Delineation of groundwater protection zone in a fractured rock aquifer setting

A case study of Rawsonville

By

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DECLARATION

I declare that "**Delineation of groundwater protection zone in a fractured rock aquifer setting: A case study of Rawsonville**" is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledge by complete references.

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ABSTRACT

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Keywords

Groundwater, protection zoning, fractured rock, TMG aquifer, contamination, aquifer characteristics

Abstract

The Department of Water and Sanitation (DWS) is considering the implementation of an Aquifer Protection Strategy to protect the country's critical groundwater resources. This study will assist in filling the knowledge gap in the form of a groundwater protection zoning case study in the Rawsonville area.

Understanding how groundwater is being accessed and used is required in determining the level and type of groundwater protection needed. Groundwater access points were identified as being boreholes, springs and rivers. A few potential contamination sources were identified at the site such as leachate from fertilizers and pesticides which may reach the groundwater used by the farmers for domestic water supply as well as irrigation.

Understanding the aquifer systems at the site is important as this information will help in understanding the flow processes in the aquifer. Different aquifers have different flow characteristics. Present at the research site is the quaternary sands form the primary aquifer and the Table Mountain Group (TMG) sedimentary fractured rock forms the lower secondary aquifer. A fault line also exists at the site in a northeast – southwest orientation. Groundwater flow within the shallow groundwater system consists of intergranular flow through unconsolidated sediments while groundwater flow within the secondary aquifer is controlled by the presence of non-continuous open fractures and joints.

Electrical resistivity surveying was used to get a better understanding of the subsurface geology of the site and pumping tests were conducted to obtain aquifer flow characteristics. Pumping test data were analysed which gave transmissivity values ranging between $4m^2/d$ and $14.8m^2/d$ and storativity values ranging between $1.27x10^{-7}$ and $4.6x10^{-5}$.

A 3 Dimensional (3D) numerical model was found to be optimum to meet the objectives of the study given the complexity of the study site. Various scenarios were modelled to provide conservative results for each protection zone (1yr, 10yrs and 100yrs). The fault line was found to be a key component to the local flow field around the borehole. The one year contributing area is mostly localised to the borehole.

Over a ten year period, the primary aquifer and the Molenaars River start to contribute to the water being pumped while in the secondary aquifer, the flow field expands to the east and south. Over the one hundred year period, the flow field extended to the south west mountain ridges.

Using the results obtained, a groundwater monitoring plan was developed. Land use restrictions were recommended for each groundwater protection zone and recommendations were made in order to minimise the risk of groundwater systems at the site being contaminated.

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ABREVIATIONS AND ANNOTATIONS

°C	Degrees Celsius
2D	2 Dimensional
3D	3 Dimensional
AFEC	Ambient fluid electrical conductivity
c	circa
CD	Constant Rate Discharge
DEM	Digital Elevation Model
DNAPL	Dense Non-aqueous Phase Liquids
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
FC	Flow Characteristic
EC	Electrical conductivity
FEC	Fluid electrical conductivity
K	Hydraulic Conductivity
GMWL	Global meteoric water line
GV	Groundwater Vistas
IFEC	Interference Flowing Electrical Conductivity
IGS	Institute for Groundwater Studies
LNAPL	Light Non-aqueous Phase Liquids
m	Metres
mbc	metres below collar
mamsl	Meters above mean sea level
mS/cm	milliSiemens per centimetre
ORP	Oxidation Reduction Potential
NAPL	Non-aqueous Phase Liquids
NRF	National Research Foundation
RMS	Residual Mean Square
Q	Discharge Rate
S	Storativity
SMA	Scalled Mean Absolute

T	Transmissivity
TMG	Table Mountain group
TOT	Time of Travel
US EPA	United States Environmental Protection Agency
UWC	University of the Western Cape
WRC	Water Research Commission
Yr	Year
YSI	Yellow Stone Incorporated

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CHAPTER 1

INTRODUCTION

1.1 Background

In many parts of South Africa, groundwater allocation and protection has become an important issue, as groundwater represents an important source of freshwater (Münch and Conrad, 2007). It has the potential to play a strategic role in providing water for drinking and sanitation, supporting agricultural irrigation schemes and industrial uses, reducing poverty and disease, and maintaining important aquatic and terrestrial ecosystems (Knuppe, 2011). Therefore, the protection of groundwater resources should be regarded as critical in a South African context. In 2005 the Department of Water Affairs and Forestry (DWAF) (here after referred to as Department of Water and Sanitation (DWS)) initialized the development of a policy to implement groundwater protection zoning for South Africa (Nel, 2011). The DWS is still considering the implementation of an aquifer protection strategy to protect critical groundwater resources.

An assessment conducted in 10 African cities showed that pollution of vital groundwater resources has reached critical levels and that implementation of groundwater resource protection through protection zoning should be implemented as a priority (Braune and Xu, 2006; Xu and Usher, 2006). The concept of a 'zone of protection' for areas providing groundwater for drinking water supplies has been developed and adopted in a number of countries (Chave et al., 2006). This study will assist in filling the knowledge gap in the form of a groundwater protection zoning case study in the Rawsonville area. This study forms part of a Water Research Commission (WRC) project to establish guidelines for protection zoning in a South African context. This study will also assist in getting South Africa on par with the rest of the world.

Xu and Braune (1995) describe groundwater protection zoning is a differentiated protection methodology, where land use is controlled and managed within the recharge zone or capture area of a groundwater resource to prevent contaminants reaching the water supply. The implementation of a groundwater protection zone is the process of protecting a drinking water resource by determining the surface area of land to be managed in order to minimize the potential of groundwater pollution by anthropogenic activities which occur on or below the land surface.

1.2 Research objectives

The main aim of this study is to delineate groundwater protection zones at the selected research site using specific methods. To achieve this the following steps will be followed:

- Identify groundwater uses and possible groundwater contamination sources.
- Determine aquifer properties
- Delineate groundwater protection zones using 3D numerical flow modelling.

1.3 Structure of this thesis

Chapter 1 forms a general introduction to the study. It also includes background information of the study, aims and objectives as well as the structure of the thesis.

Chapter 2 provides a literature review of the relevant and commonly used methods in fractured rock aquifer characterisation and protection zone delineation.

Chapter 3 consists of a detailed description of the Rawsonville research site. This description includes the geographical location, climate, geology and hydrology of the study area.

Chapter 4 provides a detailed description of the methods used during this study to achieve the objectives described in Chapter 1. These methods include geological mapping, surface geophysics, constant discharge tests and Fluid Electrical Conductivity (FEC) logging, groundwater flow modelling and protection zone delineation.

Chapter 5 discusses the results of the aquifer characterization methods applied at the study site.

Chapter 6 describes the site conceptual model. This mostly comprises of information gathered in Chapters 3 and 5.

Chapter 7 discusses the numerical modelling process. This includes model construction, calibration, sensitivity analysis as well as the predictive scenarios leading to the delineation of the protection zones.

Chapter 8 focusses on monitoring of protection zones to ensure drinking water protection. These include recommendations which aim to improve the conceptual and numerical models, as well as act as an early warning system to protect the drinking water of the area.

Chapter 9 provides conclusions regarding groundwater use, possible contamination sources in the area, aquifer characterization and delineating groundwater protection zones.

Recommendations regarding monitoring and contamination are addressed in Chapter 10.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a survey of the literature pertaining to the data required in order to delineate protection zones, aquifer type characteristics as well as the methods used to determine aquifer properties. The literature review is focused on understanding potential groundwater contamination associated with certain land uses and reviews some of the methods used to delineate groundwater protection zones.

2.1 Aquifer type characteristics

Many approaches to contaminant transport assume that the contaminant flow is the same as the average linear groundwater flow (Taylor et al., 2004). However, knowledge of characteristics for different aquifer types is of the utmost importance when it comes to flow and contaminant transport as groundwater flow could generally be used to infer contaminant migration processes. Knowledge of typical aquifer characteristics could also aid in the development of a conceptual model and the numerical simulation of protection zones.

Typical aquifer types in South Africa are (Jonck and Meyer, 2002):

- Intergranular;
- Fractured;
- Intergranular and fractured; and
- Karstic.

2.1.1 Intergranular Aquifers

Primary aquifers, also known as porous or intergranular (primary) aquifers, consist of unconsolidated or semi-consolidated rock material. These aquifers store water in the openings (pores) between the loosely packed rock material and flow is dependent on the interconnectivity of the pores (Vance, 2002). High hydraulic conductivity (*K*) and high discharge (Q) rates are often expected in intergranular aquifers. Since the aquifer is unconfined at the site, it is vulnerable to contamination and in need of protection. The upper aquifer system at the site is considered to be an intergranular aquifer.

2.1.2 Fractured Rock Aquifers

Fractured rock aquifers are secondary aquifers found in areas with hard rock geological settings. Flow occurs through individual fractures, however these fractures are not infinite in extent and therefore the conductivity of a fractured aquifer system is dependent on the connectivity, orientation and density of the fractures (Vance, 2002).

Characterizing fractured rock flow is dependent on the scale at which the flow is being analysed as these saturated media are synonymous with heterogeneity and anisotropy. The K of a fractured rock aquifer is dependent on the fracture density with low porosity expected for bulk properties. Contaminants have the potential to move much faster through fractured rock aquifers when compared to intergranular aquifers, due to the high transmissive rates of the fractures, which makes it very important to protect them. (Vance, 2002). Fractured rock constitutes the deeper aquifer system at the study site.

2.1.3 Intergranular and Fractured Rock Aquifers

Intergranular and fractured aquifers represent a multi-porous medium. These media have the flow characteristics of both intergranular porous material as well as fractured hard rock which represent "dual porosity". Characterising flow may prove to be difficult as both diffuse and conduit flow occurs in these types of systems. This type of system may be present at the site under pumping (and transport) conditions.

Similar to fractured rock aquifers, if the fracture density is high enough in an intergranular and fractured aquifer, the aquifer may display porous media flow properties, similar to primary aquifers (Vance, 2002).

2.1.4 Karstic

Although no Karstic aquifers exist at the site, they are found in South Africa. Karstic aquifers are formed due to the dissolution of carbonitic rocks. Weak carbonic acid flows through cracks or fractures in the carbonic rock causing it to dissolve. Over time, the dissolution process will cause fractures to enlarge and this will lead to the Formation of sinkholes or even caves. This makes them potentially susceptible to water quality deterioration. (Vance, 2002).

2.2 Groundwater access point characteristics

Groundwater can be accessed for drinking water in various ways. Nel (2011) defines groundwater access points as any groundwater accessed via a borehole, dug well, spring, wetland or contribution to a surface water source and used for drinking water purposes (Figure 2.1). It is extremely important that water access points provide clean and safe drinking water. Protection zoning is seen as a proactive step towards protecting the water resources feeding these drinking water access points.

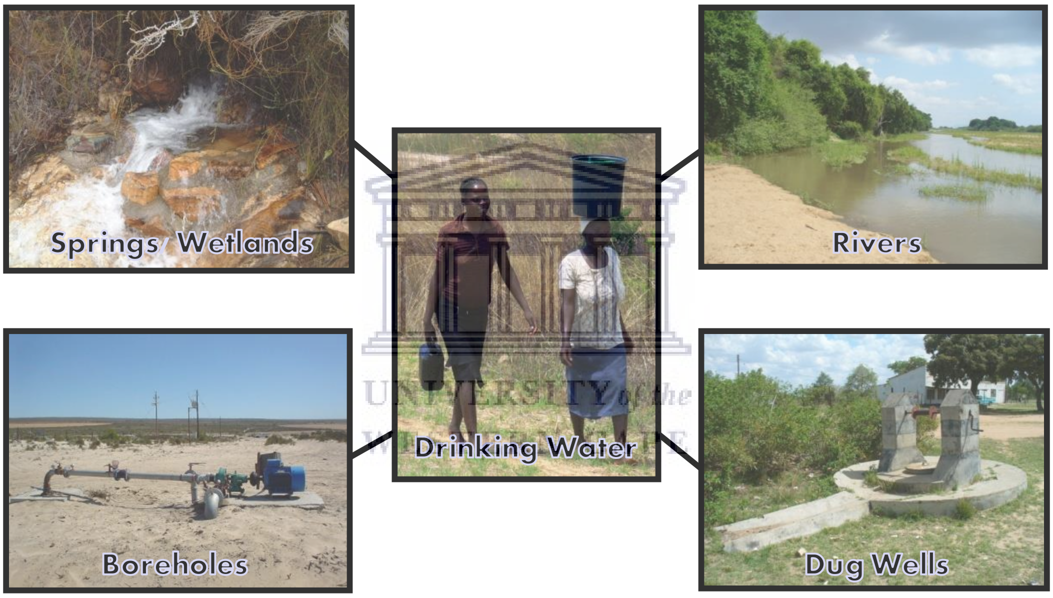

Figure 2.1: Types of groundwater access points where groundwater can be collected according to Nel (2011).

2.2.1 Boreholes

A large portion of South Africa is underlain by fractured rock and intergranular aquifers. In most cases a borehole is usually required to access this groundwater. In some cases, the integrity of the drinking water quality is reliant on the construction of the borehole. If an unconfined aquifer has contaminated water but a deeper confined aquifer has clean, potable water, poor borehole construction resulting in cracked casings may lead to contaminants seeping in through cracks and polluting the abstracted water.

Unconfined aquifers are very vulnerable to pollution resulting from land use. For example, nitrate contamination due to nearby stock watering points or fertilizers can be a problem for water supply from shallow unprotected boreholes (Heath, 1983; Nel, 2001).

2.2.2 Surface water

During the dry season, groundwater may contribute to surface water bodies such as streams. This can be observed through groundwater springs or seeps.

Contaminated groundwater can cause surface water resources to be contaminated (Ford, 2005) with contaminated groundwater resulting in regional changes in surface water quality. An example of this can be the increase in regional surface water salt loads and possible lowering of the pH around some defunct coal, platinum and gold mines (Hodgsen and Krantz, 1998; King, 2003).

