. The majority of the WRIMS data stations have data since 1903 and continues until 1999 while two stations have data up to 2008. The variability in rainfall can be seen from the graphs.

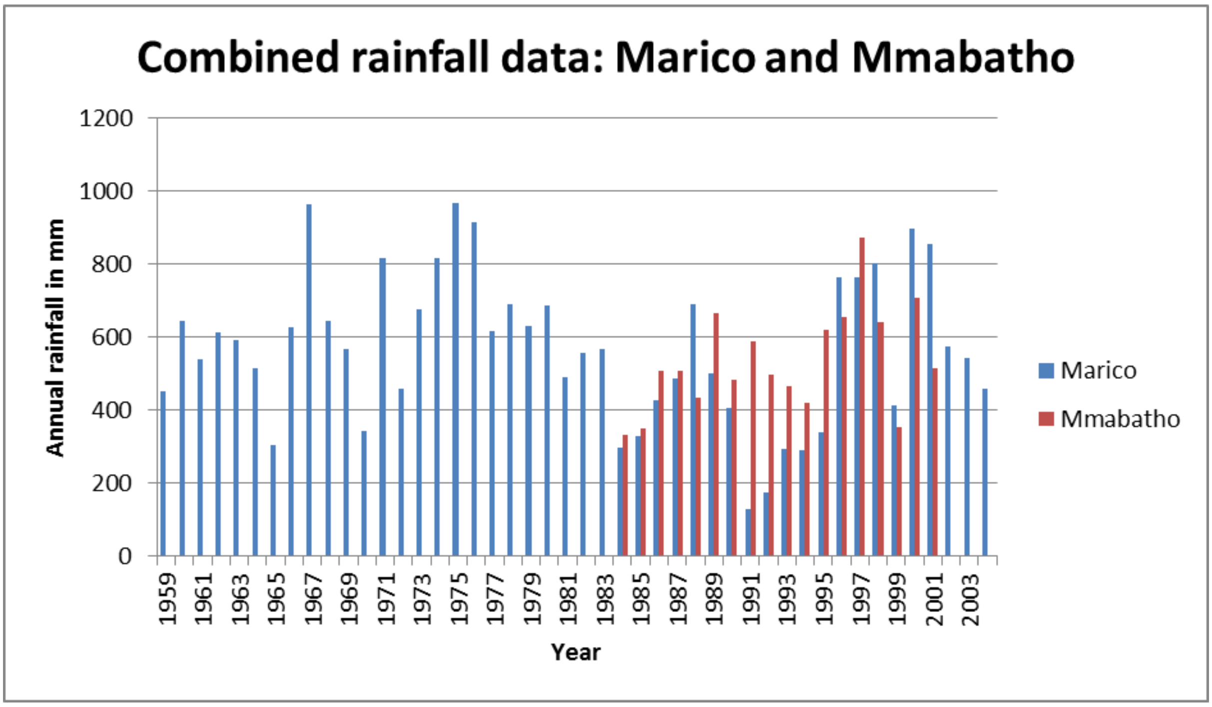


Figure 3-8 Combined rainfall data for Mmabatho and Marico

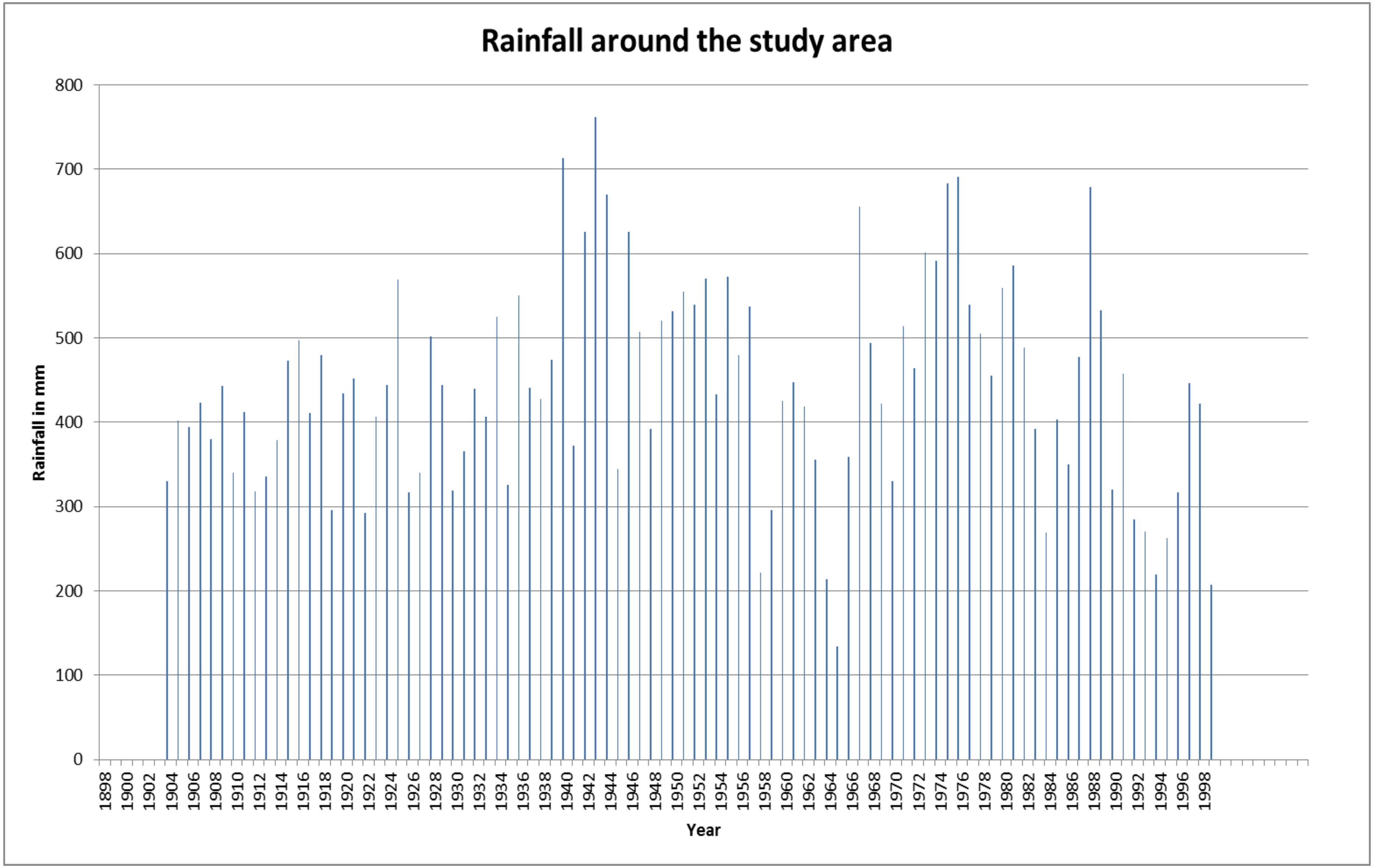


Figure 3-9: Cumulative rainfall data around the study area from six stations

4 APPROACH

4.1 Introduction

The approach followed in this investigation is similar to that documented in the DWA (2006b) and includes the following steps:

- Step 1: Desk study

The objective of a desk study is the collection and evaluation of available and relevant data.

- Step 2: Hydrocensus

A hydrocensus is essentially site familiarisation and the collection of data from the study area. It comprises a census of boreholes and springs. The hydrocensus involves the collection of data including: co-ordinates, details concerning ownership, groundwater/spring use, yield, borehole depth, groundwater level and existing equipment (e.g. pump installed).

- Step 3: Conceptual groundwater model

The conceptual groundwater model is prepared using the data collected during the previous steps. The conceptual model includes compartmentalising of the aquifer, presence of springs/eyes, recharge potential and distribution of water levels. The model constitutes the conceptual level understanding of the aquifer and its behaviour, and provides the basis for the development of an analytical or numerical model.

- Step 4: Groundwater modelling

Models were prepared to assess various scenarios and make predictions concerning the behaviour of the aquifer. Initially only a numerical model was developed, however additional analytical models had to be developed as well.

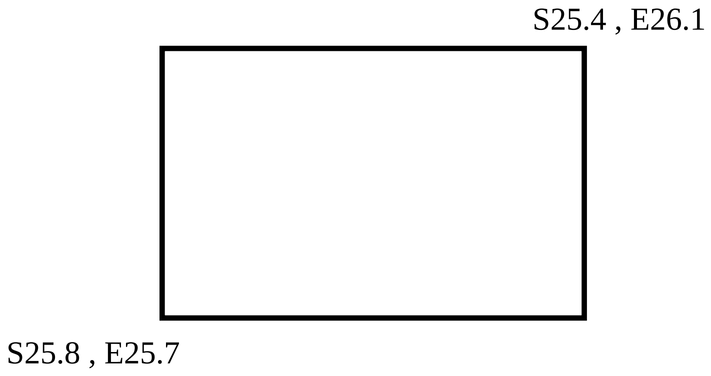
Due to budget constraints additional field work such as drilling and aquifer testing could not be conducted.

4.2 Desk Study

Borehole data for existing databases were sourced for the area. Three databases from DWA were used including the National Groundwater Archive (NGA), the Water Resource Management System (WARMS) and the HYDSTRA database containing monitoring data. The NGA database contains borehole records that includes monitoring boreholes and data, but are outdated in some instances. The WARMS database is a current database of water users who registered boreholes for the specific purpose of registering abstraction, or applying for authorisation in terms of the uses defined in Section 21 of the NWA (1998). The data indicate borehole locations, use, volumes abstracted and whether authorisation was granted yet or not. The HYDSTRA database contains monitoring data for both surface and groundwater points (stream-flow, spring-flow, groundwater levels etc. measured over time) and is highly valuable to this investigation.

4.2.1 NGA data

NGA data were retrieved for an area with the following dimensions:



A total of 1112 unique records were retrieved of which 1100 were boreholes, 6 were springs, 5 were dug boreholes and one a sinkhole.

A total of 134 geosites were located using a handheld GPS, while the rest (978) were all estimated from the 1:50 000 topographical map with varying levels of accuracy. Various data fields are included in the data that are not applicable to this investigation. Some boreholes do have water level data, but the dates of measurement differ.

No monitoring data are included in this dataset retrieved, but monitoring boreholes (especially the monitoring boreholes in and around the VWF) are included as data points – albeit without water level data.

The data are generally incomplete and difficult to use, but will be used as reference where needed to compare current water level data to historical data. All boreholes are indicated on Figure 4-1.

4.2.2 WARMS data

Data from the Water Resource Management System (WARMS) from DWA was obtained and also plotted on Figure 4-1. This database contains records of water uses registered, or applied for authorisation at DWA (which might or might not yet have been authorised). Only the groundwater abstraction data from boreholes and springs were requested.

This database does not contain information on water levels and monitoring and will not be used in this regard. What is interesting to note from this database is that none of the bulk abstraction boreholes of either of the borehole abstraction fields (Rietpoort, Uitvalgrond and Vergenoegd) exists on this database.

4.2.3 HYDSTRA data

The HYDSTRA data proved the most valuable to this investigation. Monitoring data for both springs and boreholes were obtained with varying degrees of completeness.

4.2.4 Monitoring data

A set of DWA monitoring data was obtained for several boreholes in the area. The applicable boreholes (located in the study area) were filtered and used for interpretation purposes.

4.2.5 Data discrepancies

When the locations of the applicable boreholes are plotted on a map, a discrepancy between borehole numbers exists. Before 2012 certain monitoring boreholes had numbers that do not correspond to the coordinates assigned to them after 2012.

This could be due to the fact that prior to the use of GPS systems, a central co-ordinate on a farm was used as a reference point.

New numbering formats were assigned to the boreholes, which add to the confusion. The co-ordinates of the boreholes were used to compare the different boreholes from the various datasets, and create a table to clarify the numbering and locations of the monitoring boreholes (Table 1). From the table it can be seen that before 2012, the numbering of the monitoring boreholes differed from the numbering assigned to them post-2012, when the Hydstra numbers were allocated. For the sake of consistency, the new 2012 numbers will be used as indicated on the NGA.

Table 1: Monitoring boreholes on record

Lat	Long	NGA (2012)	Hydstra (2012)	DWA Monitoring (post 2012)	DWA Monitoring (pre-2012)	Khulani (2008)
-25.61603	25.95831	**21-00061**	**D4N2514**	D4N2514 (21 - 00061)	21 - 00065	21-00065
-25.59944	25.95817	**21-00062**	**D4N2515**	D4N2515 (21 - 00062)	21 - 00064	21-00064
-25.60242	25.96867	**21-00063**	**D4N2516**	D4N2516 (21 - 00063)	21 - 00062	21-00062
-25.59964	25.97367	**21-00064**	**D4N2517**	D4N2517 (21 - 00064)	21 - 00061	21-00061
-25.60467	25.97164	**21-00065**	**D4N2518**	D4N2518 (21 - 00065)	21 - 00063	21-00063

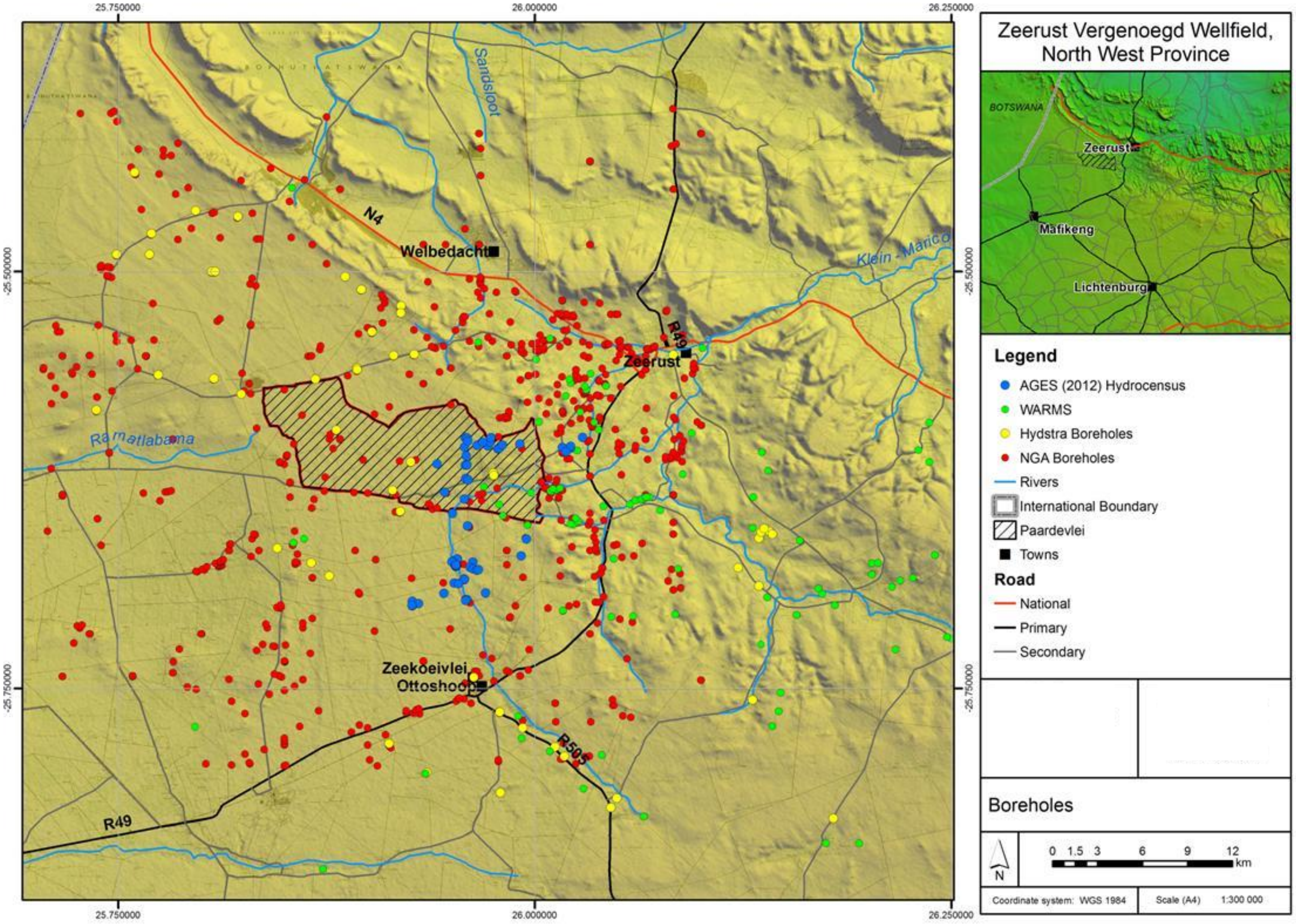


Figure 4-1: Boreholes obtained from existing database

4.2.6 Interpretation of Data

4.2.6.1 Spring-flow data

Spring-flow data were obtained from the Hydstra system from DWA for all the springs in the area. The data are incomplete. To assess the impact of the VWF on the aquifer and surrounding environment it is necessary to look at the springs occurring downstream of the abstraction borehole field.

4.2.6.1.1 Vergenoegd Eye (A3H011)

The Vergenoegd Eye(s) are located due east of the borehole field in the same compartment. The data however, was only recorded for the period between 1960 and 1992 (Figure 4-2) and therefore no monitoring took place around the time of the development of the borehole field.

Since June 1983 the readings were all zero except for February and March 1991. The last reading prior to the zero readings was 0.065 cumec which corresponds to the flow during the period between 1973 and 1975. Since the inception of the monitoring in 1960 up to 1967, the readings were even lower - mostly below 0.05, but never was a zero value registered. Therefore the zero readings post-1983 are suspect. It is doubtful if the spring ceased flowing completely. During the visit to the eyes and monitoring station in 2010, the eyes were flowing albeit at a reported reduced discharge rate. In 2012 it was again observed to be flowing.

The flow data from the monitoring station at Vergenoegd does not cover the period when the borehole field was commissioned and no conclusions could be drawn in terms of the alleged impact on the spring-flow. DWA was consulted for corrected data but none was available at the time of investigation.

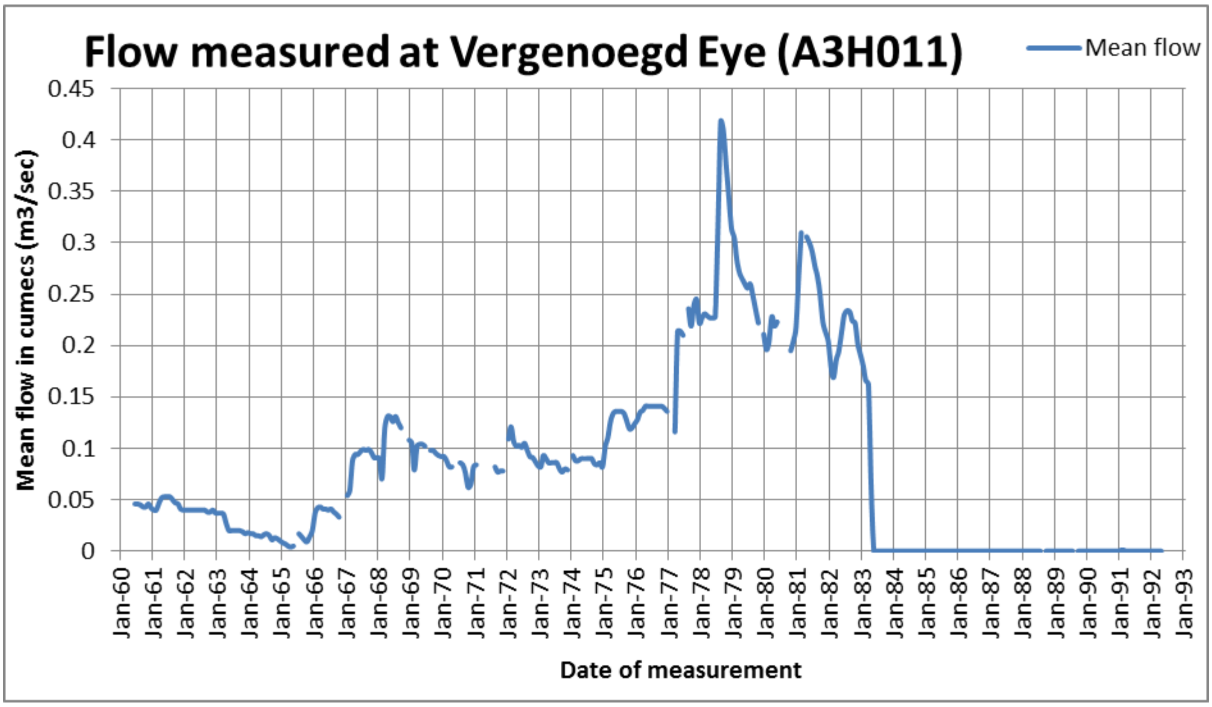


Figure 4-2: Flow data graph for Vergenoegd Spring

4.2.6.1.2 Paardenvallei Eyes (A3H021 and A3H022)

The data for the two Paardenvallei springs were combined on Figure 4-3. A correlation between the two springs can be observed – the Upper eye having a stronger flow than the Lower eye.

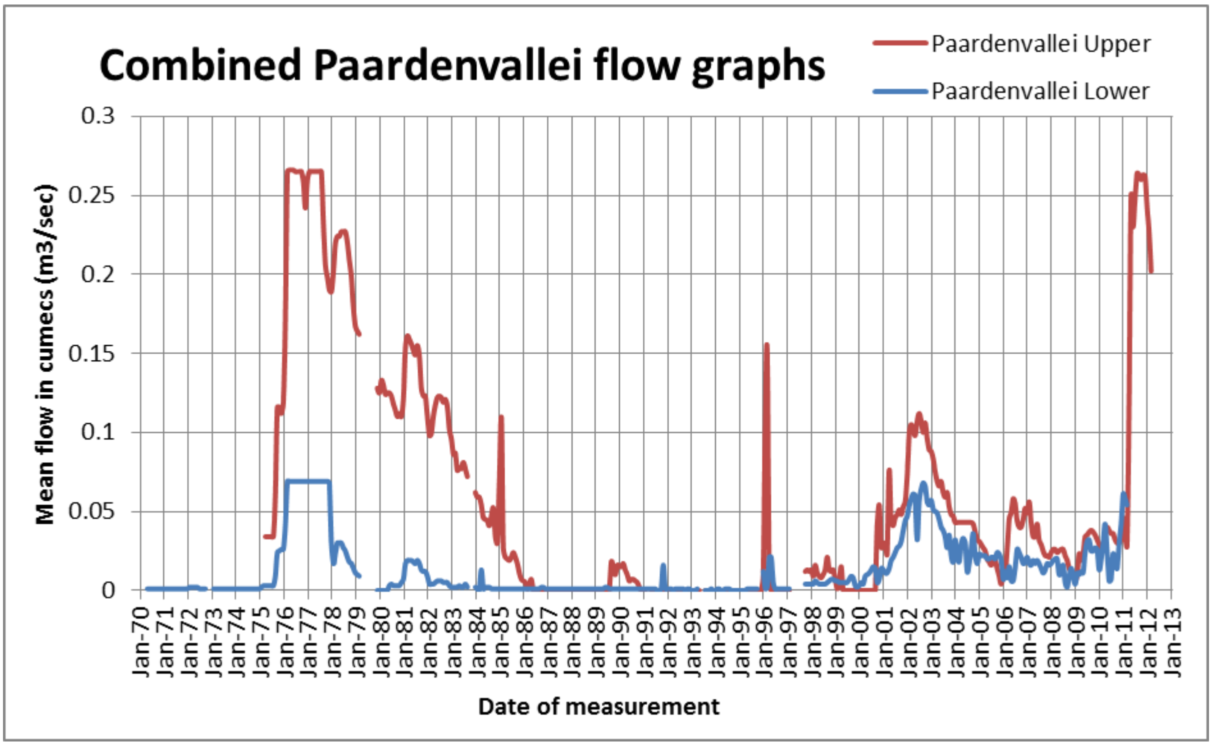


Figure 4-3: Combined flow data graph for the Paardenvallei springs

During the period between 1976 and 1978 both springs overflowed the monitoring weir, as can be seen by the flat topped graphs. Thereafter the flow gradually declined to almost nil in 1986 (the Upper eye ceased flowing). A period of low flow was experienced for almost a decade before good rains recharged the compartment again in 1996 and another flow peak was observed for a short time period. The low flow continued and only increased significantly after 2001 and 2002. A period of sustained flow with seasonal fluctuations was observed for about a decade before a significant spike in flow was observed after rains at the beginning of 2011. This high flow in the Upper eye especially was observed throughout 2011 and into 2012, but can be seen to be tapering off after the 2012 dry season. This recharge event happened after the production of the VWF has been in full production.

During the 2002 numerical modelling exercise, the reduction in spring-flow was simulated for the various affected springs. A spring-flow reduction of between 10 and 30 L/s was simulated for the Paardenvallei Spring and between 5.0 and 15 L/s for the Vergenoegd Spring. The prediction was that significant rainfall recharge events would recharge the aquifer to normal conditions again (Aquisim, 2002).

4.2.7 Monitoring boreholes

The monitoring boreholes listed in Table 2 are located inside the boundaries of the Paardevlei GMU (compartment) which should reflect the impact of the newly developed VWF.

Table 2: List of DWA monitoring boreholes in the Paardenvallei GMU

Station number	Site Name	Latitude	Longitude	Lat/Long Datum	Position Accuracy	Meters of Elevation	Active	Commence	Cease	Site Type
A3N0014	Doornfontein	-25.63111	25.91444	Cape Datum		1410	F	1976/04/23	2003/03/15	Groundwater
A3N0015	Doornfontein	-25.61417	25.92556	Cape Datum		1410	T	1977/01/21		Groundwater
A3N0016	Paardenvallei	-25.62083	25.97500	Cape Datum		1400	T	1977/01/21		Groundwater
A3N0017	Paardenvallei	-25.62233	25.97536	WGS84		1403	T	1977/01/21		Groundwater
D4N1468	Olyfenbult	-25.59500	25.88083	Cape Datum		1424	T	1997/07/15		Groundwater
D4N2514	Vergenoegd	-25.61603	25.95831	WGS84	1/250000	1415	T			Groundwater
D4N2515	Uitvalgrond	-25.59944	25.95817	WGS84	1/250000	1410	T			Groundwater
D4N2516	Uitvalgrond	-25.60242	25.96867	WGS84	1/250000	1405	T			Groundwater
D4N2518	Uitvalgrond	-25.60467	25.97164	World Geodetic	1/250000	1405	T			Groundwater

4.2.7.1 A3N0014

Monitoring borehole A3N0014 is located west of the borehole field on the farm Doornfontein. This is an inactive monitoring station since monitoring ceased in March of 2003 – the reason is unknown. The available data for the period between 1976 and 2003 was plotted on a graph and missing data indicated as such. From the graph (Figure 4-4) a dynamic water level of around 18 mbgl can be observed. The water table fluctuated both upwards and downwards from this level, but time and again returned to this level. A significant period of low water table was recorded between 1985 and 1988, reaching a low of eight metres below the dynamic water level.

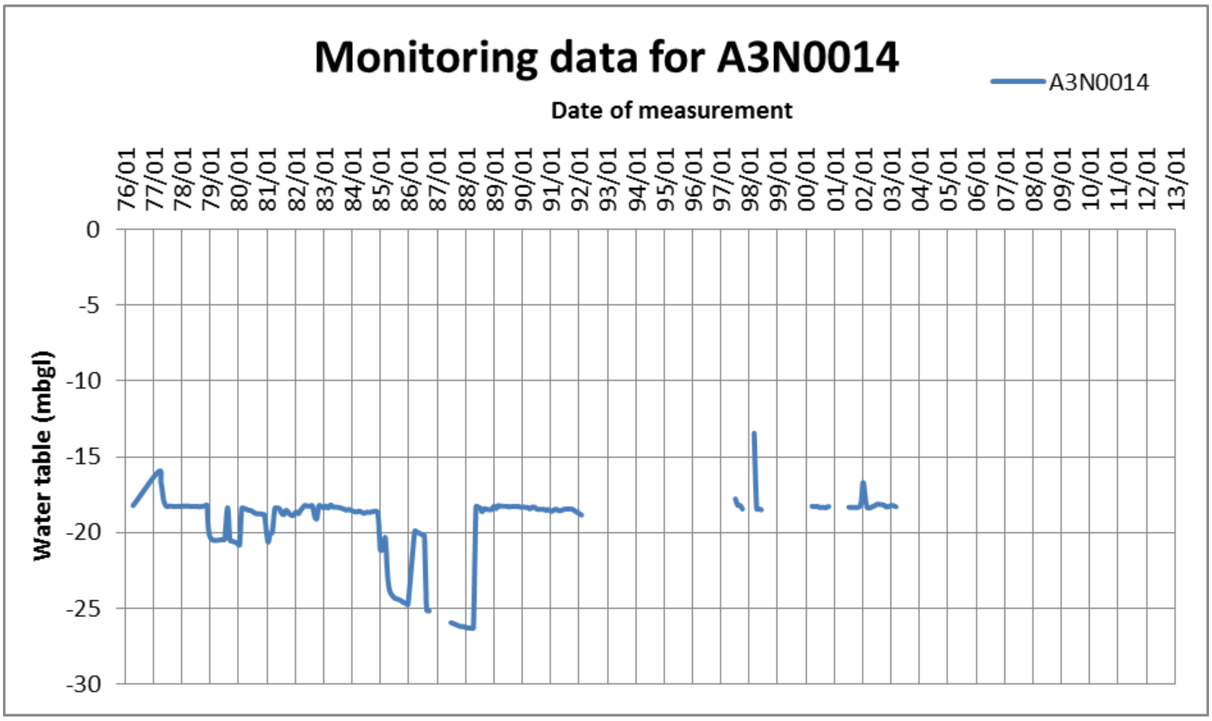


Figure 4-4: Groundwater level monitoring data for A3N0014

4.2.7.2 A3N0015

Monitoring borehole A3N0015 is located north of the Vergenoegd Dyke in the Klaarstroom South DCU. This borehole shows significantly pronounced fluctuations. Since 1977 the water table dropped from above 5 mbgl to below 20 mbgl, and never recovered again to that level (Figure 4-5). Periods of recovery after recharge events are noted, and these vary between a recovery of two to three metres up to eight metres (1997).

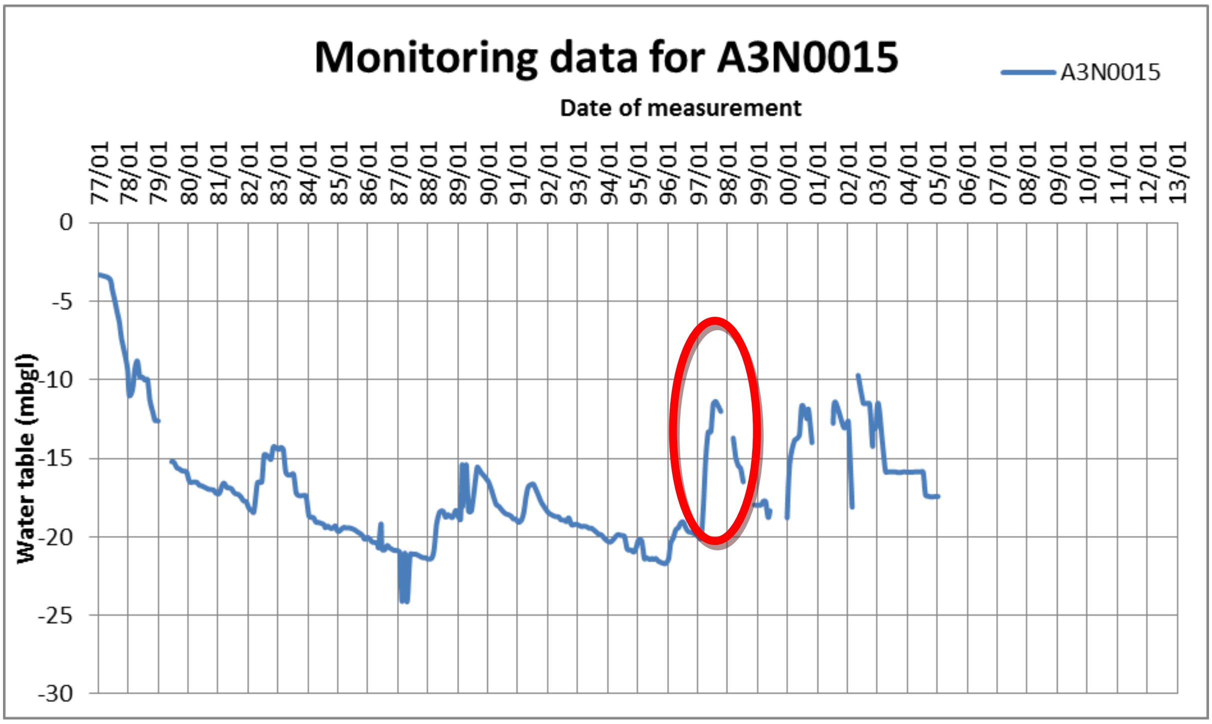


Figure 4-5: Groundwater level monitoring data for A3N0015

4.2.7.3 A3N0016 and A3N0017

Monitoring boreholes A3N0016 and A3N0017 are located north of the road leading to the VWF from Zeerust. The boreholes are some 170 m apart and show vastly different data sets (Figure 4-6 and Figure 4-7). A3N0016 has data since 1977 and 1999, and data patches exist up to 2005 when monitoring ceased. It was resumed again in 2011. The recharge event registered in A3N0015 during the end of 1997 is also evident in A3N0016 but not in A3N0017 which has a more stable water table. The monitoring data measured since 2011 in A3N0016 indicated that the water table recovered significantly from a previous level of 10 mbgl (2005) to 8 mbgl after the 2010/11 rainy season, but soon after the water table dropped significantly again (below 11 mbgl).