2.2.3 Springs and seeps

Springs and seeps may provide water long after a rainfall event has occurred. Three main types of springs include shallow seasonal (seeps), lithologically controlled and fault controlled. In South Africa, water is collected from many unprotected springs. This water may be collected either by hand or it can be piped or pumped to supply water to municipalities or farms (Baran and Dziembowski, 2003; King, 2003; Meyer, 2002; Pearson et al., 2003; Ravenscroft, 2003; Weaver, 2003). Groundwater protection zoning may minimize or prevent these water sources from being degraded due to contamination.

2.3 Groundwater contamination

Groundwater contamination may either come from naturally occurring processes or due to anthropogenic interferences (Hem, 1985). Natural processes include but are not limited to leaching of mineral deposits and decomposition of organic matter in soils. These processes result in the occurrence of certain substances which can be harmful to human health e.g. radionuclides such as radon (natural radioactive decay).

Contamination caused due to anthropogenic activities can be divided into non-point source and point source pollution. Activities associated with point source pollution are agriculture (nitrates) leaking sanitation systems or underground storage tanks, accidental spills in industry, mining and traffic.

2.3.1 Contaminant characteristics and risks

Groundwater contaminants exist in many forms and contaminant classification schemes can be based on any of the biological, physical or chemical characteristics (Usher et al., 2004). Natural processes such as biodegradation, volatilization, radioactive decay, dispersion, dilution and sorption occur, which may reduce the quantities/concentrations of a particular contaminant in the soil or water (U.S. EPA, 1999). A water resource manager should at least consider contaminant distinction based on phase preference as the phase a contaminant associates with can affect its transport behaviour and toxicology (Blatchley and Thompson, 2007). The following contaminant characteristics play important roles in determining which phase the contaminant will assume in the groundwater system:

- Aqueous Solubility
- Inorganic constituents
- Organic constituents
- Particulate matter.

2.3.1.1 Aqueous solubility

The aqueous solubility of a contaminant compound, and its ability to stay in solution through its pathway, will determine the fate and toxicology of that compound in a groundwater system (Blatchley and Thompson, 2007). Some of the important factors controlling the solubility are sorption, pH and temperature.

2.3.1.2 Inorganic Constituents

Inorganic groundwater contaminants may come in the form of:

- increases in the concentration of the natural constituents, above their naturally occurring concentrations; and
- the introduction of constituents that would not be expected at all.

Some of the most important inorganic contamination problems related to soil/water interaction are related to the oxidation of pyrite (FeS_2). Although this is a naturally occurring process it is greatly accelerated by the introduction of oxygen, mostly due to mining activity (Downing and Mills, 2000). Protecting groundwater used for drinking water in these mining areas is therefore important.

2.3.1.3 Organic constituents

Organic compounds that display extremely low aqueous solubility can exist as a separate liquid phase in groundwater systems, if present in sufficient quantities. These contaminant phases are referred to as non-aqueous phase liquids (NAPLs). In the case of a NAPL with density less than the surrounding water, the non-aqueous phase is referred to as a light NAPL (LNAPL), and will generally be found at or near the phreatic surface. LNAPL sources are often related to underground fuel tanks with an estimated 50% of fuel tanks in South Africa leaking (Usher et al., 2004).

Low solubility organic compounds with density greater than water can exist as a Dense NAPL (DNAPL) phase. Because of their high density, DNAPL compounds tend to sink in groundwater systems. As in the case of LNAPLs, the source of DNAPL spills is often leakage or failure of underground storage tanks (Blatchley and Thompson, 2007). The NAPL characteristics must therefore be considered when attempting protection of groundwater in areas with underground storage tanks or industrial areas.

2.3.1.4 Particulate matter

Micro-organisms are one of the most important particulate contaminants in groundwater systems. Important categories of microbial groundwater contaminants include viruses, bacteria, and protozoan cysts. These can exist naturally or can occur as a result of contamination from human or animal waste (Health Canada, 2006), and are capable of causing illness in humans. Surface water sources, such as lakes, rivers, and reservoirs, are more likely to contain micro-organisms than groundwater sources, unless the groundwater sources are under the direct influence of surface water (Health Canada, 2006) or if the groundwater resource has been directly contaminated by land based activities such as irrigational systems on a farm or pit latrines.

2.4 Aquifer Tests

Aquifer testing is done in order to determine aquifer hydraulic characteristics. It is also a tool used to determine an aquifers response to groundwater abstraction. Aquifer testing aids in the determination of well performance and sustainability. These tests are also used to obtain estimates of hydraulic conductivity (K), Transmissivity (T) and storativity (S) of the aquifer material (Aitchison-Earl and Smith, 2008; National Research Council, 1996).

Knowledge of aquifer parameters is essential in realistic parameterization of groundwater models to simulate groundwater movement and thus critical in groundwater protection zoning. The most common and probably most reliable types of aquifer tests are pumping tests (Osborne, 1993). There are various types of pumping tests, some of which were used in this study and will be explained at a later stage.

2.4.1 Pumping tests

Understanding aquifer behaviour is important in protection zoning as it also helps to establish aquifer boundaries which will support protection zone delineation.

Pumping tests operate on the principle that if water is pumped from a borehole and the discharge and drawdown of the borehole is measured in the pumping borehole, as well as in observation boreholes at a known distance from each other, the aquifer parameters can be calculated from an appropriate well-flow equation (Kruseman and De Ridder, 1994).

Normally pumping tests are carried out alongside other tests such as tracer test and slug tests in order to yield reliable data by means of collating aquifer properties and characteristics using these tests. The hydraulic parameters obtained (transmissivity and storativity) are used in building models of the aquifers in order to accurately simulate real life conditions. This will aid in protection zoning, planning and management.

2.4.2 Tracer tests

Tracer tests provide a vital tool for characterising complex aquifers. In these aquifers, solute transport is a major concern in many hydrogeological problems related to contaminant flow. During a tracer test, a substance (tracer) is injected in the aquifer (via a borehole) and its movements and distribution are observed (Vandenbohede and Lebbe, 2003).

These observations are usually done at the pumping borehole or any other point where the tracer is expected to arrive. Although tracer tests are essentially used to illustrate the advection and dispersion processes in an aquifer, aquifer porosity can also be estimated from the results of a tracer test as well as flow velocities. These parameters are important in accurately simulating real world conditions and predicting contaminant movement in the aquifer.

2.5 Methods of groundwater protection zone delineation

Groundwater protection zones have developed historically, using a variety of concepts and principles and has been incorporated into groundwater management systems by numerous countries. Although some include prioritization schemes for land use, all aim at controlling polluting activities around abstraction points to reduce the potential for contaminants to reach the groundwater supply (Chave et al., 2006; Margane, 2003).

Ideal conditions do not always exist as lack of data or budget constraints will often determine the complexity of groundwater protection approaches. Approaches to protection zone delineation range from relatively simple methods based on fixed distances, to more complex methods based on travel times and aquifer vulnerability (Figure 2.2). Uncertainty of the underlying assessment of contamination probability is reduced with increasing complexity (Chave et al., 2006).

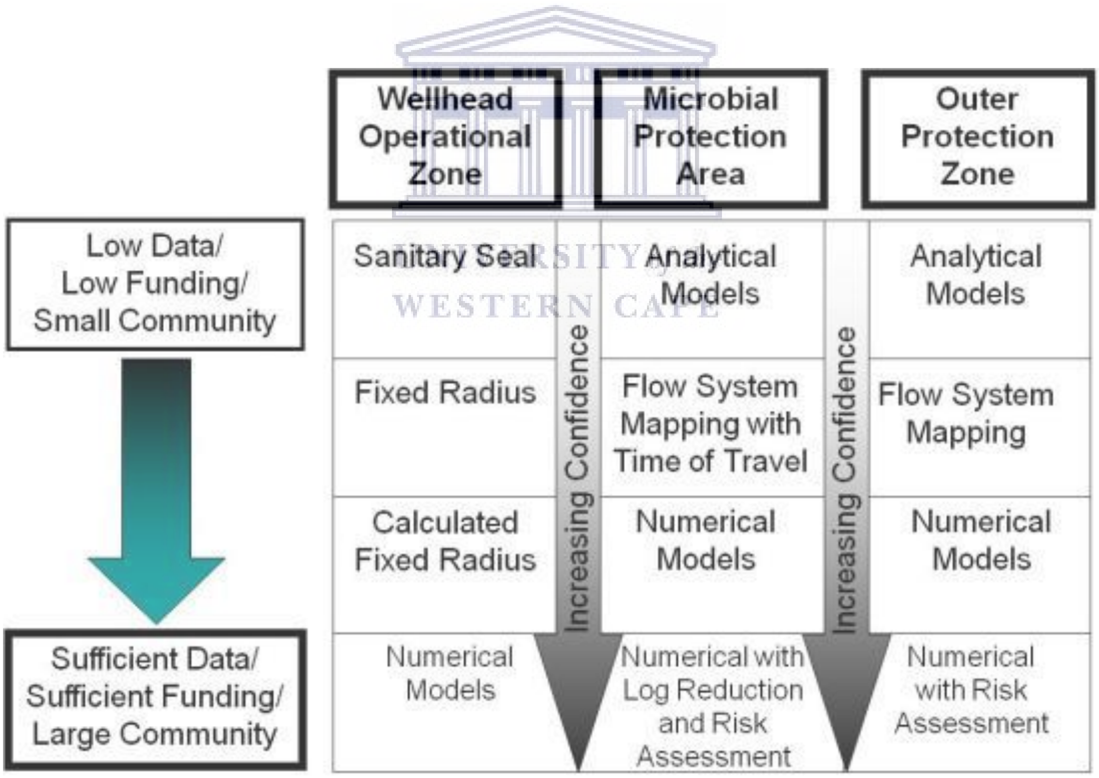

Figure 2.2: Data needs and uncertainty related to the delineation of groundwater protection zones (Nel, 2011).

Groundwater analytical or numerical modelling is done in order to establish the flow field/capture zone of an abstraction borehole. According to Stauffer et al. (2005), the flow field can often be approximated by a horizontal two-dimensional (2D) flow and transport approximation. Moreover, compared to three-dimensional (3D) flow, the formulation and numerical implementation of 2D models is usually much simpler than in the 3D case. Nevertheless, it should be kept in mind that 3D effects may be important in practice. For instance, the evaluation of a 3D capture zone or catchment, at least in the vicinity of the borehole, is (in principle) required when dealing with partially penetrating or partially screened pumping boreholes, in multi-layer aquifer systems or in situations of river-bank filtration.

2.5.1 Calculated Fixed Radius Methods

This is the simplest form of protection zoning where activities are excluded within a uniformly applied specified distance around abstraction points. These methods use expert judgement and experience and have been widely applied. Calculated Fixed Radius methods do not take into account local hydrogeological conditions and aquifer vulnerability or the interaction between adjacent boreholes and the impact that this may have on local flow conditions. This reduces the confidence in the degree of protection that is provided.

These approaches are often used when there is limited information on the hydrogeology of an area and are a practical means of ensuring a measure of immediate protection. An example of this can be a minimum of 10 metres for boreholes, 20 metres for springs and 30 metres for boreholes in karst aquifers, as is the case in Germany (Chave, 2006).

2.5.2 Analytical Models

The Analytical Model approach uses well established hydrologic equations to model groundwater flow and pollutant transport. It often uses computer codes to solve the analytical equations for 2D flow to a borehole, considering various combinations of parameters. A linked particle-tracking code can then be used to delineate the zone of contribution for the borehole (Muldoon and Payton, 1993).

2.5.3 Numerical Models

Numerical models use computer code to approximate 2D and 3D groundwater flow systems and simulate contaminant flow paths (Muldoon and Payton, 1993). Numerical models allow intricate subsurface conditions and hydrologic features to be represented with a fair degree of accuracy. This is a very powerful tool in groundwater protection zoning as it is capable of simulating groundwater movement over time. Time-of-travel analysis is one of the key outputs of groundwater protection zoning.

2.5.4 Mapping Methods

A number of countries (e.g. the United Kingdom, Australia and Ireland) have introduced different types of groundwater mapping into their protection policies. These can refine protection categories defined by fixed distance and/or travel time approaches and allow a differentiated management response within a protection area. These systems are also useful outside of drinking-water protection zones for long term planning of the protection of groundwater resources. These methods also provide guidance to organisations concerned with major anthropogenic activities which might adversely impact groundwater quality (Muldoon and Payton, 1993)).

2.5.4.1 Flow-System Mapping with Time of Travel Calculations

For defining protection zones targeting effective attenuation of pathogens and/or substances to acceptable levels, distance approaches are also used, often underpinned by travel time concepts. Flow system mapping with Time of Travel (TOT) calculations uses water-table map to estimate groundwater velocity. The velocity, in combination with a specified time of travel, can be used to limit the protection zone to that portion of the Zone of Contribution (ZOC) that will contribute water to the borehole within a specified amount of time (Muldoon and Payton, 1993).

2.5.5 Risk assessment

The Risk Assessment approach is based on a maximum acceptable infection risk associated with drinking water consumption and dose response relationships for pathogens (Chave et al., 2006). In the case of viruses, it is based on the dose response relationship of rotavirus and poliovirus, as a worst-case. Drinking water companies are obliged to conduct a risk analysis to demonstrate adequate drinking water treatment.

2.6 Typical Data Requirements

For the evaluation of protection zones the following parameters and conditions are generally required (adapted from Stauffer et al., 2005):

1) The piezometric head of the aquifer or the level of the groundwater table: *this information is generally obtained from boreholes and/or geophysical investigations.*
2) The levels of the bottom and of the top of the aquifer: *this information is generally obtained from borehole logs and/or geophysical investigations.*
3) The location of the boundary of the flow domain to be investigated: *this information is obtained from a regional geological, hydrogeological and hydrological investigation. The boundaries are often chosen in such a manner that a feasible formulation of the numerical model boundary conditions (fixed head, streamline or geological boundary) can be obtained.*
4) The boundary conditions: *this consist of the piezometric heads at the boundary (or portions of it) or of the water flux through the boundary (or portions of it) and can be obtained from hydrological and hydrogeological investigations.*
5) Groundwater access points: *this may include things such as springs, wetlands, rivers, boreholes and dug wells. Identifying and understanding how groundwater is being accessed will assist in determining the level and type of groundwater protection needed.*
6) The abstraction rates of boreholes or well fields in the domain: *the planned schedule of the abstraction should be taken into account.*
7) The infiltration rate from rivers and streams: *the rate can be estimated on the basis of hydrological considerations, or by calibration of a flow model using nearby piezometric head and/or solute concentration data.*
8) The groundwater recharge rate: *the rate can be estimated on the basis of hydrological considerations. In the case of confining low-permeability layers, their hydraulic properties and areal extent has to be assessed by hydrogeological and hydraulic investigations.*
9) Characteristics associated with the aquifer: this includes hydraulic conductivity, transmissivity and storativity) of the aquifer: *this information can be obtained through analysis of pumping or slug test data.*

10) The effective porosity of the aquifer (with respect to solute transport): *this information is relevant for proper isochrones prediction and is best determined from field tracer tests.*

CHAPTER 3

SITE DESCRIPTION

3.1 Geographical setting

The study site is located on the Gevonden farm near the town of Rawsonville in the Western Cape of South Africa and is located south of the Goudini hot springs. The N1 highway and the R101 are situated approximately 1.5km N from the Gevonden site (Figure 3.1). The site forms part of the Breede River Catchment Management Area and the coordinates used for site location are E19.24696 S33.71790. The borehole network has an average elevation of 260mamsl however; surrounding mountain ranges may reach up to 1900mamsl.

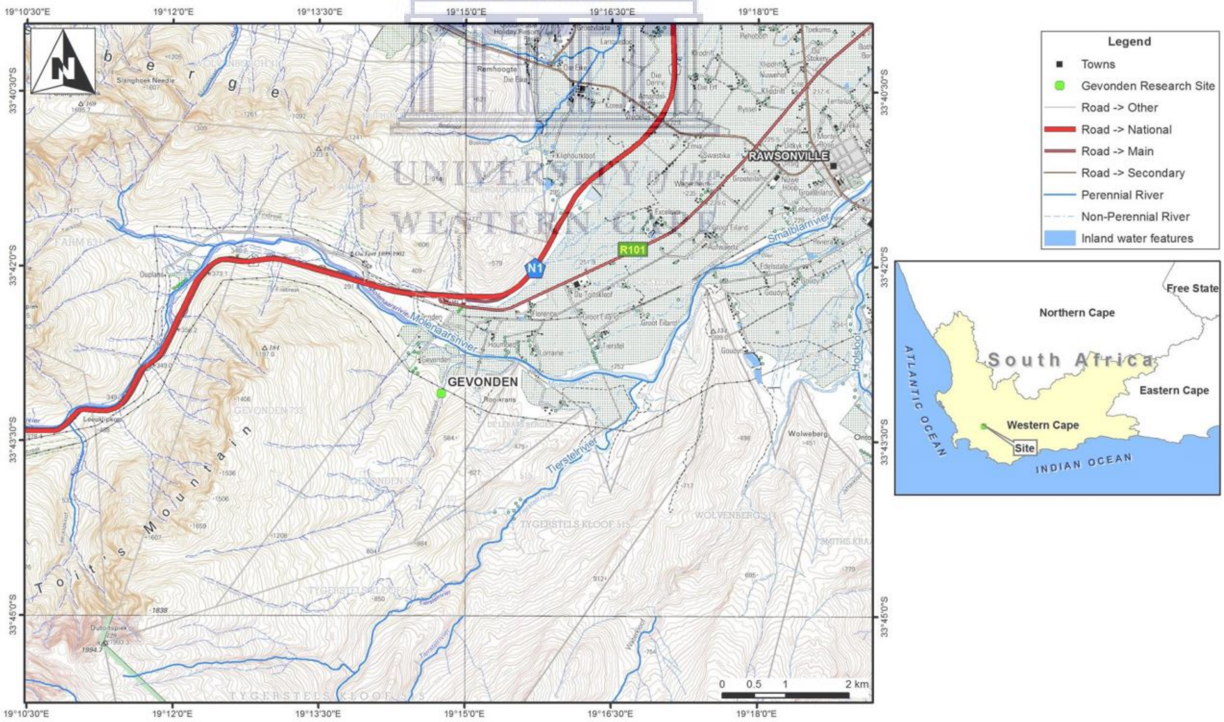

Figure 3.1: Geographical location of the Gevonden research site with the town of Rawsonville to the East. Source: 1:50000 3319 map of the Chief Directorate Mapping and Surveying, South Africa

3.2 Geology

The geology at the Gevonden site comprises Formations which form part of the Table Mountain Group (TMG). The basement rock is made up of the Peninsula Formation. This is overlain by the Pakhuis, Cederberg and Goudini Formations respectively. The geological setting of the research site is shown in Figure 3.2.

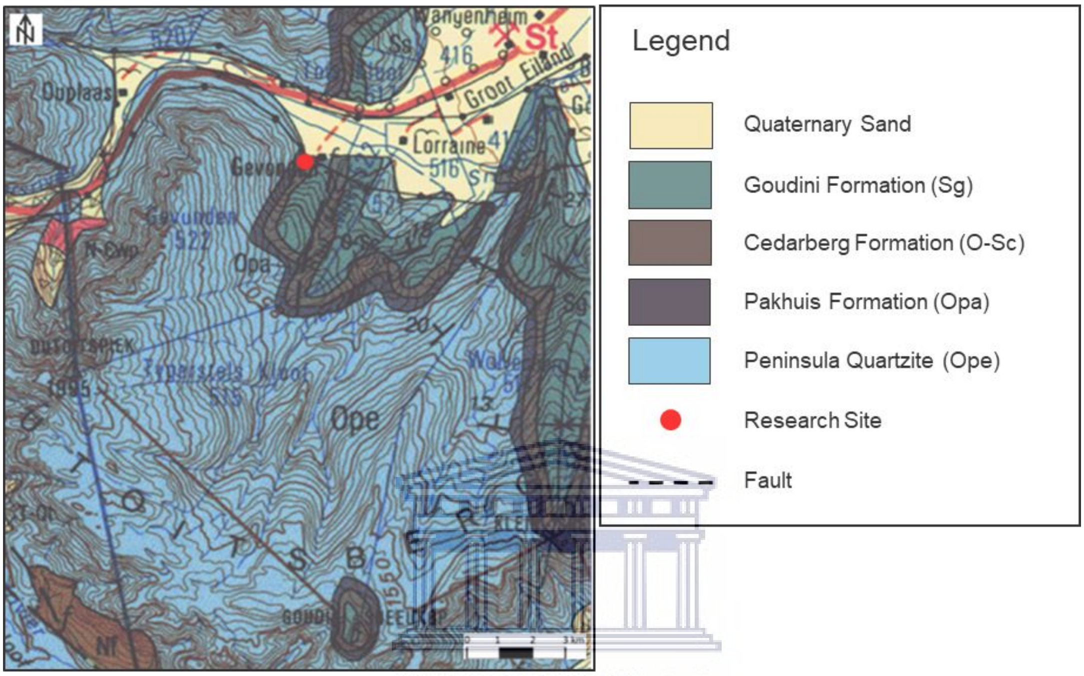

Figure 3.2: Geology map of the research site. Source: 1:250000 3319 map of the Chief Directorate Mapping and Surveying, South Africa

The catchment is intersected by the Waterkloof Fault which is approximately 80m wide (Lin, 2008). The geological setting of the site resulted in the Formation of two aquifer systems. The quaternary sands form the primary aquifer and the TMG fractured rock forms the lower secondary aquifer. Figure 3.3 shows the conceptual geological setting of the site.

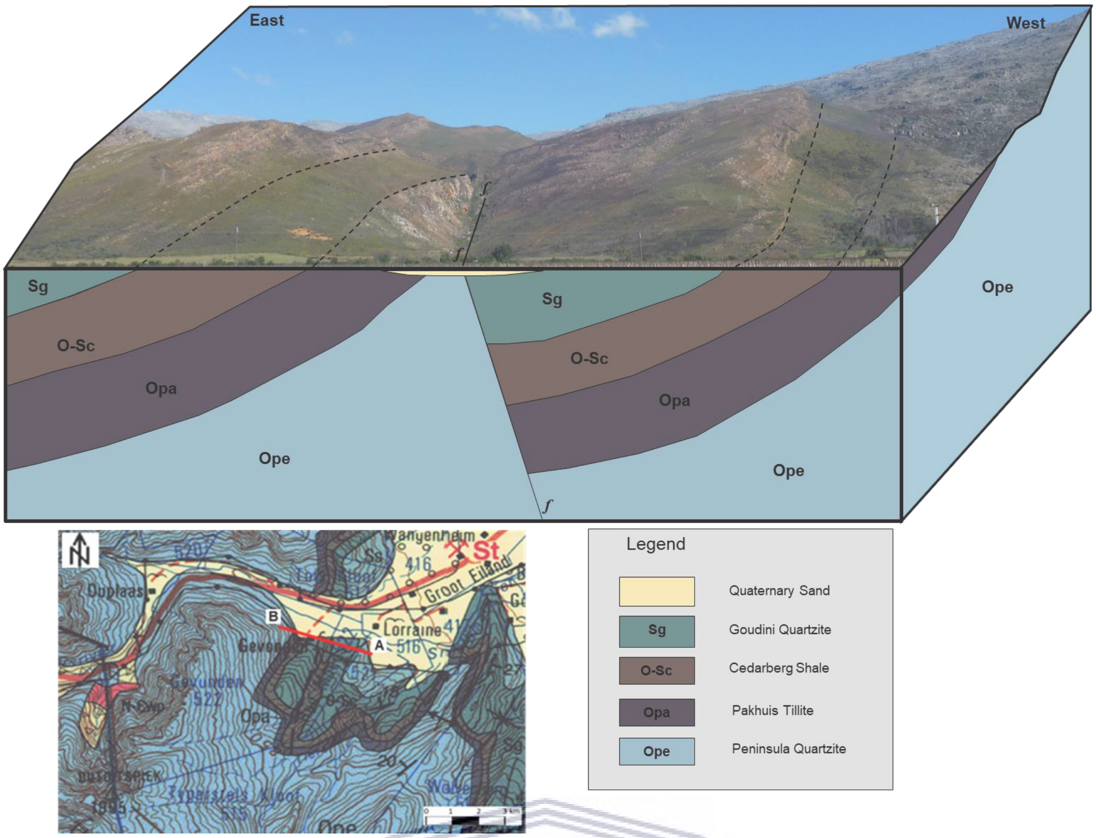

Figure 3.3: Conceptual geologic cross section of the research site (adapted from Nel, 2011). Image is not to scale.

3.2.1 Peninsula Formation

The Peninsula Formation is characterised by planar beds comprising light grey quartzitic sandstones that are generally coarse grained in texture and well bedded. From the Du Toitskloof pass area (along the N1 road) in the north of the study area, black and white chert pebbles are common (Rust, 1967) and the quartzitic sandstone of the Peninsula Formation rests unconformably on granite (Gresse and Theron, 1992). Layers of shale and siltstone are also present in some areas but they tend to be thin when compared to the thick beds of sandstone. Fold zones are observed in the upper contacts of the Peninsula Formation in some surrounding locations at the study site.

3.2.2 Pakhuis Formation

The Pakhuis Formation is identified in the area by the sharp, narrow cuspate anticlinal folds that alternate with broad bottomed synclines and near vertical or even over folded flanks (Gresse and Theron, 1992).

3.2.3 Cedarberg Formation

The Cedarberg Formation comprises two members; the Disa and the Soom shale Members of which the Soom shale member is the most well exposed in Rawsonville at the Gevonden farm and surrounding areas (Gresse and Theron, 1992). The rocks of the Cedarberg Formation are thinly laminated and consist of black silty shales that grade into brown siltstone and fine sandstone from the bottom to the top of the Formation layers. In some parts, the black shales weather out to ash white clays that are thinly laminated (Gresse and Theron, 1992).

3.2.4 Goudini Formation

The Goudini Formation comprises brownish-weathering, quartzitic sandstone with thin shale and siltstone beds. (Johnson et at., 2006). The thickness of the Formation ranges from 0.5 m in the Kliphout Kloof area which is south of Goudini spa in Rawsonville to about 75 m heading north of Ceres (Gresse and Theron, 1992).

3.2.5 Quaternary Sand

These deposits mostly consist of well-rounded boulders and cobbles of weathering-resistant rocks such as sandstone and quartzite. Older gravels are locally cemented into a matrix. The pore spaces between these boulders and cobbles are filled with coarse to medium sand.

3.2.6 Geological features

The site is situated in the southern domain of the syntaxis which is the most fractured part of the Cape Fold belt as faulting from the southern and western branch are both present (de Beer, 2002). The Waterkloof fault runs through the research site and is orientated in a *c.*northeast – southwest direction. Upward displacement exists on the western side (hanging wall) of the fault plane exposing the Cedarberg and Packhuis Formations.

3.3 Hydrogeology

The geology at the site forms an anticline with the Waterkloof fault running along its axis. The fault acts as a flow boundary. A brecciated zone also exists on either side of the fault. Most groundwater flow is likely to be restricted to any open fractures.

3.3.1 Local shallow groundwater system

The local shallow groundwater system incorporates unconsolidated sedimentary units originating from a Quaternary drainage and depositional environment. Groundwater flow within the shallow groundwater system consists of intergranular flow through unconsolidated sediments. Flow follows the river channel in a NE direction.