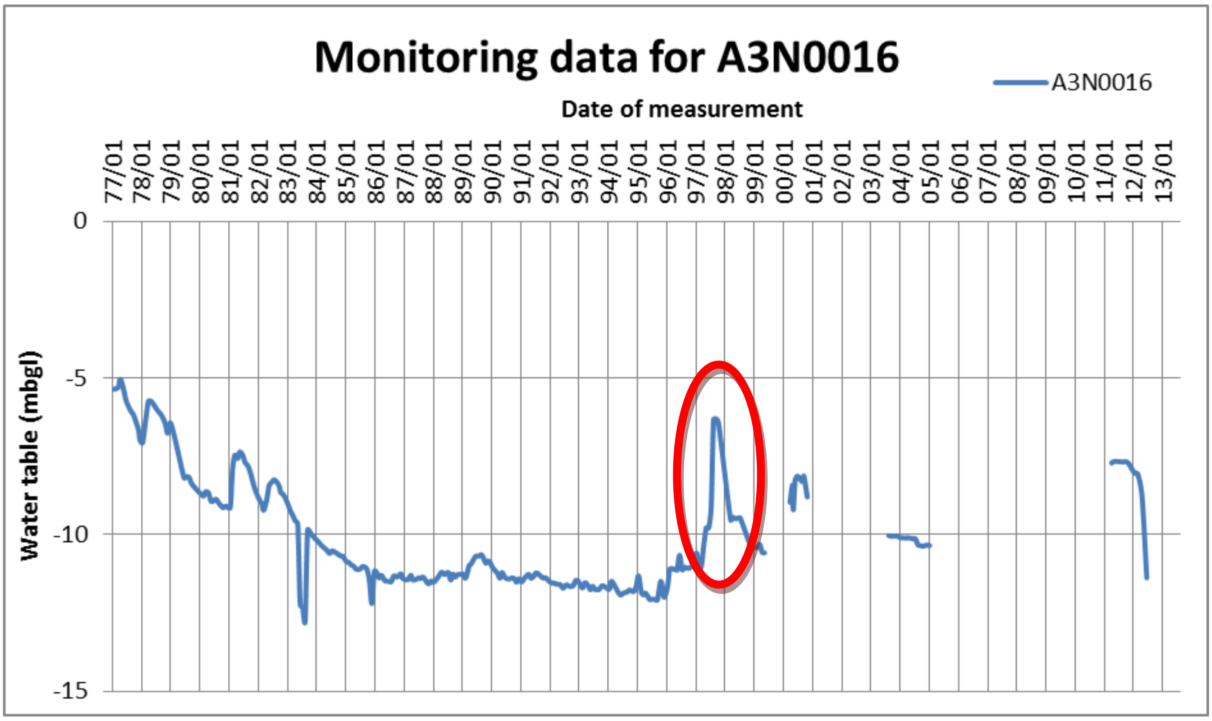


Figure 4-6: Groundwater level monitoring data for A3N0016

The water table in A3N0017 is steady around 20 mbgl. The last measurement was in 2005 prior to the VWF development. Since then bees were reported in the monitoring borehole making it impossible to measure the water level. The bees should be removed and the monitoring reinstated at this borehole.

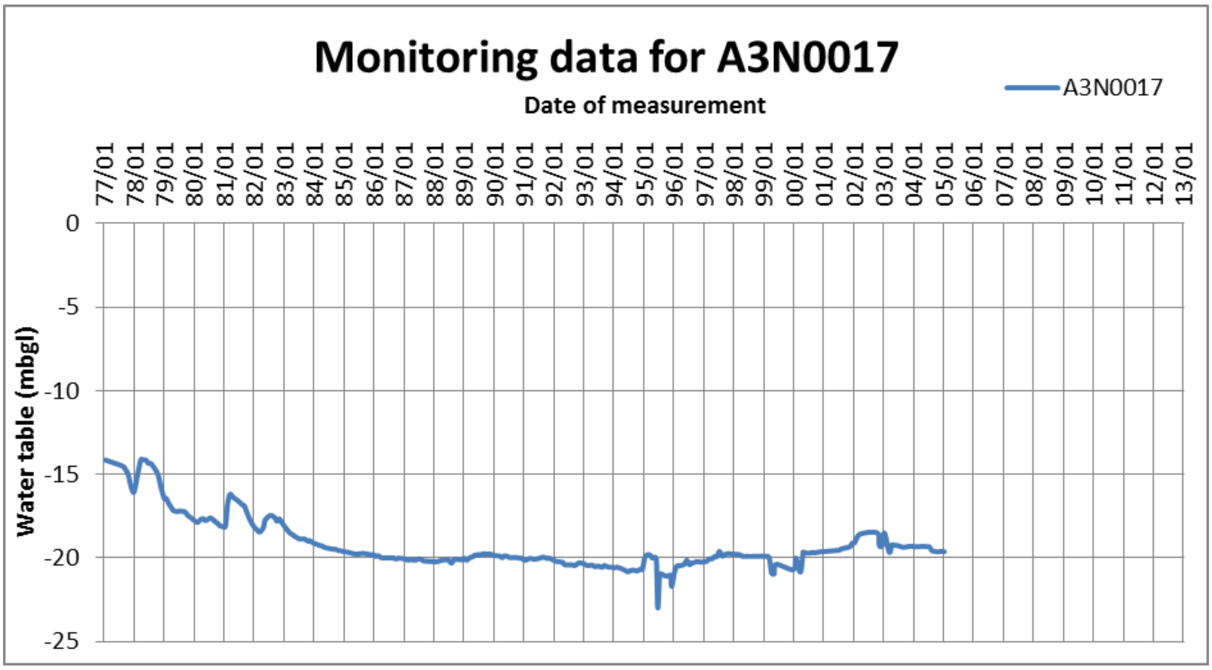


Figure 4-7: Groundwater level monitoring data for A3N0017

4.2.7.4 D4N1468

This borehole is located far northwest of the VWF, also in the Paardevlei GMU. The data for D4N1468 are sparse and interpretation is difficult (Figure 4-8). A data gap exists between 2005 and 2011. The level was at 18 mbgl when monitoring recommenced in 2011, and rose sharply by more than five metres at the end of 2011 after the summer season. It dropped again by some two metres during the following winter season (2012).

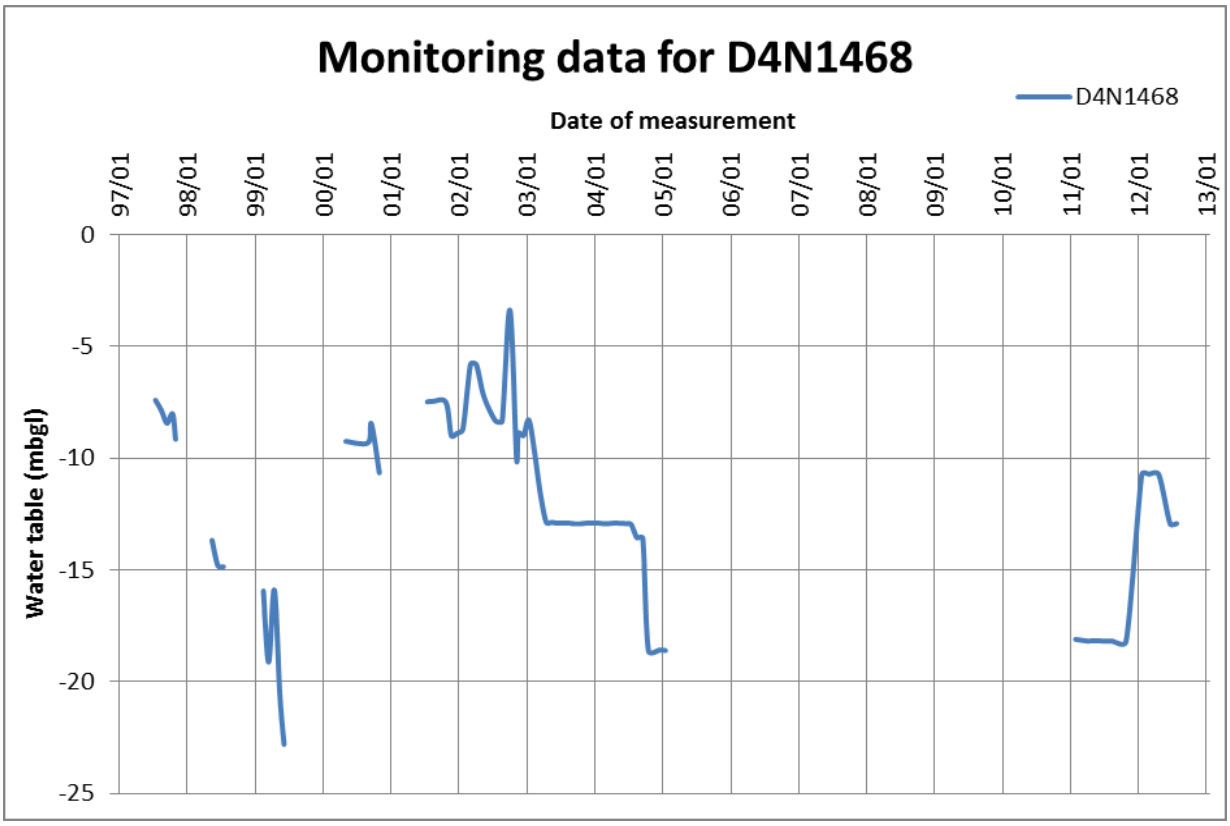


Figure 4-8: Groundwater monitoring data for D4N1468

4.2.7.5 D4N2514 (21-00061)

Boreholes D4N2514 to 2518 from the Hydstra database correspond to the monitoring boreholes drilled for the VWF named 21-00061 to 00065 respectively. The boreholes have Hydstra monitoring data available since June 2011 only (Figure 4-9). Borehole D4N2514 is located south of the Vergenoegd Dyke, in the eastern portion of the Paardevlei GMU. The water table varied between 32 and 33 mbgl for the year except for a reading of 39 mbgl in April 2012. If this is a legitimate reading, it represents a drawdown of six metres, which recovered to the dynamic level several months later. It is more likely that it is a typing error and should read 29.27mbgl since the rest of the boreholes in the vicinity all recorded a spike in the water level during the same period. This would represent a spike of almost three metres instead of a drop of six metres.

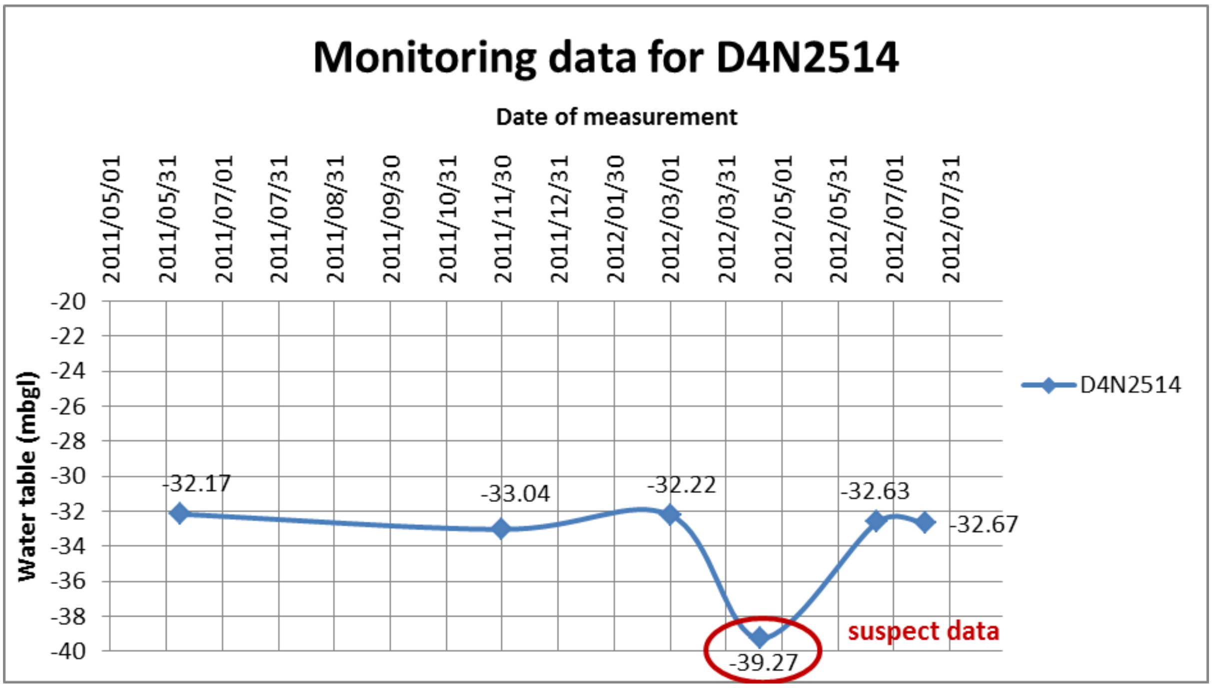


Figure 4-9: Groundwater level monitoring data for D4N2514

4.2.7.6 D4N2515 (21-00062)

Similarly the data are only available since May 2011. A steady decline from 22 mbgl to 25.6 mbgl is observed. This is a drop in water level of close to four metres within the span of a year. The spike in water level recorded in April 2012 is not as well defined in this borehole (Figure 4-10).

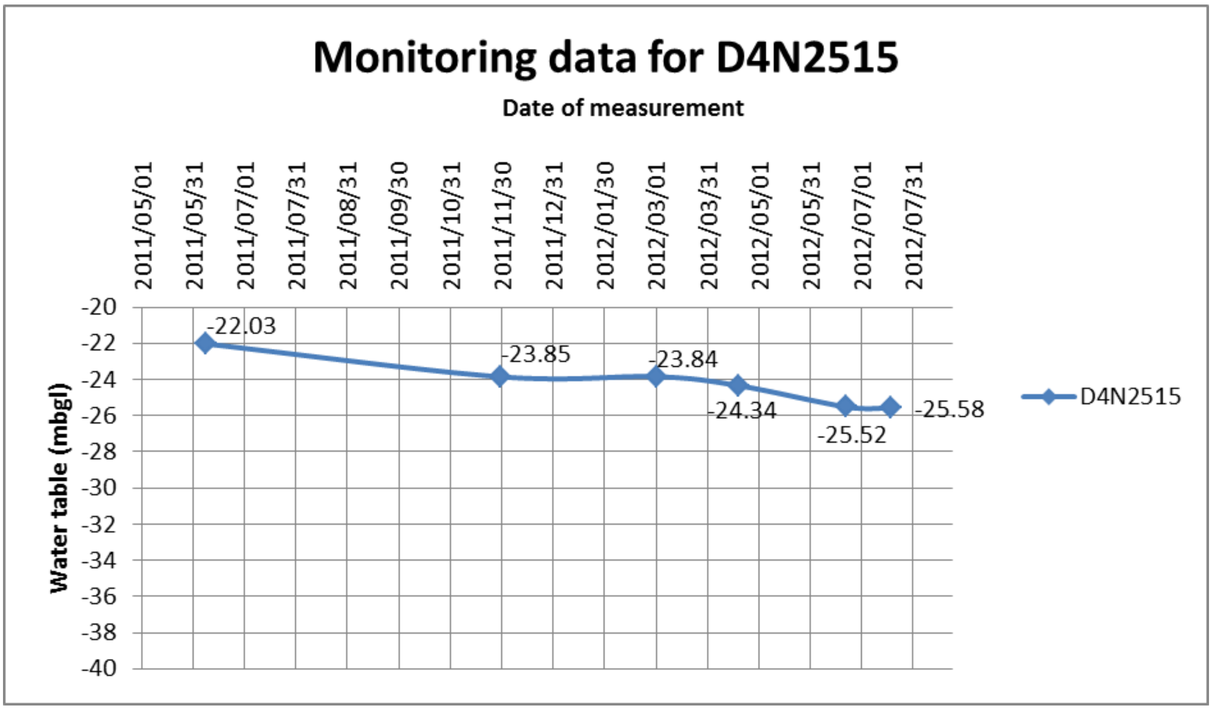


Figure 4-10: Monitoring data for D4N2515

4.2.7.7 D4N2516 (21-00063)

This borehole also shows a steady decline in the water level (almost two metres) apart from the small spike in April 2012 (Figure 4-11).

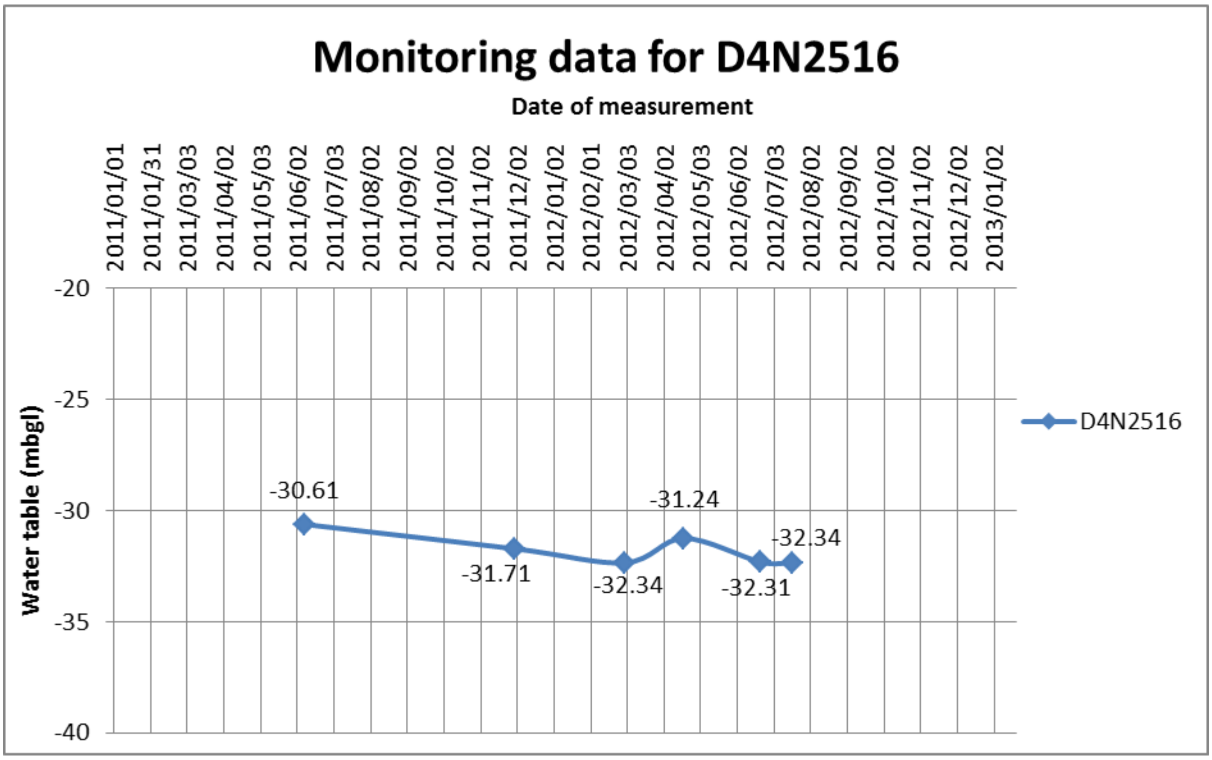


Figure 4-11: Groundwater monitoring data for D4N2516

4.2.7.8 D4N2517 (21-00064)

This borehole showed a drop in water level from 17.75 mbgl to 22.66 mbgl in nine months. This is a drop of almost five metres which is significant. It recovered in April 2012 together with the other VWF monitoring boreholes (Figure 4-12).

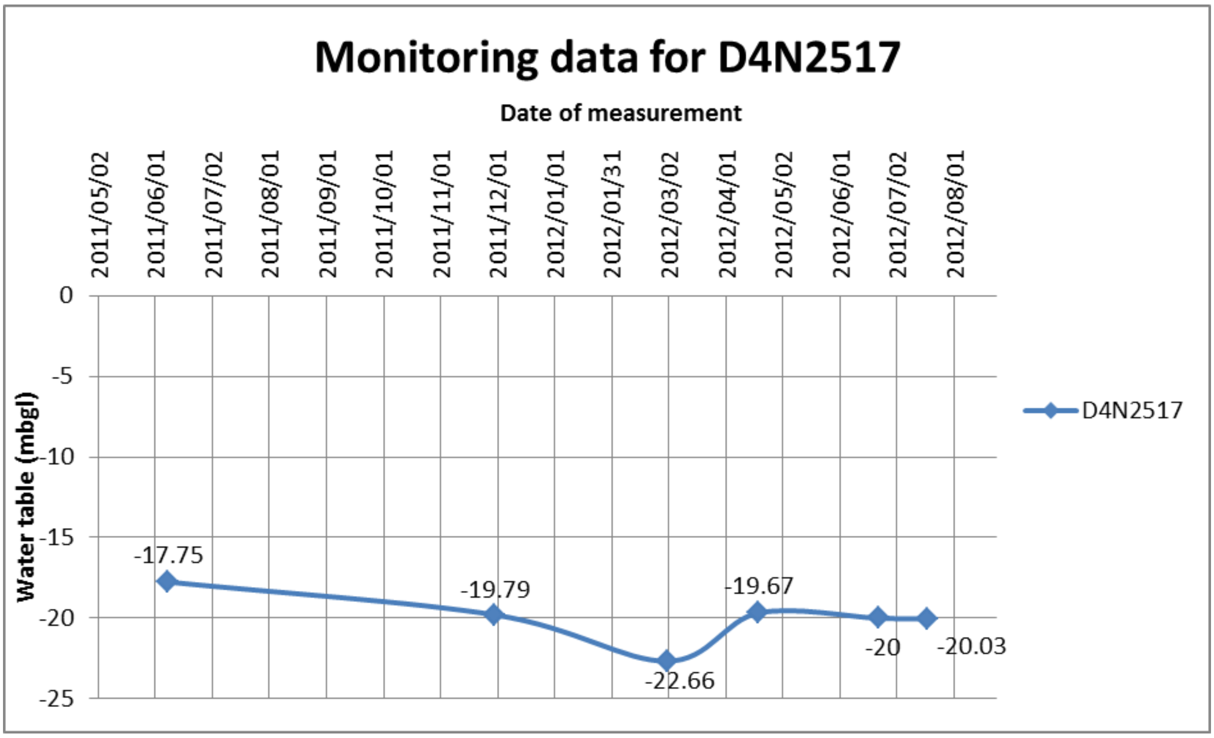


Figure 4-12: Groundwater monitoring data for D4N2517

4.2.7.9 D4N2518 (21-00065)

This borehole follows the same trend as the majority of the other boreholes (Figure 4-13).

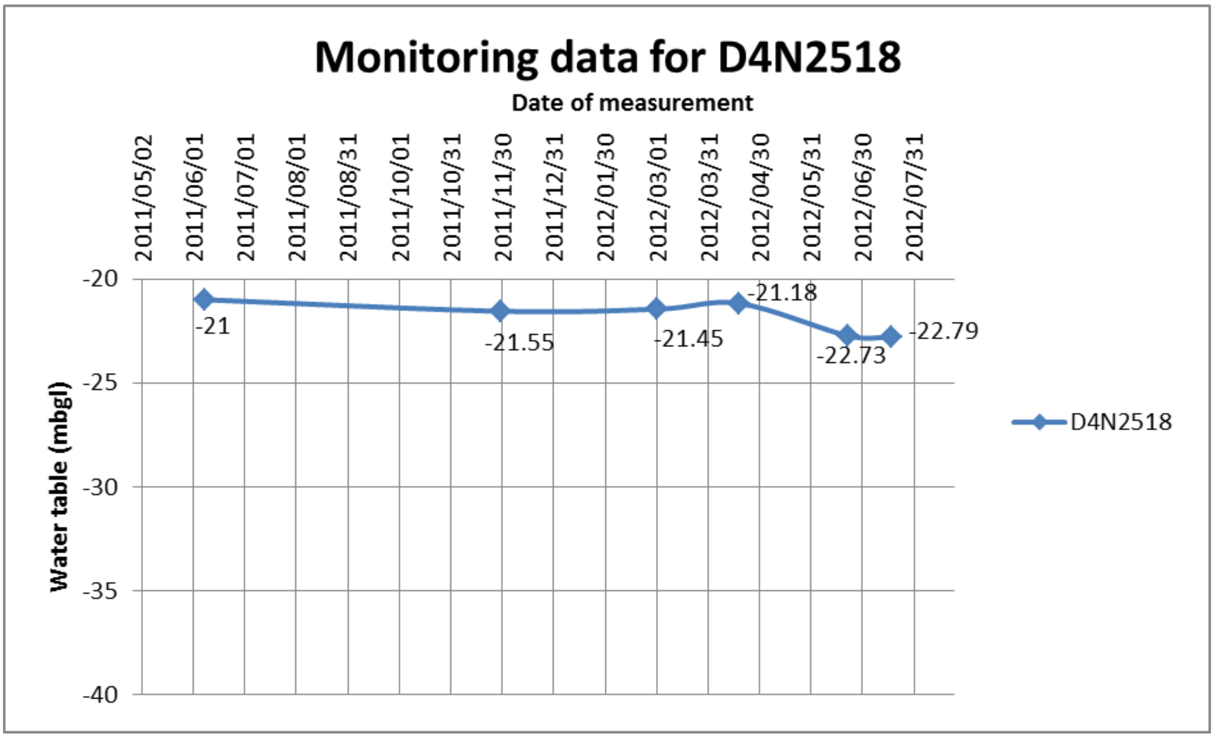


Figure 4-13: Groundwater level monitoring data for D4N2518

4.2.8 VWF and UWF combined monitoring data

When combining the VWF monitoring borehole data with historical data as obtained from other sources, Table 3 can be compiled. The table indicates the various data sources, as well as data points in time for each monitoring borehole. A comment column puts the time of observation in perspective relative to the abstraction borehole field operations. It can be seen that the first data available for the boreholes were measured right after the UWF failure – with recovery still evident in 21-00061 and 00062. A graph of the UWF recovery was constructed (Figure 4-14).

Table 3: Monitoring data from in and around the Uitvalgrond Well Field, values in mbgl

Date	21-00061	21-00062	21-00063	21-00064	21-00065	21-00072	Comment
2005/03/21	73.22	31.01	33.45	19.98			After Uitvalgrond dewatering
2005/03/23	71.47	27.42	33.45	19.98	24.41		After Uitvalgrond dewatering
2005/03/24	70.57	26.41	33.45	19.98	24.41		After Uitvalgrond dewatering
2005/03/29	66.49	24.77	33.45	19.98	24.41		After Uitvalgrond dewatering
2005/04/01	64.07	24.62	33.45	19.98	24.41		After Uitvalgrond dewatering
2005/04/13	54.84	24.6	33.45	19.98	24.41		After Uitvalgrond dewatering
2007/11/08						19	Before Vergenoegd abstraction
2010/10/21	32.76	23.84	33.4	19.45			During Vergenoegd abstraction
2010/11/08	32.41	24.02	33.41	19.62			During Vergenoegd abstraction
2010/11/23	32.41	24.16	33.42	19.75			During Vergenoegd abstraction
2010/12/14	32.44	24.3	33.45	19.82			During Vergenoegd abstraction
2011/01/28	32.44	24.18	33.4	19.67			During Vergenoegd abstraction
2011/06/08	32.17	22.03	30.61	17.75	21		During Vergenoegd abstraction
2012/03/01	32.22	23.84	32.34	22.66	21.45		During Vergenoegd abstraction
2012/09/06	33.31	25.44	33.61		24.07		During Vergenoegd abstraction
2012/11/14		25.43	32.68	20.9	23.5	18.4	During Vergenoegd abstraction

Data source	Khulani, 2008
Data source	Masilo and Associates, 2011
Data source	Botshelo monitoring data
Data source	Rassie Jacobs Waterdienste

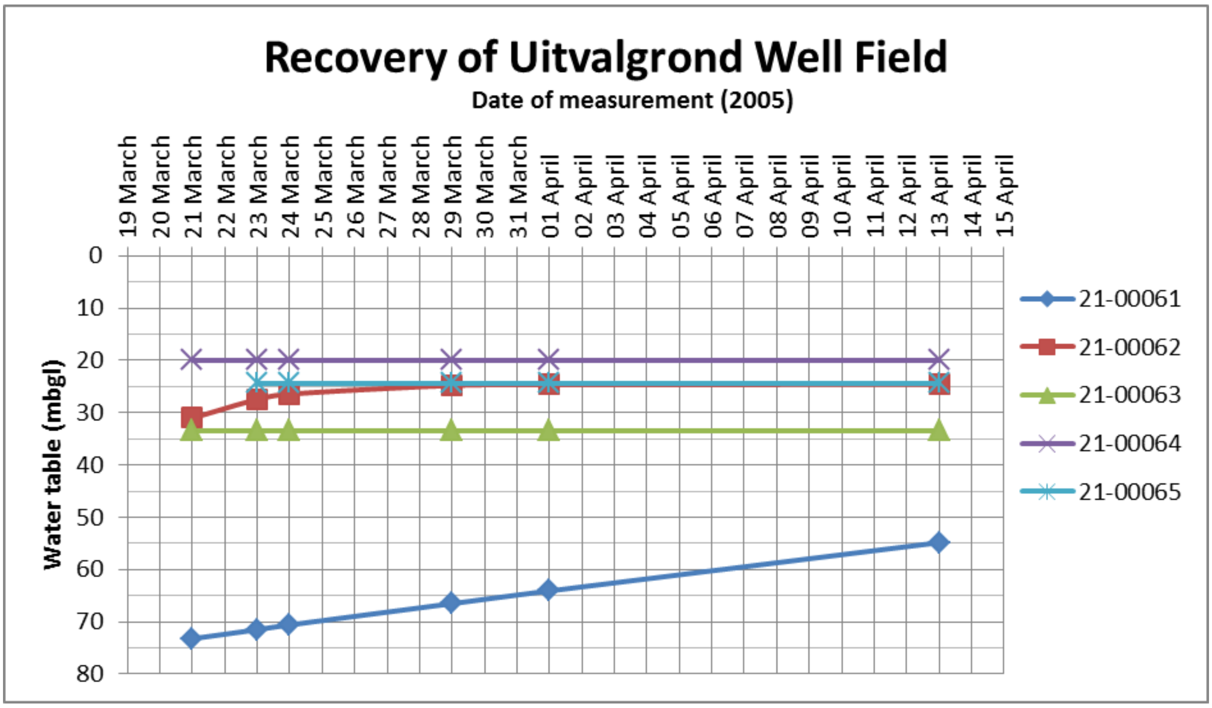


Figure 4-14: Recovery of the aquifer after the Uitvalgrond Well Field failure as measured in monitoring boreholes

When the entire period of data availability is plotted in Figure 4-15, with borehole locations been shown in Figure 4-16. Following the UWF recovery and the inception of the VWF, no impact of the VWF abstraction can be observed. The water levels in all of the monitoring boreholes except 21-00061 were on the same basic level at the last measurement as it was prior to the development of the VWF. Even 21-00061 recovered to a level around 32-33 mbgl from a dewatered state of sub-70 mbgl.

Most notably is the water level in 21-00072, which is located near the entrance to the abstraction borehole field and within 200 m from the first production borehole (21-00071). The level was recorded at 19 mbgl during the pumping tests performed prior to the borehole field development, and measured at 18.4 mbgl on the 14th of November 2012. Although it only has two data points, it is sufficient to conclude that no long term impact from the VWF could be observed over the period. It is however possible that the water table fluctuated on a short term basis in between the two dates of measurement, as was observed in the other monitoring boreholes.

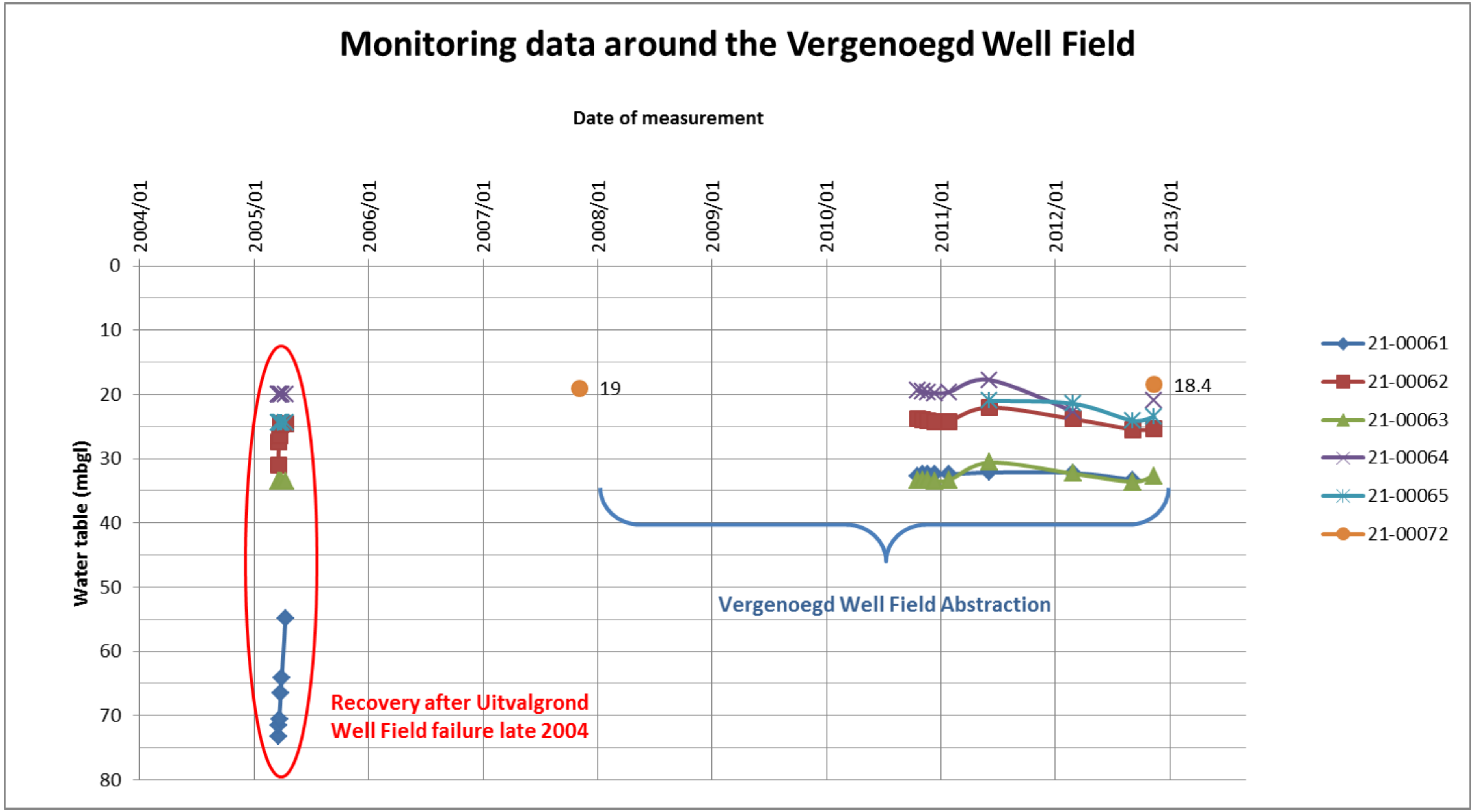


Figure 4-15: Monitoring data of boreholes in and around the Vergenoegd Well Field

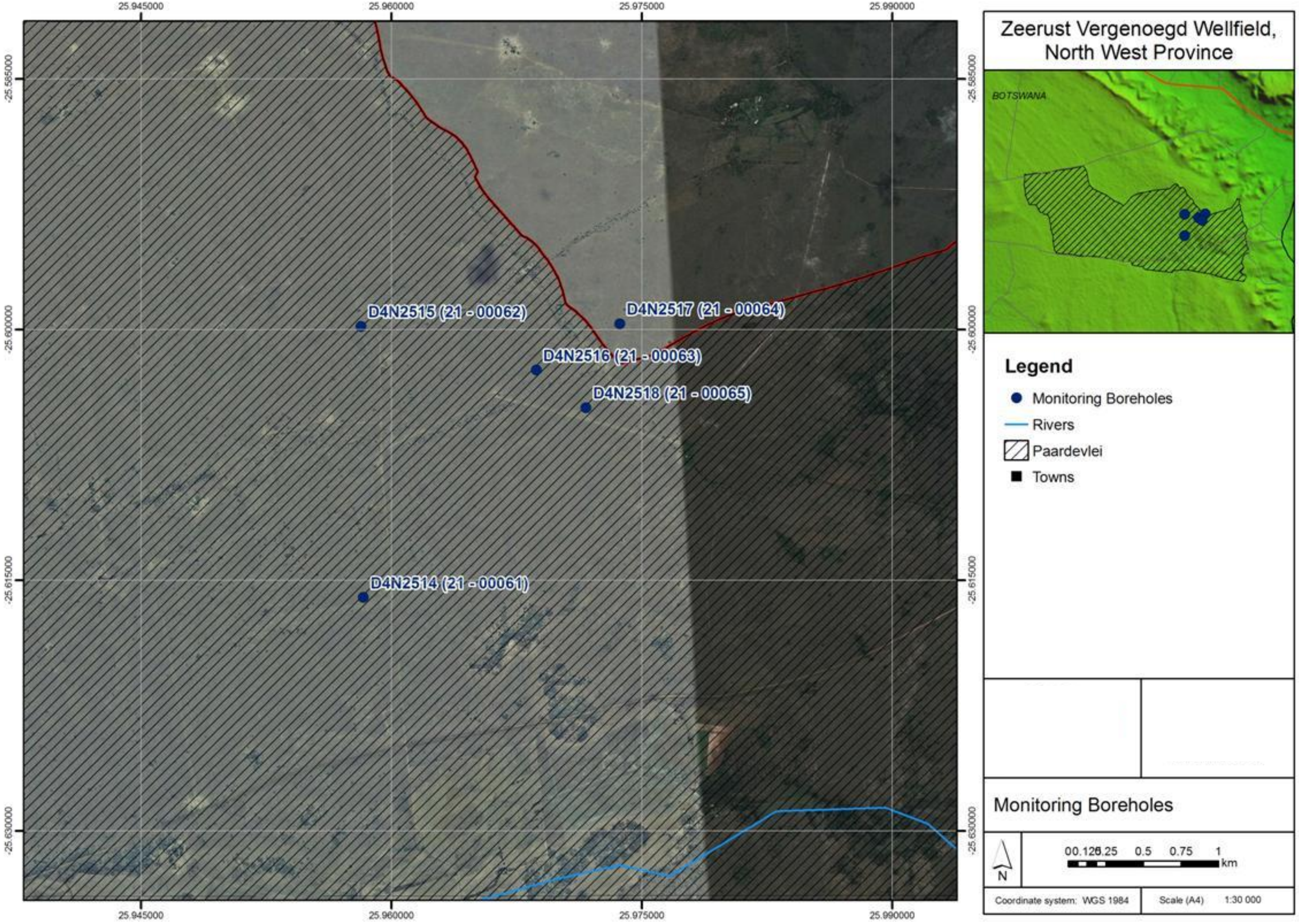


Figure 4-16: Monitoring borehole numbers around the Vergenoegd Well Field

4.3 Hydrocensus

4.3.1 Methodology

On the 20th of September 2012, a field visit hydrocensus was conducted in the area under investigation to obtain data of groundwater levels, abstraction (boreholes, pumping volumes/schedules, equipment etc.), surface water features like springs and wetlands, and other features that can be linked to groundwater abstraction like sinkholes and dolines. Water quality did not form part of this investigation. The Welbedacht pipeline was also visited (see Figure 2-4).

The methodology entailed gathering local knowledge from the land owners and neighbouring farmers, and visits to the various points of interest (POI) like boreholes and springs. Local knowledge included personal observations with regards to spring-flows, rainfall, abstraction, sinkhole formation. During the gathering of local knowledge the locals indicated the presence of a new plant species that sprouted in areas where sinkholes were forming or were predicted to form, but no reliable information or scientific substantiation could be made. All concerns were noted and those relevant to the this study are documented. Other data measured in the field were captured in a spread sheet for interpretation and reporting.

4.3.2 Findings

4.3.2.1 Vergenoegd Well Field

The production boreholes of the VWF were visited during this hydrocensus as well. Other than in 2010, all pump houses were locked and no access was gained to monitor the state of the equipment housed inside. The pump houses consist of corrugated iron shacks housed inside a razor wire fence.

Monitoring boreholes drilled as part of the abstraction borehole field development were identified during the literature study. These and other monitoring boreholes were plotted on the field map and also visited during the hydrocensus. All of the Vergenoegd monitoring boreholes were locked at the time of the visit and no water level measurements could be taken. Of the DWA monitoring boreholes, a water level could only be taken in one of the boreholes.

4.3.2.2 Rietpoort Well Field

The RWF was also visited. There are six abstraction boreholes as well as a large monitoring borehole with a monitoring station built around it. All of the abstraction pumps were running at the time of visit. The water from the abstraction boreholes is pumped into a large reservoir on site from where it is distributed through two pipelines; one serving Zeerust and the other Witkop Fluorspar Mine.

The individual abstraction boreholes were inspected and the following was observed (Table 4).

Table 4: Inspection of Rietpoort pumps

Pump	Abstracting	Total Reading (m^3)	Comment
1	Yes	9881345	Gauge broken, leaking water from outlet
2	Yes	-	Gauge covered by ant nest, non-operational. Leaking water from outlet
3	Yes	-	Gauge covered by ant nest, non-operational.
4	Yes	-	Pump cover missing, vegetation growing out of casing for some time
5	Yes	5697994	Gauge not working
6	Yes	0866704	Only working flow gauge of all pumps

Photo 4-1: Breached retention wall at Rietpoort Spring

4.3.2.3 Rietpoort Spring

The Rietpoort Spring and monitoring station were visited. There was no water flowing over the measuring weir, but it was reported by the land owner that water does flow over the weir during the summer months. There was a wall constructed to dam up the water to flow over the weir. This wall was however observed to be breached, bypassing the weir (Photo 4-1).

4.3.2.4 Vergenoegd Spring

The Vergenoegd Springs were visited. The land owner mentioned that four farmers irrigate using the water from these springs fed via a canal system. It is alleged that the yield of the spring diminished since the inception of the abstraction borehole field. Previously the irrigation farmers were able to irrigate 1000 ha, recently the volume only enabled the irrigation of 200 ha.

4.3.2.5 Kraalfontein Spring

The Kraalfontein Spring was observed to be flowing. This spring was pointed out to AGES during the 2010 hydrocensus as the Doornfontein Spring, whereas the Doornfontein Spring is located further to the west on the neighbouring farm Doornfontein. The Kraalfontein Spring is located on the farm Kafferskraal 60 JO and was referred to as the Kafferskraal Spring. Recently the name changed to Kraalfontein Spring.

4.3.2.6 Other boreholes

Several other private and monitoring boreholes were surveyed in the vicinity. Where possible the abstraction volumes and water levels were recorded. All data are included in the summary table (Table 5) and plotted on Figure 4-17.

Table 5: Hydrocensus results

Map No.	Site Name	GPS Waypoint #	Site Type	Engine	Purpose	Water Level	GPS Position		Field Comments
							Latitude	Longitude	
1	PBH-08	46	Borehole	Windmill	Abstraction	17.62m	S25.65253	E25.95960	
2	PBH-07	47	Borehole	None	None	20.12	S25.67229	E25.95342	
3	Rietpoort Pumps	48	Borehole	Electric	Abstraction	6.47m (monitoring)	S25.67596	E25.95239	6 Boreholes that are pumping. One monitoring hole. Pipes from reservoir split into two, the left goes to Zeerust and the right goes to a mine.
4	PBH-06	50	Borehole	Windmill	Abstraction	Not Accessible	S25.67425	E25.96266	Feeds cattle trough.
5	Trough	51	Trough	N/A	Water Provision	N/A	S25.67733	E25.96108	Cattle trough with ball valve. Taps from mine pipeline.
6	Pipe Fix	52	Pipeline	N/A	Water Provision	N/A	S25.67827	E25.96286	Place where pipeline has been fixed. Hole left open.
7	Pipe Leak	53	Pipeline	N/A	Water Provision	N/A	S25.67909	E25.96499	Place where pipeline used to leak. Fixed in 2011.
8	Sinkhole-3	54	Sinkhole	N/A	None	N/A	S25.67878	E25.96603	Sinkhole. Dead cow therein.
9	MON-01	55	Borehole	N/A	Monitoring	Not Accessible	S25.68459	E25.95761	Also rainwater guage that's non-operational.
10	PBH-05	56	Borehole	Windmill	Abstraction	Not Accessible	S25.69285	E25.97034	Farmer calles windmill "Swartpomp"
11	PBH-04	57	Borehole	Windmill	Abstraction	3.38m	S25.69673	E25.95919	
12	DBH-03	58	Borehole	Windmill	None	None/Bees Nest	S25.69724	E25.95841	Dried up/abandoned windmill. Dried up 16 years ago.
13	PBH-03	59	Borehole	Windmill	Abstraction	5.09	S25.68686	E25.95155	Windmill without pump. Has not been pumping since mid 2011.
14	PBH-02	60	Borehole	Windmill	Abstraction	9.40m	S25.69306	E25.94540	Feeds cattle trough.
15	PBH-01	61	Borehole	Windmill	Abstraction	18.05	S25.69786	E25.92637	Feeds cattle trough.
16	Rift	62	Rift	N/A	N/A	N/A	S25.69916	E25.93002	Farmer states that this N/S running rift splits water into shallow WL in in East and Deep WL in West.
17	DBH-1	63	Borehole	None	None	12.93m	S25.70049	E25.92630	Dried up/abandoned windmill.
18	DBH-2	64	Borehole	None	None	None/Bees Nest	S25.70023	E25.92608	Dried up/abandoned borehole.
19	Diamond Trap	65	Furrow	N/A	Diamond Trap	N/A	S25.68717	E25.95416	Old Furrow that was aparrently used to trap Diamonds. Presumably used diverted water.
20	RPS	66	Spring	N/A	Water Provision	N/A	S25.67380	E25.95050	Water runs through grids toward Zeerust. V-Notch is installed. Water is not flowing over V-noth at present but Farmer states that it does in summer.
21	Dam Wall	67	Dam Wall	N/A	Dam Wall	N/A	S25.67403	E25.95011	Dam wall has been damaged and eroded away. Water now bypasses infrastructure placed to measure water
22	PBH-11	68	Borehole	Diesel	Abstraction	Not Accessible	S25.63244	E25.94589	Operates 24/7. Feeds Cattle.
23	PBH13	71	Borehole	Diesel	Abstraction	Not Accessible	S25.61540	E25.94125	Operates twice a week for 24hrs.
24	Sinkhole-4	72	Sinkholes	N/A	N/A	N/A	S25.60427	E25.96519	
25	MON-2	73	Borehole	None	Monitoring	32.59m	S25.60469	E25.97163	
26	DBH-06	74	Borehole	None	None	None/Full of debris	S25.60174	E25.97342	Dried up/abandoned borehole.
27	PBH-16	75	Borehole	Windmill	None	Not Accessible	S25.60167	E25.97332	Non-operational windmill
28	Sinkhole-6	76	Sinkholes	N/A	N/A	N/A	S25.60637	E25.97775	
29	Sinkholes	77	Sinkholes	N/A	N/A	N/A	S25.60606	E25.97857	Sinkholes have been filled up.
30	Sinkhole-5	78	Sinkholes	N/A	N/A	N/A	S25.60406	E25.98040	

Map No.	Site Name	GPS Waypoint #	Site Type	Engine	Purpose	Water Level	GPS Position		Field Comments
							Latitude	Longitude	
31	VGS-1	79	Spring	N/A	Water Provision	N/A	S25.60343	E25.99097	Uitvlugfontein Spring. Farmer states that flow is much slower at present than in the past. 4 Farmers irrigate with this water. Farmer states that the farmers could once irrigate 1000ha but can now only irrigate 200ha
32	PBH-15	80	Borehole	Unknown	Abstraction	Not Accessible	S25.60600	E26.02142	Feeds two houses, cattle and sheep
33	Pivot Pipe	81	Pipeline	N/A	Irrigation	N/A	S25.60472	E26.02142	Pipeline for old 18ha irrigation field 'spulpunt'. Water obtained from irrigation dams that accumulate water from the Uitvlugfontein Spring
34	Furrow	82	Furrow	N/A	Irrigation	N/A	S25.60553	E26.01643	Water furrow running parallel to road
35	DBH-04	83	Borehole	None	Abstraction	Not Accessible	S25.59941	E26.02857	Borehole not in use. Abandoned.
36	PBH-10	84	Spring	N/A	Water Provision	N/A	S25.64503	E25.95041	Spring has waterworks infrastructure. Cannot determine what equipment is present as kiosks are locked.
37	DBH-05	85	Borehole	None	None	18.87m	S25.60234	E25.97306	Non-functional borehole.
38	PBH-09	86	Borehole	Windmill	Abstraction	Not Accessible	S25.65253	E25.95960	
39	PBH-12	87	Borehole	Electric	Abstraction	Not Accessible	S25.6365	E25.9576	
40	PBH-14	88	Borehole	Electric	Abstraction	Not Accessible	S25.6081	E26.0187	
41	Sinkhole-2	89	Sinkhole	N/A	N/A	N/A	S25.660513	E25.994854	Sinkhole next to reservoir. Farmer states that it fell during 2008 when there was a lot of rain. Right next to a
42	Sinkhole-1	90	Sinkhole	N/A	N/A	N/A	S25.670552	E25.991771	Deep sinkhole. Estimated at 15m+. Dead chickens thrown therein. Eskom truck almost fell through while
43	MON-03	91	Borehole	None	Monitoring	Not Accessible	S25.624182	E25.958377	
44	MON-04	92	Borehole	None	Monitoring	Not Accessible	S25.616152	E25.958199	
45	MON-05	93	Borehole	None	Monitoring	Not Accessible	S25.599836	E25.958180	
46	MON-06	94	Borehole	None	Monitoring	Not Accessible	S25.602433	E25.968609	
47	MON-07	95	Borehole	None	Monitoring	Not Accessible	S25.599613	E25.973639	
48	WBD-01	96	Borehole	Electric	Supply	Not Accessible	S25.625079	E25.959835	
49	WBD-02	97	Borehole	Electric	Supply	Not Accessible	S25.616053	E25.959293	
50	WBD-03	98	Borehole	Electric	Supply	Not Accessible	S25.610632	E25.958722	
51	WBD-04	99	Borehole	Electric	Supply	Not Accessible	S25.605237	E25.957714	
52	WBD-05	100	Borehole	Electric	Supply	Not Accessible	S25.599750	E25.959150	
53	WBD-06	101	Borehole	Electric	Supply	Not Accessible	S25.601631	E25.959657	
54	RPP-01	102	Borehole	Electric	Supply	Not Accessible	S25.676205	E25.952299	Meter: 9881345, standing still althouh pump is pumping
55	RPP-02	103	Borehole	Electric	Supply	Not Accessible	S25.676480	E25.952153	Broken, hasn't been opened in months.
56	RPP-03	104	Borehole	Electric	Supply	Not Accessible	S25.676867	E25.952310	Broken, hasn't been opened in months.
57	RPP-04	105	Borehole	Electric	Supply	Not Accessible	S25.676718	E25.952946	Overgrown and unreadable.
58	RPP-05	106	Borehole	Electric	Supply	Not Accessible	S25.676287	E25.952754	Meter:5697994 and standing still although pump is pumping.
59	RPP-06	107	Borehole	Electric	Supply	Not Accessible	S25.675996	E25.952593	Meter: 0866704. Working.

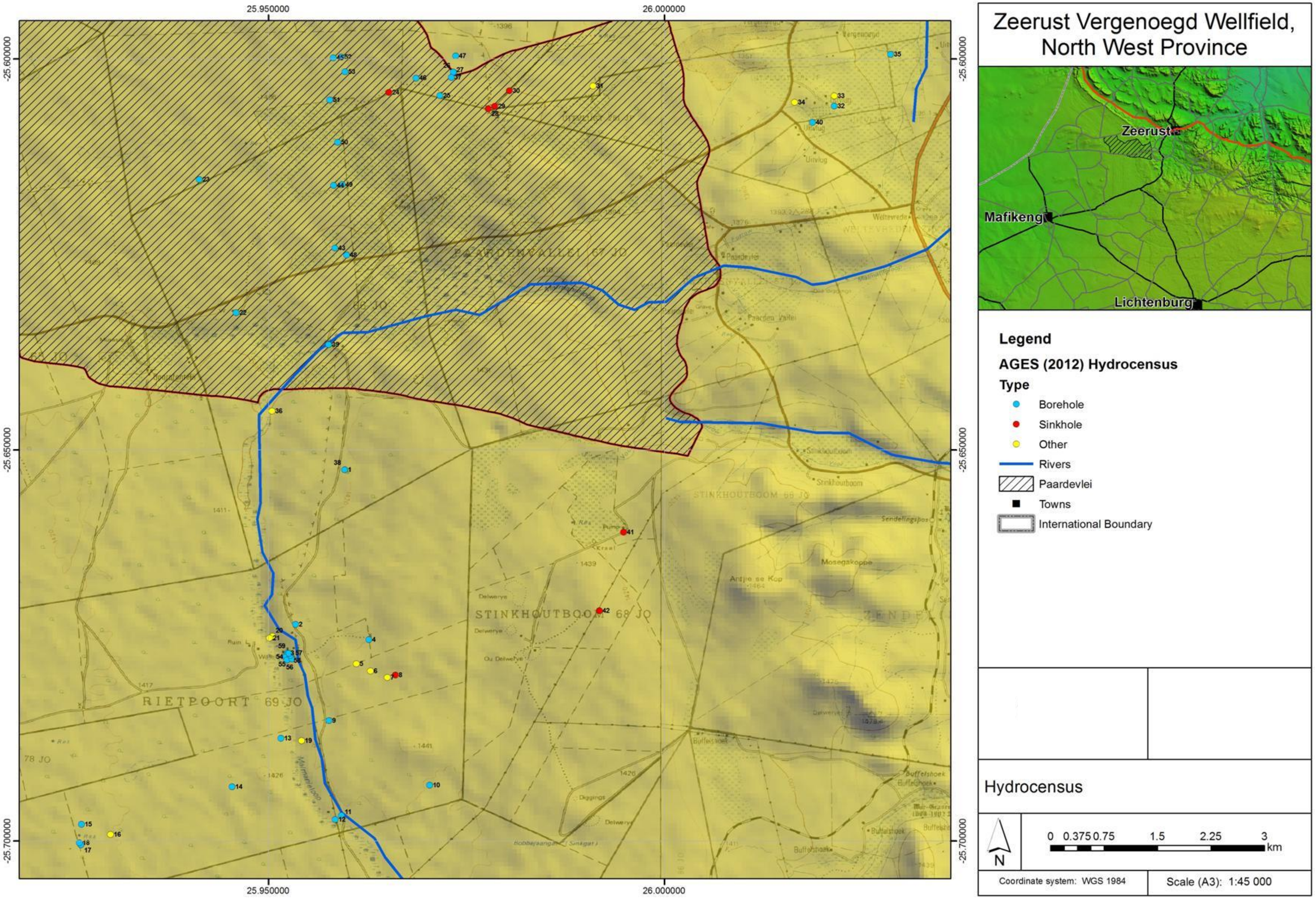


Figure 4-17: Hydrocensus results focussing on borehole survey

4.3.2.7 Sinkholes

Several sinkholes were pointed out by various land owners in and around the study area (Figure 4-18). The most notable are the sinkholes that fell recently along the extended Welbedacht pipeline from the VWF. These sinkholes were first reported in 2011 and made newspaper headlines.

The owners of the farm alleged that the sinkholes formed as a direct result of the new bulk abstraction from the VWF (see Photo 4-2). However, these sinkholes are located on the eastern side of a dyke, and along the route of the main supply pipeline that has been laid underground. The land owners also indicated that the sinkholes were filled (presumably by Botshelo Water) shortly after forming, without informing them thereof.

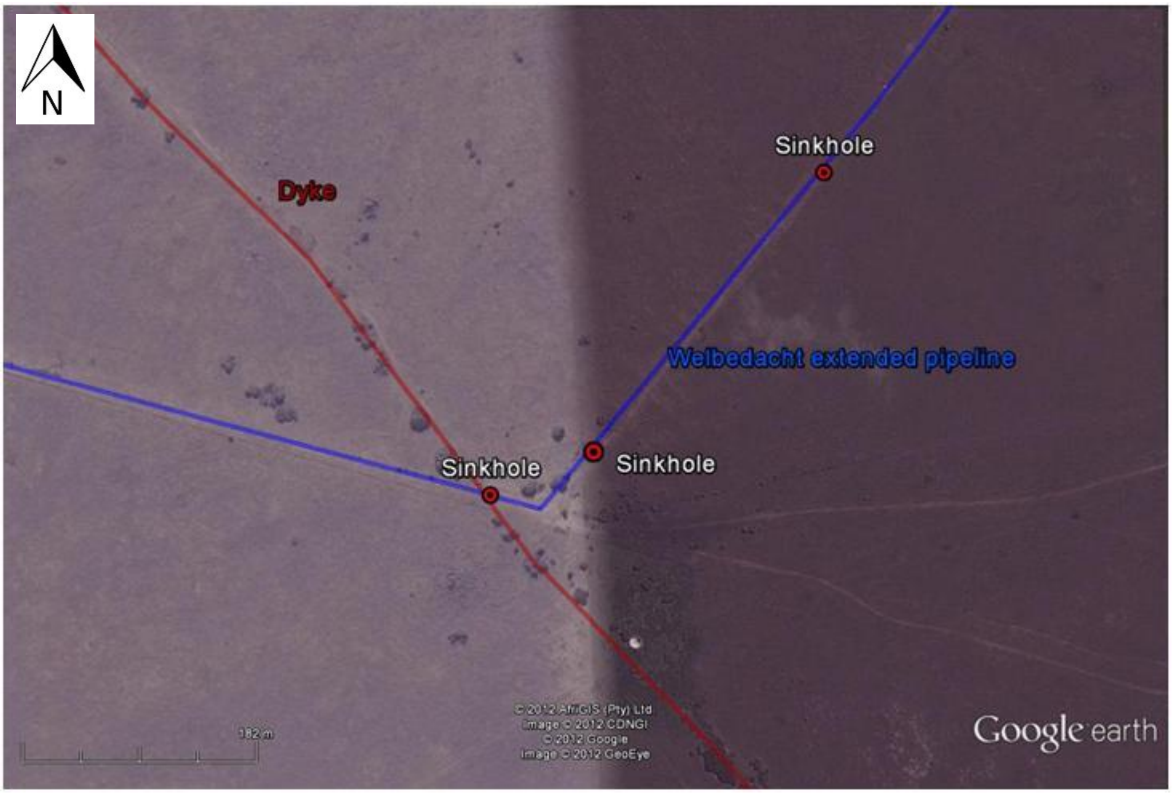


Figure 4-18: Google Earth graphic indicating sinkholes relative to pipeline

Photo 4-2: Land owner pointing out a sinkhole that formed on the extended pipeline

In the Completion Report conducted on the handover of the VWF (Phumelela, 2008) nothing is mentioned on the construction methods or guidelines for the laying of the pipeline, but photo's indicate blasting of the dolomite was involved. This fractured the hard rock dolomite, and most probably created new pathways for water to infiltrate into the subsurface. In the event of a constant supply of water, like a leaking water pipeline, this source of water can create subsurface erosion of weathered material into the dolomite cavities to eventually reach the surface as sinkholes. This might explain why the sinkholes are all aligned along the buried pipeline route.

Other sinkholes were identified during the hydrocensus:

- On the farm Rietpoort, some 1600 m southeast of the RWF. This sinkhole measured some two metres by two metres.
- Two other sinkholes were identified on the farm Stinkhoutboom, 1100m and 2200m south of the Stinkhoutboom Spring respectively.
- Sinkhole 1 on Stinkhoutboom was found to be of significant size. An Eskom truck reportedly almost fell into the sinkhole (the sinkhole is located near a power line). Currently the sinkhole is being used as a dump site for dead chickens. This creates a point source of bacterial and other contaminants that pollute the dolomite aquifer.
- Sinkhole 2 fell next to a borehole in 2008 after heavy rains. The borehole was drilled north of a dyke where fractured ground is expected. This sinkhole was presumably formed by a combination of the constant water table fluctuation due the pumping of the borehole (and boundary conditions created by the dyke causing the water table to fluctuate more around the borehole), and ingress of rainwater. The borehole itself is a preferred pathway for ingress of surface water as water infiltrates on the outside of the casing into the borehole.

4.3.2.8 Miscellaneous

The land owners reported that occasionally a strange rumbling sound can be heard in the area. This sound reminds one of an earthquake, although no seismic activity can be felt. This sound was apparently also heard by neighbouring farmers. The Council for Geosciences does not have any record of seismic activity for that period.

4.4 Conceptual Site Model (CSM)

4.4.1 Preamble

A conceptual model is crucial to the effectivity and accuracy of a model. The conceptual model includes designing and constructing equivalent but simplified conditions for the real world problem (Beal and Read, 2013). It's based on a number of assumptions that need to be verified in a later stage of the study. The processes and interactions taking place within the study area that will influence the movement of groundwater need to be quantified as well as simplifying all assumptions for the development of a model and the selection of a suitable numerical code.

4.4.2 Study area and groundwater levels

The study area for the conceptual model encompasses the Paardevlei and Klaarstroom dolomitic compartments. These compartments include the VWF and UWF as shown in Figure 4-19.

Even though the RWF is discussed in previous sections it does not form part of the CSM. Also the focus is on the Paardevlei Compartment but as discussed in the previous sections; abstraction in this compartment is expected to impact the water levels in the Klaarstroom compartment. The boundaries of the of the study area are therefore taken as the dolomitic compartments.

A conceptual cross-section through the study area is shown in Figure 4-20. The associated conceptual groundwater levels are shown in Figure 4-21.

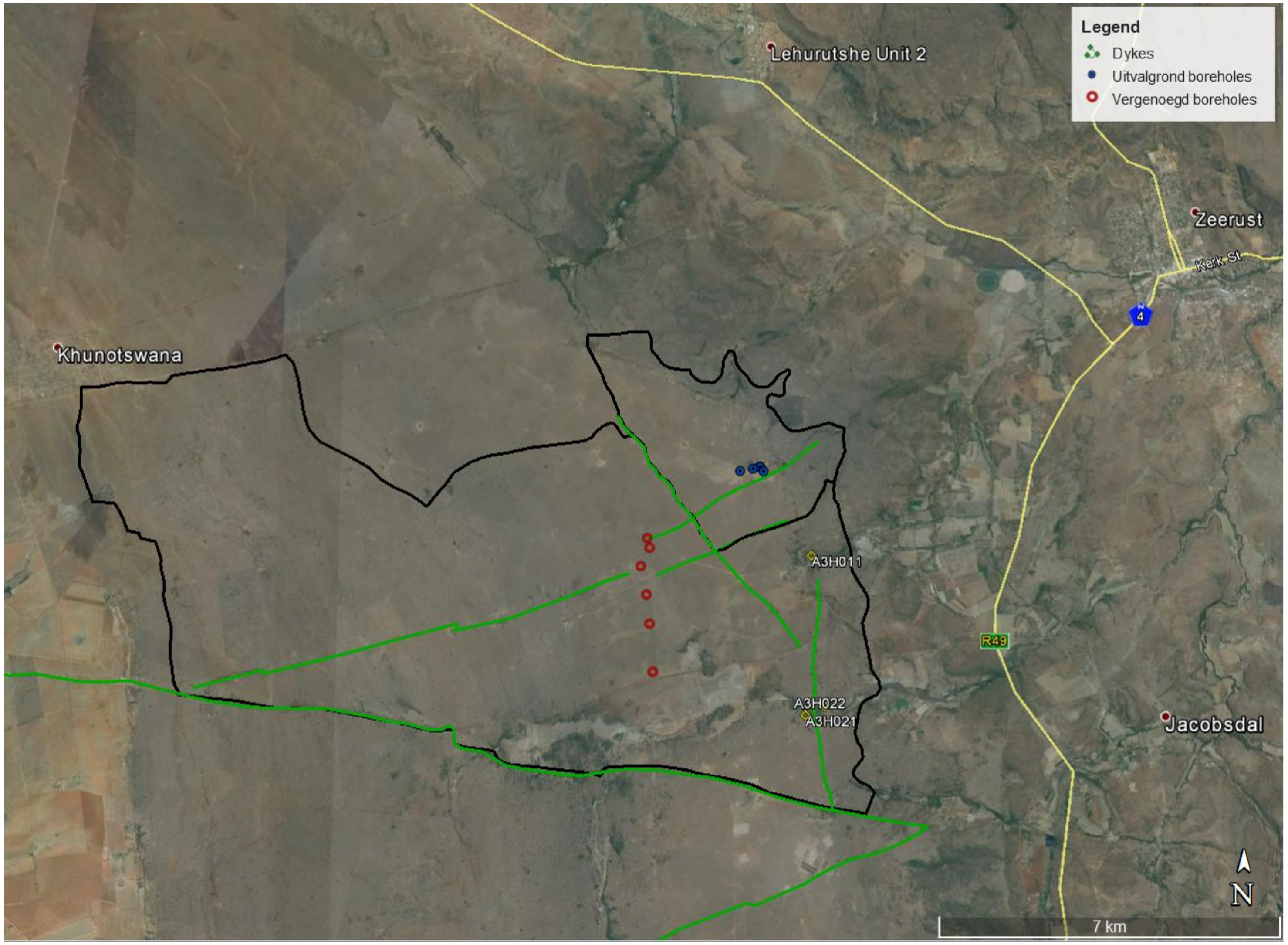
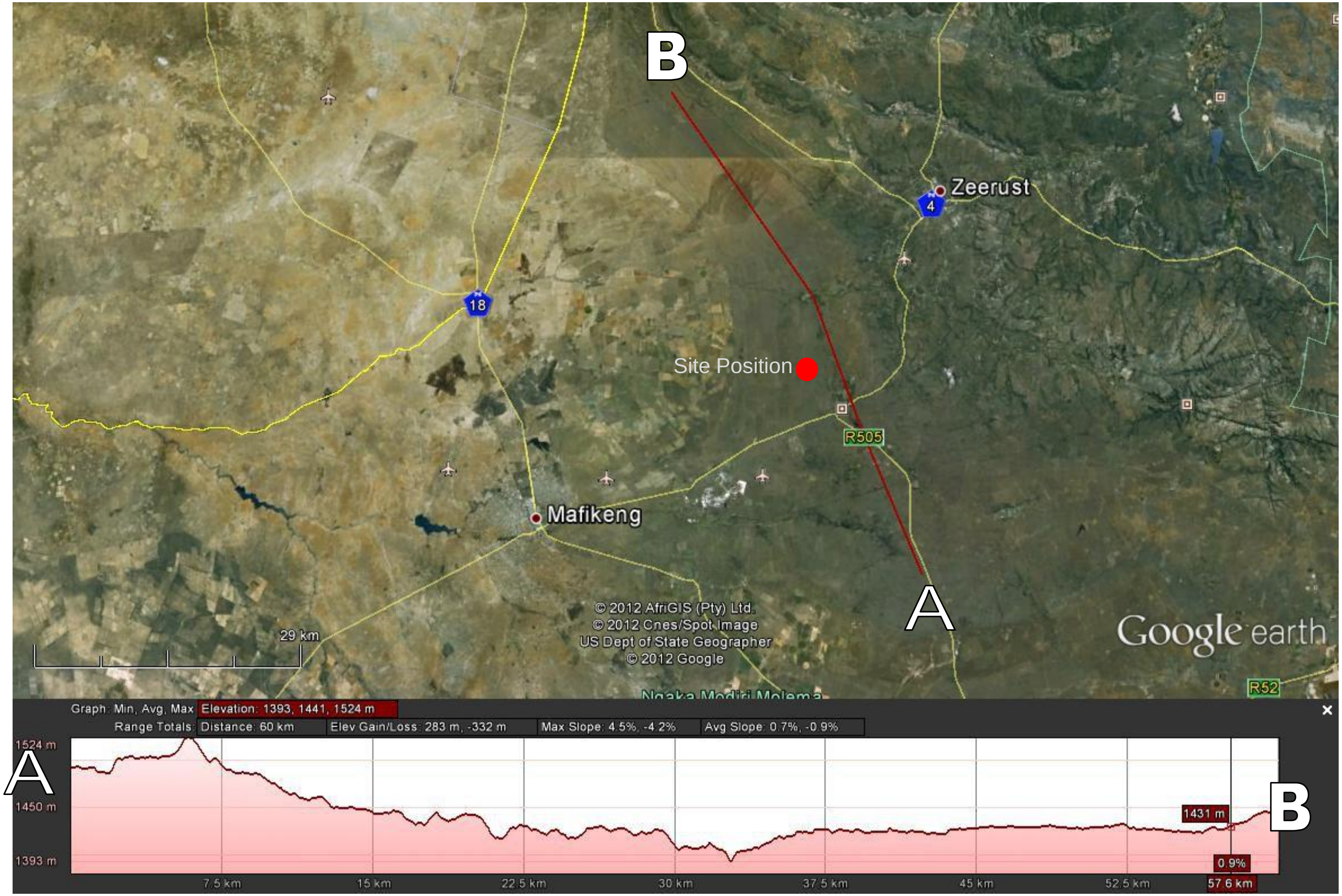