3.3.1.1 Regional Bedrock Groundwater System

The regional groundwater system is associated with fractured bedrock units. Groundwater flow within the aquifer is controlled by the presence of non-continuous open fractures and joints that increase secondary permeability but do not greatly enhance bulk hydraulic conductivity. The Cedarberg and Pakhuis Formation acts as an aquitard due to the shale having such low hydraulic conductivity.

3.4 Surface Hydrology

Surface water drainage occurs through two rivers running through the research area. One of these rivers is the Gevonden River which originates from the mountains, flows along the alongside the borehole network and joins the Molenaars River downstream. For the most part, the Gevonden River is perennial up to approximately 100m after it leaves the mountain ridges. The Molenaars River (perennial) leads to the town of Rawsonville situated approximately 7km NE of the site (Figure 3.4).

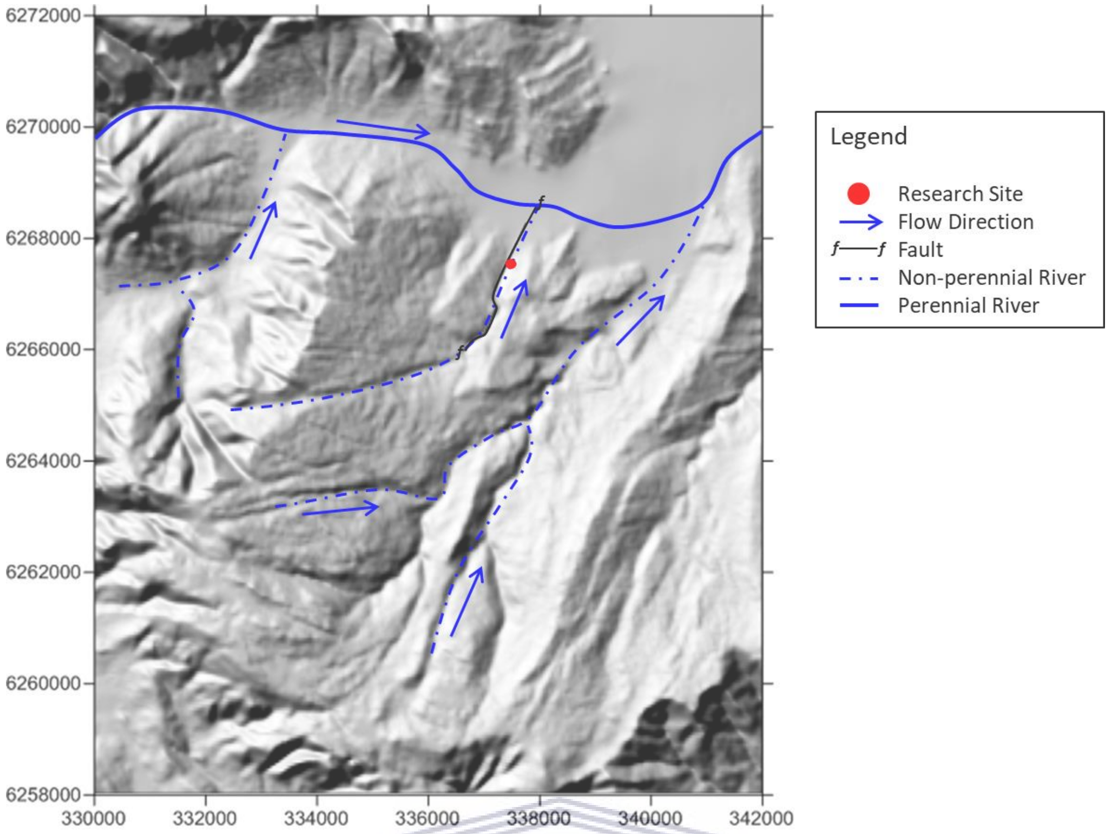

Figure 3.4: Surface water flow and drainage direction

3.5 Regional Climate

The Rawsonville research site experiences a Mediterranean climate which brings warm, dry summers and cold, wet winters. The rainy seasons generally occur between April and October. The site experiences a mean annual precipitation of 1595mm/a (WR, 2005).

3.6 Borehole Network

The borehole network was established in 2006 by the University of the Western Cape and was intended solely for research. The borehole network consists of 5 boreholes (Figure 3.5). Three boreholes are drilled approximately 200m deep (BH2, BH3 and BH5) and penetrate the Peninsula Formation, and one borehole is drilled to a depth of 8m (BH4) penetrating only the upper quaternary Sandy aquifer. Another borehole is drilled 260m deep at an angle of 60° (BH1). This borehole draws water from the Peninsula Formation on the Western side of the Waterkloof fault. The Cederberg and

Pakhuis Formations act as aquitards to the Peninsula fractured rock aquifer. This can be inferred as the cause of BH1 being an artesian borehole.

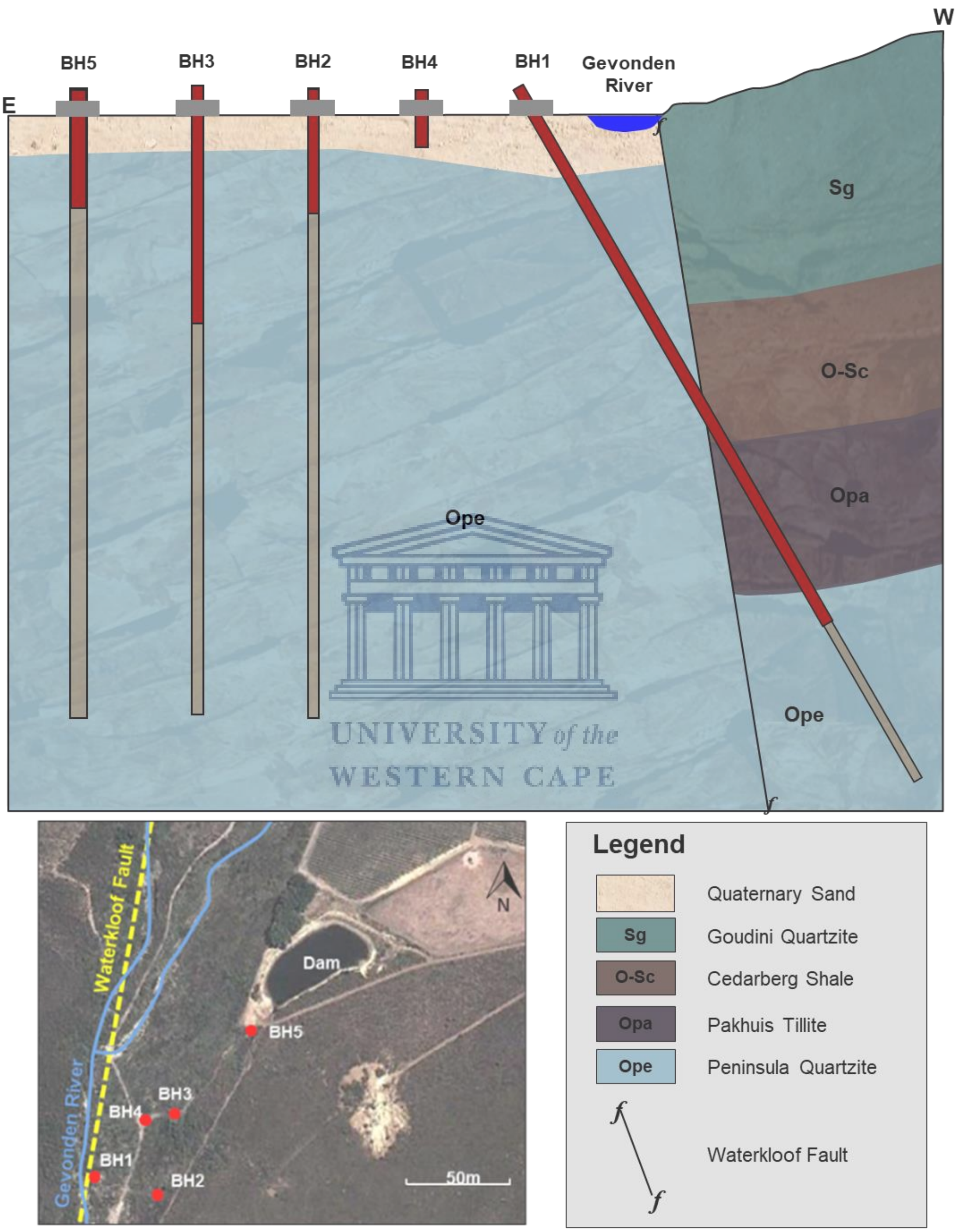

Figure 3.5: Conceptual setting of the borehole network and geology. Illustrated borehole depths and lithology thicknesses are relative and not to scale.

CHAPTER 4

MATERIALS AND METHODS

Various techniques were used in order characterise the Rawsonville research site. These include conducting a hydro census, aquifer testing and numerical modelling. Aquifer tests conducted include constant head discharge test, constant rate discharge tests, Flowing Electrical Conductivity (FEC) logging and tracer tests. The properties include transmissivity, storativity, effective porosity and hydraulic conductivity. MODFLOW© was used to model groundwater movement at the site.

4.1 Hydro Census

A hydro census was carried out in order to obtain basic background information on the study area. This information ranged from surface drainage sources and directions, land and groundwater use in the area, average water table, and possible groundwater contamination sources.

A printed satellite map was used as a reference document when meeting with farmers and land owners. One-on-one meetings were held to ask for permission to access farms and also to get as much baseline information of the area as possible. This information would include things such as land uses, types of fertilizer and pesticides used, sewage systems, irrigation methods, groundwater and surface water access points, groundwater abstraction data and borehole structure characteristics.

4.2 Constant Rate Discharge Tests

The Constant Rate Discharge (CD) method was conducted to characterise hydraulic properties of the aquifers at the research site.

Static water levels were taken of all boreholes with the exception of BH1 as it is a flowing artesian borehole. Data loggers were lowered into the boreholes in order to record changes in water level before, during and for a short period after the test. Manual water level readings were also taken using electrical contact meters in order to calibrate and ensure the correctness of the data logger readings. These reading intervals increased as the test progressed. A barometric data logger was also used to measure atmospheric pressure in order to correct for any atmospheric pressure interference that may have occurred during the test.

Once all preparations were completed, the generator was turned on and allowed to idle for a brief moment before the pump was switched on. Discharge was measured using a 20L bucket and a stopwatch.

4.2.1 BH3 CD test

Preparations for the test started by inserting a submersible pump into the borehole at approximately 25m below the collar (mbc). A lie-flat irrigation pipe was connected to the pump to transport the discharge water away from the pumping borehole. Power to the pump was supplied by a generator.

Once turned on, the pump was manually adjusted to pump at 1.6l/s. The pumping rate for BH3 was strategically chosen to compensate for the later decrease in discharge due to an increase in drawdown. The water was discharged approximately 50m away from the pumping borehole into a stream down gradient. BH2, BH4 and BH5 were used as observation boreholes for this test.

4.2.2 BH5 CD test

A submersible pump was lowered into BH5 at approximately 15mbc. Once turned on, the pump was manually adjusted to pump at 0.2l/s. A Garden hose was used to transport the discharge water away from the pumping borehole. Power to the pump was supplied by a generator.

The water would be discharged approximately 7m away from the pumping borehole into a stream down gradient. BH3 was used as an observation borehole for this test. Due to the hot weather conditions, low pumping rate and depth of the water table, the influence of the discharged water on the water table was considered to be negligible.

4.2.3 Data interpretation of CD test

Interpretations of CD tests were done using the excel based spread sheet programme called Flow Characteristic (FC) (Van Tonder et al., 2002) which was developed by the Institute for Groundwater Studies (IGS), University of the Free State, Bloemfontein. The FC method, which utilises the Cooper Jacob and Theis methods, was used to estimate aquifer hydraulic properties, such as transmissivity, storativity, flow characteristics and boundary conditions.

4.3 Tracer tests

A forced gradient tracer test was conducted between BH3 and BH5 using Rhodamine as the tracer. This was done in order to determine the transport properties of the aquifer and also to evaluate the fracture connectivity between boreholes BH3 and BH5. BH3 was used as the pumping borehole and BH5 the injection hole and BH2 acting as an additional observation borehole.

4.3.1 Tracer test Preparation

A submersible pump was lowered into BH3 to a depth of 20mbc. A data logger was taped to the lower most part of the pipe (just above the pump). A specially designed flow-cell was connected at the discharge point of the pumping borehole and an YSI 6600 multi-parameter sonde (YSI) was placed inside it (Figure 4.1). The YSI was used to measure the pH, EC, ORP, temperature and Rhodamine concentration of the water being pumped from BH3 and was programmed to take readings at 2min intervals. The lid of the flow cell was kept closed for the duration of the test to allow for the optical readings of the Rhodamine censor to be as accurate as possible.

Figure 4.1: Flow cell with the YSI 6600 multi parameter sonde inside it.

Background FEC logs were also taken of BH2 and BH5. A PVC pipe measuring 30mm in diameter and 160m in length was lowered 154m into the borehole (Figure 4.2). A mixture of 340g of Rhodamine powder, 500g of salt (NaCl) and 92*l* (volume of PVC pipe inside the borehole) was prepared to ensure that a known concentration of tracer was injected into the borehole.

BH3 was being pumped to reach steady state conditions (8hrs) before the tracer was injected.

4.3.2 Tracer Injection

The tracer solution was then poured into the pipe through a funnel at a slow constant rate. This procedure was followed to minimise spillage and the risk of any air bubbles forming inside the pipe between the funnel and the water level. Salt was simultaneously being injected into BH2 using the salt sock method.

Figure 4.2: Insertion of PVC injection pipe into BH5

Once the entire tracer solution was poured into the pipe, the pipe was pulled out of the borehole as fast as possible in order for the tracer to be injected as instantaneously as possible at a uniform concentration within the borehole. Once the full length of the pipe was removed from the borehole, the borehole water was mixed using the mixing tool. An initial FEC log was then taken of BH5 and BH2. Once this was completed, the pump was turned on. BH3 was pumped at a constant rate of 1.4l/s.

FEC logging was conducted for the duration of the experiment in order to monitor tracer movement in BH5, and water movement in BH2. The YSI was rinsed after every BH5 log and separate ropes were used to minimise Rhodamine contamination in BH2.

4.3.3 Data analysis

Tracer test data were analysed using the SOLVER analytical software (Akoachere II, and Van Tonder, 2011) which is able to give aquifer characteristics such as flow velocity and dispersion between boreholes BH3 and BH5. The data were inserted into the programme and the parameters were analysed using the best fit method where simulated test results were made to fit the actual test data.

4.4 Surface Geophysics

Surface geophysics was utilised to gain a better understanding of the hydraulic and physical properties of the aquifer at the Rawsonville research site. Two 400m electrical resistivity profile lines were laid producing two geo-electric models named Raw-1 and Raw-2 respectively. The lines were made perpendicular to each other and when combined, intercepted three of the five boreholes at the site (BH3, BH4 and BH5).

The Schlumberger measuring protocol was used which consisted of a combination of a long and short measuring protocol of which the long protocol was read first. Readings were made at 10m intervals along the long protocol and at 5m intervals on the short protocol.

Using a combination of the long and short electrode spacing protocol allows for better investigation of both deep lying geological structures as well as improving the visibility of structures in the alluvial deposits at the top. This particular protocol that was used is ideal for hard rock conditions such as the fractured TMG fractured rock at Rawsonville. The Abem SAS 1000 terrameter was used for the resistivity measurements through a set of electrodes after transmitting electrical current into the ground through another set of electrodes. Upon completion, two geo-electric models were produced from the two lines that were measured.

4.5 Groundwater modelling

In order to determine whether a site will require a 2D or 3D model, a conceptual understanding of the site and its hydrological processes must first be obtained. Using the information gathered in sections 4.1-4.4 along with a Digital Elevation Model (DEM), a conceptual model was developed in order to integrate and asses all the information gathered on the site. The conceptual model will be used in a numerical model to evaluate the capture zones of the production borehole and then delineate groundwater protection zones.

4.5.1 Conceptual model

Relevant data collected from the hydro census and from field experiments were combined in order to establish a conceptual understanding of the hydrological processes at the site. A 3D visualisation of the site was created using the Surfer™ visualisation software. This programme was used to digitize features such as rivers, faults, geological Formations etc.

4.5.2 Model Construction

The model was built using a MODFLOW© based finite difference grid using the Groundwater Vistas interface as the base for the model domain. Model inputs such as hydraulic properties, recharge, rivers and other hydrogeological features were added to the model domain in accordance with the conceptual model.

4.5.3 Model Calibration

The model was calibrated under steady state as well as transient conditions. Steady state calibration aided in testing the conceptual model and was also used to conduct a sensitivity analyses. Transient calibration helps to ensure that the model is sufficiently calibrated on a small scale to enable predictions regarding overall wellfield behaviour.

4.5.4 Sensitivity Analysis

The sensitivity analyses is an important part of the modelling process as it indicates, among other things, the contribution of each parameter to the final estimate of model calibration. The higher sensitivity of the parameter, the more important role it plays during the model calibration. Therefore, more attention should be placed on monitoring of parameters with higher sensitivity as they will benefit future model updates the most.

4.5.5 Predictive Scenarios

The primary objective of the predictive scenarios is to simulate the distance a water/contaminant particle will travel over a specific period of time towards the abstraction borehole. These periods will represent the protection zones and can range from 1yr to 100yrs time of travel (TOT).

Various abstraction scenarios were simulated for the site. This was done by adjusting the hydraulic properties of the zones most sensitive to change as indicated by the sensitivity analysis mentioned in section 4.5.3 by 20% and recording their capture zones. Two scenarios were also simulated for the Waterkloof fault. One where the fault acts as a conduit for flow and another where it acts as a boundary.

Protection zones will be divided into three time zones:

- Zone 1: 1 year
- Zone 2: 10 years
- Zone 3: 100 years.

These time zones were modelled for each predictive scenario and the outer boundary of the collective capture zones was used to include the uncertainty in the model and represent the protection zone for that specific time of travel. This is to allow for conservative protection zone delineation using a range of unknowns. Time zones were selected in order to make provision for potential persistent contaminants. Though half-lives of common organic pesticides and herbicides do not generally exceed 90 days (Hanson et al., 2015), some inorganic pesticides (e.g. DDT) can have a half-life of 100 years (NPIC, 2000). Zones were also selected based on the potential increased life expectancy of microbes/bacteria due to the higher groundwater temperatures in the area (Chapelle, 2001).

CHAPTER 5

AQUIFER CHARACTERIZATION

5.1 Surface Geophysics

Surface geophysics was utilised to characterise the electrical resistivity properties of the rock at the Rawsonville research site. Two 400m electrical resistivity profile lines were laid producing two geo-electric models. The lines laid perpendicular to each other and when combined, intercepted three of the five boreholes at the site (BH3, BH4 and BH5). The lines were Raw-1 (Figure 5.2) and Raw-2 (Figure 5.3) respectively. Raw-1 was recorded in from northeast to southwest and Raw-2 followed a northwest – southeast direction.

Figure 5.1 shows the relative positions of the two electrical resistivity profile lines

5.1.1 Geo-electric Model Raw-1

The geo-electric model Raw-1 (Figure 5.2) was laid along the Waterkloof fault. The profile shows a general trend of high resistivity values. Such high resistivity values indicate that the water potential along that profile is generally low. This may be attributed to the sandstone or quartzite of the Peninsula Formation being unweathered or unfractured as seen in the core logs retrieved by Lin (2008).

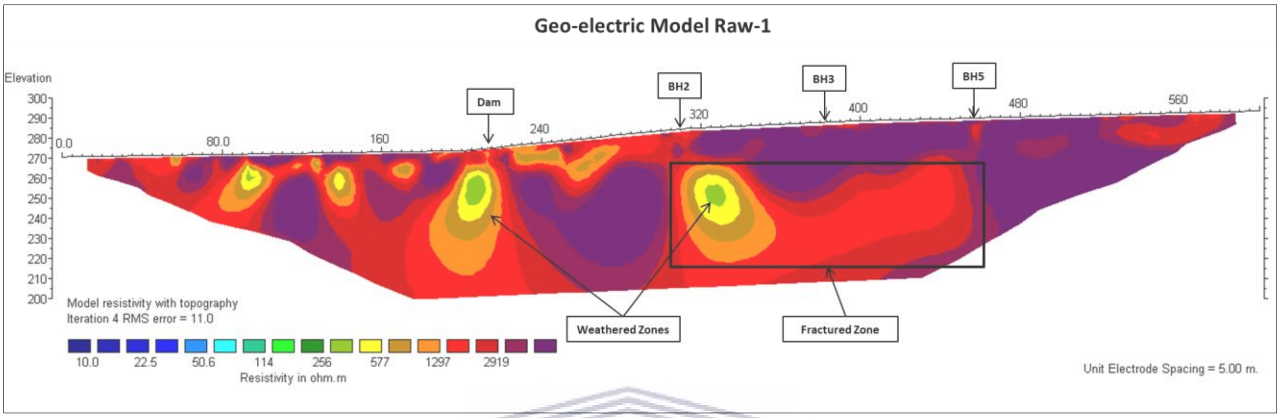

Figure 5.2: Geo-electric model Raw-1 showing a profile that cuts across BH2, BH3 and BH5.

Although Raw-1 is dominated by zones of high resistivity (higher than 2919ohm/m), areas of slightly lower resistivity are also present (resistivity between 577 and 1297ohm/m). The sandstone and quartzite rock in these zones are assumed to be fractured. These assumptions are confirmed through field observations done on boreholes BH2, BH3 and BH5. There is a possibility that the fractures in this zone are interconnected however, more evidence is needed to prove this theory.

There are zones displaying moderate resistivity values (between 257 and 577 ohm.m) which are considered to be weathered and more likely to be highly fractured. A manmade dam is situated at station 200 m of the geo – electric profile. During construction, the underlying rock was altered. This alteration is assumed to contribute to saturation within the surrounding rock material through seepage occurring along connected fractures which may be present. This may attribute to the lower resistivity values observed in this zone.

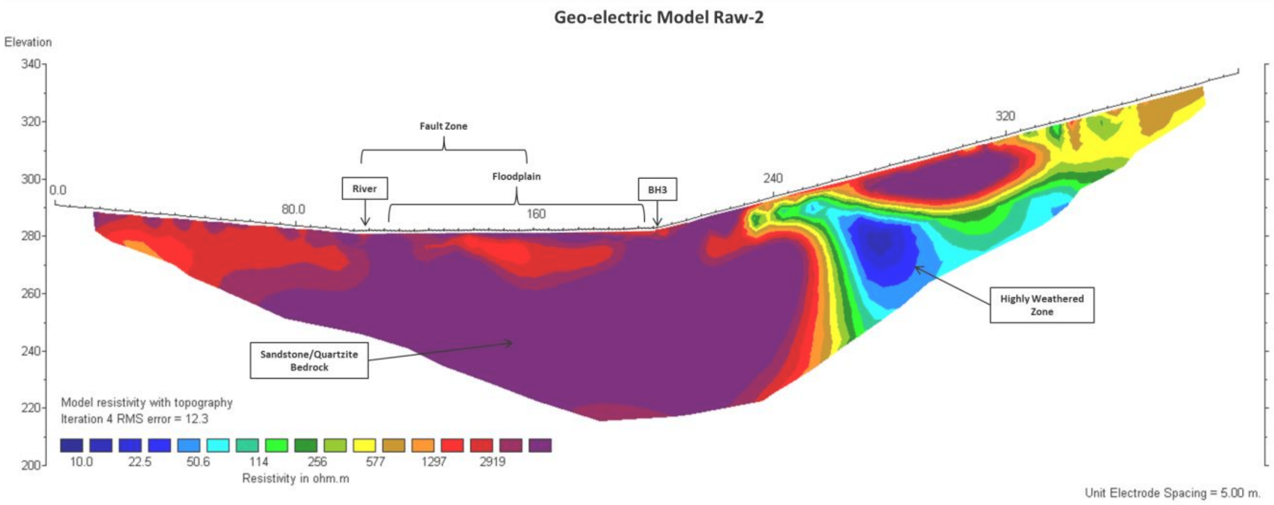

Figure 5.3: Geo-electric model Raw-2 showing a profile that cuts across the Gevonden River and BH3.

Raw-2 was laid perpendicular to the Waterkloof fault and was made to cross the Gevonden River. Between station 1 and station 215, the profile shows a dominance of high resistivity values (above 2919 ohm.m) with shallow zones of slightly lower resistivity (577 - 1297 ohm.m). This image suggests that the area is dominated by solid sandstone or quartzite with the presence of shallow weathering and slight fracturing. The influence of the Gevonden River can also be seen at station 110.

At approximately station 240, a sudden change in resistivity is observed. The resistivity values suddenly drop from high to moderate values (between 257 and 577 ohm.m). This is assumed to be due to a change in geology.

The low resistivities observed between stations 250 and 300 (between 10 and 114 ohm.m) suggest that the area is highly weathered and has a high water potential as it matches up with Telford et al.'s (1990) interpretations of fresh groundwater in fractured rock.

In both profiles, it can also be noted that the areas with the highest resistivities are in proximity to the Waterkloof fault in the area. The interpretations made for Raw-1 and Raw-2 fit the criteria required for fractured sandstone (10^3 – 2 x 10^8 ohm.m) and quartzite (8 – 4 x 10^3 ohm.m) as described by Telford et al., (1990).

5.2 Aquifer tests

Boreholes BH5 and BH3 were pumped in order to establish aquifer characteristics such as storativity and transmissivity. Pumping test data was analysed using the analytical software for windows SOLVER (van Tonder, 2011).

5.2.1 Pumping tests

BH5 CD test

BH5 is 200m deep with a casing depth of 30m. The BH penetrates the fractured rock aquifer of the Peninsula Formation and is 65m away from BH3 and about 130m from BH2. A submersible pump was lowered 18m into BH5. A data logger was also lowered into the borehole to measure the change in water level during pumping. The borehole was pumped for 3 hours at a rate of 0.2l/s in order to determine the transmissivity and storativity values of the aquifer.

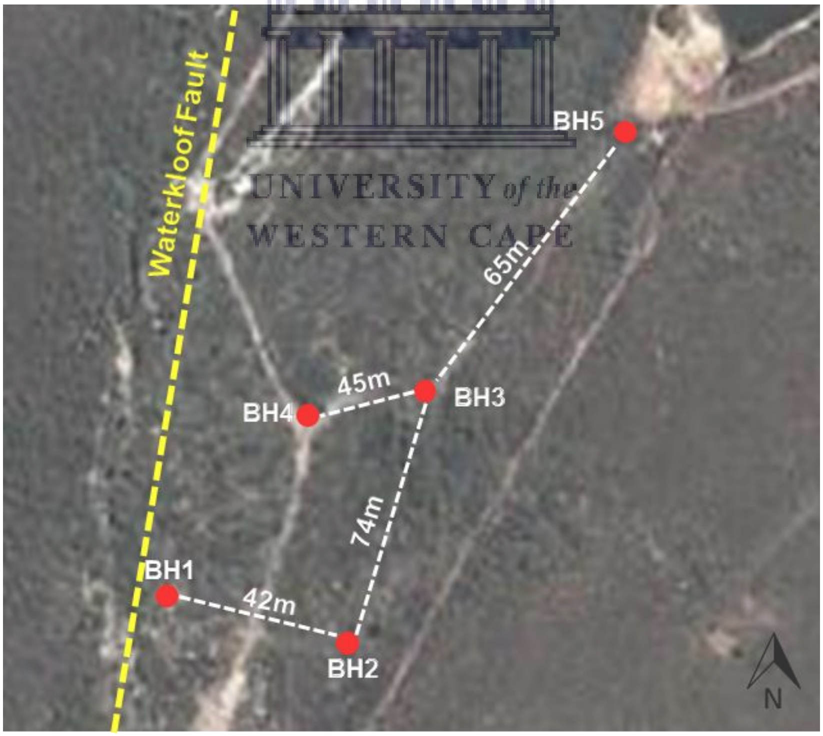

Figure 5.4 shows the spatial distribution of the boreholes at the study site.