Figure 4-19: Study Area



Graph: Min, Avg, Max Elevation: 1393, 1441, 1524 m

Range Totals: Distance: 60 km | Elev Gain/Loss: 283 m, -332 m | Max Slope: 4.5%, -4.2% | Avg Slope: 0.7%, -0.9%

Figure 4-20: Elevation profile over a regional part of the Zeerust Dolomites

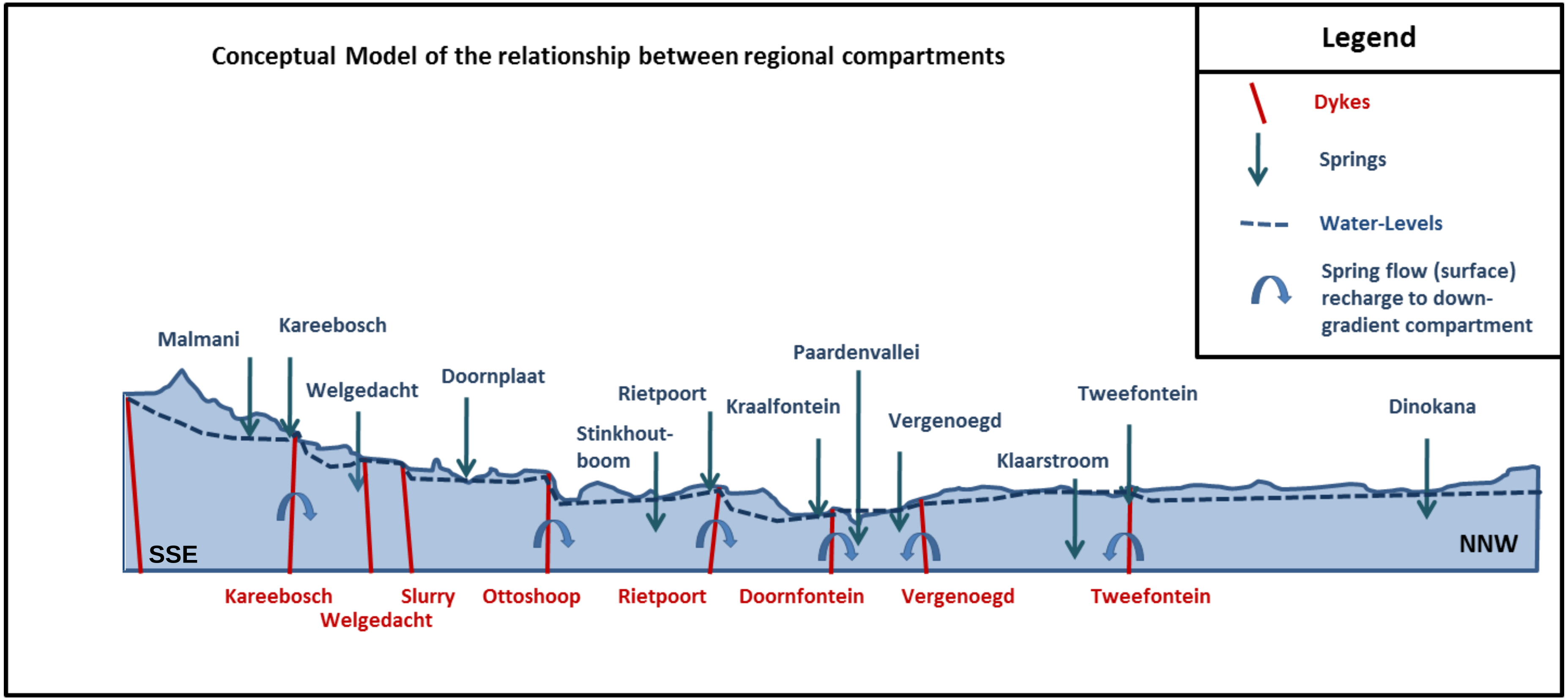


Figure 4-21: Conceptual model of the hydraulic relationship between the compartments on a regional scale. Based on the elevation profile in Figure 4-20

4.4.3 Aquifer Characteristics

Water in a fractured/dolomitic rock aquifer flows along fractures, faults, joints, solution cavities and bedding planes within the rock matrix (Cowell and Ford, 1980).

No aquifer tests were conducted during this study, therefore the aquifer parameters are discussed in Section 3.4.4.

4.4.4 Groundwater Recharge Calculation

A recharge spread sheet created by Van Tonder and Xu (2001) uses the formulas for CRD and SVF (see literature review section) to estimate recharge values. Two boreholes were selected for the recharge estimation calculations. These boreholes are all in relatively close proximity to the VWF and are also in close proximity to a weather station that has high confidence rainfall data. One possible limitation was encountered in the fact that the rainfall station falls outside the boundary of the study area. The rainfall station is still within close proximity to the borehole cluster and is thus still useable. When the historical rainfall data for the weather stations in the vicinity was reviewed it was noted that the rainfall data is very similar, indicating that the rainfall in the area is fairly homogenous.

Water level data is available from January 1977 up until October 1997. However datasets from October 1980 to September 1982 were chosen as this is the period that the spring data is most complete.

Rainfall, water level and outflow data are entered into the software opposite the relevant month. The software then produces a graph for the CRD and SVF methods. The observed water levels are then fitted to the calculated water levels by means of adjusting recharge, specific yield and inflows. The recharge slide-bar is set to a default of zero. The bar is then manually moved until a satisfactory “best-fit” is achieved between the rainfall and recharge values (see Figure 4-22 and Figure 4-23). The Route Mean Square Error (RMSE) value provides an indication of “best-fit”. The results of the calculations are documented in Table 6.

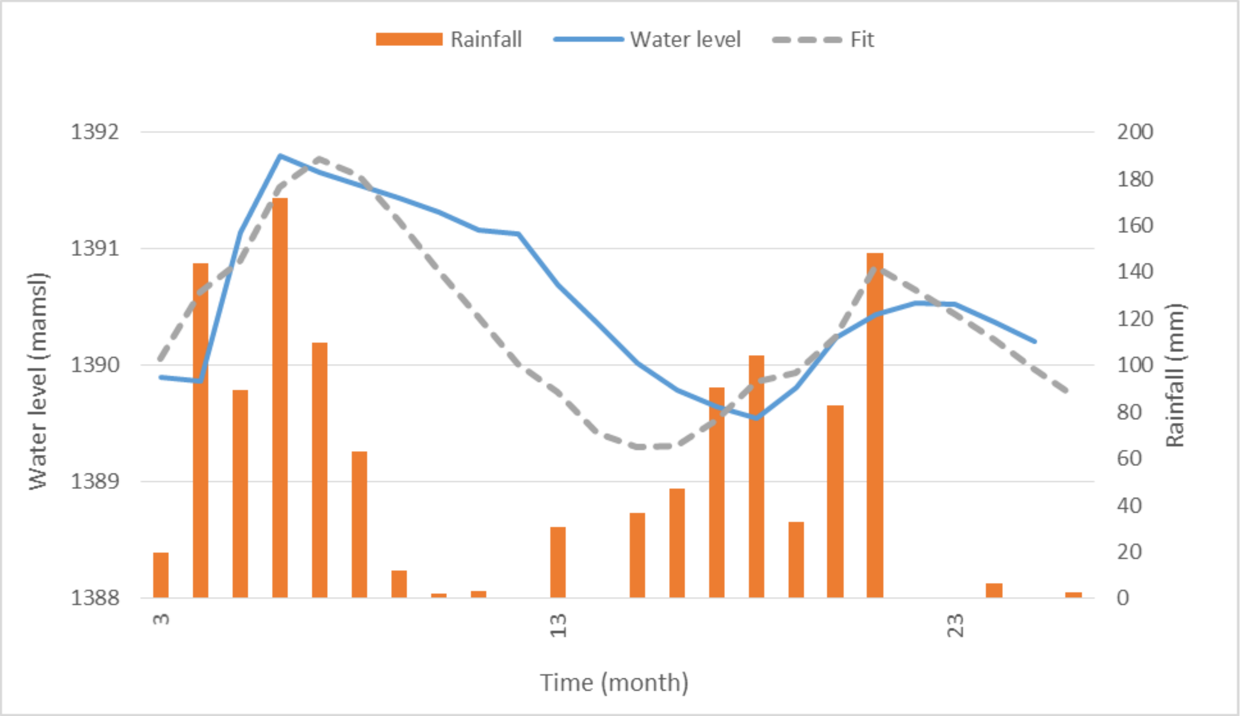


Figure 4-22: SVF (A3N0017)

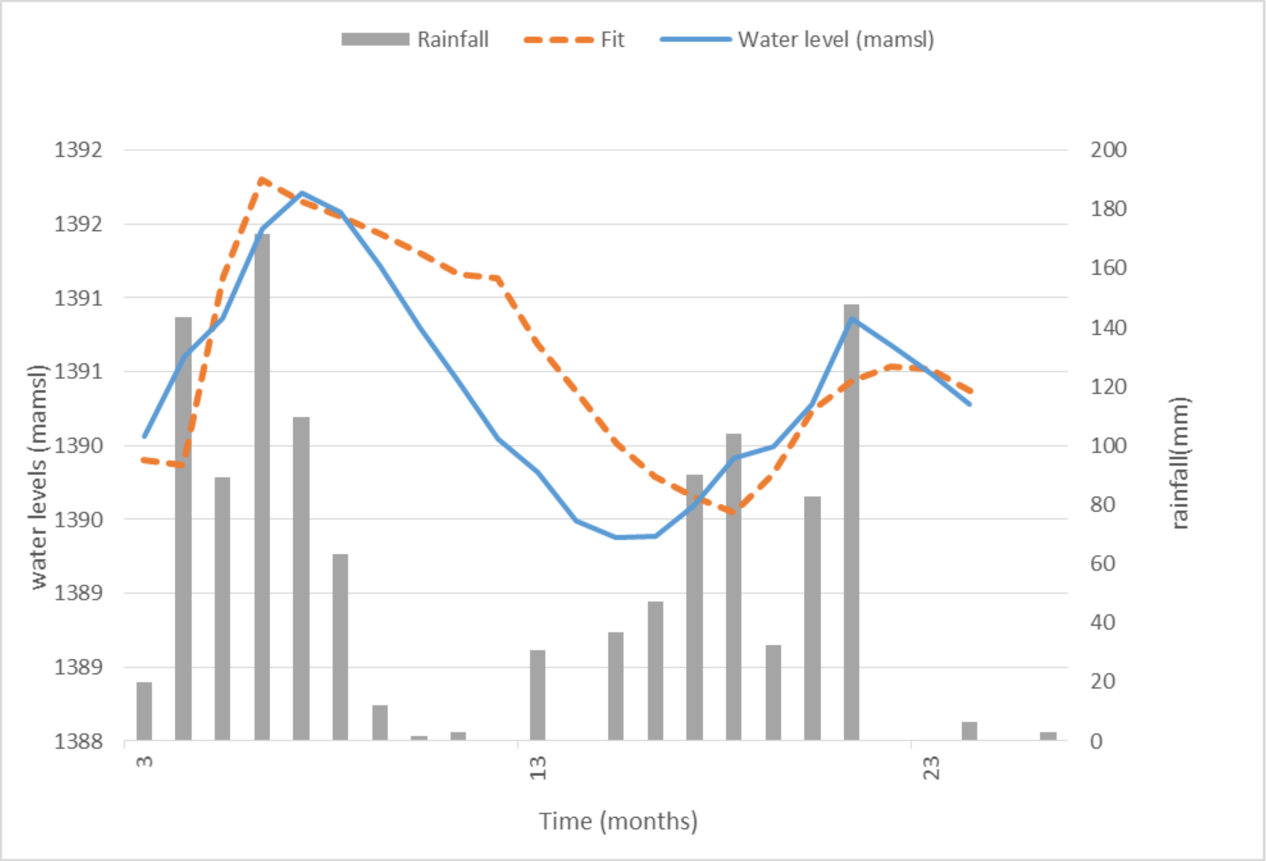


Figure 4-23: CRD (A3N0017)

Table 6: Results of Recharge Estimates

Borehole	SVF				CRD				Time lag
	Recharge (%)	Specific yield	Inflow (m^3/d)	RMSE	Recharge (%)	Specific yield	Inflow (m^3/d)	RMSE	
A3N0017	9.3	0.018	17200	0.168	9.4	0.019	17200	0.166	Water levels were shifted by 3 months
A3N0016	9.8	0.02	17200	0.160	10	0.019	17200	0.168	Water levels were shifted by 3 months

The graphs for A3N0016 are attached as Appendix C.

4.5 Modelling

4.5.1 Analytical approach

The analytical approach followed is based on the SVF method and is essentially a water balance. The equation used in this calculation is defined below:

$$I - O + RE - Q = S.\frac{\Delta V}{\Delta t}$$

Where I = $\frac{I1+I2}{I2}$ that is, the mean lateral inflow during the time increment Δt;

O = $\frac{O1+O2}{2}$ that is the average lateral outflow from the system;

RE = groundwater recharge to the aquifer system, which is the unknown parameter to be estimated

Q = net discharge or abstraction from the groundwater system

ΔV = change in saturated volume of the aquifer; and

Δt = $t_2 - t_1$ that is, the time increment over which the water balance is executed.

4.5.1.1 Calibration

An initial recharge of 9.6 per cent was assigned to the model. This value is the average of the values documented in Table 6. Spring-flow data, water levels and rainfall data were used for the period Oct 1980 to May 1983 for the calibration. A specific yield of 0.015 was used for the model, this figure is based on previous work done by Aquisim (2002). The results of the calibration are shown in Figure 4-24. The location of the springs and dykes are shown in Figure 4-19. Lag times have been included in the calibration.

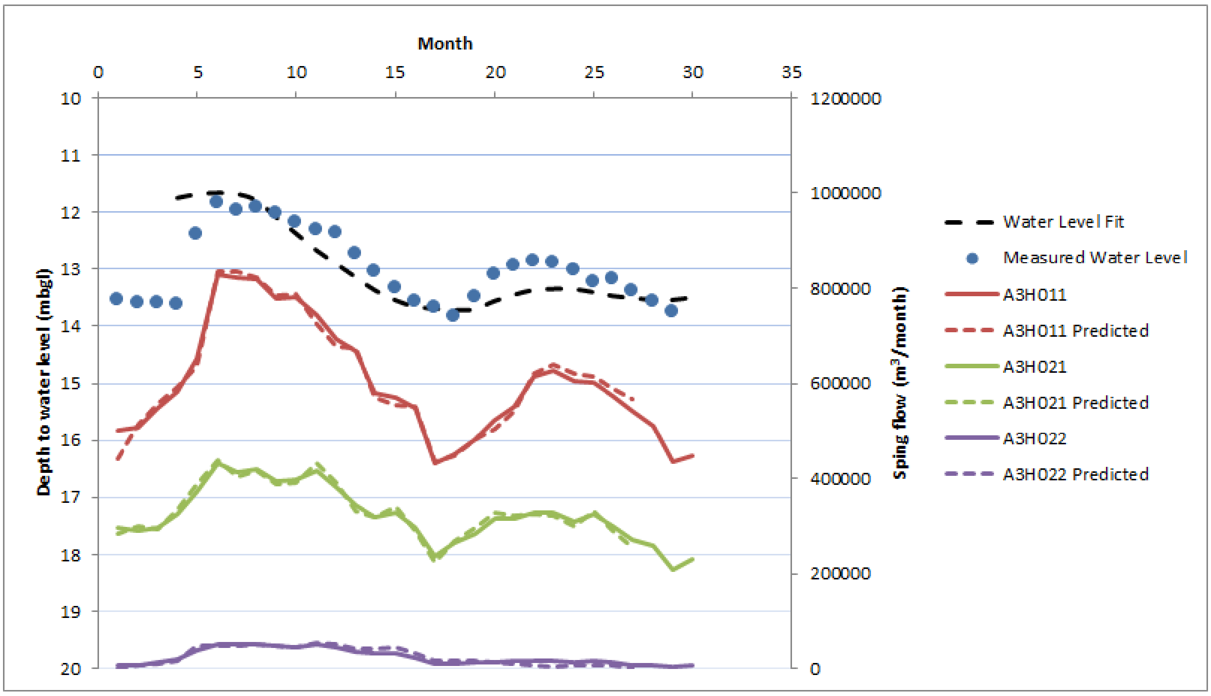


Figure 4-24: Calibration

Please note: A3H011is the Vergenoegd Spring, A3H021 is the Upper Paardenvallei Spring and A3H022 is the lower Paardenvlei Spring.

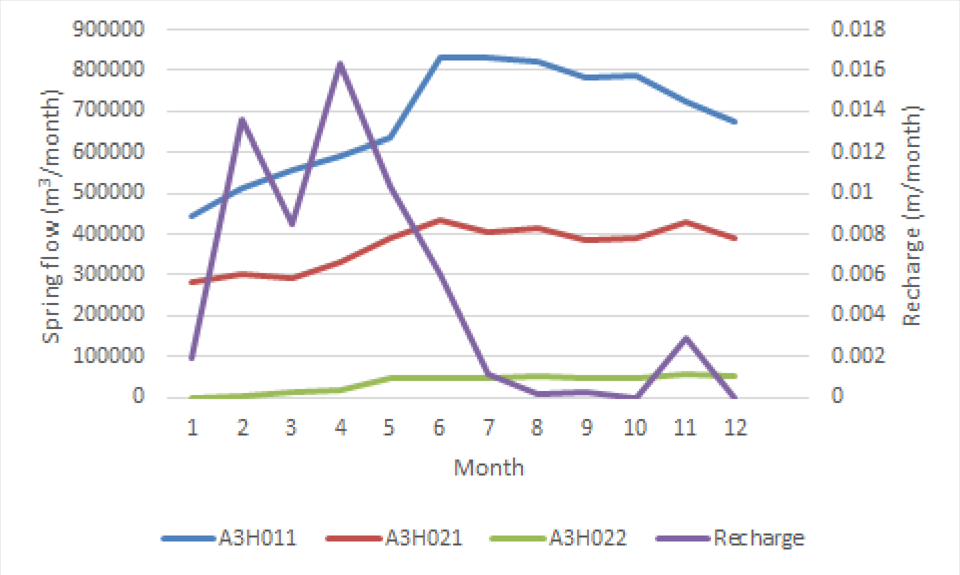
4.5.1.2 Impacts

Once the model was calibrated the impacts of the VWF on the Upper Paardenvallei, Lower Paardenvallei and Vergenoed Springs. The following sections illustrate:

1. Spring-flow and rainfall with no abstraction present
2. Abstraction included in the system
3. Abstraction included in drought conditions (reduced precipitation recharge component)

The spring-flow was plotted together with the associated recharge conditions, without any abstraction present. Figure 4-25 illustrates that there is also approximately a 6 month time lag between recharge events until being observed in spring-flow which reaffirms the relationship between recharge and spring-flow in the study area.

Figure 4-25: Recharge versus spring flow



To determine the effects of abstraction (change in water level), a simulation was run including abstraction rates. The 2010 abstraction rates for this field of boreholes were simulated and are documented in Table 7.

Table 7: Abstraction rates

Month	Abstraction (m^3/d)
Jan	2964
Feb	1927
Mar	2292
Apr	2578
May	2398
Jun	2034
Jul	2114
Aug	0
Sep	2452
Oct	2285
Nov	2489
Dec	2613

A challenge arose with regards to relating spring-flow to the change in water level, so that the effects of abstraction can be simulated. This was overcome by plotting the simulated spring-flow (scenario 1) against the change in simulated water level as shown in Figure 4-26. A high correlation was achieved and a relationship could be determined. The results of results of the scenario are shown in Figure 4-27. The figure illustrates a clear effect of abstraction on the groundwater levels and spring-flow.

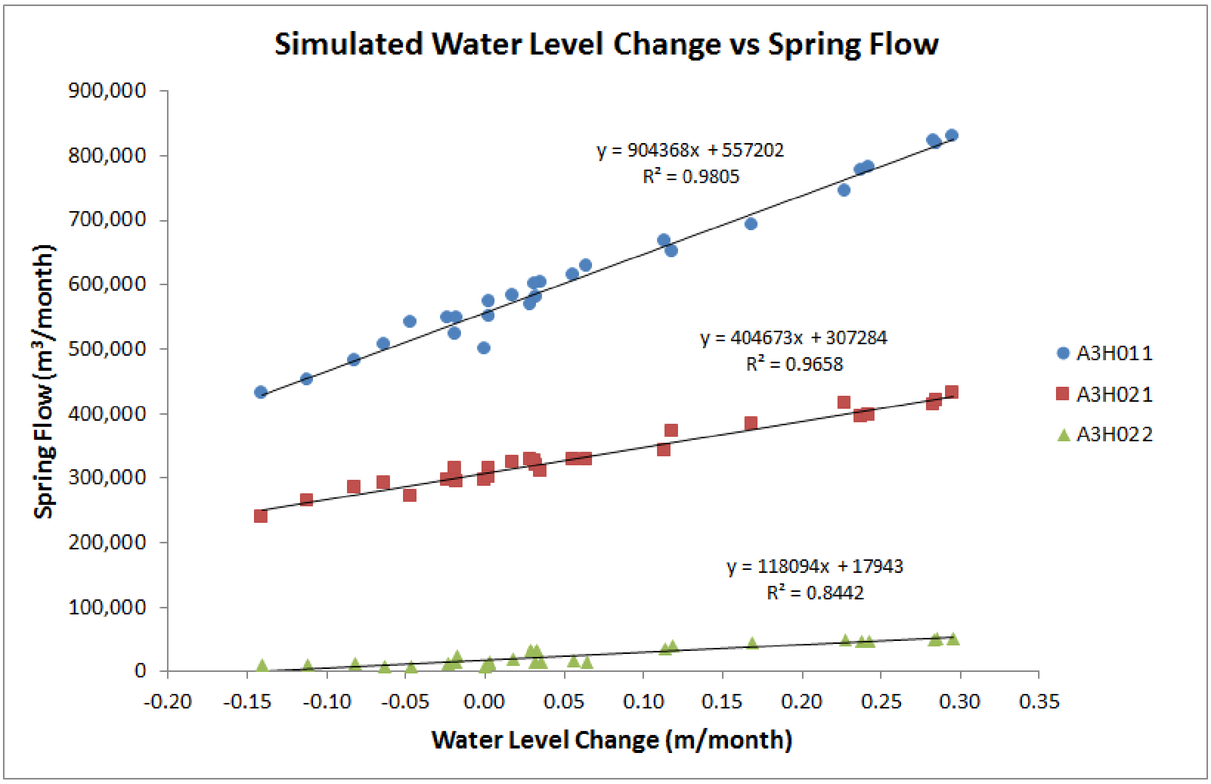


Figure 4-26: Relationship between water level and spring-flow

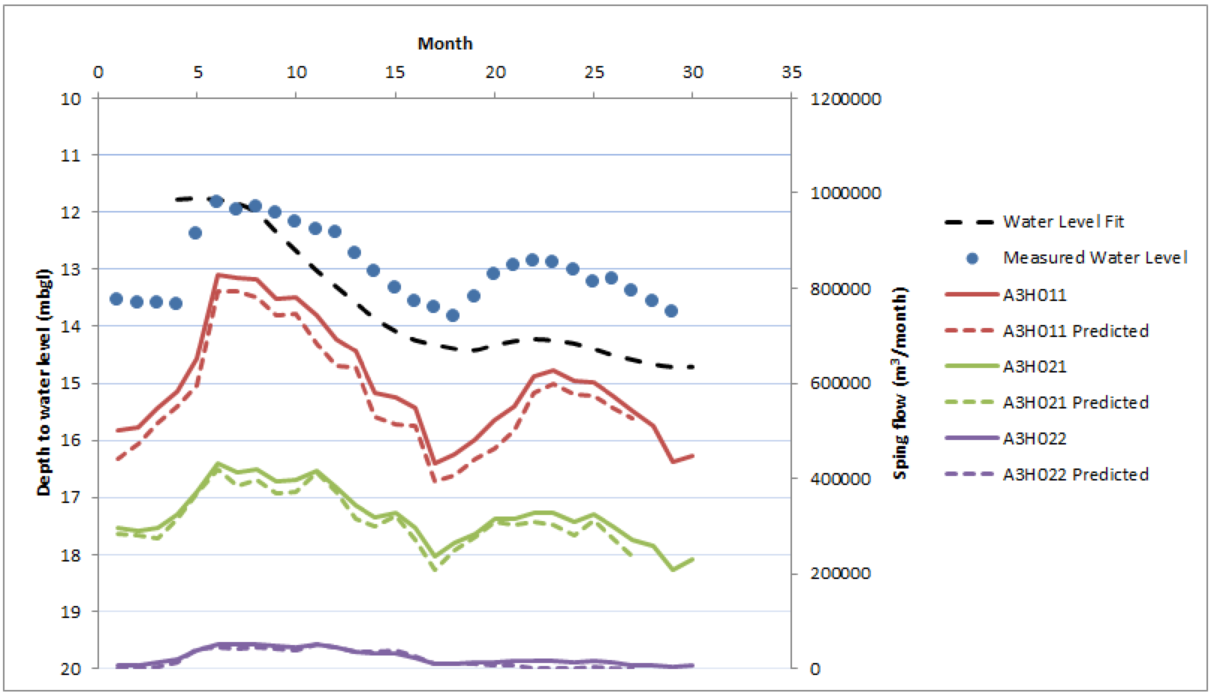


Figure 4-27: Impacts of abstraction

The third and final scenario is identical to scenario 2, except drought conditions are simulated. The rainfall is dropped to a third of normal conditions to simulate the drought conditions. The results of this scenario are shown in Figure 4-28. This scenario is based on the assumption that it is only the recharge from rainfall that changes (reduced recharge). Please note an average water level for the area was used in this simulation.

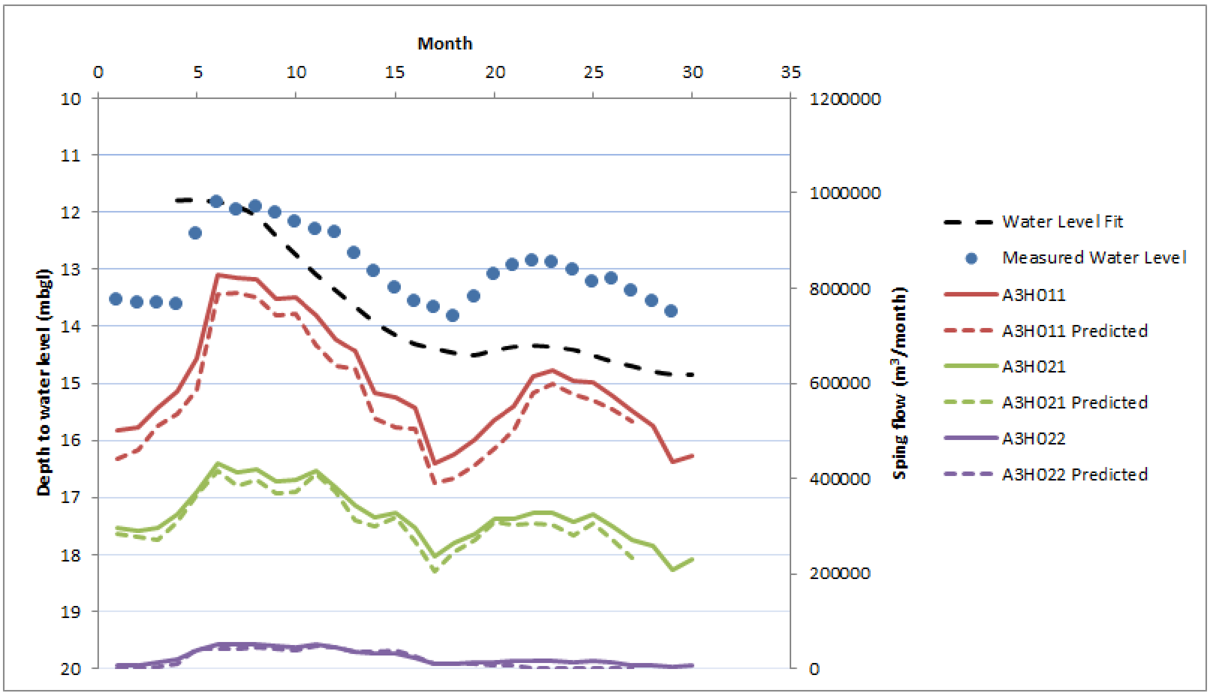


Figure 4-28: Results of Scenario 3

When all three scenarios of the model are compared, a few things become evident and some conclusions can be made. Firstly, the confidence in the simulation is fairly high as the scenarios are in-line with the conceptual understanding of the area and they also closely mimic known conditions. This in-turn reaffirms that the recharge value of 9.5 per cent calculated in the CRD section is correct for this study area. If the recharge value was off, issues would have arisen during the model's calibration process, which they did not.

In conditions where no abstraction is present, the water levels react in relation to the quantity of precipitation received within the model's boundary. This recharge only manifests and becomes visible in spring-flow approximately three months later. When abstraction is added to the system, the relationship between recharge, spring-flow closely mimics the results obtained in the natural conditions.

The relationship is evident again when drought conditions are simulated – when there is a reduction, this is a directly correlated reduction in spring-flows.

4.5.2 Data availability

Previous reports have indicated that data availability is a concern. The same theme repeated itself during the modelling phase.

Data are needed to assess the performance of borehole fields and the impact they have on the aquifer and surrounding geohydrological environment on both short and long term bases (see Appendix D on groundwater management in South Africa). Although the data was sufficient to populate and calibrate a model when the patched rainfall and spring-flow data was used to simulate the relationship between the three major components of this aquifer, there is a definite need for enhanced monitoring in this area especially when the demand on this aquifer is considered.

5 CONCLUSIONS

- Monitoring data are sparse. The lack of continuous monitoring data makes data interpretation challenging and can lead to compromised conclusions about short term fluctuations. There is a need for more reliable data in this area as well as an enhanced monitoring protocol.
- Based on DWA's published 'dolomite guideline' (see Appendix B) on assessing, planning and managing water resources in dolomitic areas of South Africa (DWA, 2006), as well as the findings of this investigation it can be concluded that:
- The methodology used to investigate the relationship between abstraction, recharge and spring-flow with regards to aquifer parameters such as recharge was effective and similar results obtained were in-line with previous studies' results.
- The VWF was hydrogeologically well assessed and planned, but the management of the borehole field is compromised by the lack of proper and on-going monitoring of both the abstraction volumes and water levels.
- When the available monitoring data is evaluated and run in the analytical model, it can be deduced that there is a seasonal fluctuation in water levels. This fluctuation is as a result of the precipitation variations between wet and dry months.
- Based on the available monitoring data, including spring-flow and groundwater level data, it can be concluded that the VWF's abstraction might show a long term impact on the aquifer.

- There exists a large correlation between recharge, abstraction and spring-flow in a Dolomitic aquifer with a time-lag between recharge events and being observed in spring-flow increases (2 - 3 months in the case of this study area) and that the reduction in spring-flow in the Zeerust area can be due to reduced recharge and/or over abstraction.
- Stemming from the analytical model, abstraction has a marked influence on the groundwater levels and associated spring-flow, especially when drought conditions are simulated. From the recharge calculations and subsequent modelling, it can be deduced that there is a definite relationship between the recharge, abstraction and spring-flow components. It is also apparent that these factors influence one another greatly and that variance in one of the inputs will have a significant effect on the rest and will change the system's response significantly while still maintaining direct correlation due to the strong relationship.

6 RECOMMENDATIONS

- NMMDM as the Water Services Authority and DWA as the custodians of water resources in South Africa are mandated to ensure that proper monitoring is done. This includes monitoring of the abstraction volumes, groundwater levels and spring-flows from the affected compartment. To ensure the continuous monitoring of the abstraction borehole fields, the monitoring can be outsourced on a tender basis to external contractors. The monitoring reports must be audited annually.

- Other than this study, there are no data to prove that the abstraction does not adversely affect the spring-flow from the Vergenoegd Eyes, and the farmers might be entitled to compensation due to loss of income. This issue must be investigated further on a legal basis.

- Monitoring of the spring-flow from the Vergenoegd Eyes must be reinstated as a matter of priority.