Data plots suggest that the aquifer is feeding the borehole (Figure 5.5). Pumping test data were inserted into the FC programme and the data was analysed. This gave transmissivity results of 4.1m^2/d when analysed using the Cooper-Jacob method.

The results were estimated using the FC Programme (Figure 5.5).

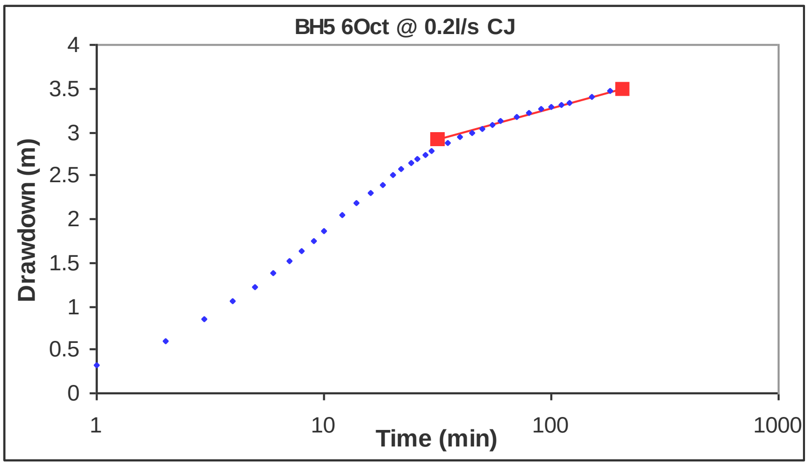

Figure 5.5: Data analysis showing the late time data Cooper-Jacob fit of BH5 being pumped at 0.2l/s.

BH3 CD test

BH3 is 191m deep with a casing depth of 60m. The BH penetrates the fractured rock aquifer and is 65m away from BH5 and 74m away from BH2. BH3 was pumped for 24hrs @ 1.6l/s in order to determine the transmissivity and storativity values of the aquifer.

Data analyses (Figure 5.6, Figure 5.7, Figure 5.8) gave transmissivity values of 14.8m^2/d for BH2, 11m^2/d for BH3 and 9.3m^2/d for BH5 using the Cooper-Jacob method. The analysis showed storativity values of 4.33x10^{-5} for BH2 and 5.16x10^{-06} for BH5 when using the Cooper-Jacob method. Both lines were fitted to late time data as this is when matrix flow most likely took place.

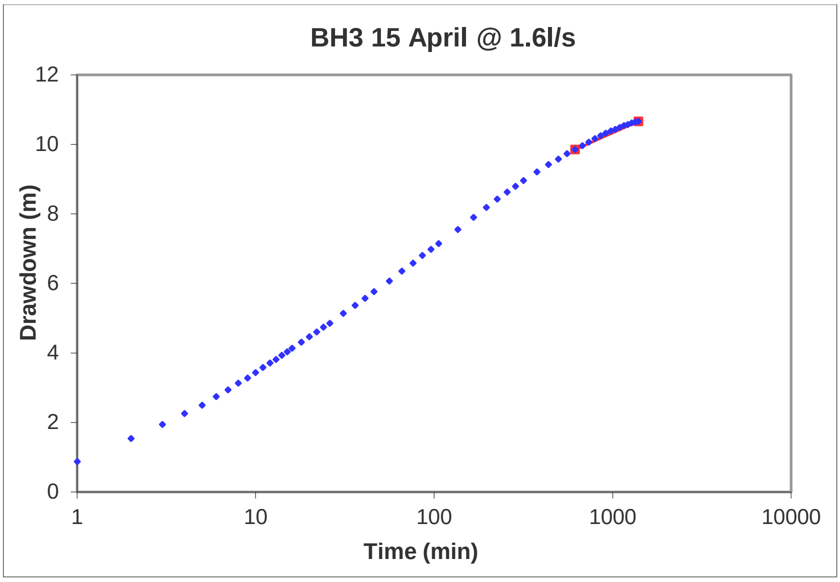

Figure 5.6: Data analysis showing the late time data Cooper-Jacob fit for BH3 being pumped at 1.6l/s.

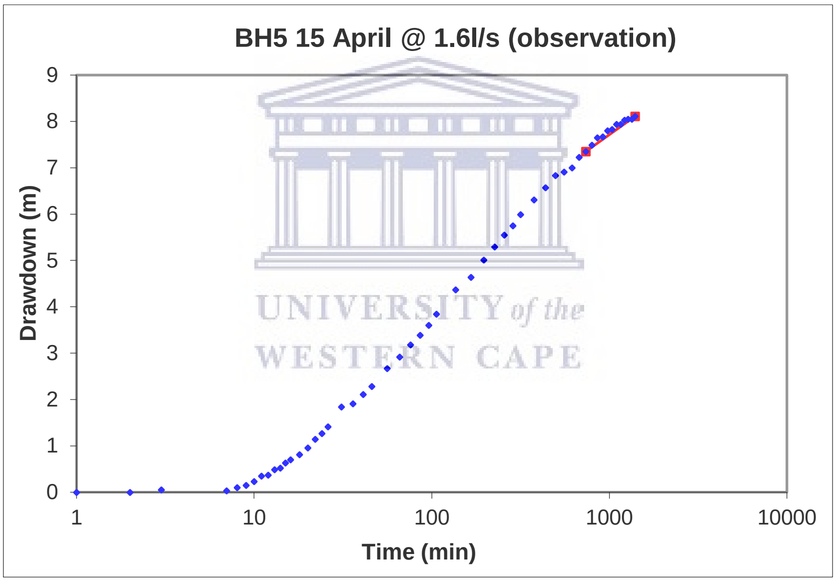

Figure 5.7: Data analysis showing the late time data Cooper-Jacob fit for BH5 which was used as an observation borehole during the pumping test.

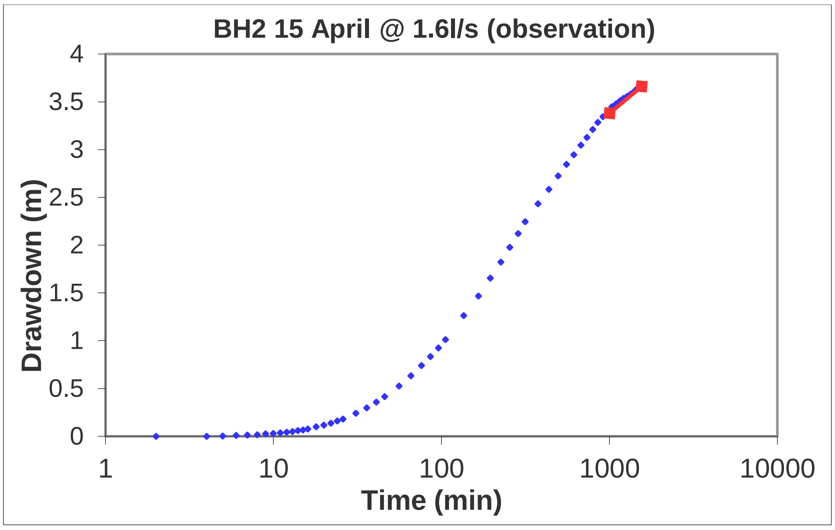

Figure 5.8: Data analysis showing the late time data Cooper-Jacob fit for BH2 which was used as an observation borehole during the pumping test.

5.2.2 Tracer tests

A forced gradient tracer test was conducted between BH3 and BH5 in order to determine porosity using Rhodamine as the tracer. BH3 was used as the pumping borehole and BH5 the injection borehole.

From the Rhodamine sensor data logging it can be seen that the tracer arrived at BH3 after about 28min and passed after about 50min. The smaller peaks which follow suggest that the tracer is moving through smaller discrete fractures linked to BH3. The flow velocity within the borehole was then calculated using the following formula:

$$V = \frac{d}{t}$$

Where: V = Linear flow velocity

d = Linear distance between the injection and abstraction boreholes

t = Time taken for tracer to reach abstraction borehole

Using the above formula with the aid of an analytical software, the linear flow velocity was calculated to be 2300m/d as shown in Figure 5.9.

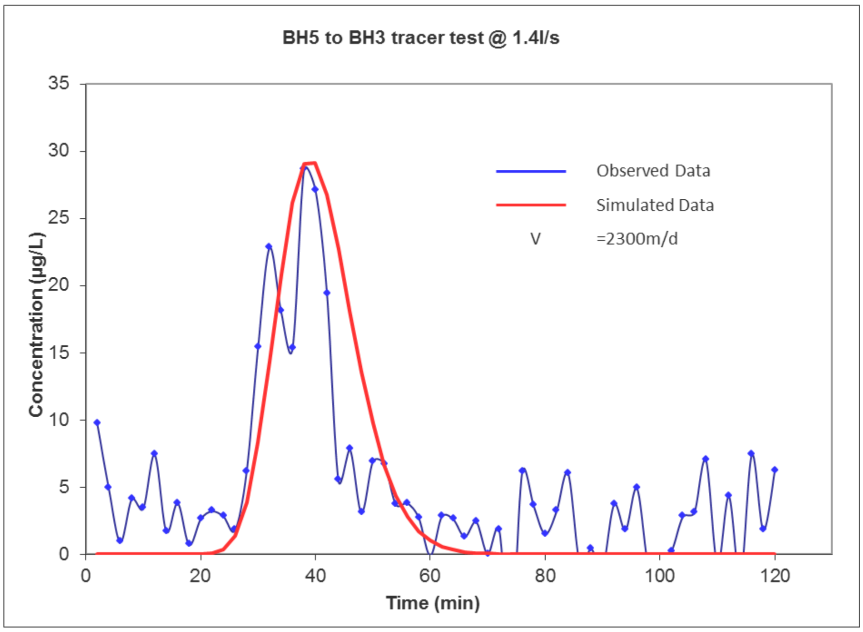

Figure 5.9: Results of the tracer test conducted between boreholes BH3 and BH5.

5.3 Summary

Electrical resistivity profiles show patterns indicative of fractured sandstone. They also show low resistivity values associated with fracturing along the Waterkloof fault zone. The resistivity profiles suggest that BH3 and BH5 may be connected by fractures in the sandstone.

Pumping tests were conducted on BH3 and BH5 which showed interconnectivity between boreholes BH2 BH3 and BH5. This correlates with what was shown in the electrical resistivity logs discussed above. The pumping tests gave transmissivity and specific yield values which are important in understanding flow characteristics of the aquifer and will also be used to provide input data for the numerical model later on.

A forced gradient tracer test was conducted which confirmed fracture connectivity between boreholes BH3 and BH5. The breakthrough curve arrived 28min after the tracer was injected. Minor spikes in concentration suggest that the boreholes are also connected via discrete fractures within the sandstone aquifer.

CHAPTER 6

SITE CONCEPTUAL MODEL

A hydro census was carried out in order to obtain basic background information on the study area. The results of the hydro census were collated and presented in a conceptual model which in turn will be used to build the numerical model in section 7.1. This information ranged from surface drainage sources and directions, land and groundwater use in the area, average water table, and possible groundwater contamination sources.

6.1 Land Use and Potential Contaminants

Land use in the area is dominated by agriculture although some farm housing is present. The research site is adjacent to the N1 national road and the R101 which is used by a weigh bridge (Figure 6.1). The produce from the farms are transported via dirt roads and the R101 tar road to distilleries in the area. Some farmers also breed cattle and chickens and have dams on their farms.

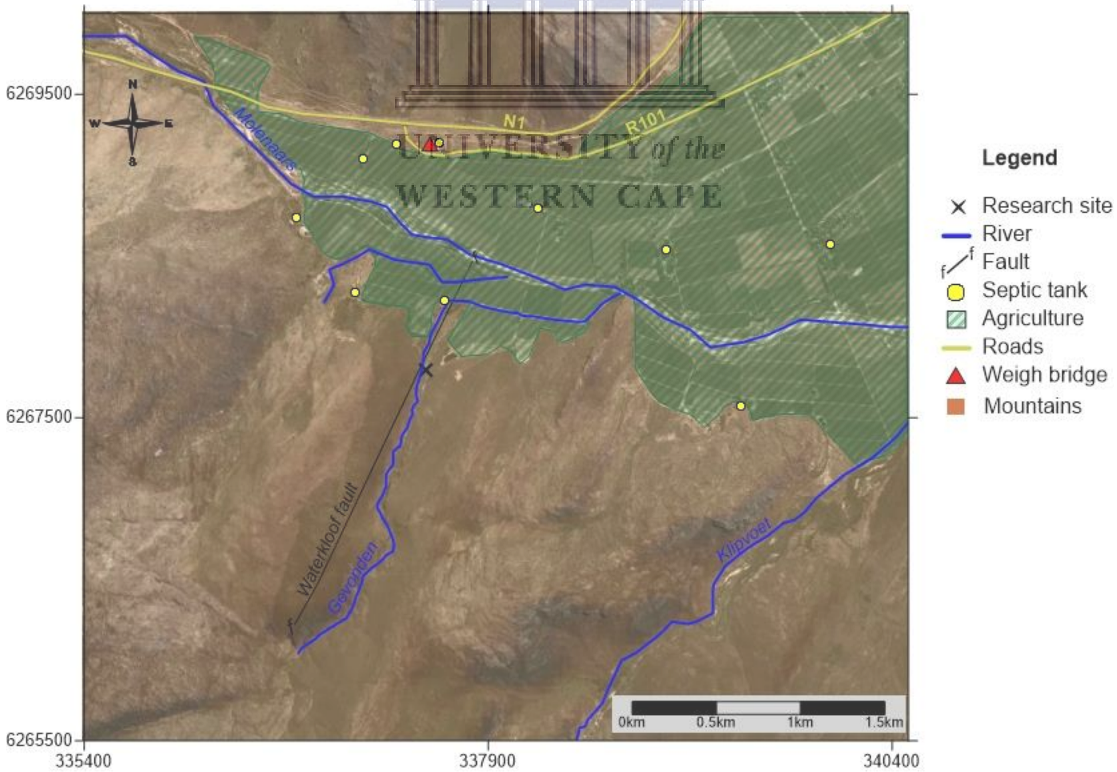

Figure 6.1: Types of land use and potential contamination sources. Base map taken from Google Earth

Figure 6.1 shows a few potential sources of contamination identified in the area surrounding the site during the hydro census. Being an area dominated by wine farming, one of the main potential pollution sources is agriculture. Both organic and inorganic fertilizers are used along with pesticides (Figure 6.2). Leachate from these chemicals may reach the groundwater used by the farmers for domestic water supply as well as irrigation.

Figure 6.2: Application of pesticides onto grapevine crops.

The Molenaars River runs through the densely farmed area (Figure 6.1) and is vulnerable to leaching farm chemicals. Groundwater contribution to the river could cause the river to carry contaminants to the town of Rawsonville where the water is consumed by many people living next to the river. If any contamination should occur upstream of the research site and the river gets contaminated, the river will become a contaminant carrier.

The national road N1 and the R101 are frequently used by long distance trucks transporting various cargos. These cargos can contain things such as fuel, livestock, fruit and vehicles. Some trucks passing this area are required to stop at the weighbridge indicated in Figure 6.1. Any liquids which leak from these trucks will be washed to the side of the road during a rain event. Depending on their chemical compositions, the chemicals will reach either the river or the groundwater systems.

6.2 Groundwater Use

Groundwater access points were identified as (Figure 6.3):

- Boreholes
- Springs
- Rivers.

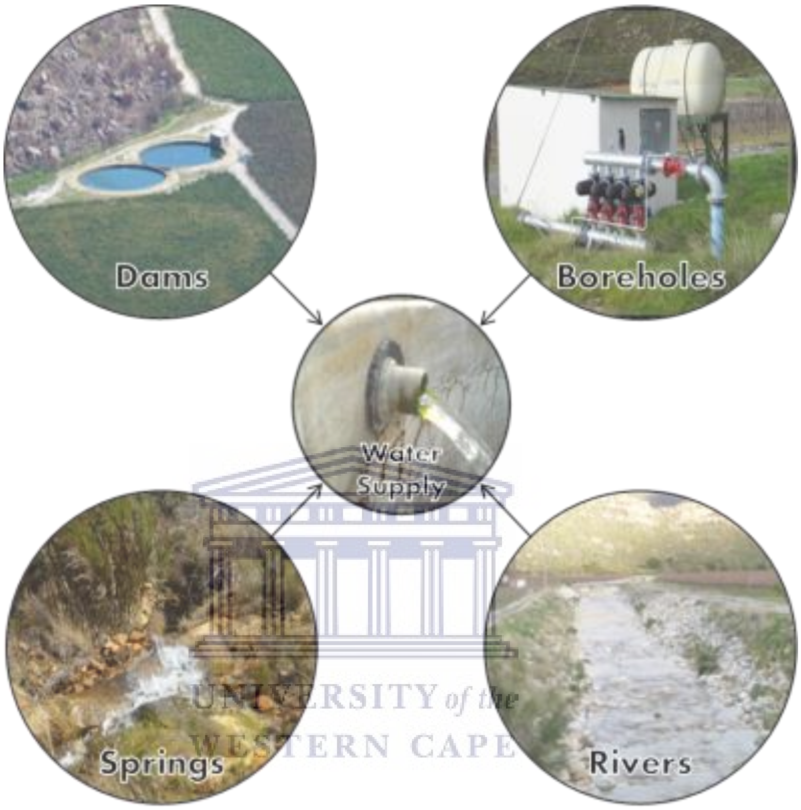

Figure 6.3: Types of water access points identified at the site.

Groundwater usage peaks during the dry seasons and is very minimal during other parts of the year. Groundwater in the area is mainly used for agricultural irrigation. Boreholes, springs and rivers are used to fill farm dams which act as reserves for the dry seasons. These reserves are also used as a domestic water source.

6.3 Conclusion

The conceptual model of the research site is characterized by a two layer hydrogeological system, namely a shallow primary aquifer and a deeper fractured aquifer. The geology at the site forms an anticline with the Waterkloof fault running along its axis. Uplift on the eastern side of the fault exposes the Cedarberg and Pakhuis

Formations. The fault is assumed to act as a flow boundary which can account for the flowing artesian conditions experienced at BH1.

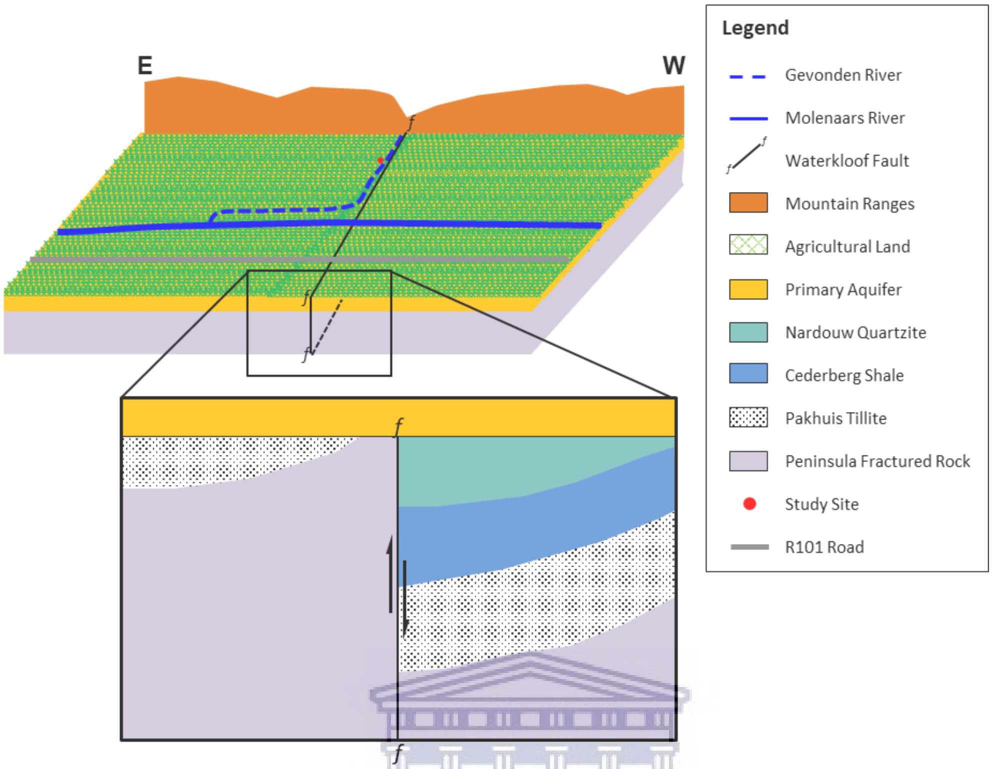

Figure 6.4 shows the conceptual model of the study site

The average annual precipitation in the Rawsonville area is estimated to be 1595mm (WR2005). It is assumed that recharge to the primary aquifer occurs through infiltration from precipitation in the area whereas recharge mechanisms to the bedrock occurs through precipitation and snow melt coming from the mountain ridges. Discharge from the aquifers occurs as drainage by the local streams during the dry season as well as through springs at the foot of the mountains. Flow direction from the mountain ridges are toward the Molenaars River where it then flows north. Potential contamination sources in the area are agriculture, septic tanks, traffic and river contamination.

Aquifer tests have shown that the three boreholes (BH2, BH3, and BH5) are connected. Analysis of the pumping test data reveals that the drawdown curve produced is that typical to a confined fracture flow system, however, late time data may lean towards a leaky aquifer system. Available literature suggests that the bulk rock hydraulic conductivities of the Peninsula Formation ranges from 0.21 to 3.6m/d (Lin, 2007) and 3 to 15 for sandstone (Kresic, 2007).

CHAPTER 7

PROTECTION ZONE DELINEATION

7.1 Model construction

The numerical model for the project was constructed using Groundwater Vistas© (GV6), a pre- and post- processing package for the modelling code MODFLOW©. The numerical model was based on the conceptual model developed in chapter 6.

7.1.1 Model Limitations and Assumptions

Data used in modelling the influence of the Gevonden capture zones are based on the hydro census and site specific wellfield results. These data represent a snapshot in time, while predictions are made well into the future. Uncertainty in rainfall and recharge rates, together with heterogeneous aquifer properties, results in a degree of uncertainty in the modelled predictions.

Monitoring of the water balance of the surface water/groundwater system, groundwater levels and groundwater quality during wellfield operation would provide useful data with which to update the conceptual model and improve confidence in the predicted impacts.

The following data gaps were identified during the numerical model construction and calibration (*Assumption for use in model in italics and brackets*):

- No pumping test history of boreholes from the primary or secondary aquifer. (*Some of the boreholes measured showed depressed groundwater levels assumed to be due to localized pumping*.)
- Groundwater calibration data for the entire model domain were mostly only available in the primary aquifer while the fractured rock aquifer data is limited to the site scale. (*Groundwater model fractured rock properties were not calibrated in distant areas*.)
- Borehole construction and depths for the hydro census boreholes could not be obtained in all cases. The available water level response therefore cannot be related to the different aquifer units and could influence the confidence of the

model predictions. (*For the calibration of the model, the monitoring boreholes were placed into the primary aquifer (layer 1) and shallow fractured aquifer (layer 2*).

- No monitoring boreholes are associated with the fault to evaluate the hydraulic properties or the response to natural or pumping induced stresses. (*It was assumed that the hydraulic conductivity along the fault is approximately 25% higher in comparison to the surrounding aquifer*.)
- Limited data on hydraulic properties from the deep fractured aquifer is available. The availability of data in this regard will improve the confidence of the model calibration and predictions. (*It was assumed that the hydraulic conductivity is constant with the depth.*)

7.1.2 Boundary conditions

Local hydraulic boundaries were identified for model boundaries. They were represented by local watershed boundaries and were delineated as no flow boundaries around the entire model domain. These hydraulic boundaries were selected far enough from the area of investigation to not influence the numerical model behaviour in an artificial manner.

Outflows from the model domain are represented as rivers and drains. The Gevonden and Klipvoet Rivers are represented by the MODFLOW© Drain package as they are largely non-perennial rivers and the Molenaars River as River cells (Figure 7.1).

7.1.3 Model Domain, Mesh and Layers

The model domain is defined by topography and surface water catchment boundaries. As per the WGS 1984 UTM 345 coordinate system, the model covers the area between coordinates 330000, 625700 and 342500, 6272500. The rectangular grid consists of 7 layers (representative vertical hydraulic conductivity distribution to allow for more accurate depth movement of particles) with a total of 283 185 cells (155 x 261 x 7 layers). A grid of 100 m x 100 m refined to a 6.25m cell size around the borehole network was allocated to the model.

Smaller cell sizes were specified in the areas of the wellfield where a more accurate solution of the groundwater flow equation is required. Slightly larger cell sizes were specified in other areas as seen in Figure 7.1. Cell size refinement across the model domain did not exceed 0.5 times the neighbouring cells.

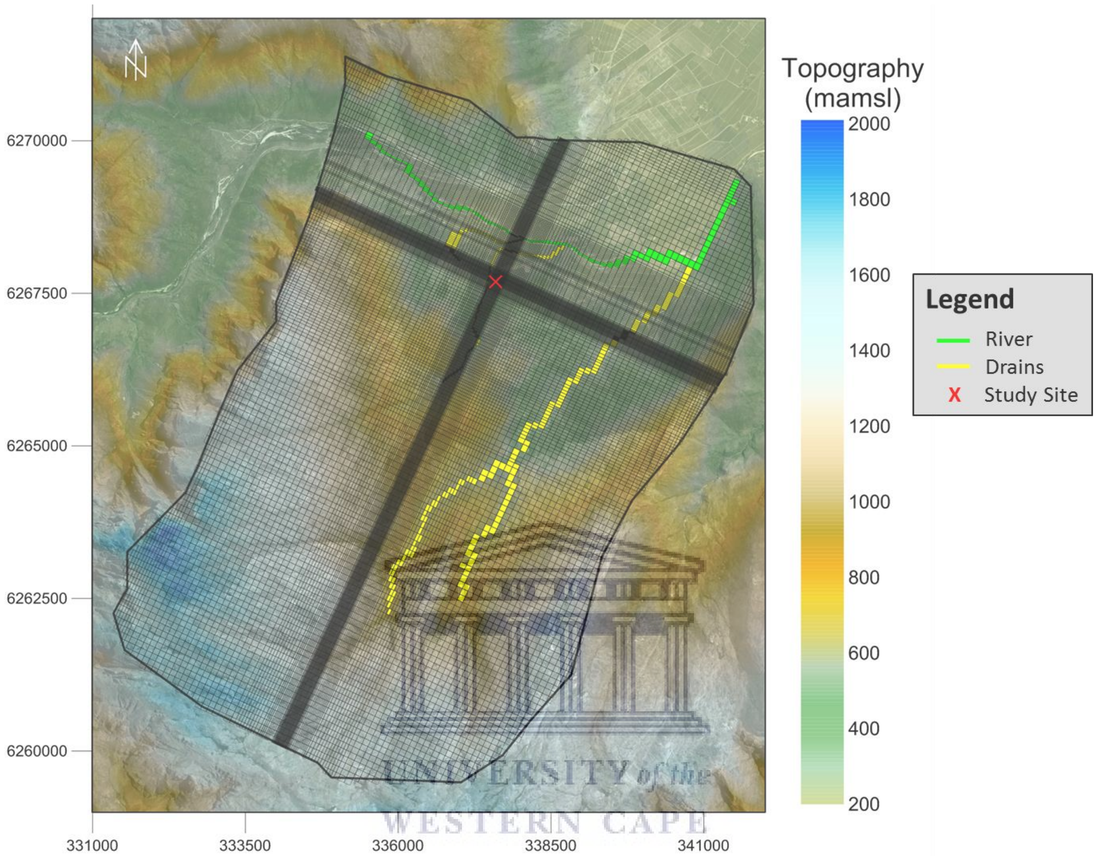

Figure 7.1: Model grid overlain onto the model domain.