- The management of the VWF must be audited on a catchment and national level as per the 'dolomite guideline'. The lack of proper and continuous monitoring data being the most important factor hindering proper management must be addressed.

- Once monitoring data collection has been reinstated and a sufficient amount of time series data has once again been recorded, a similar research study to this should be completed. This would improve upon the quantification methods and would be initiated by conducting another comprehensive hydrocensus in which important data and observations should be made. Any changes to the area should be noted and recorded. It would be beneficial to conceptualise the system if changed and based thereupon, run another numerical model to determine if the correlation between recharge, abstraction and spring-flow has changed and if so, to what extent.

7 REFERENCES

AGES, 2010. Initial Groundwater Status Assessment of the dolomitic aquifer underlying the Vergenoegd Well Field south west of Zeerust. (Report prepared for Cornelius Durand Attorney's Office by JJ Smit p. 10–55).

AGES, 2013. Integrated Groundwater Assessment. Assessment of the Vergenoegd wellfield bulk groundwater abstraction on the environment. (Report prepared for Cornelius Durand Attorney's Office by JJ Smit p. 3-97).

Africon, 2002. Final Report on the Evaluation of the Groundwater Resources at Uitvalgrond 60 Jo, Zeerust. Pretoria. p. 3–84.

Aquisim, 2002. Determination of Aquifer Abstraction Potential of the Uitvalgrond Dolomitic Area near Zeerust. Report submitted to Africon. Report No. AQS/Africon/2002/001. Aquisim, 2002. Welbedacht Bulk Water Supply: Numerical Modelling of Groundwater Potential – 2005 Model Update. Report submitted to Khulani GeoEnviro Consultants (Pty) Ltd. Report No. AQS/KHULANI/2005/001. Pretoria. p. 16-43.

Beale, G. & Read, J. 2013. Guidelines for evaluating water in pit slope stability. Australia: CSIRO. p. 153-215.

Botha, L.J. 1993. Estimation of the Zeerust/Rietpoort groundwater potential. GH 3815 Report. Pretoria: Directorate of Geohydrology. p. 18-25.

Bredenkamp, D.B., Botha, L.J., van Tonder, G.J. & Janse van Rensburg, H. 1995. Manual on quantitative estimation of groundwater recharge and aquifer storativity. Pretoria. p 73-351.

Bredenkamp, D.B & Vogel, J.C. 2007. Use of natural isotopes and groundwater quality for improved estimation of recharge and flow in dolomitic aquifers. Water Research Commission Report No. KV 177/07, Water Research Commission, Pretoria. p. 35-53.

Bredenkamp, D.B. 2009. Groundwater Recharge and Mean Residence Time in Dolomitic Aquifers using the Thermo-nuclear injected 14C as a Natural Tracer. Pretoria. p. 1-12.

Bredenkamp, D.B. 2010. Flow in Dolomitic Aquifers Using the Thermo-Nuclear 14C Isotope Injected into the Atmosphere as a Tracer. Pretoria. p. 36–47.

Brink, D. 1992. Zeerust Grawitasie en Elektromagnetiese Ondersoek. DWAF Report GH3770. Pretoria. p. 1-6.

Buttrick, D. & Van Schalkwyk, A. 1998. Hazard and Risk Assessment for Sinkhole Formation on Dolomite Land in South Africa. Germany: Springer-Verlag. p. 9-18.

Button, A. 1970. The Stratigraphic History of the Malmani Dolomite in the Eastern and Northeastern Transvaal. Johannesburg: Economic Geology Research Unit, University of the Witwatersrand. p. 1-26.

Clay, A.N., 1981. The Geology of the Malmani Subgroup in the Carletonville Area, Transvaal. Johannesburg: University of the Witwatersrand. p. 55-61.

Coetzee, H.P.A., 1996. The Stratigraphy and Sedimentology of the Black Reef Quartzite Formation, Transvaal Sequence, in the area of Carletonville and the West-Rand Goldfields. Potchefstroom: University for Christian Higher Education. p. 9-71.

Cowell, D.W. & Ford, D.C. 1980. Hydrochemistry of a Dolomite Karst: The Bruce Peninsula of Ontario. Canada: Burlington. (17)520-526.

Dooge, J.C.I. 1973. Linear theory of hydrologic systems: U.S. Department of Agriculture Technical Bulletin. Washington: US Government Printing Office. p 290-329.

Dreiss, S. 1982. Linear kernels for karst aquifers: Water Resources Research. 18(4)865–876.

Dreiss, S.J. 1983. Linear unit-response functions as indicators of recharge areas for karst springs: Journal of Hydrology. American Geophysical Union. p. 31–44.

Dreiss, S.J. 1989. Regional scale transport in a karst aquifer, Linear systems and time moment analysis: Water Resources Research. p. 126–134.

DWA, 2011. North West Groundwater Master Plan. Pretoria: Department of Water Affairs and Forestry. p. 10–24.

DWAF, 1999. Inspection of Molopo River and report of inspection of Zeerust Springs. Report No. GH3357 (II). Pretoria: Department of Water Affairs and Forestry. p. 6–15.

DWAF, 2006. Vaal River System: Large bulk water supply reconciliation strategy, Groundwater assessment: Dolomite aquifers. Pretoria :Department of Water Affairs and Forestry. p. 19–22.

DWAF, 2006a. A Guideline for the Assessment, Planning and Management of Groundwater Resources within Dolomitic Areas in South Africa: Volume 1 – Conceptual Introduction. Pretoria: Department of Water Affairs and Forestry. p. 9-18.

DWAF, 2006b. A Guideline for the Assessment, Planning and Management of Groundwater Resources within Dolomitic Areas in South Africa: Volume 2 – Process and Related Activities. Pretoria: Department of Water Affairs and Forestry. p. 25–33.

DWAF, 2006c. A Guideline for the Assessment, Planning and Management of Groundwater Resources within Dolomitic Areas in South Africa: Volume 3 – Procedures. Pretoria: Department of Water Affairs and Forestry. p. 5–15.

DWAF, 2008. A Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa. Pretoria: Department of Water Affairs and Forestry. p. 5–7.

Freeze, R.A. & Cherry, J.A. 1979. Groundwater. New Jersey: Prentice-Hall International. p. 604-607.

Girish, C.S. & Joshi, V. 2004. Rainfall and Spring Discharge Patterns in Two Small Drainage Catchments in the Western Himalayan Mountains, India. Netherlands: Springer. p. 19-30.

Goldbury-Murray. 2010. Groundwater terms and Definitions. p. 6-15.

Hammett, K.M. 1990. Land Use, Water Use, Streamflow Characteristics, and Water Quality Characteristics of the Charlotte Harbor Inflow Area. Oklahoma: U.S. Geological Survey. p. 64-65.

HES (Hydrologic Evaluation Section). 2003. Long-term variation in Rainfall and its effect on Peace River Flow in West-Central Florida. p. 1-33.

Hughes, D.A. 2004. Incorporating groundwater recharge and discharge functions into an existing monthly rainfall-runoff model. South Africa: Taylor & Francis. Hydrological Sciences Journal. p. 297-311.

Khulani, 2006. Proposal for Abstraction of groundwater for Bulk Water Supply Augmentation in Welbedacht Reservoir in the Zeerust Local Municipality, North West Province of South Africa: Final Scoping Report. Reference No. EIA_507/2005NW_Zeerust/KGC_FSR_002. East London, South Africa. p. 21-33.

Khulani, 2008. Welbedacht Bulk Water Supply: Groundwater Resource Augmentation – Phase 2. Report submitted to Phumelela Africa Professional Engineers (Pty) Ltd. Report No. 2008-0233. April 2008. East London, South Africa. p. 17-26.

Lewelling B.R., Tihansky, A.B. & Kindinger, J.L. 1998. Assessment of the Hydraulic Connection between Ground Water and the Peace River. Oklahoma: U.S. Geological Survey Water Resources Investigations Report 97-4211. p. 96-97.

Marshall, T.R. & Norton, G.A. 2009. The nature of the alluvial diamond deposits of the Ventersdorp district, Northwest Province, South Africa. Pretoria: South African Journal of Geology, 112(2): 109-124.

Masilo and Associates. 2011. Final EIA Audit Report. Report submitted to Thekgano Trading. Fancistown, Botswana. p. 15-55.

National Weather Service. 2009. Point Precipitation Measurement Areal Precipitation Estimates and Relationships to Hydrologic Modeling. Arkansas. p. 1-2.

Obbes, A.M. 1995. The Structure, Stratigraphy and Sedimentology of the Black Reef-Malmani-Rooihoogte Succession of the Transvaal Supergroup Southwest of Pretoria. Pretoria: Council for Geoscience. p. 1-89.

Paul, E. 1996 Calibration and reliability in groundwater modelling. Golden: IAHS Publication (237). 31–40.

Phumelela, 2008. Welbedacht Bulk Water Augmentation. Contract No: MIG/NW/0604/S/07/08. Report submitted to Ngaka Modiri Molema District Municipality by Phumelela Africa Professional Engineers. p. 16-42.

South African Council for Stratigraphy (SACS). 1980. Stratigraphy of South Africa, Part 1. Lithostratigraphy of the Republic of South Africa , South West Africa / Namibia, and the Republics of Bophuthatswana, Transkei and Venda. p. 686-690.

Stogner, R.W. 2000. Trends in Precipitation and Stream-flow and Changes in Stream Morphology in the Fountain Creek Watershed, Colorado. p. 2-34.

Taylor, C.J. & Greene, E.A. 2008. Hydrogeologic Characterization and Methods Used in the Investigation of Karst Hydrology. Oklahoma: US Geological Survey. p. 77-106.

Thomas, B.E. & Pool, D.R., 2006. Trends in streamflow of the San Pedro River, southeastern Arizona, and trends in precipitation and streamflow in northwestern New Mexico and southeastern Arizona: Oklahoma: U.S. Geological Survey. p. 79.

Van Tonder, G.J. & Xu, Y. 2001. The estimation of recharge using a revised CRD method. Pretoria: Department of Water Affairs and Forestry. p. 341-343.

Zhang, Y.K. & Bai of spring discharge charge from a limestone aquifer in northeastern Iowa. Oklahoma: US Geological Survey. p. 71-86.

8 APPENDIX A: DETAILED DISCUSSION OF PREVIOUS WORK

8.1 Historical Work

The significant groundwater potential of the North West dolomites in the Zeerust Area was realised as early as 1906 when the first report on the water potential of the numerous springs in the area was submitted to the government. the potential for large scale groundwater supply was also recognised (Enslin and Kriel, 1967). Since then many studies were commissioned on various levels to investigate the potential of supplying bulk municipal water from the dolomite, as well as the impacts thereof.

These reports were sourced from the Geohydrological Report Archive of DWA to investigate the geohydrological character of the area prior to the development of the VWF (see Table 8). Not all reports were relevant to the study. Only relevant data and findings will be listed and discussed.

Table 8: List of historical reports obtained from DWA's archives

Report No	Date	Title	Author(s)
GH3357 (II)	1906/10/10	Report of inspection of Zeerust Springs	Mr. Karlson
GH0149	1937/07/21	Boring for water, Zeerust District: Native Affairs Dpt	NP de Wet
GH0005	1946	Boorplekke vir padkampe in Zeerusdistrik	JJ Taljaard
GH0904	1954/01/05	Opname van Waterbron te Rietpoort 95 Munisipaliteit van Zeerust	FW Schumann
GH0956	1955/04/30	Munisipaliteit Zeerust: Opname van Waterbron te Rietpoort 95, Marico	FW Schumann
GH0983	1956/09/08	Verslag oor Pomptoets van Boorgat Nr. 6 Klein Marico's Poort Nr. 71, Munisipaliteit Zeerust	JR Vegter
GH1268	1960/09/13	Grondwqatervoorrade in die Dolimiet, Omgewing van Zeerust, Transvaal	JF Enslin
GH0151	1961/05/14	Report on pumping test of an excavation for the municipality of Zeerust on the Farm Vergenoegd, 3.	JF Gordon-Welsh
GH1283	1964/05/16	Die Bo-Molopo Ondergrondse Waterbeheergebied	DB Bredenkamp
GH1278	1965	Report on the weakening of the Vergenoegd Spring - Distr. Marico	PT Wilson
GH3293	1975/02/28	Aanbevelings vir 'n beleid van grondwatertoekenning in die Bo-Molopo Ondergrondse Waterbeheergebied	WL van Wyk, MP Mulder
GH2.2(2)	Sep-81	Investigation and conceptual design of a fluorspar tailings disposal complex Summary Report	GI McPhail, ME Smith, J Robbertze
GH3395	1981/07/31	Studie oor die voorkoms en vloei van fonteine in die Bo-Molopo OWBG	JL Muller
GH3602	1988/10/06	Ondersoek na beweerde invloed van die Bo-Molopo Staatswaterskema op die Olievendraai Fontein van die Rietvallei/Weltevrede Besproeiingsraad	DB Bredenkamp
GH3603	Oct-88	Ontginning van die Rietpoort Grondwaterbron wat Zeerust van water voorsien	DB Bredenkamp, A Zwarts
GH3770	Apr-92	Zeerust Gravitasie en Elektromagnetiese ondersoek	D Brink
GH3815	Aug-93	Estimation of the Zeerust/Rietpoort Groundwater Potential	LJ Botha
GH3948	Mar-00	Drilling results of Boreholes Drilled in the Bo-Molopo Dolomites	JM Nel

8.1.1 GH3357 (II) (Karlson, 1906)

This is an inspection report from 1906 of the "Zeerust Springs" and includes discharge volumes in gallons per day for the majority of the springs surveyed.

The report mentions the Rietvlei Springs, presumably upstream of Kafferkraal which do no longer exist. Mention is also made of the discharge of the Buffelshoek Spring that "dwindled down to nothing" during the six months prior to the report, forcing the people from Jacobsdal downstream to leave the area.

The Vergenoegd Springs are mentioned as being the largest springs in the valley with a combined discharge of 1 020 000 gallons/day (4 637 m^3/d). The Kareespruit Spring on Tweefontein Klaarstroom eye discharges 80 000 gallons/day (364 m^3/d), but this spring is reported to have been much larger prior to 1906 and has been opened up to increase flow.

The Malmani Spring (eye) is reported to yield more than 4.2 million gallons of water per day (19 094 m^3/d), while six months prior it was measured at 5 million gallons (22 730 m^3/d).

Tweefontein Spring is mentioned as a small spring discharging 110000 gallons (500 m^3/d) while the Linokana (Dinokana) Spring discharges 2140000 gallons (9 729 m^3/d).

Furthermore the Rietpoort Spring is mentioned but was not measured, and the Paardenvallei Spring is reported to have dried up.

8.1.2 GH0904 (Schumann, 1954)

This report was submitted in 1954 to the Geological Survey on the water resources at Rietpoort 95 (96 JO) as a possible augmentation source to the town of Zeerust. This investigation surveyed the geology and topography of the area. The report contains elevations (in feet above sea level, measured with a barometer) of the main springs as well as discharge yields in cubic feet per second (cusec).

8.1.3 GH0983 (Vegter, 1956)

Although not in the immediate area under investigation, this report mentions low water levels in 1951 to the south-east of Zeerust (not on dolomite). According to the report the average rainfall for the Zeerust area between 1921 and 1950 is 600 mm/a, while the rainfall between 1949 and 1951 dropped to 503 mm/a, and in the 1951/2 season only 377 mm was registered. Table 9 summarises rainfall measured at the Zeerust jail.

Table 9: Rainfall measured at Zeerust Jail

Season	Rainfall (mm/a)
1949-50	503
1950-51	503
1951-52	377
1952-53	610
1953-54	614
1954-55	601
1955-56	624

The lower water table is attributed to the lower than average rainfall.

8.1.4 GH1268 (Enslin, 1960)

Continuing on previous work, this report contains a similar table (Table 10) with elevations and more refined discharge rates for the various dolomitic springs. It also ventures to predict a preliminary safe yield from the dolomites by assuming a groundwater recharge percentage of 6% (based on work on the Far West Rand gold fields dolomite) of the rainfall of ~21.6 inches (549 mm/a).

Table 10: Summary of data from Report GH1268

Report GH1268	**Original Data**		**Converted**		
Spring	**Height (fasl)**	**Yield (cusec)**	**Height (mamsl)**	**Yield (L/s)**	**Comment**
Linokana upper eye	4422	3.36	1348	95.1	(Dinokana Upper)
Linokana lower eye		0.9		25.5	(Dinokana Lower)
Tweefontein upper eye		0.53		15.0	
Tweefontein lower eye		0.42		11.9	
Klaarstroom		0.13		3.7	
Vergenoegd	4527	1.47	1380	41.6	
Paardevlei	4526	0.6	1380	17.0	
Doornfontein	4587	0.4	1398	11.3	
Kafferkraal	4575	0.71	1394	20.1	Now called Kraalfontein
Stinkhoutboom	4572	0.55	1394	15.6	Elevation between 4582 and 4562
Rietpoort	4626	2	1410	56.6	
Buffelshoek	4606	1.47	1404	41.6	
Malmani eye	4810	5.50	1466	155.7	Yield between 5 and 6 cusec
Molopo eye	4810	3.00	1466	85.0	Yield between 2 and 4 cusec
Grootfontein	4741	4.10	1445	116.1	

8.1.5 GH0151 (Gordon-Welsh, 1961)

A pumping test on an excavation on Vergenoegd 3 was performed in May 1961. Water was encountered in the surface alluvium (sand and boulders) and the excavation did not penetrate the hard bedrock, which is described as shale and quartzite.

8.1.6 GH1283 (Bredenkamp, 1964)

The report mentions the proclamation of the “Bo-Molopo Ondergrondse Waterbeheergebied” or ‘subterranian water control area’. Although the map indicating the area could not be sourced, it could be deduced from the report that this area falls south of the area under investigation. Several springs to the south of the area are mentioned.

The report found a correlation between the water levels, the abstraction of dolomitic water and the average rainfall between September 1958 and June 1964. It also found a steady decrease in water levels in three separate compartments between 1958 and 1961, based on below average rainfall. After good rains in 1961 the levels recovered drastically.

No conclusive evidence could be found that the increasing groundwater abstraction (due to a significant increase in boreholes) in the Blaauwbank area was affecting the Grootfontein Spring. The report states that **water level measurements** are incomplete, **and abstraction figures** are insufficient – and that both **are of great importance to determine the safe yield of compartments**.

8.1.7 GH1278 (Wilson, 1965)

A geohydrological survey was carried out in February of 1965 into the ‘*extreme weakening of the flow from the spring at Vergenoegd No. 3*’. The matter was brought to the attention of Water Affairs by Mr Cornelis Hogendyk of the farm Uitvlucht 63, who alleged that it was a direct result of excessive pumping on the farm Kafferkraal 93 (by Mr. Konie Snyman) and Doornfontein 289 (by the Zeerust Municipality).

During this survey the levels of the spring outlets were re-determined, the water levels in observation boreholes were measured and the bounding dyke to the north of the Vergenoegd compartment was delineated using geophysical techniques.

Flow data for certain springs were obtained from Water Affairs, while others were estimated. The report gives names to the various compartments, and discusses them in terms of spring-flow and geological characteristics:

Tweefontein – Klaarstroom Compartment

The northern most compartment is called the Tweefontein – Klaarstroom compartment. The northern boundary is a WSW-striking dyke inferred from aerial photography, causing the Tweefontein springs to emerge. The southern boundary is a diabase dyke striking E-W through the northern portion of Doornfontein 289 and the southern portion of Wolwekoppies 104. Although the continuity of the dyke appears to be broken, the water levels on Doornfontein 289 and Olyfenbult 30 indicate separate groundwater bodies. The groundwater gradient in this compartment is towards the northeast where the springs discharge.

Spring-flow for June 1960 and January 1965 were compared for the springs in this compartment and illustrated in Table 11, and a decrease in spring-flow of between 50 and 74 % was observed:

Table 11: Spring-flow for June 1960 and January 1965

Spring Name	Flow in cusec		Percentage decrease
	Jun-60	Jan-65	
Tweefontein Upper*	0.53	0.14	74
Tweefontein Lower*	0.38	0.16	58
Klaarstroom Spring*	0.12	0.06	50

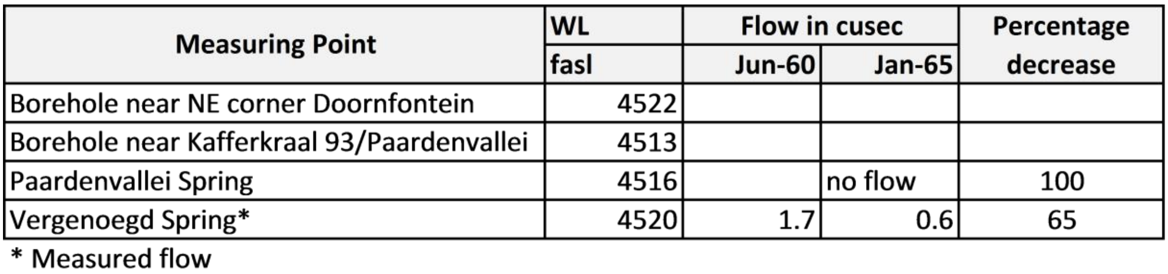
*Measured flow

The Vergenoegd – Paardenvallei Compartment

This compartment lies south of the Tweefontein – Klaarstroom Compartment and is the compartment referred to above. The southern bounding dyke strikes across the central part of Doornfontein 289 and Kafferkraal 93, and the south-western portion of Paardenvallei 62 into Stinkhoutboom 269.

The springs all occur in the eastern portion of the compartment, and therefore depend on a groundwater gradient from west to east. Water level measurements confirmed this gradient in the report, which also states that a flattening and in fact a cone of depression is observed around the two new Zeerust supply boreholes near the Kafferkraal – Paardenvallei boundary.

Table 12: Measured points



Measuring Point	WL	Flow in cusec		Percentage
	fasl	Jun-60	Jan-65	decrease
Borehole near NE corner Doornfontein	4522			
Borehole near Kafferkraal 93/Paardenvallei	4513			
Paardenvallei Spring	4516		no flow	100
Vergenoegd Spring*	4520	1.7	0.6	65

* Measured flow

The locations of the boreholes mentioned in Table 12 above could not be determined, but it can be seen that the borehole near the Kafferkraal – Paardenvallei boundary to the west of the Paardenvallei Spring, has a lower water table than the spring itself, causing the author to interpret a cone of depression around the points of abstraction. Furthermore the decrease in spring-flow in Vergenoegd Spring can be seen here, while the Paardenvallei Spring ceased flowing completely.

The abstraction figures from this compartment were added as an addendum to the report. Three boreholes on Doornfontein were developed between 1961 and 1963. Each pumped 0.07 cusec (2.0 L/s), totalling 6.0 L/s. The Zeerust supply boreholes on Kafferkraal are listed as delivering a combined volume of 0.19 cusec (5.4 L/s) since December 1964. Therefore the total abstraction from these five boreholes amounts to 11.4 L/s.

The Doornfontein – Kafferkraal Compartment

This compartment is bounded to the north by the southern bounding dyke of the Vergenoegd – Paardenvallei Compartment, and to the south by the Rietpoort Dyke across the central parts of Rietpoort 95 and Stinkhoutboom 269. Three groups of springs exist on the northern boundary (i.e. the Doornfontein-, Kafferkraal- and Stinkhoutboom Springs) indicating a general hydraulic gradient from SW to NE. The spring elevations and flows from the report are documented in Table 13.

Table 13: Measuring points

Measuring Point	WL fasl	Flow in cusec		Percentage decrease
		Jun-60	Jan-65	
Doornfontein Spring*	4585	0.4	0.01	98
Kafferkraal Spring*	4575	0.7	0.03	96
Stinkhoutboom Spring**	4562	0.55	0.32	42

* Measured flow

** Estimated flow

It can be noted that the topographically higher springs experienced a more severe decrease in flow than the lowest outlet of the compartment, the Stinkhoutboom Spring. Having said that, the report also mentions the possibility that the Golden Calf quartz vein, which strikes NNE between the Kafferkraal and Stinkhoutboom Springs, can act as a groundwater barrier creating sub-compartments.

The Rietpoort – Buffelshoek Compartment

This compartment occurs south of the Rietpoort Dyke and is probably bounded in the south by the parallel dyke that runs through Ottoshoop.

Table 14: Springs

Spring Name	Water Level	Flow in cusec		Percentage decrease
		Jun-60	Jan-65	
Rietpoort Spring**	4626	2	1	50
Buffelshoek Spring**	4606	1.5	1.11	26

** Estimated flow

The springs in this compartment shows a much smaller decrease in flow compared to the springs in the compartments to the north. Nevertheless, the Rietpoort Spring has weakened to such a level that augmentation from the Kafferkraal boreholes was required.

The report concluded the following:

- In general there was a weakening in spring-flow at the time of the report (1965) since records were started in June 1959. This is attributed to a '*lack of natural recharge of the past few years*', although rainfall figures are not given.
- The water level in the Vergenoegd – Paardenvallei compartment is flat, indicating a 'system of relatively freely connected underground openings'.

- Indications were that heavy pumping on Kafferkraal 93 and the eastern portion of Doornfontein 289 caused a cone of depression, reversing the flow away from the Vergenoegd Spring in the absence of recharge. It was doubtful that this effect was influencing the flow of the spring at the time of Mr. Hogendyk's complaint, but the author had 'little doubt' that this situation would affect the Vergenoegd Spring-flow if continued, seeing that the Paardenvallei Spring ceased flowing.

- The flow of the Doornfontein and Kafferkraal Springs which under natural circumstances overflow into the Vergenoegd – Paardenvallei Compartment, was almost nil at the time of the survey, indicating a drop in the water level in this compartment. This is partly ascribed to the harvesting of water at Rietpoort for Zeerust's supply. The Rietpoort Spring overflows into the Doornfontein – Kafferkraal Compartment under natural conditions.

- The decrease in flow in the springs in the Rietpoort Compartment (Rietpoort- and Buffelshoek Springs), was less than the springs in the compartments to the north. This is explained by the fact that the Rietpoort Compartment is greater in size than the others, giving rise to greater proportional recharge from rainfall.

- The weakening of the springs in the Vergenoegd – Paardenvallei Compartment between 1960 and 1965 is therefore attributed to a below average rainfall and increased abstraction during the time period. The report also mentions several 'strong boreholes' have been drilled on Paardenvallei 62 since the beginning of 1965, of which the abstraction rates are unknown.

8.1.8 GH3293 (Van Wyk and Mulder, 1974)

This report gives recommendations for regulations in terms of groundwater allocations in the newly established Bo-Molopo groundwater control area. The groundwater control area was established to control the large scale groundwater abstraction from the highly productive dolomitic aquifers.

Mention is made of the two production boreholes on Kafferskraal (mentioned in GH1278) that augmented the supply form the Rietpoort Well Field, that were decommissioned in 1967.

In discussing the status quo, the report mentions a hydrocensus performed prior to October 1974 on the 3 000 km^2 Bo-Molopo Groundwater Control Area. The following findings are listed in Table 15.

Table 15: Hyrdocensus data

Hydrocensus: Bo-Molopo Groundwater Protection Area				
Defined use	**Boreholes**	**Annual use (Mm3)**	**% of BH**	**% of Use**
Domestic/Livestock	1210	0.6	81	1.4
Irrigation	250	38	17	90.3
Municipal/Industrial	29	3.5	2	8.3
Total	1489	42.1	100	100.0

It can be seen that 17% of the boreholes are responsible for above 90% of the water use due to irrigation requirements. It must also be noted that irrigation requirements is mostly restricted to the southern portion of the Control Area where arable land is found (estimated at 16% of the total Control Area). It is interesting to note that only 6% of the arable land is under irrigation.

Concerning spring-flow, 21 flow stations were erected at springs since 1960, while a further 21 smaller springs are known, but not monitored. The combined average spring-flow of the monitored springs is 41.1 Mm^3, while the estimated flow of the smaller springs is 6 Mm^3 giving a combined average flow of 47 Mm^3. The loss of groundwater from the dolomitic area is defined as spring-flow leaving the dolomites (springs on the dolomite recharges downstream compartments), and loss from evapotranspiration. These losses were calculated at 26 Mm^3, of which 8 Mm^3 is due to evapotranspiration.

The report states that the spring water is used inefficiently. More than half of the spring-flow of 14 springs are used for irrigation purposes (18 Mm^3/a), of which between 40 and 70% is lost through leaking canals to the irrigated lands, distribution losses and rapid infiltration. Due to the lack of arable land in the northern portion of the Control Area (the area under investigation here), little to no water is allocated to irrigation. Two springs are used for domestic purposes: Grootfontein supplies 65% of its flow to Mafikeng, while around 50% of Rietpoort's flow is used to supply the town of Zeerust. At the time that the report was written, the Rietpoort Well Field boreholes were being developed.

The fluctuations in spring-flow are also discussed in the mentioned report.

It states that the highest flow observed was for the hydrologic season ending 30 September 1974 in all springs. Some springs exhibited high flow in 1972 and others in 1967. **Apart from seasonal fluctuations** due to rainfall, the report found **no long term change in spring-flow rates**. A weakening of the flow in the Grootfontein Spring during 1970-71 might be attributed to an increase in abstraction at Blaauwbank. The flow however recovered in 1974 to such a degree that the canal walls were breached.

The report mentions the development of monitoring boreholes in die Control Area, and that since monitoring started as early as 1959, the highest recorded water levels was also in 1974 (apart from at Blaauwbank in 1967). It further states that since the large increase in abstraction in the area since the early 1950’s, no irrefutable evidence of **permanent** over-abstraction could be found.

The groundwater contours in the Control Area indicate a large underground reservoir (>800 km^2) in the eastern portion, flowing south and south-westwards. This creates stable groundwater conditions in spite of the heavy abstraction in areas around Lichtenburg, Dudfield and Manana. However, at Blaauwbank where concentrated abstraction occurs, a prominent cone of depression can be observed indicating local over-abstraction. Since the highest recorded groundwater levels here in 1967, a gradual drop in water level was observed, contrary to observation elsewhere in the Control Area.

A basic water balance of the Control Area determined a positive balance of 11 Mm^3/a over the portion of the area occupied by white occupied and residential areas (about two thirds of the area) in 1975. A projected surplus of 9 Mm^3/a was predicted for 1990.

Although most of the work was concentrated in the Grootfontein Compartment, Table 16 documents the spring-flow discharges and percentages of flow utilised were given for the entire area.

Table 16: Spring-flow discharges and flow utilised

Spring	Ave flow (Mm3/a)	Use as % of flow	Comments
Grootfontein Eye	4.2	25	Irrigation
		60	Urban/municipal
		15	Other losses
Kleinfontein Eye	0.05	0	Perennial flow
Molopo Eye	8	5	
Olievendraai Eye	0.9	90	
Weltevreden Eye	0.1	60	
Buffelshoek Eye	1.8	80	
Stinkhoutboom Eye	0.6	90	
Vergenoegd Eye	3.1	90	
Klaarstroom Eye	0.2	90	
Kafferskraal Eye	0.7	0	
Rietpoort Eye	2	50	Urban/municipal
Doornfontein Eye	0.9	90	
Renosterfontein Eye	0.3	90	
Doornplaat Eye	6	45	
Karreebos Eye	3	70	
Paardevlei Eye	0.2	90	
Malmani Eye	4	60	
Welgedacht Eye	0.3	90	
Dinkona Upper	3.6	0	
Tweefontein Upper	0.8	80	
Tweefontein Lower	0.2	60	
Total	**41.0**		

8.1.9 GH3395 (Muller, 1981)

This 1981 report on the flow measurements of springs in the Bo-Molopo Groundwater Control Area contains detailed flow measurement charts of springs surveyed between 28 April and 20 May 1981. The spring-flows are summarised in Table 17.

Table 17: Spring-flows

Station No.	Name	Discharge in L/s
D4M14	Molopo Eye	851.3
D4M16	Welgedacht Eye	14.7
D4M17	Olievendraai Eye	71.9
A4M10	Stinhoutboom Eye	14.2
A3M11	Vergenoegd Eye	292.6
A3M15	Doornfontein Eye	79.4
A3M17	Renosterfontein Eye	28.6
A3C19	Doornplaat Upper	70
A3M19	Doornplaat Lower	527.8
A3M20	Kareebosch Eye	115.9
A3M21	Paardevlei Eye (District I)	145.8
A3M22	Paardevlei Eye (District II)	4.2
A3M23	Malmani Eye	219.8
A1M03	Tweefontein Upper	45.6
A1M04	Tweefontein Lower	0
D4M04	**Total**	**2481.8**

8.1.10 GH3602 (Bredenkamp, 1988)

This report on the alleged influence of what is here referred to as the Bo-Molopo State Water Scheme on the Olievendraai Spring documents the weakening of the spring between 1981 and 1987. The water scheme referred to here is the harvesting of water from the Molopo Eye via a canal to supply Mafikeng/Mmabatho. The Rietvallei/Weltevrede Irrigation Board alleged that this scheme negatively influences the Olievendraai Spring due to the weakening of the spring. The scheme commenced in October 1985 and reliable measurements have been taken since inception.

Problems with flow measurements at the Olievendraai Spring are mentioned, but a correlation between spring-flow and the water level in Wondergat of 0.96 enabled a graph of spring-flow for the Olievendraai Spring to be constructed between 1980 and 1988, the time of the report. A clear decline in spring-flow can be observed between roughly 1981 and 1988, leading to the alleged impact of the State Water Scheme on the spring. This decline is however attributed to the '*serious drought*' experienced between 1977 and 1988. The spring has an average flow of 1.5 Mm^3/a and experienced a maximum flow of estimated 6 Mm^3/a in 1976 after the good rains between 1974 and 1976. The low flow experienced in 1988 compared to flows measured during the drought in 1964-1966, prior to the commencement of the scheme.

It was however pointed out as early as 1964 that the pumping of a certain borehole 300 m upstream from the spring (DN1) directly influences the spring-flow. It is even more pronounced during periods of low flow.

8.1.11 GH3603 (Bredenkamp and Swartz, 1988)

This is the first modelling report known on the Rietpoort Compartment to determine supply potential based on groundwater recharge and abstraction. Other than report GH1278 (1965), this report differentiates between the Rietpoort and Buffelshoek Springs in terms of catchments (invoking separate compartments), although no clear boundary could be delineated.

The model was calibrated using simulated and observed water levels in monitoring boreholes (A3N11,12,13) and three scenarios were modelled. The model concluded that the compartment was not over-utilised, in spite of the lower than average rainfall, and that increased abstraction might even be considered. It was proposed that abstraction be increased by 30% to put pressure on the system in order to determine whether the aquifer reacts as predicted.

The six production boreholes at the Rietpoort scheme were pumped in schedule to produce the required 7500 m^3/day. The observation borehole located in the well field (OBS7) was monitored electronically, and remained in a constant state of drawdown. The other monitoring boreholes used in the simulation showed fluctuations varying depending on its location. A3N11 being the furthest south (near Ottoshoop) showed prominent increases in water levels of between three and four metres due to recharge between 1978 and 1982. Between mid-1982 and March 1988 there was a continual drop in water level of around 10 m, with a subsequent recovery of five metres. The drop in water level is also reflected in the other two monitoring boreholes nearer to the well field; even borehole A3N13 located only 300 m from the production boreholes which showed a drop in water level of around seven metres with no subsequent recovery. Borehole A3N12, located 1.3 km south of the well field followed the same downward trend, but only for two metres. Due to the constant drop in the water level between 1984 and 1987 in A3N11 near Ottoshoop, it was deduced that the Ottoshoop Dyke forms an impermeable boundary with the only recharge from the compartment to the south coming in the form of the Malmani River during wet seasons.

In Figure 8-1 it can be seen that the water level in A3N11 is the shallowest, fluctuating between 3-4 and 8-9 mbgl while the level dropped to as low as 13 mbgl during the dry period. Borehole A3N12 showed the least fluctuation with a level around 12-14 mbgl. The water level in borehole A3N13 located 300 m to the north of the well field had the deepest water level at 20-21 mbgl, and showed the same drop in water level down to 28 mbgl during the dry period.

Aquifer parameters for the Rietpoort Compartment were derived from the testing of the six production boreholes at Rietpoort. A transmissivity of between 3 000 and 5 000 m^2/d and storativity of between 0.004 and 0.016 was derived using the Jacob equation. It is also noted that the transmissivity values might be overstated since some of the boreholes were further developed using dynamite (to increase the borehole transmissivity and yield).

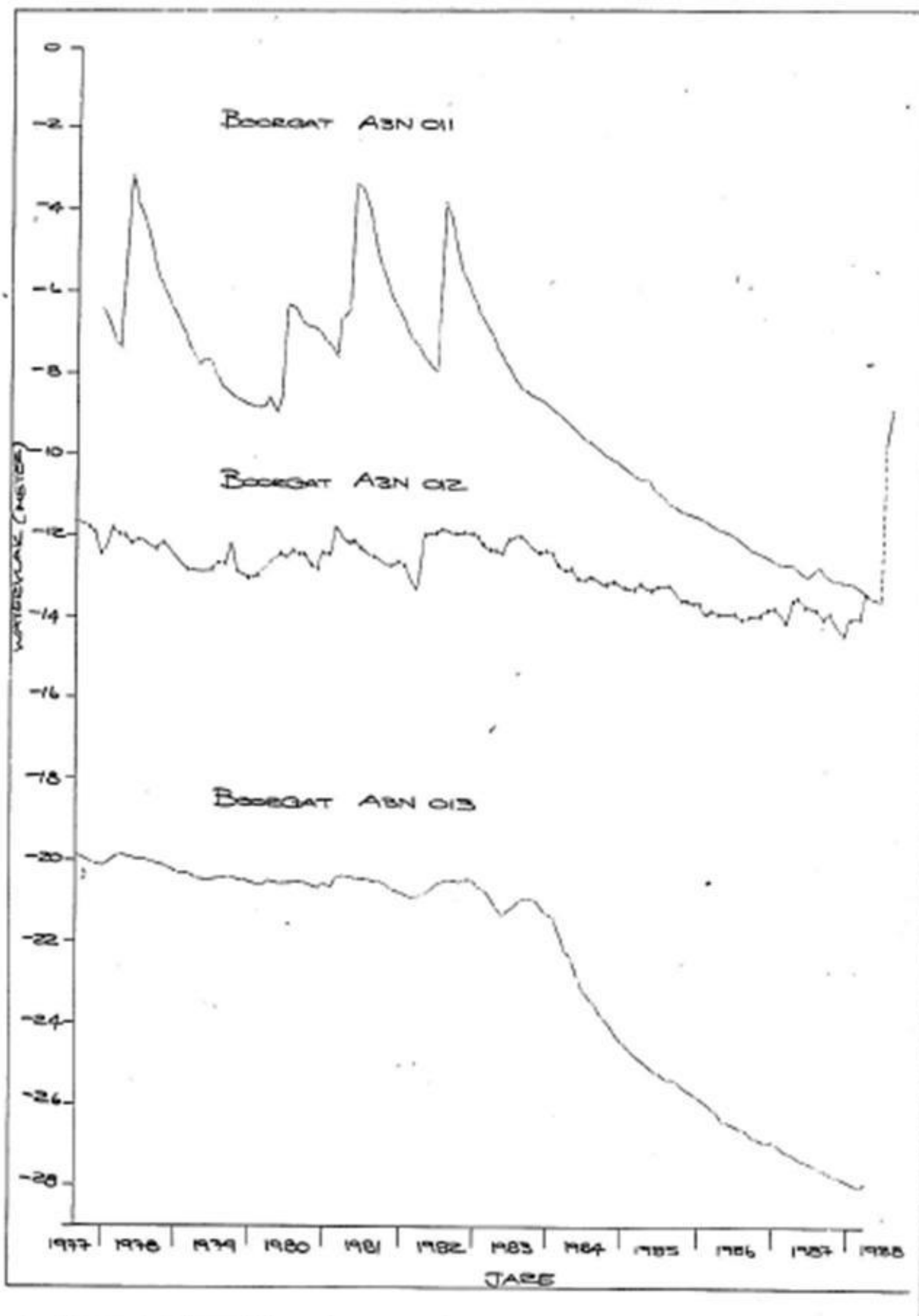


Fig. 4. Watervlakskommelings in waarnemingsboorgate binne die Rietpoortkompartement.

Figure 8-1: Figure 4 from report GH3603 indicates the water levels and fluctuations in monitoring boreholes in the Rietpoort Compartment

The model was however calibrated with a transmissivity of 600 - 800 m^2/d (except for OBS7 T = 350 - 400 m^2/d) and storativity of 0.02 and 0.04 for the entire aquifer.

8.1.12 GH3770 (Brink, 1992)

A geophysical investigation was conducted focussing on the fault that cuts through Zeerust with the aim of finding additional water sources. Gravity and electromagnetic methods were used. As part of this investigation, a hydrocensus was conducted in a predefined area around Zeerust. Only one borehole however could be found from this data that plots inside the area under investigation. This borehole is located near the Vergenoegd Spring (Latitude: -25.60555, Longitude: 25.9925) and had a water level measured at 17.5 mbgl, which translated to 1300.5 mamsl from a collar height of 1318 mamsl.

8.1.13 GH3815 (Botha, 1993)

This is another report to investigate the potential of the Rietpoort Catchment as a source of water to Zeerust. It starts off by mentioning that Zeerust and the fluorspar mines were allocated a total of 4.2 Mm^3/a from the Rietpoort Compartment as part of the Bo-Molopo Groundwater Control Area, although the current (1993) demand is only 2.8 Mm^3/a. In 1965 the town of Zeerust was allocated 98.75 % of the flow from the Rietpoort Spring, while additional permits for groundwater abstraction were issued to the town and the mines. The Rietpoort well field was developed in 1975 when the spring-flow proved insufficient for the combined needs. It was found that abstraction from the compartment was much higher during 1978 and 1982 than during the period 1983 to 1993.

Recharge over the compartment was previously calculated at 10% of rainfall (being an average of 480 mm/a over the 15 years prior to 1993), amounting to 3.37 Mm^3/a (taking the Buffelshoek Spring into account). In 1989 future water demands were predicted at 3.3 Mm^3/a for the year 2000, but this did not make provision for the upgrading of services to townships, and it was estimated that this figure would have to be adjusted upwards.

This report's objective is to re-evaluate the groundwater potential. Data used included continuous water levels, abstraction rates, spring-flow and rainfall data for Rietpoort between 1977 and 1993.

The availability of data is discussed in detail in the report.

The report mentions that the Rietpoort Spring has effectively ceased flowing in March of 1984 due to the intensive pumping of the Rietpoort Well Field. The abstraction does not seem to have an effect on the Buffelshoek Spring due to the overriding effect of rainfall. The correlation between spring-flow and water levels as monitored in the compartment is much stronger, and this relationship was used to correct faulty spring-flow readings at both springs.

Abstraction records from the Rietpoort WellFfield were kept consistently for the period, and it is reported by the municipality’s electrical engineer that water levels drop by only one metre during pumping, despite the high yields of the production boreholes. Monthly abstraction during the period 1982 to 1993 averaged around 0.2 Mm^3. The main limiting factor to the supply of water to Zeerust is the capacity of the pipeline (75 L/s) and the small reservoir at Zeerust.

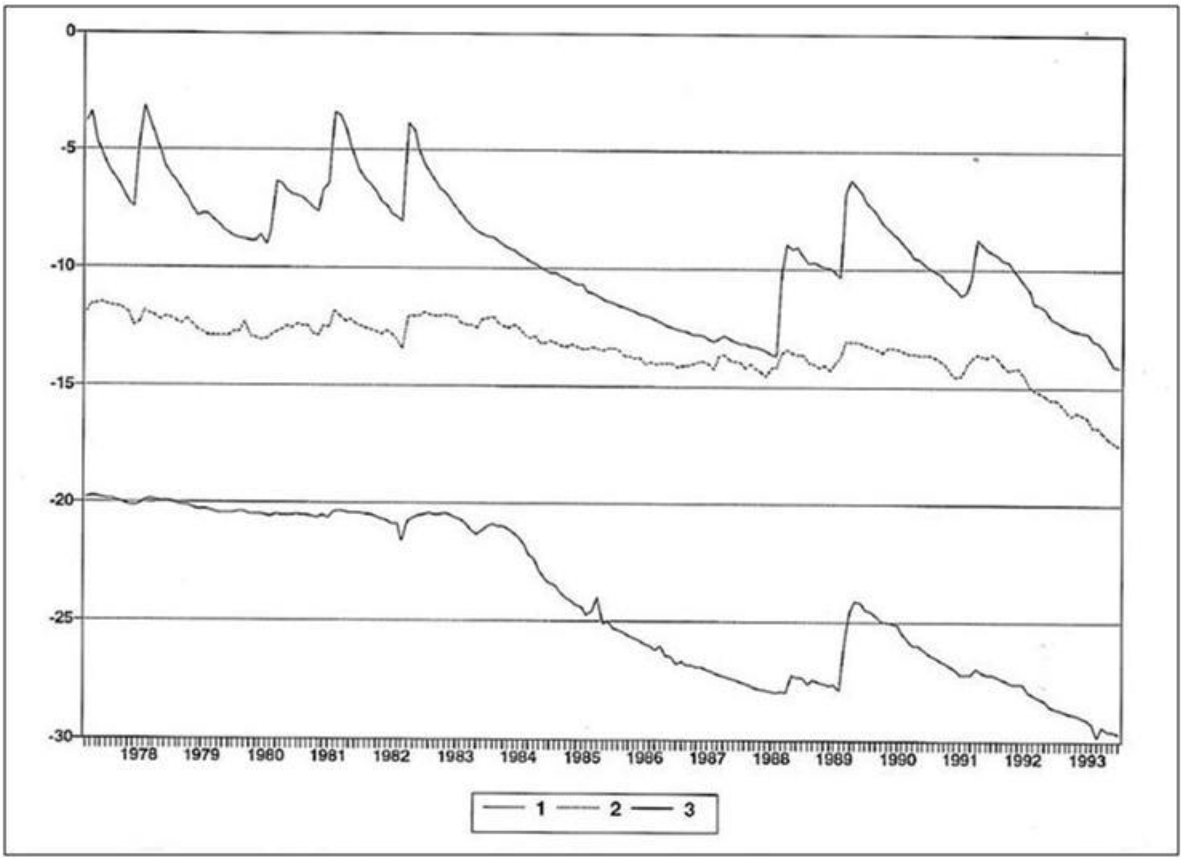


Figure 8-2: Comparison in the water levels in monitoring boreholes A3N11, 12 and 13 (GH3815).

Water level fluctuations in the same three monitoring boreholes mentioned in GH3603 are discussed, and graphs covering the same time frame (see Figure 8-1) but extended up to 1993 are drawn (see Figure 8-2). From these graphs it can be seen that after the prolonged drop in water levels in A3N11 and A3N13, two distinct recharge events were recorded in 1988 and 1989. Another recharge event was registered in A3N11, after which a consistent drop in all levels was recorded. Even A3N12 which did not drop below 15 mbgl since 1977 showed a drop in water level down to below 17 mbgl.

Various methods were used to assess the situation. A water balance was done using the SVF method, while the recharge and storativity was determined using the CRD method and Direct Parameter Estimation Method (DPEM). Recharge was also determined using spring-flow and the chloride method.

In summary, an average recharge of 10% was determined for the compartment (but has realised up to 14% on occasion), while the storativity ranges between 2.5 and 5%. The recharge volume of 3.37 Mm^3/a calculated is still more than the 1993 abstraction rate of 2.8 Mm^3/a. However, if the flow of the Buffelshoek Spring of approximately 1.0 Mm^3/a is subtracted, it leaves a balance of 2.37 Mm^3/a which is less than the 1993 abstraction. It is therefore concluded that the entire recharge volume can be utilised, provided that the capacity of the Buffelshoek Spring is harvested.

8.1.14 GH3948 (Nel, 2000)

After realising that a shortage in monitoring data proved to be a limiting factor in calibrating groundwater models, a decision was made to drill new boreholes in the three dolomitic areas in the Bo-Molopo Groundwater Protection Area: Zeerust, Grootfontein and Lichtenburg. The Zeerust area received a total of 26 boreholes. This report documents the drilling results and geohydrological findings. A small map indicates the position of each borehole relative to the extent of the dolomite, while a log containing the coordinates (decimal degree format) details the geology and several geophysical logs.

This report is practically of no use since the two sets of coordinates for each borehole differs from each other and from the positions indicated on the maps. Therefore all three methods of locating the individual boreholes differ from each other and therefore it is not possible to locate the data geographically.

8.1.15 Report No. AQS/AFRICON/2002/001 (Africon, 2002)

In 2002 Aquisim was contracted by Africon to conduct aquifer test analyses and groundwater flow modelling to determine the long term abstraction potential from the dolomite underlying the farm Uitvalgrond 60 JO to supply the Welbedacht Area. This report concluded that three of the five boreholes tested are capable of yielding more than 30 L/s on a short to medium term based on aquifer tests. The compartment was modelled based on the assumption that it is in hydraulic equilibrium, i.e. recharge to the aquifer is balanced out by spring-flow and other losses (evapotranspiration). Recharge was calculated at 12% of rainfall (in line with previous studies), or 4 048 m^3/d over the compartment. It was concluded that spring-flow would be sensitive to well field drawdown, and that for a drawdown of one metre, the Wolvekoppies Spring-flow would reduce from 8 L/s to 2 L/s, and the Klaarstroom Spring-flow from 22 L/s to 15 L/s. An optimal borehole field yield of 31 L/s was recommended, although the springs were anticipated to cease flowing (the Wolvekoppies after six months and the Klaarstroom only after 20 years). Monitoring of the abstraction rates and water levels were also recommended from the inception of the borehole field.

8.1.16 Report No. 2005/0076-02 (Bogare, 2005)

Also available as Report No 22(953) on DWA's archive system

The Uitvalgrond Well Field was developed and commissioned in April 2003 as per the above recommendations. In March 2004 the wellfield started to fail and abstraction was reduced. By early September 2004 the abstraction was discontinued as all boreholes failed. This prompted urgent measures from the NMMDM who appointed Bogare Consultants Consortium (BCC) to re-evaluate the well field and augment supply from neighbouring compartments. A required yield of 40 L/s was specified. Khulani GeoEnviro Consultants (part of the consortium) sought involvement from other specialists VSA and Aquisim (Khulani, 2005).

According to this report, another consortium of companies comprising VSA, Africon and Environmental Management Accountants commenced with a detailed regional study of the North West Dolomites. It involved the delineation of 50 compartments with the aid of aeromagnetic surveys and groundwater levels, a comprehensive 3D numerical flow model over a 30 year period, and the identification of areas where an additional 230 L/s could be developed sustainably.

A map was reproduced in this report indicating the positions of dykes and newly described compartments, referred to as ‘dolomite compartment units’ or DCU’s. The Vergenoegd Dolomite Compartment Unit (DCU) was identified as an area where 40-45 L/s could be developed sustainably with predicted long term drawdowns of less than five metres. The Vergenoegd Springs (average 80 L/s) and Paardenvallei Springs (average 66 L/s) discharges water from this compartment and it was identified as the main target to source water to augment supply to Welbedacht.

In investigating the failure of the Uitvalgrond Well Field, the report admits that monitoring data are limited. Only once the boreholes started to fail was water levels recorded and a drawdown in the order of 14 m was reported. After complete failure in September 2004 the NMMDM monitored water level recovery from November 2004 to early 2005. The monitoring data indicates a further decline in water levels from 8 November 2004 to 23 December 2004 (attributed to natural losses during a period of insignificant or no recharge from rainfall), after which it recovered by a mere one metre or less in the space of a month.

The volume meter readings on the abstraction boreholes were measured on 19 May 2004 after 13 months of abstraction. The report mentions that it is possible that some of the meters got stuck since the measured volume gives an average daily abstraction of 17.2 L/s whereby the estimated abstraction (based on the larger meter reading and recommended rate) is 25.6 L/s. The measured data therefore seems to be incomplete and unreliable.

This report concluded that the main reasons for failure of the Uitvalgrond Well Field were the limited area of investigation in 2002, and the existence of a previously unknown flow barrier between the Wolvekoppies and Klaarstroom Springs, which were thought to be in hydraulic connectivity. The flow height of the Klaarstroom Eye was found to be about 10 m higher than the Wolvekoppies Spring confirming the flow barrier. The sustainable yield from the Uitvalgrond Well Field was recalculated as being 6.0 L/s, which can be increased to 9.0 L/s once water levels have recovered to within five metres.

An in-depth investigation into the relationship between rainfall and recharge was also described. The findings were that should the monthly CRD be negative, the system was still in debt and groundwater levels below equilibrium.

Any effective recharge during the negative CRD period would practically be restoring the aquifer to equilibrium conditions. During positive CRD conditions sufficient monthly rainfall would recharge the aquifer to above equilibrium conditions. A threshold of 65 mm within a month was identified as being a cut-off value for effective recharge to occur. Above this threshold, recharge increased exponentially. It was further proposed that the 70 percentile effective annual recharge value of 55 mm (or 1.75 L/s/km^2) be used in evaluating sustainable abstraction from the dolomites. This means that a more conservative approach to the water balance was used.

A comparison between the groundwater levels and spring-flow data from DWA, indicated a strong relationship, where it was observed that when the groundwater levels rose, spring-flow would increase. Variations in both could also be strongly linked to variations in recharge. For example, a 12 year period of no/very little recharge was calculated between 1983 and 1995 which corresponded with a decline in spring-flow and water tables. The Vergenoegd Spring effectively ceased flowing during this period, while the Paardenvallei, Kraalfontein, Tweefontein Upper and Stinkhoutboom Springs experienced periods of low flow, followed by periods of no-flow.

This study also resulted in the revision of the DCU's based on new data. The Klaarstroom DCU (previously 13 km^2) was divided into a new smaller Klaarstroom compartment (5 km^2) and the Wolvekoppies compartment (7.1 km^2) in which the Uitvalgrond Well Field is situated because of the identified flow boundary. The Tweefontein DCU of 38.4 km^2 was also sub-divided into the Tweefontein (22.3 km^2) and the Tweefontein South (16.1 km^2) compartments.

The report proposed the augmentation of water to the Welbedacht Scheme from boreholes spread over the Wolvekoppies, Tweefontein South and Paardenvallei-Vergenoegd DCU's to limit the impact on drawdowns and spring-flow.

A target yield of 45 L/s was chosen to include a spare capacity of >10 L/s for optimal well field management. Eight new production borehole sites were finally identified based on the gravity survey over two compartment units: the Vergenoegd DCU and the Tweefontein South DCU. The boreholes were sited in high transmissive zones called major saturated leached zones. A storage volume of 2 898 000 m^3 was calculated for the upper five metres of the targeted aquifer zones, which was believed to be sufficient to supply the demand of 3 456 m^3/d for an abstraction period of 3.2 years.

The total Welbedacht water demand (40 L/s) represents 38% of the recharge over the DCU's (105.6 L/s) while the inflow into the Paardenvallei-Vergenoegd DCU from the surrounding compartments was modelled at 116.7 L/s during the regional dolomite study.

It further recommended the registration of the water use from the four Uitvalgrond Well Field boreholes with DWA (max 10 L/s) and the monitoring of water levels with a bi-annual monitoring report to be compiled. Continuous monitoring equipment was recommended for boreholes 21-00036 and PV-20 and a rain gauge to monitor rainfall. Furthermore the monitoring of the spring-flow at Vergenoegd weir (A3H011 which closed in 1992) was recommended to be reinstated.

The drilling of five proposed monitoring/exploration boreholes was recommended to obtain critical water level data and the updating of the 3D numerical model with the new data. Finally an EIA was recommended as per relevant legislation to assess the impact of the proposed new abstraction to augment the Welbedacht Scheme. Only once authorisation was obtained and land owner agreements were in place the drilling of production boreholes could commence (Khulani, 2005).

8.1.17 Report No. AQS/KHULANI/2005/001 (Khulani, 2005)

Aquisim updated the 2002 model in this 2005 report after the Uitvalgrond Well Field failure with new data which became available. The investigation had as objectives the following:

- Determine the feasibility to supply 6 L/s from the Uitvalgrond Well Field
- Determine the feasibility to supply 10 L/s from the Tweefontein South compartment
- Determine the feasibility to supply 30 L/s from the Paardenvallei compartment (in addition to existing use of 29 L/s)
- Determine the impact of abstraction on the water levels and spring-flow rates and other natural system losses.

The following were concluded:

- The abstraction of 6 L/s from the Uitvalgrond Compartment was deemed feasible as the long term average spring-flow of the Wolvekoppies Spring was calculated at 8 L/s. At this abstraction rate an 80% chance was calculated that the Wolvekoppies Spring would cease flowing and a 40% chance of a drawdown exceeding six metres. Recharge events would however recover water levels.

- The minimum simulated recharge rate to the Tweefontein South Compartment is ~25 L/s, making the abstraction of 10 L/s feasible, although a drawdown of more than six metres has a 60% probability in the worst case scenario, and 20% probability in the most likely scenario. Similarly recharge events are expected to recover water levels and no long term detrimental impacts are foreseen. The water level in this compartment is also expected to be influenced by abstraction from the Paardenvallei Compartment.

- The minimum simulated long term potential from the Paardenvallei Compartment is in the order of 146 L/s. Together with the current abstraction of ~30 L/s, the compartment is deemed fit to yield a further 30 L/s. Similarly a drawdown in excess of six metres has a 60% probability in the worst case scenario, and a ‘low risk’ of achieving this drawdown exists in the most likely scenario. It was concluded that the proposed abstraction would have no detrimental effect on the water levels in the long term. The simulations indicated that the water levels do recover in this compartment even after periods of drought. The reduction in spring-flow of the Paardenvallei Spring was anticipated to be between 10 and 30 L/s and the Vergenoegd Spring between 5 and 15 L/s.

The report recommended the drilling of the production boreholes as Khulani (2005) suggested, and the establishment of a monitoring programme to be established from the inception of the well field to monitor abstraction rates and water levels. The data must be used to evaluate the aquifer and well field performance bi-annually in order to take corrective measures where needed. The groundwater flow model was recommended to be updated every year with the monitoring data.

8.1.18 EIA_507/2005NW_Zeerust/KGC_FSR_002 (Khulani, 2006)

This is the final scoping report of the EIA proposed by Khulani in 2005. It stipulates the processes followed in the investigation, describes the baseline environment and identifies the foreseen impacts in various biophysical fields like: climate, soil, geology/geohydrology, vegetation, fauna, etc. Sinkholes are described as forming part of the pre-development natural environment (one sinkhole was identified during the survey) but are also flagged as being exacerbated by human actions. The direct link between excessive groundwater abstraction and new sinkhole formation is however not addressed. This is deemed a critical impact to consider where bulk groundwater abstraction from dolomitic areas is concerned. Neither is the construction activities of the pipeline on the dolomite stability addressed.

An Environmental Management Plan (EMP) was compiled for the project based on the identified impacts, and the project go-ahead was recommended based on the adherence to the EMP.

The boreholes were drilled, tested and equipped to augment the Welbedacht Bulk Water Supply Scheme from the Uitvalgrond Well Field (UWF). The newly drilled boreholes are referred to as the Vergenoegd Well Field (VWF). This investigation was launched into the alleged impact of the bulk abstraction from the VWF on the environment.

The NMMDM initiated an audit of the activities surrounding the bulk groundwater abstraction from the VWF. The final audit report was submitted in September 2011 in which the operation and maintenance of the borehole field was scrutinised against the recommendations of both the final scoping report and EMP (Khulani, 2006 and the 2005 modelling update (Aquisim, 2005). The findings of this report will be discussed in section 8.2.

8.1.19 Department of Water Affairs (DWA) compartment delineation studies undertaken in 2009

The Department of Water Affairs (DWA) published a series of reports and maps in 2009 on the delineation of ‘compartments’ on the major dolomitic areas in South Africa. This included the Far West Rand (FWR) dolomites between Krugersdorp and Carletonville and further west towards Potchefstroom, as well as the North West dolomites between Ventersdorp and Lichtenburg and northwards towards Zeerust and Lobatse.

In the report (booklet), the delineation methodology is described as follows (Holland and Wiegmans, 2009):

- Groundwater Resource Unit
- *A groundwater body that has been delineated or grouped into a single significant water resource based on one or more characteristics that are similar across that unit.*
- Groundwater Management Unit
- *An area of a catchment that requires consistent management actions to maintain the desired level of use or protection of groundwater.*
- *The GMU's are based on surface water drainage and hydrogeological considerations, each of which represents a hydrogeologically homogeneous zone wherein boreholes tapping the shallow groundwater system will be, to some degree or other, in hydraulic connection.*
- Groundwater Management Area
- *GMAs generally coincide with surface drainage boundaries (e.g. quaternary catchments)*
- *Does not necessarily represent a dolomite compartment or unit (larger area comprising a number of GMU's and GRU's)*

A map was produced for the North West Dolomites indicating the Groundwater Management Areas (GMA) and Groundwater Management Units (GMU) as well as the locations of springs, monitoring stations and quaternary catchments draped on a geology basemap (Holland and Wiegmans, 2009).

The major GMA's and GMU's are given in Table 18 together with associated spring names and station numbers.

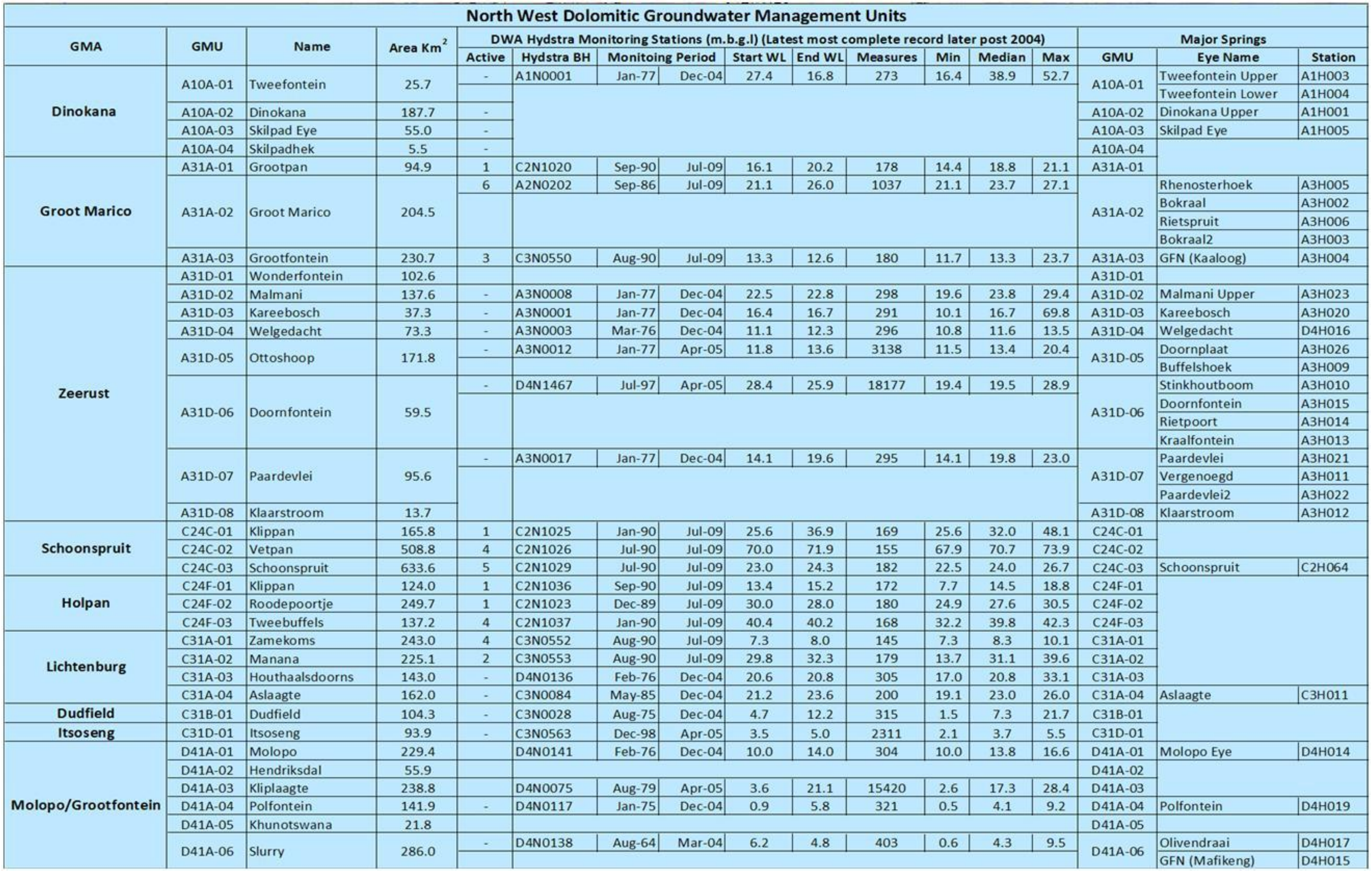
The area under investigation forms part of the Zeerust GMA hence it is generally referred to as the Zeerust Dolomites. Inside this GMA are several smaller GMU's, of which the Paardevlei GMU will form the area of investigation. The Paardevlei GMU is 95.6 km^2 in size and has three springs: the two Paarde(nval)lei springs and the Vergenoegd Spring.

The Paardevlei GMU is separated from the Doornfontein GMU to the south by the Doonfontein Dyke while the Doornfontein GMU is separated by the Rietpoort GMU to its south by the Rietpoort Dyke.

The Vergenoegd Dyke located in the Paardevlei GMU used to be seen as a compartment boundary dividing the Vergenoegd DCU from the Tweefontein and Klaarstroom in previous work (Aquisim, 2005; Khulani, 2005) whereas here it is not seen as a dividing boundary.

The Paardevlei and Klaarstroom GMU's form the northernmost GMU's of the Zeerust Dolomites. North of the Zeerust GMA, the Dinokana GMA is located.

Table 18: North West Dolomitic Groundwater Management Areas and Units (Holland and Wiegmans, 2009)



North West Dolomitic Groundwater Management Units

GMA	GMU	Name	Area Km^2	DWA Hydstra Monitoring Stations (m.b.g.l) (Latest most complete record later post 2004)										Major Springs		
				Active	Hydstra BH	Monitoing Period		Start WL	End WL	Measures	Min	Median	Max	GMU	Eye Name	Station
Dinokana	A10A-01	Tweefontein	25.7	-	A1N0001	Jan-77	Dec-04	27.4	16.8	273	16.4	38.9	52.7	A10A-01	Tweefontein Upper	A1H003
															Tweefontein Lower	A1H004
	A10A-02	Dinokana	187.7	-										A10A-02	Dinokana Upper	A1H001
	A10A-03	Skilpad Eye	55.0	-										A10A-03	Skilpad Eye	A1H005
	A10A-04	Skilpadhek	5.5	-										A10A-04		
Groot Marico	A31A-01	Grootpan	94.9	1	C2N1020	Sep-90	Jul-09	16.1	20.2	178	14.4	18.8	21.1	A31A-01		
	A31A-02	Groot Marico	204.5	6	A2N0202	Sep-86	Jul-09	21.1	26.0	1037	21.1	23.7	27.1	A31A-02	Rhenosterhoek	A3H005
															Bokraal	A3H002
															Rietspruit	A3H006
															Bokraal2	A3H003
	A31A-03	Grootfontein	230.7	3	C3N0550	Aug-90	Jul-09	13.3	12.6	180	11.7	13.3	23.7	A31A-03	GFN (Kaaloog)	A3H004
Zeerust	A31D-01	Wonderfontein	102.6											A31D-01		
	A31D-02	Malmani	137.6	-	A3N0008	Jan-77	Dec-04	22.5	22.8	298	19.6	23.8	29.4	A31D-02	Malmani Upper	A3H023
	A31D-03	Kareebosch	37.3	-	A3N0001	Jan-77	Dec-04	16.4	16.7	291	10.1	16.7	69.8	A31D-03	Kareebosch	A3H020
	A31D-04	Welgedacht	73.3	-	A3N0003	Mar-76	Dec-04	11.1	12.3	296	10.8	11.6	13.5	A31D-04	Welgedacht	D4H016
	A31D-05	Ottoshoop	171.8	-	A3N0012	Jan-77	Apr-05	11.8	13.6	3138	11.5	13.4	20.4	A31D-05	Doornplaat	A3H026
															Buffelshoek	A3H009
	A31D-06	Doornfontein	59.5	-	D4N1467	Jul-97	Apr-05	28.4	25.9	18177	19.4	19.5	28.9	A31D-06	Stinkhoutboom	A3H010
															Doornfontein	A3H015
															Rietpoort	A3H014
															Kraalfontein	A3H013
	A31D-07	Paardevlei	95.6	-	A3N0017	Jan-77	Dec-04	14.1	19.6	295	14.1	19.8	23.0	A31D-07	Paardevlei	A3H021
															Vergenoegd	A3H011
															Paardevlei2	A3H022
	A31D-08	Klaarstroom	13.7											A31D-08	Klaarstroom	A3H012
Schoonspruit	C24C-01	Klippan	165.8	1	C2N1025	Jan-90	Jul-09	25.6	36.9	169	25.6	32.0	48.1	C24C-01		
	C24C-02	Vetpan	508.8	4	C2N1026	Jul-90	Jul-09	70.0	71.9	155	67.9	70.7	73.9	C24C-02		
	C24C-03	Schoonspruit	633.6	5	C2N1029	Jul-90	Jul-09	23.0	24.3	182	22.5	24.0	26.7	C24C-03	Schoonspruit	C2H064
Holpan	C24F-01	Klippan	124.0	1	C2N1036	Sep-90	Jul-09	13.4	15.2	172	7.7	14.5	18.8	C24F-01		
	C24F-02	Roodepoortje	249.7	1	C2N1023	Dec-89	Jul-09	30.0	28.0	180	24.9	27.6	30.5	C24F-02		
	C24F-03	Tweebuffels	137.2	4	C2N1037	Jan-90	Jul-09	40.4	40.2	168	32.2	39.8	42.3	C24F-03		
Lichtenburg	C31A-01	Zamekoms	243.0	4	C3N0552	Aug-90	Jul-09	7.3	8.0	145	7.3	8.3	10.1	C31A-01		
	C31A-02	Manana	225.1	2	C3N0553	Aug-90	Jul-09	29.8	32.3	179	13.7	31.1	39.6	C31A-02		
	C31A-03	Houthaalsdoorns	143.0	-	D4N0136	Feb-76	Dec-04	20.6	20.8	305	17.0	20.8	33.1	C31A-03		
	C31A-04	Aslaagte	162.0	-	C3N0084	May-85	Dec-04	21.2	23.6	200	19.1	23.0	26.0	C31A-04	Aslaagte	C3H011
Dudfield	C31B-01	Dudfield	104.3	-	C3N0028	Aug-75	Dec-04	4.7	12.2	315	1.5	7.3	21.7	C31B-01		
Itsoseng	C31D-01	Itsoseng	93.9	-	C3N0563	Dec-98	Apr-05	3.5	5.0	2311	2.1	3.7	5.5	C31D-01		
Molopo/Grootfontein	D41A-01	Molopo	229.4		D4N0141	Feb-76	Dec-04	10.0	14.0	304	10.0	13.8	16.6	D41A-01	Molopo Eye	D4H014
	D41A-02	Hendriksdal	55.9											D41A-02		
	D41A-03	Kliplaagte	238.8		D4N0075	Aug-79	Apr-05	3.6	21.1	15420	2.6	17.3	28.4	D41A-03		
	D41A-04	Polfontein	141.9	-	D4N0117	Jan-75	Dec-04	0.9	5.8	321	0.5	4.1	9.2	D41A-04	Polfontein	D4H019
	D41A-05	Khunotswana	21.8											D41A-05		
	D41A-06	Slurry	286.0	-	D4N0138	Aug-64	Mar-04	6.2	4.8	403	0.6	4.3	9.5	D41A-06	Olivendraai	D4H017
															GFN (Mafikeng)	D4H015

8.2 2011 Audit (Masilo & Associates, 2011)

In September 2011 Masilo & Associates submitted an EIA audit report on the activities surrounding the abstraction. Audit activities focussed mainly on recommendations made during the updated modelling excercise (Aquisim, 2005) and the EIA preceding the development (Khulani, 2005).

Concerning the geohydrological parameters, the approach of the EIA audit report was similar to this investigation, in that it used existing data from the monitoring of the production boreholes and from DWA's historical monitoring records to draw conclusions. The four UWF boreholes and six VWF boreholes' monthly abstraction volumes were used to compare the abstraction against the recommendations.

Water level data measured from the VWF were also analysed to determine drawdown. Data from DWA monitoring boreholes and spring-flow monitoring stations were analysed to determine trends that could be ascribed to the pumping of the well field. The data were also compared to rainfall data.

Monitoring protocol

The report states that all steps in the establishment of the well field were undertaken by the NMMDM, but that the adequacy of the steps will be audited. The following table summarises recommendations regarding monitoring made in the EMP (Khulani, 2005).

Table 19: 2011 Audit findings

2005 Model and EMP recommendations	2011 Audit findings
Monthly monitoring	Monthly monitoring
To be established from inception	Data since establishment not available
Monitor abstraction rates, water level drawdown and spring-flow	Only abstraction rates available since October 2009
Bi-annual re-evaluation of aquifer performance	No information on recommended re-evaluation available

The monitoring therefore was not fully in accordance with the 2005 modelling update and EMP recommendations.

Abstraction volumes

Estimates of the water abstraction from each of the Welbedacht boreholes were made from abstraction readings received for the period between September 2009 and March 2011. Daily abstraction rates were derived from the data, and compared to recommendations. Findings of all the production boreholes' data are presented in graph format.

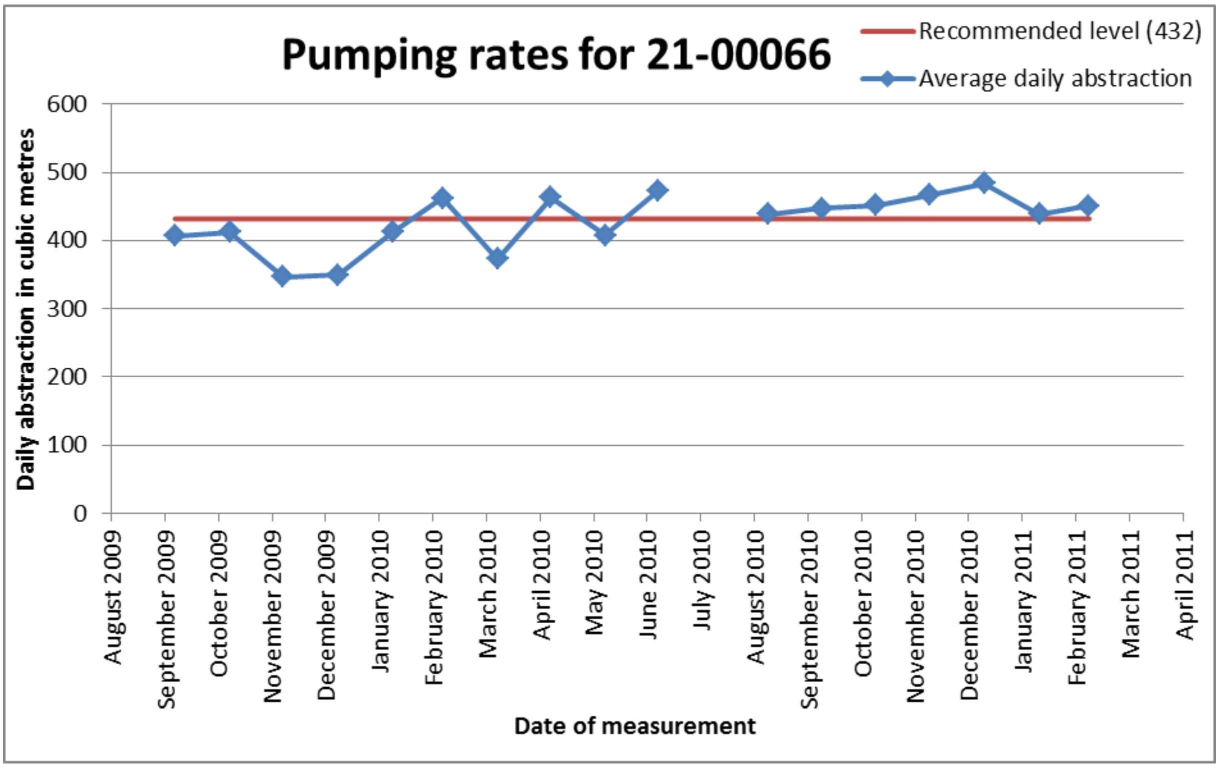


Figure 8-3: Pumping rates for borehole 21-00066

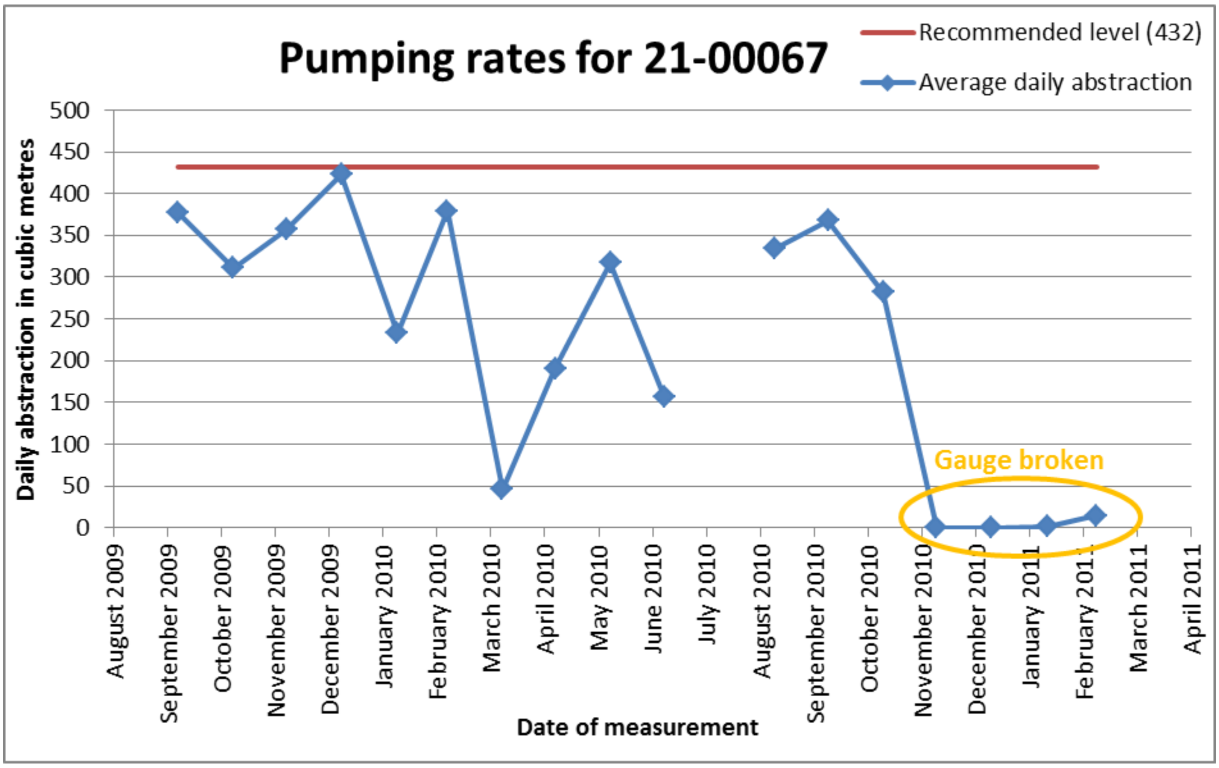


Figure 8-4: Pumping rates for borehole 21-00067

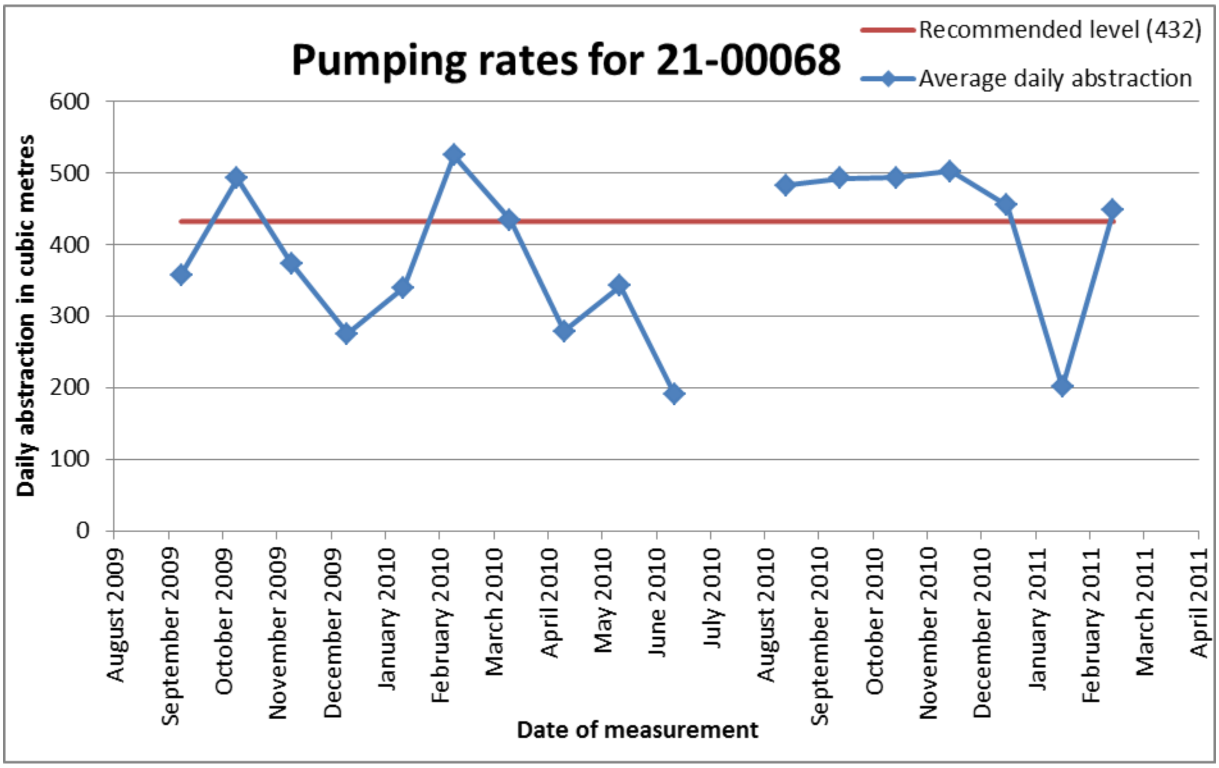


Figure 8-5: Pumping rates for borehole 21-00068

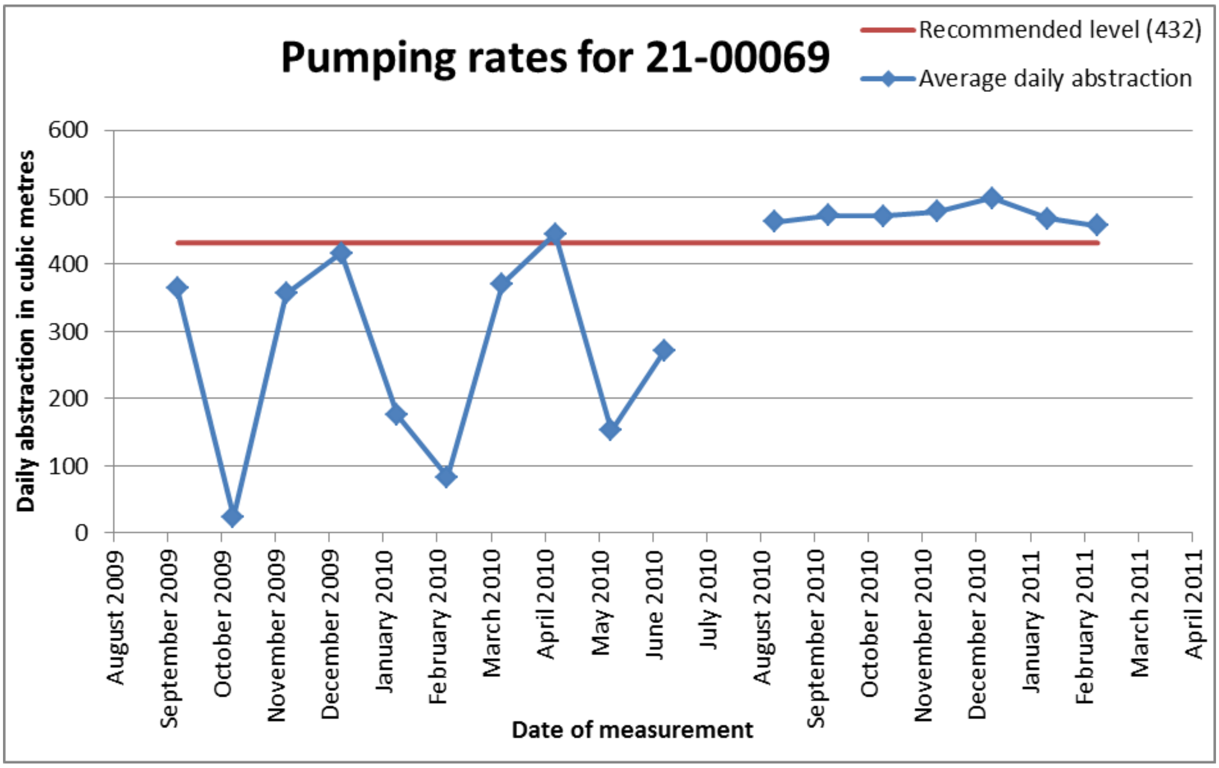


Figure 8-6: Pumping rates for borehole 21-00069

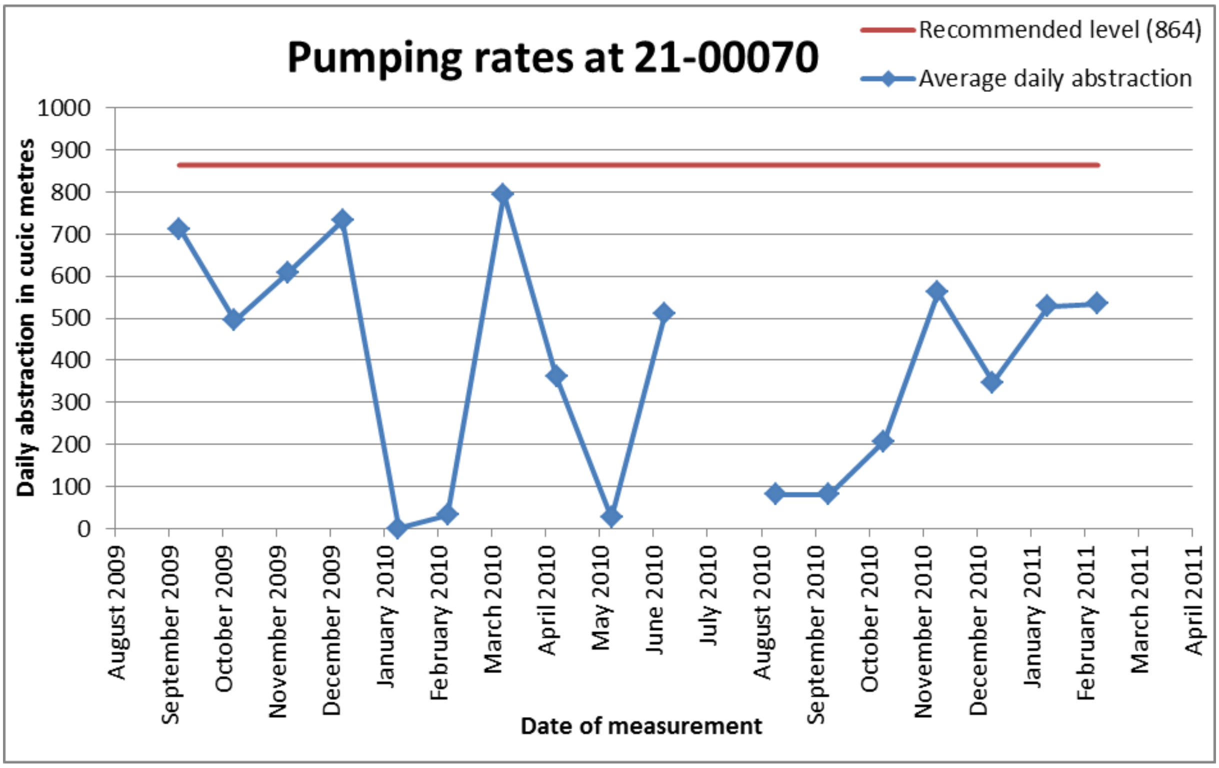


Figure 8-7: Pumping rates for borehole 21-00070

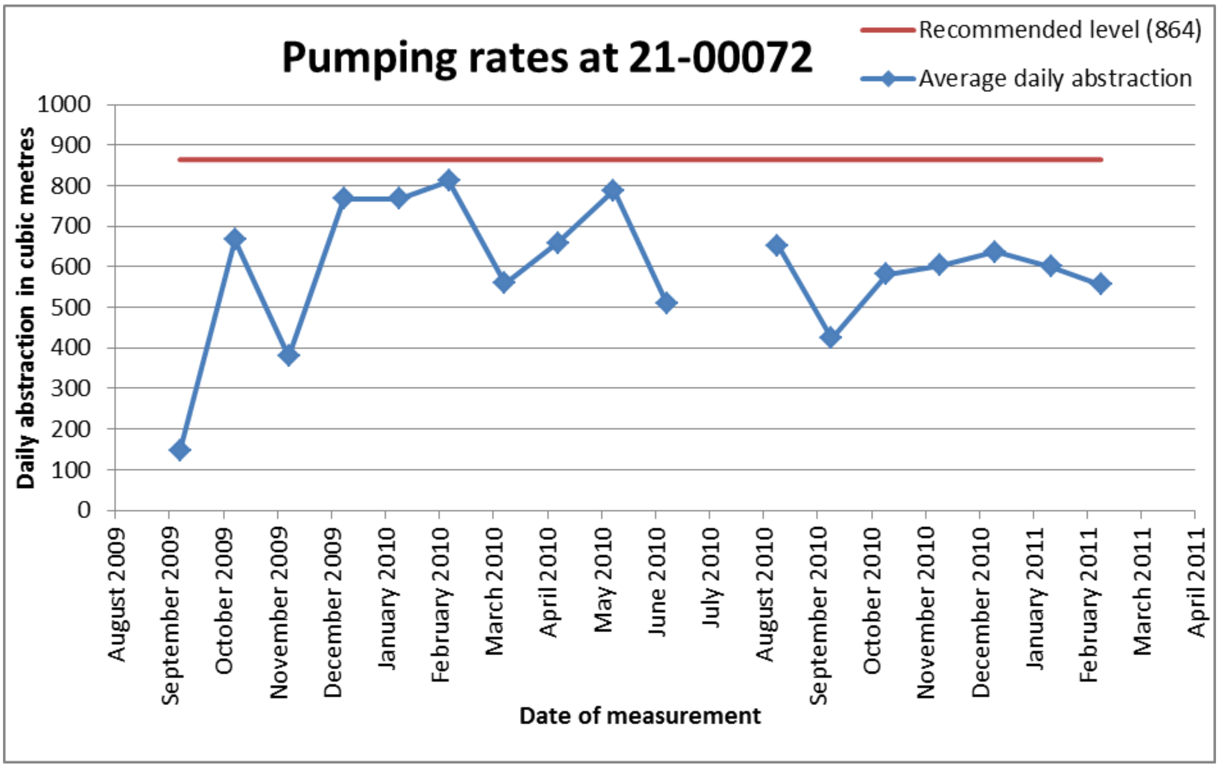


Figure 8-8: Pumping rates for borehole 21-00072

From the data it can be concluded that:

- Borehole 21-00066 exceeded the recommended abstraction limit of 432 m^3/d in March, May and July 2010, and for a continuous period between September 2010 and March 2011.
- Borehole 21-00068 exceeded the recommended daily abstraction limit of 492 m^3/d by 60 m^3/d in November 2009, by 92 m^3/d in March 2010, by two m^3/d in April 2010 and a continuous period of above recommended limit abstraction occurred between September 2010 and March 2011 by at least 50 m^3/d.
- Borehole 21-00069 exceeded the recommended abstraction (432 m^3/d) between September 2010 and March 2011 by up to 67 m^3/d.

However, when combining the data, the average abstraction rate was 32 L/s which is below the 2008 recommendations of 40 L/s.

Water levels

Water level data were derived from a monitoring report referenced (unavailable for this investigation) and monitoring data from DWA. Water level data of available and relevant monitoring boreholes were stacked to represent fluctuations over time. Most of the DWA monitoring data only goes up to 2004. The fluctuations between 2004 and 2011 are reported to only be recorded in boreholes:

- O14 (2525DB00002 or A3N0015),
- PV19 (2525DB00009 or A3N0016) and
- PV20 (2525DB00010 or A3N0017).

Although the data referring to (post-2004) could not be sourced, the report states that the water levels “were markedly constant and low” in all three boreholes, and began to recover again in 2010 (presumably at the end of 2010).

The report concludes that in terms of the 2005 hydrological management recommendations for the borehole field:

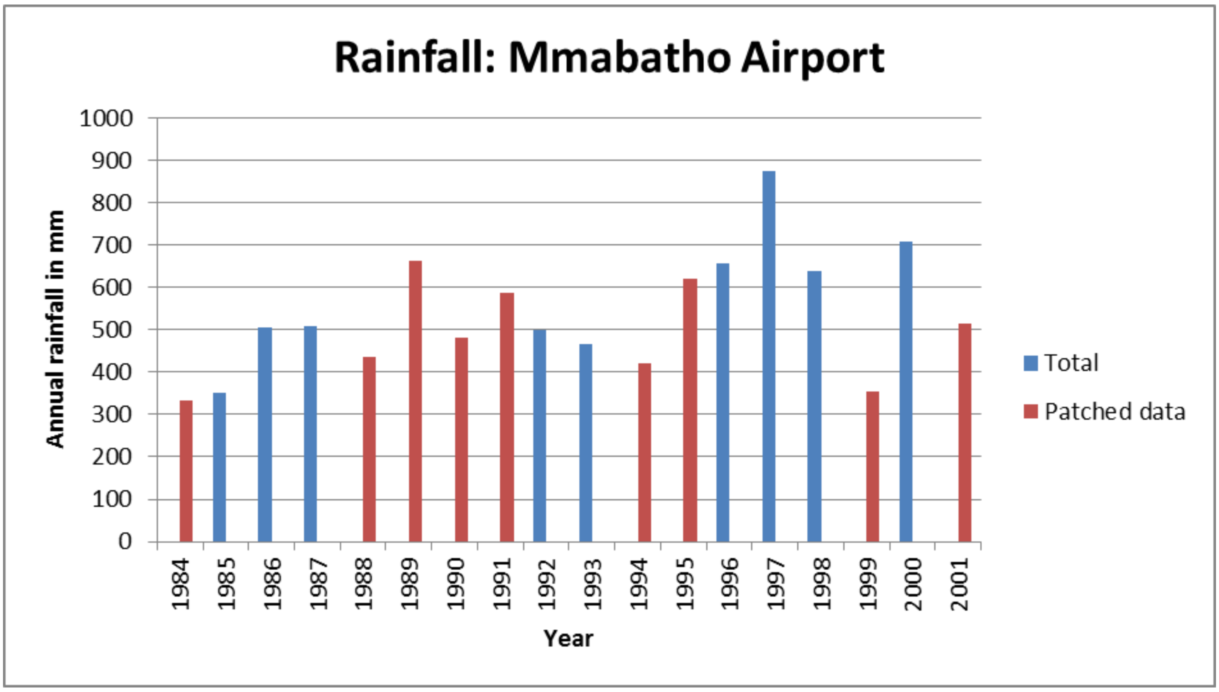
- The recommendations on site-specific monitoring were not adhered to (especially in terms of frequency of recording water levels). Subsequent management steps were therefore not adequately addressed.
- Unknown resting periods were implemented on the production boreholes to help the water level recover.
- Abstraction rates were found to be within the total recommended levels between October 2009 and March 2010.
- Abstraction rates in some production boreholes exceeded the specified limit on occasion

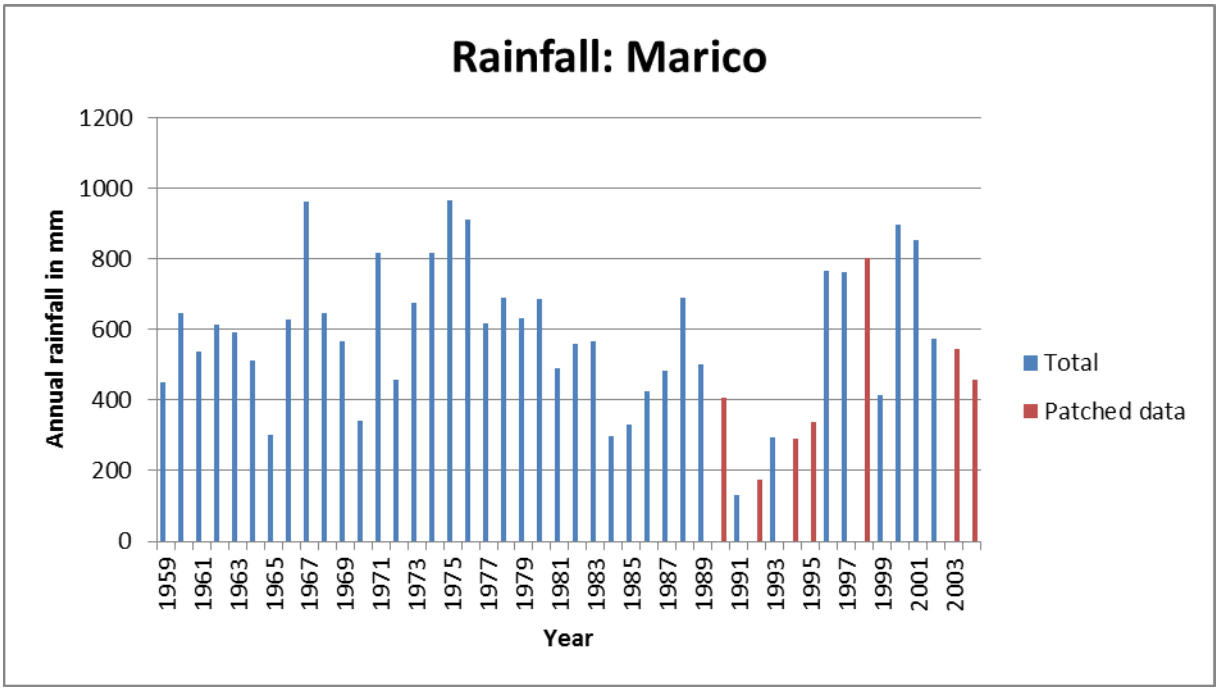
In terms of compliance to the EIA/EMP recommendations, the following were concluded:

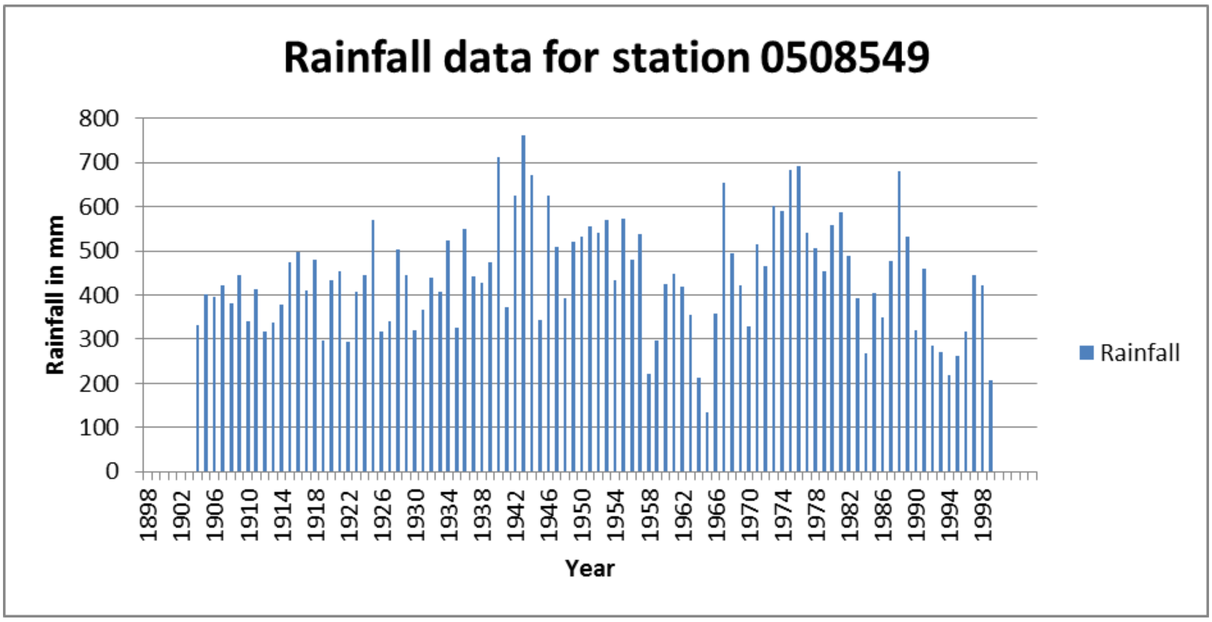
- The recommendations on monitoring, auditing, mitigation reporting of changes to DACE and DWA, and abstraction limits were not satisfactorily adhered to. This compromised subsequent management steps
- No correlation was found between water levels and the impact of the development from available data.

- Spring-flow failure was identified as an aspect, however no correlation between the abstraction and spring-flow could be found based on the available data.

9 APPENDIX B: RAINFALL GRAPHS






Rainfall data for station 0508549
Rainfall in mm
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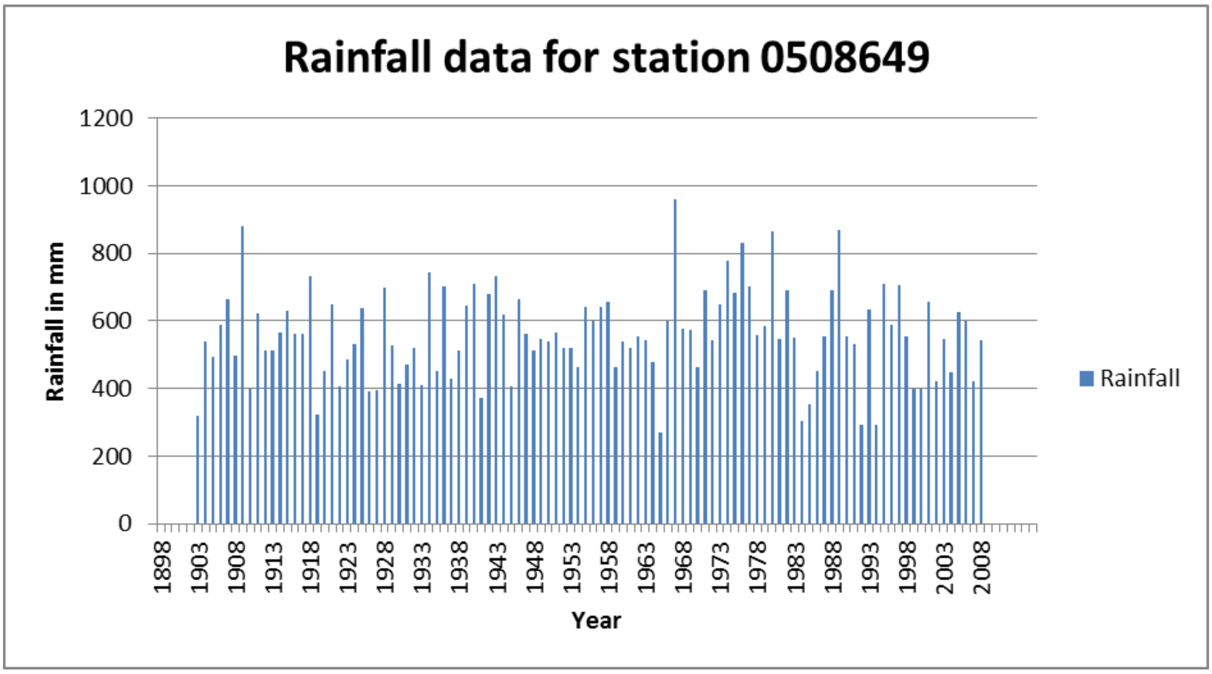
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Rainfall in mm
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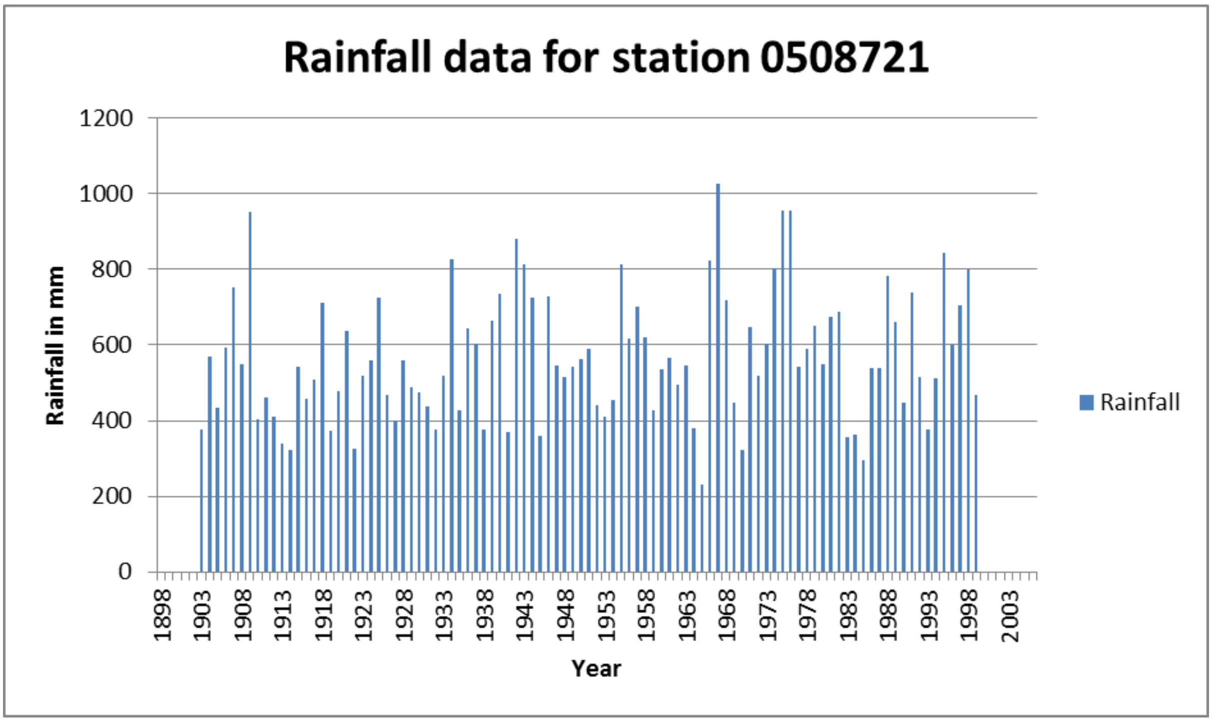
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Rainfall in mm
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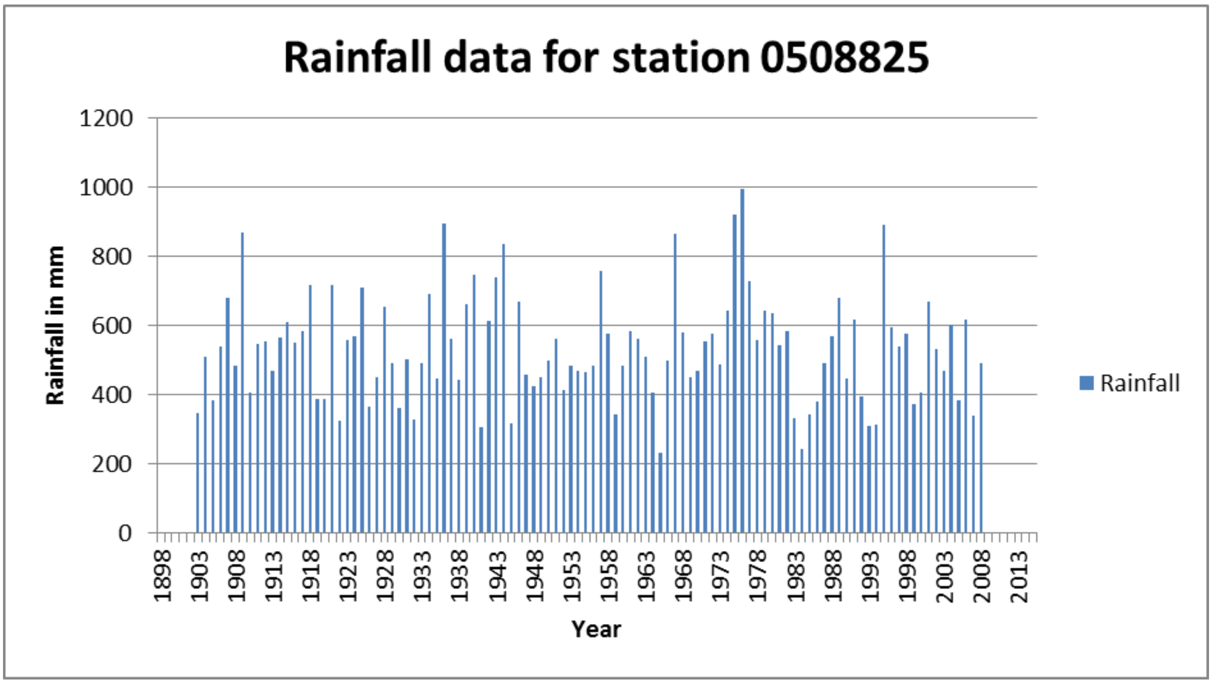
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Rainfall in mm
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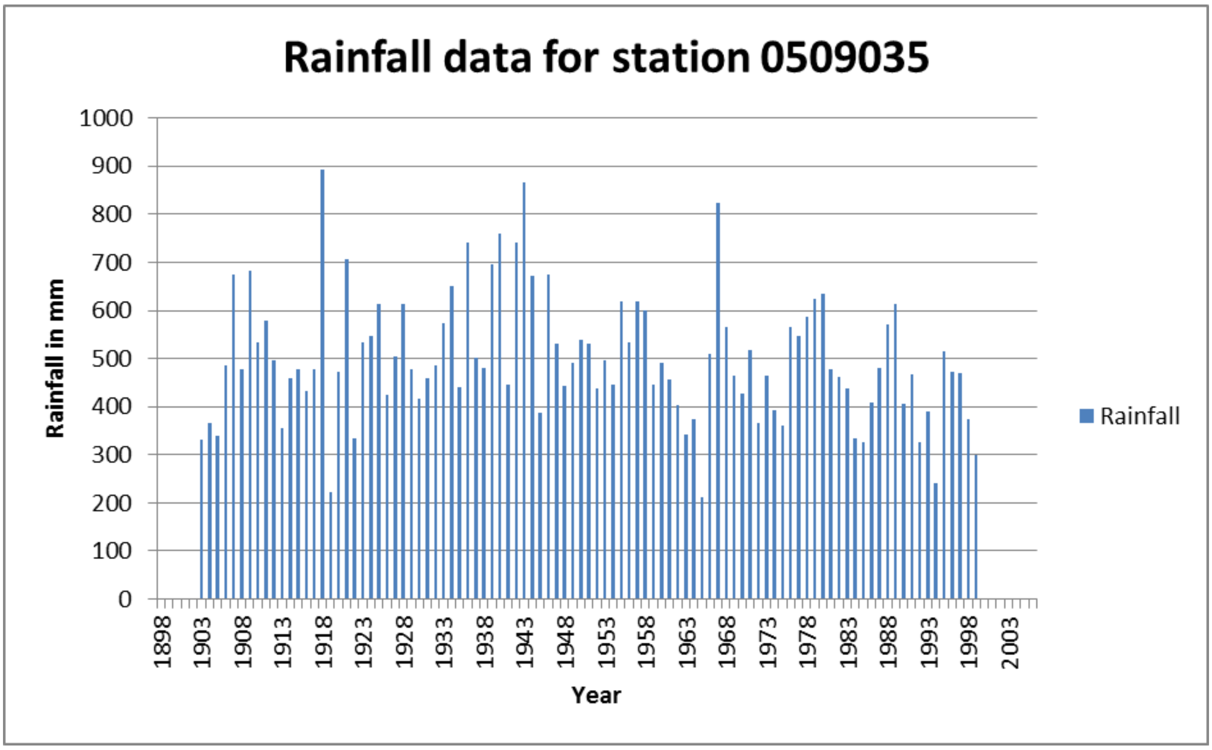
Rainfall data for station 0509035
Rainfall in mm
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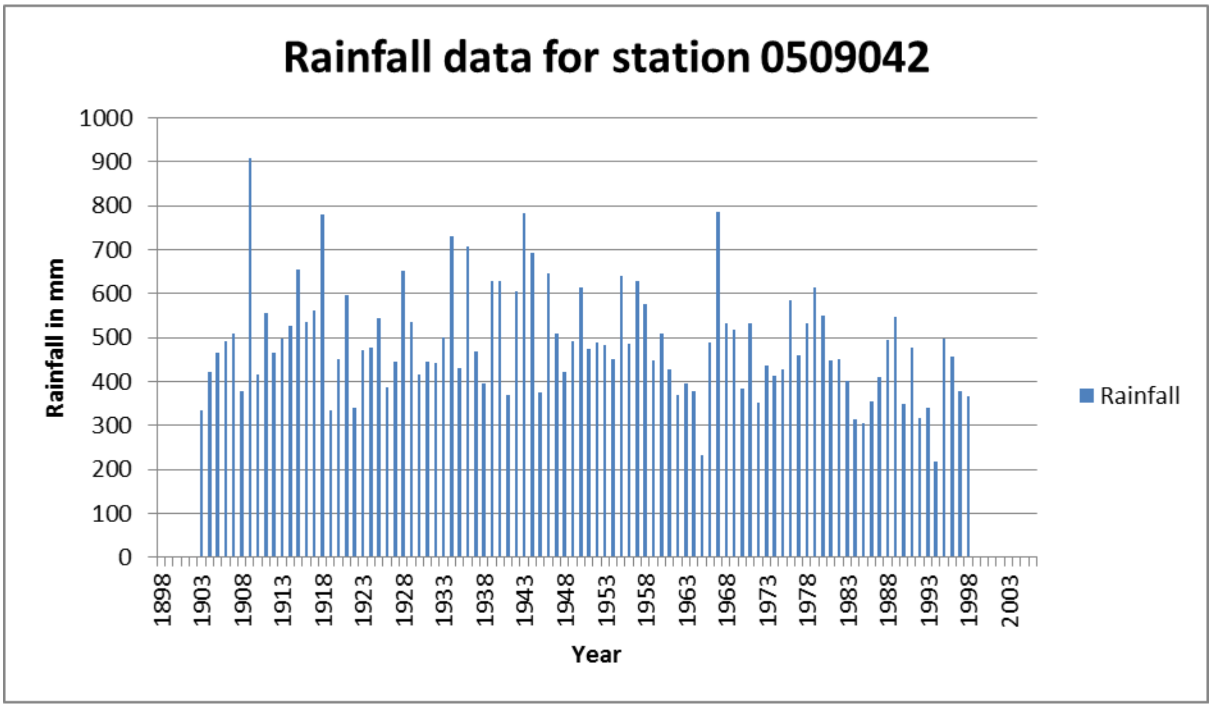
Rainfall data for station 0509042
Rainfall in mm
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10 APPENDIX C: RECHARGE CALCULATIONS

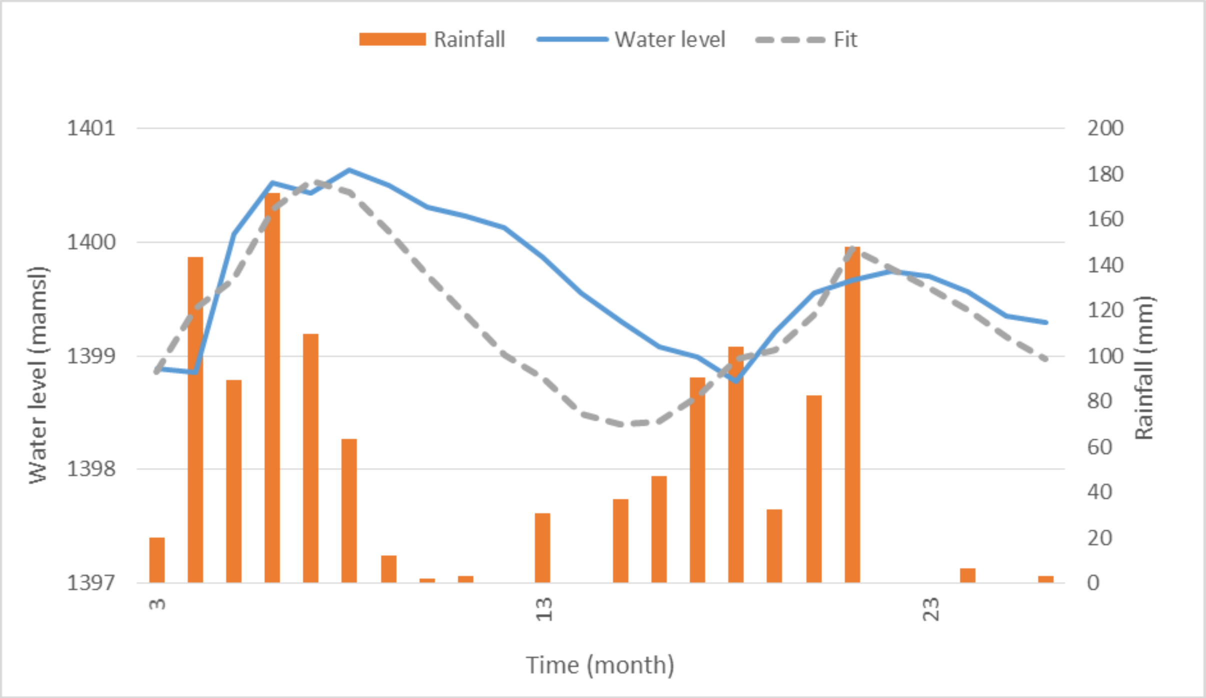


Figure 10-1: SVF (A3N0015)

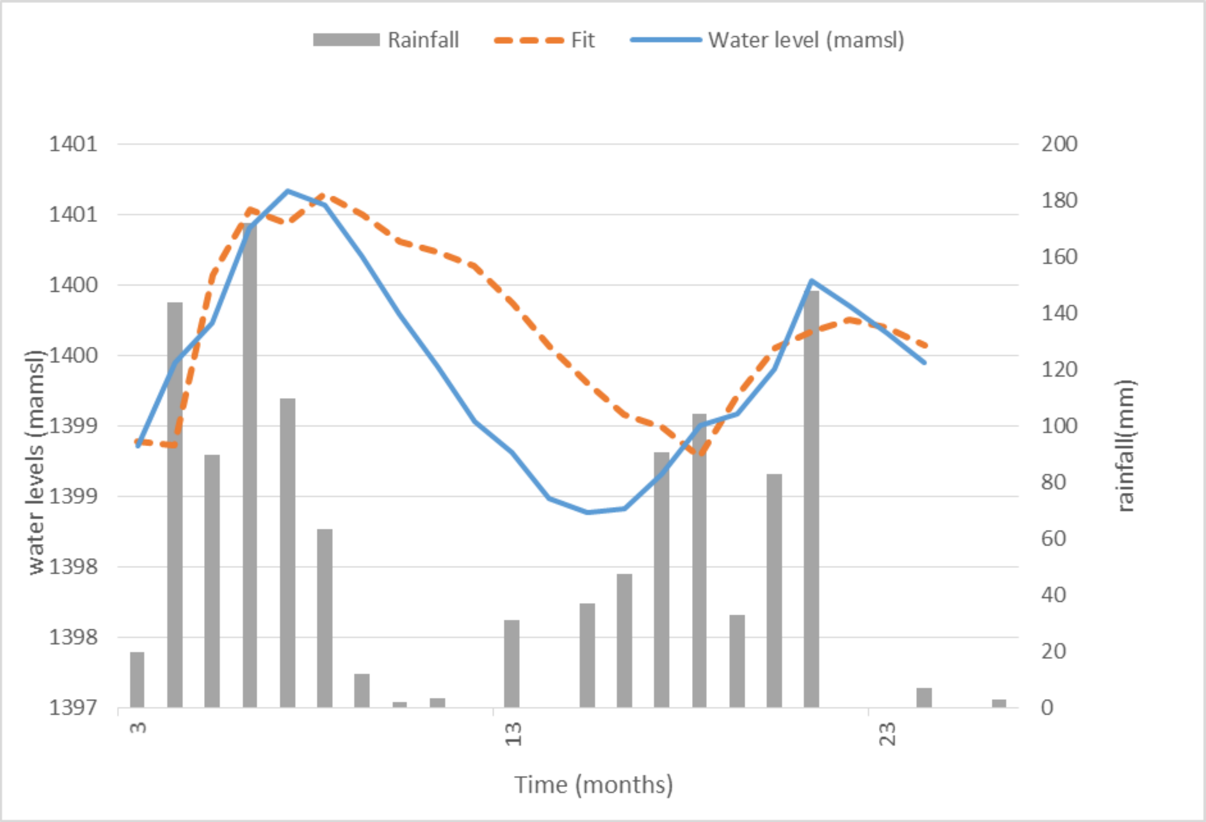


Figure 10-2: CRD (A3N0015)

11 APPENDIX D: GROUNDWATER RESOURCE MANAGEMENT IN SOUTH AFRICA

It is deemed necessary to include a section on groundwater resource management in South Africa, and what DWA considers to be guidelines and guiding principles. This is included as an appendix, but forms an integral part of the report.

11.1 DWA Guidelines

The National Water Act (Act 36 of 1998) mandated DWA to protect, use, develop, conserve, manage and control water resources in South Africa in an integrated manner (NWRS, 2006).

Dolomite aquifers constitute some of the most important aquifers in the world (DWA, 2006). DWA therefore initiated the compilation of a guideline in assessing, planning and managing water resources in dolomitic areas of South Africa (DWA, 2006). This document led to an overarching guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa (DWA, 2008).

The 2006 publication is commonly referred to as the Dolomite Guideline, with the aim of assisting sustainable development, protection and management of groundwater resources and achieving the Department's overall goal of Integrated Water Resource Management (IWRM) (DWA, 2006).

The 2006 Dolomite Guideline is divided into three volumes as follows:

***Volume 1**: Provides a conceptual overview of the Dolomite Guideline in terms of the purpose of the guideline, the location of the dolomite resources, the regulatory framework, principles and approaches, and the institutional arrangements. **Volume 1** can be used by role-players who seek to gain an initial insight into the assessment, planning and management of water resources in dolomitic areas*

***Volume 2**: Provides details of the process and related activities that should be followed during the assessment, planning and management functions. This volume is aimed at the role-players who require a detailed understanding of the processes to be followed during assessment, planning and management, to enable the overall management, integration and control of these processes, and*

***Volume 3**: Provides detailed procedures, in the form of check-lists with guiding notes, for carrying out the assessment, planning and management functions. This volume is aimed at those role-players tasked with the operational aspects of these functions* (DWA, 2006b)

The differences between the assessment, planning and management steps are described as follows (DWA, 2006b):

Assessment: This is the first step in the IWRM process and determines the status quo of the resource. It also determines the capability of the resource in terms of sustainable, economic and technical feasible abstraction and the impact on the environment in terms of spring and river flow, ecological requirements and ground stability. The steps in the assessment process are:

Undertake desk study and remote sensing

Identify areas for additional work

Hydrocensus

Siting of monitoring/exploration boreholes

Drilling and testing of boreholes

Prepare conceptual groundwater model

Risk Assessment

Spring capture and surface water-groundwater interaction

Present to stakeholders and obtain input

Prepare assessment report

Planning: This requires the matching of water availability to the water requirements. Steps are given for planning on national, catchment level and site specific levels.

Management: Management relates to the sustainable use and development of the dolomitic water resources, without compromising the resource integrity (quantity and quality).

It thus involves monitoring of the integrity over a long term period and the use of this information to determine compliance against set goals, and to assess whether DWA’s strategic goals are being met. It generally is an iterative process involving the setting management objectives (various levels) and monitoring and reporting against these objectives (compliance assessment).

> The management function is considered important since it provides a continuous record of the response of the aquifer to various inputs and outputs (recharge, baseflow, abstraction, evapotranspiration etc.) through monitoring.
>
> Management steps are also given for national, catchment level and site specific levels. The ground-level operation and maintenance and monitoring implementation occurs in the last level, but feeds back to catchment and ultimately national levels. The Dolomite Guideline contains detailed guidelines on the collection, storage and communication of monitoring data which will not be repeated here.

The importance of integrating the assessment, planning and management functions is given in Volume 1 (DWA, 2006a) as follows:

- Poor assessment can lead to poor planning, which in turn can lead to the adoption of unsuitable options and the unsustainable use of the resource. (The failure of the Uitvalgrond Well Field is a prime example)
- Poor management is defined as the inefficient use of the time and budget of the Department’s operational personnel. Nothing is however mentioned here about monitoring of the resource as part of management, but lack of monitoring can lead to situations where a well field is overexploited (like Uitvalgrond Well Field) and this has serious economic and environmental implications.

The **planning** and **assessment** of the groundwater resources being exploited as part of the Welbedacht Bulk Water Supply Scheme were completed before the onset of bulk abstraction. The nature of the complaints regarding lack of monitoring data and abstraction volumes from the Vergenoegd Well Field is therefore a function of the (site specific) **management** of the resource. Therefore the guidelines pertaining to management will be discussed here.

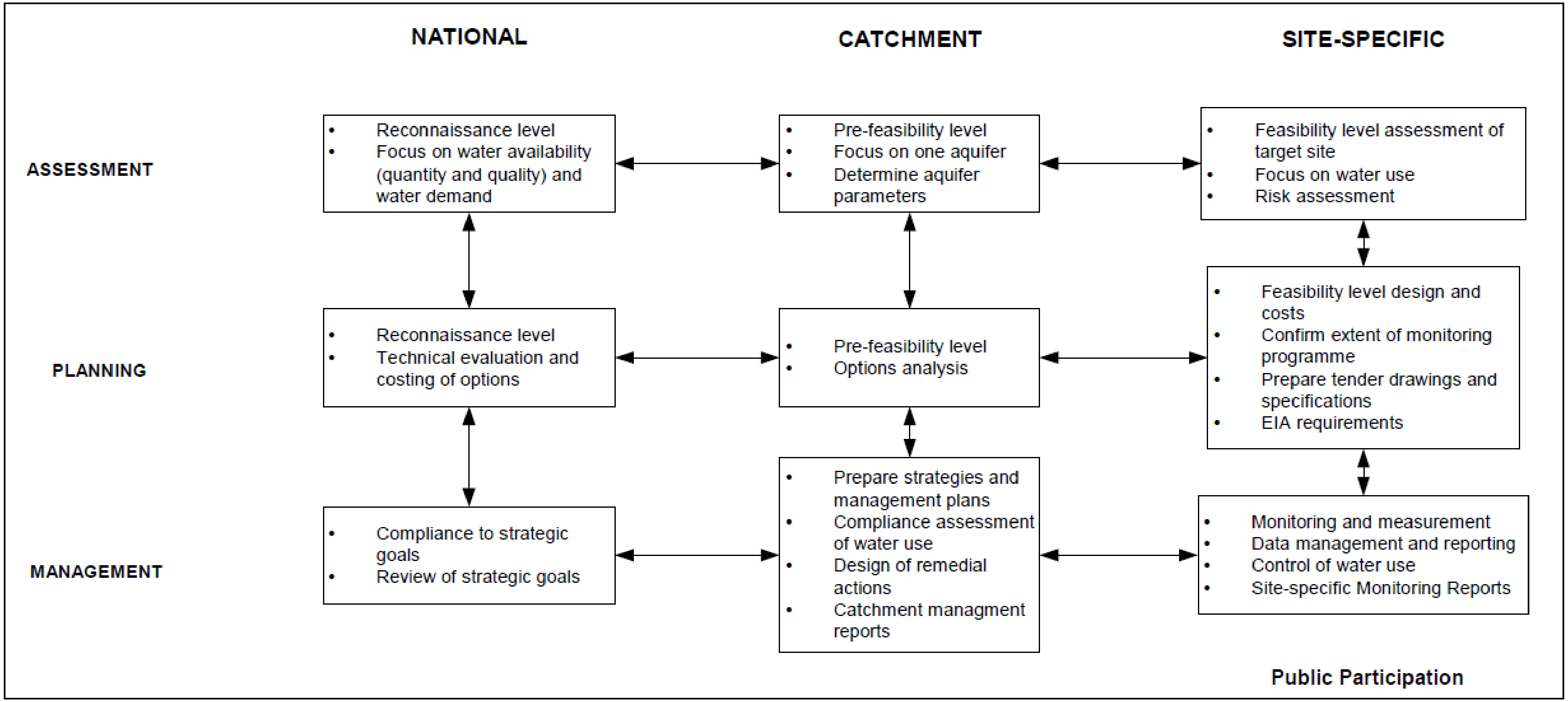
11.1.1 Management of dolomitic groundwater resources

The management of dolomitic groundwater resources happens at three levels: site specific (well field level), catchment level and on national level.

On a site specific level it is most important to measure and monitor. These are the data that eventually feeds the rest of the decision-making process. It is equally important that the data gets managed properly and converted to information through the proper reporting process (monitoring reports). The reports are needed to make well field adjustments where necessary, and analysed on a catchment level.

On catchment level strategies and management plans are drawn up based on the monitoring data. Compliance assessment and possible remedial actions also stem from the data reports. Decisions made at this level then feeds into the national decision making process by means of catchment management reports.

On national level the catchment management reports are used to review strategic goals, and compliance to the set goals.



	NATIONAL	CATCHMENT	SITE-SPECIFIC
ASSESSMENT	• Reconnaissance level • Focus on water availability (quantity and quality) and water demand	• Pre-feasibility level • Focus on one aquifer • Determine aquifer parameters	• Feasibility level assessment of target site • Focus on water use • Risk assessment
PLANNING	• Reconnaissance level • Technical evaluation and costing of options	• Pre-feasibility level • Options analysis	• Feasibility level design and costs • Confirm extent of monitoring programme • Prepare tender drawings and specifications • EIA requirements
MANAGEMENT	• Compliance to strategic goals • Review of strategic goals	• Prepare strategies and management plans • Compliance assessment of water use • Design of remedial actions • Catchment managment reports	• Monitoring and measurement • Data management and reporting • Control of water use • Site-specific Monitoring Reports

Figure 11-1: Relationship between the assessment, planning and management functions at different levels (DWA, 2006b).

It is therefore clear that a lack of measuring and monitoring capacity on a site specific level like the Vergenoegd Well Field not only has an impact on a catchment level, but eventually on national level decision making too.

11.1.2 North West Groundwater Master Plan

In 2010 DWA published the North West Groundwater Master Plan (in draft format) to help structure the tasks of the groundwater staff component related to the department's mandate of development, utilisation, protection, conservation and management (DWA, 2010). In this document, it is admitted that data and information management was not specifically addressed in the NWA (Act 36 of 1998), but underpins the above functions. The term North West here refers specifically to the North West Dolomites, and specifically to the Crocodile West – Marico Water Management Area (WMA).

In this document the current situation is described pertaining to monitoring and data management. About 35 water level monitoring points are actively being monitored, but due to high staff turnover no knowledge about the specific placement of these monitoring points exists. *"A project to try and establish the value and reasons for these monitoring points has to be launched immediately"* (DWA, 2010).

The report further states that only seven points exist where chemical monitoring takes place, and no abstraction monitoring takes place in the WMA. In terms of data management the Master Plan further admits that very little data management takes place, and suggests certain short and long term actions.

The report describes the various hydrogeological regions that form part of the WMA based on the Vegter's Groundwater Regions. The area underlain by the dolomite forms part of the Karst Belt Hydrogeological Region. Interestingly it is mentioned that efforts to establish a subterranean water control area (referring to the Bo-Molopo Groundwater Control Area) failed.

When discussing the supply to Zeerust from the dolomites, the report further acknowledges that monitoring data for abstractions and water levels are unknown, and must be sourced if available. **In general, the lack of monitoring data and information/data management is seen as the key priority focus area for this region to ensure sound management decisions** (DWA, 2010).

12 APPENDIX E: CASE STUDY INFORMATION

Data used in the assessment:

	Rainfall (mm)			Flow (Mm3/m)		
Date	**508649**	**508721**	**509035**	**A3H011**	**A3H021**	**A3H022**
1980-10-01	37.4	0	22	0.155	0.296	0.007
1980-11-01	188.8	121	120.7	0.506	0.291	0.008
1980-12-01	121.1	69	78.3	0.547	0.296	0.013
1981-01-01	187.6	226	101.6	0.583	0.324	0.019
1981-02-01	80.6	169	79	0.651	0.372	0.04
1981-03-01	48.2	70	71.4	0.829	0.432	0.051
1981-04-01	14.2	12	9.9	0.824	0.413	0.05
1981-05-01	1.8	0	3.9	0.818	0.419	0.051
1981-06-01	3	0	6.1	0.778	0.395	0.047
1981-07-01	0	0	0	0.782	0.398	0.046
1981-08-01	30.8	34	27.9	0.744	0.415	0.05
1981-09-01	0	0	0	0.693	0.383	0.044
1981-10-01	42.2	34	34.3	0.667	0.343	0.036
1981-11-01	43.4	40	58.5	0.579	0.321	0.032
1981-12-01	96.5	88	86.4	0.569	0.329	0.033
1982-01-01	123.2	115	74	0.547	0.295	0.024
1982-02-01	28.6	31	38.1	0.432	0.238	0.009
1982-03-01	85.3	94	69.3	0.452	0.265	0.01
1982-04-01	164.6	206	73.3	0.482	0.285	0.012
1982-05-01	0	0	0	0.523	0.314	0.014
1982-06-01	0	0	0	0.551	0.315	0.015
1982-07-01	9.9	0	10.2	0.615	0.328	0.016
1982-08-01	0	0	0	0.627	0.328	0.015
1982-09-01	0	5	3.6	0.604	0.311	0.014
1982-10-01	155.9	148	84	0.601	0.325	0.015
1982-11-01	36.4	20	46.4	0.574	0.3	0.012
1982-12-01	87.6	69	63.6	0.541	0.272	0.007
1983-01-01	123	17	69.7	0.511	0.258	0.006
1983-02-01	90	81	47	0.435	0.207	0.005
1983-03-01	40.2	43	50.5	0.446	0.0232	0.006
1983-04-01	18.6	22	10.8	0.421	0.197	0.006
1983-05-01	23.4	24	14.5	0.175	0.21	0.007