A 7-layer, MODFLOW© finite difference grid is applied to the model area. The model layers are broadly defined by hydrogeological units, based on the site conceptual model. Table 7.1 indicates the layer elevations and thicknesses represented in the model.

Table 7.1: Model layer thicknesses and elevations

<table>
<tr><th>Model Layer</th><th>Hydro-lithological unit</th><th>Layer top elevation</th><th>Layer bottom elevation</th><th>Thickness (m)</th><th>Description</th></tr>
<tr><td rowspan="6">1</td><td>Unconsolidated alluvium</td><td rowspan="6">Topographic map</td><td rowspan="6">Base of alluvium (Topographic surface minus 40m)</td><td rowspan="4">Topography minus base elevation</td><td rowspan="6">Shallow valley groundwater system, i.e. alluvium and sedimentary and boulder cover, and exposed bedrock lithologies on the mountain slopes</td></tr>
<tr><td>Peninsula Formation</td></tr>
<tr><td>Cedarberg shale</td></tr>
<tr><td>Gevonden River</td></tr>
<tr><td>Klipvoet River</td><td rowspan="2">1</td></tr>
<tr><td>Molenaars River</td></tr>
<tr><td rowspan="4">2-7</td><td>Peninsula Formation</td><td rowspan="4">Bottom of upper layer</td><td rowspan="2">Layers 2-6: Base of upper layer minus 100m</td><td rowspan="2">100</td><td rowspan="4">Peninsula Quartzite Formation and fault.</td></tr>
<tr><td>Waterkloof fault</td></tr>
<tr><td>Waterkloof fault buffer zone</td><td rowspan="2">Layers 7-8: Base of upper elevation minus 200m</td><td rowspan="2">200</td></tr>
<tr><td>Klipvoet fault</td></tr>
</table>

7.1.4 Recharge

Effective precipitation is represented in the model as distributed recharge into the saturated groundwater system (Figure 7.2). The percentage of precipitation reaching the alluvium, sedimentary cover and bedrock as recharge was adjusted during model calibration. Infiltration of 6% for alluvium, 4% for the bedrock and negligible for the shale layer was found to be optimum.

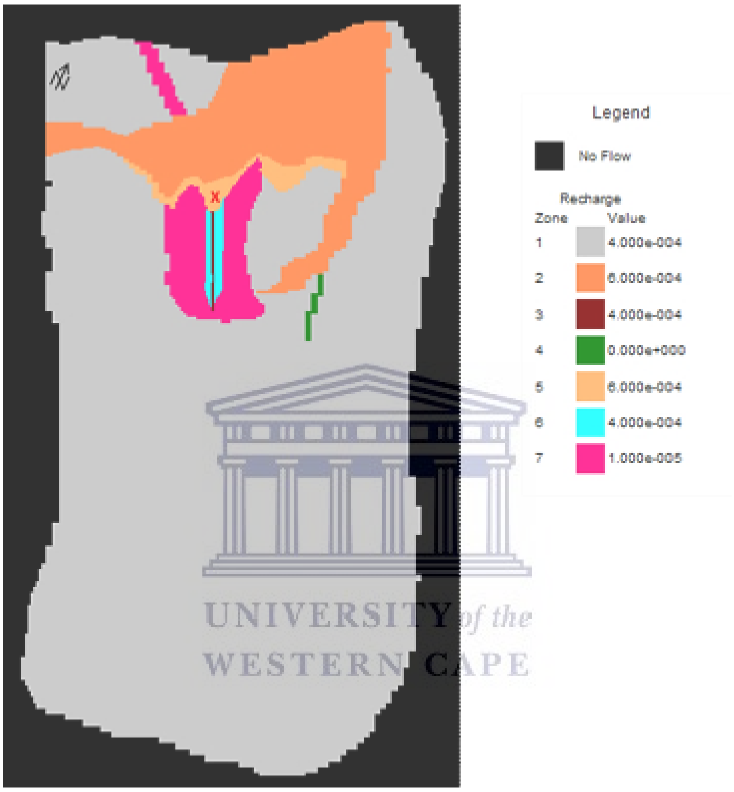

Figure 7.2: Recharge (m/d) properties for the model domain with the research site represented with a cross.

7.1.5 Hydraulic properties

Average hydraulic properties obtained from hydraulic tests were used as initial values in the model. These properties were modified during calibration within realistic ranges. Due to the orientation of the Peninsula Formation at the site, and the high infiltration rates of the alluvium, K values were adjusted to favour vertical flow. Figure 7.3 illustrates the spatial distribution of the initial hydraulic properties assigned to the different hydrogeological units. Table 7.2 shows the values obtained once the calibration process was completed.

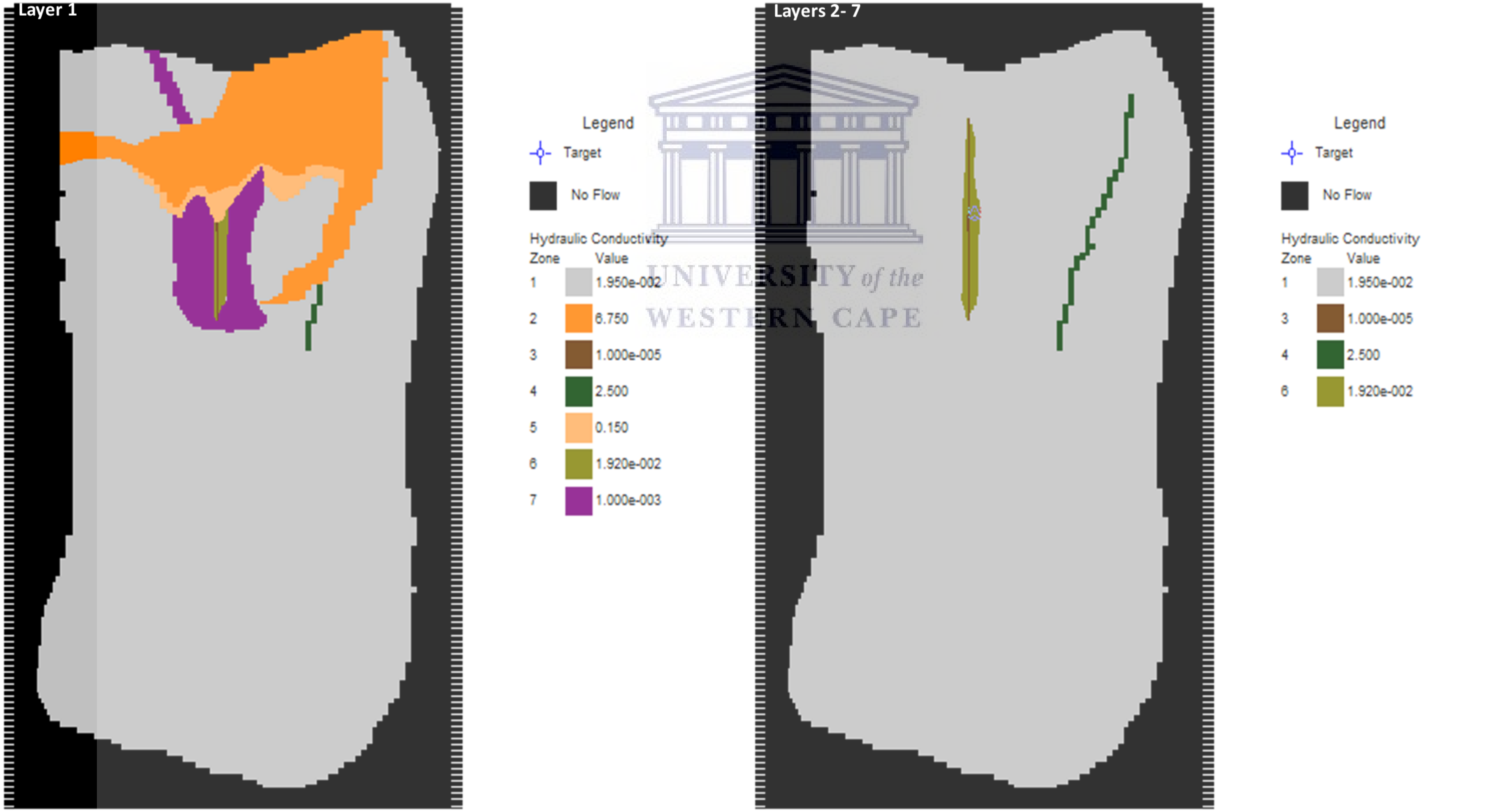

Figure 7.3: Hydraulic properties (m/d) assigned to hydrolithologic units.

Table 7.2: Calibrated model property values (m/d)

Zone	Hydrolithologic unit	Kx	Ky	Kz	Ss	Porosity
1	Peninsula Formation	0.013	0.01	0.013	1e-006	0.002
2	Unconsolidated alluvium	4.5	4.5	2	0.007	0.2
3	Waterkloof fault	1e-007	1e-007	1e-007	1e-006	0.0002
4	Klipvoet Fault	2.5	5	10	1e-006	0.0002
5	Alluvium buffer zone	0.1	0.1	0.053	0.014	0.2
6	Waterkloof fault brecciated zone	0.014	0.014	0.01	1e-007	0.006
7	Cedarberg Formation	0.001	0.001	0.0001	1e-006	0.03

Note: Infiltration characteristics of the unconsolidated alluvium as well as the dip and strike of geological formations were taken into consideration during model calibration.

7.2 Model calibration

Water level data collected from the hydro census was imported as groundwater elevation targets and used to calibrate the model. The transient model was calibrated using aquifer test data.

7.2.1 Steady State Model Calibration Results

For the UWC research site model area, calibration was done using a combination of manual and inverse calibration using aquifer zone properties for all model layers.

Steady state calibrated water levels show the steady state groundwater elevation contours (Figure 7.4). Water level contours within the alluvium and sedimentary cover (Layer 1) are largely influenced by recharge zones. Water levels measured in bedrock boreholes indicate a different hydraulic pressure compared to the water level in the primary aquifers. The bedrock borehole water levels seem to be controlled by hydraulic conductivity of the Peninsula aquifer unit while the primary aquifer water levels are mostly controlled by river and stream outflow heights.

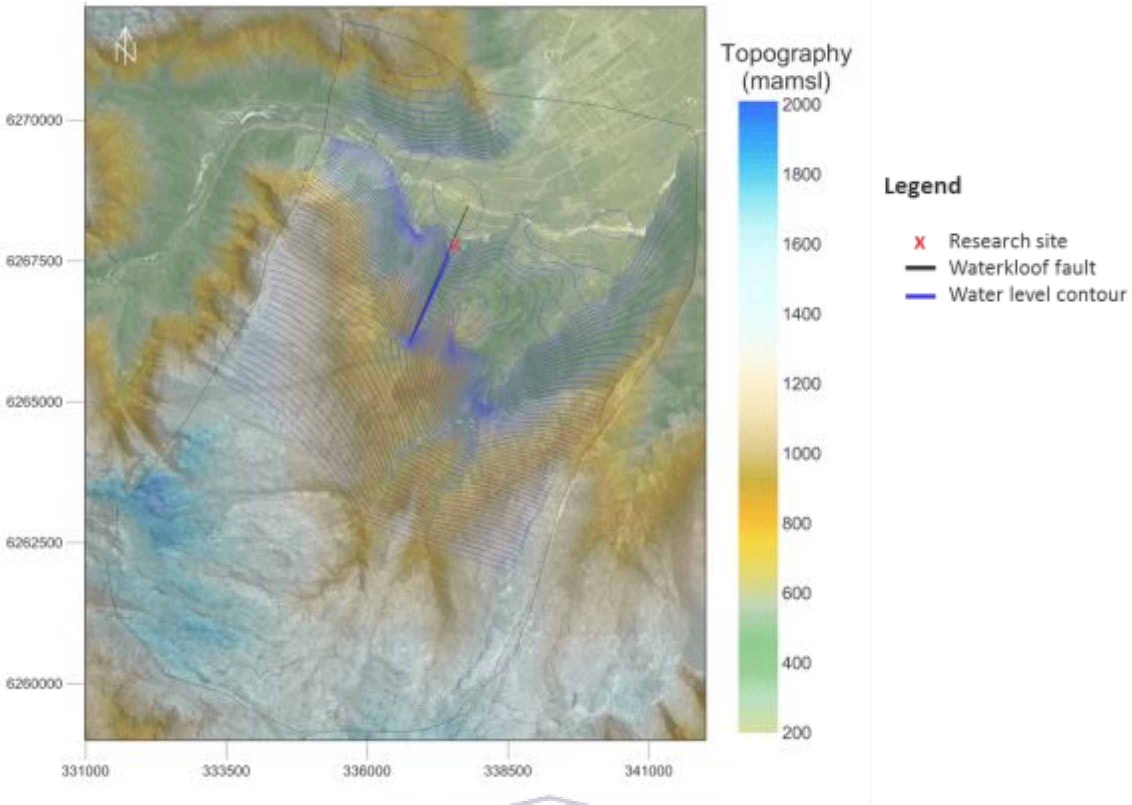

Figure 7.4: Water level contours after steady calibration

To assess the accuracy of the steady state simulation the model results are compared to monitored water level data. The degree of error, or residual, is the difference between the observed water level data and that which is simulated in the model.

The graph in Figure 7.5 shows observed versus modelled water levels. The straight line represents the ideal condition where field observations and model results are identical. In general, steady state calibration results show a good match with the observed water levels.

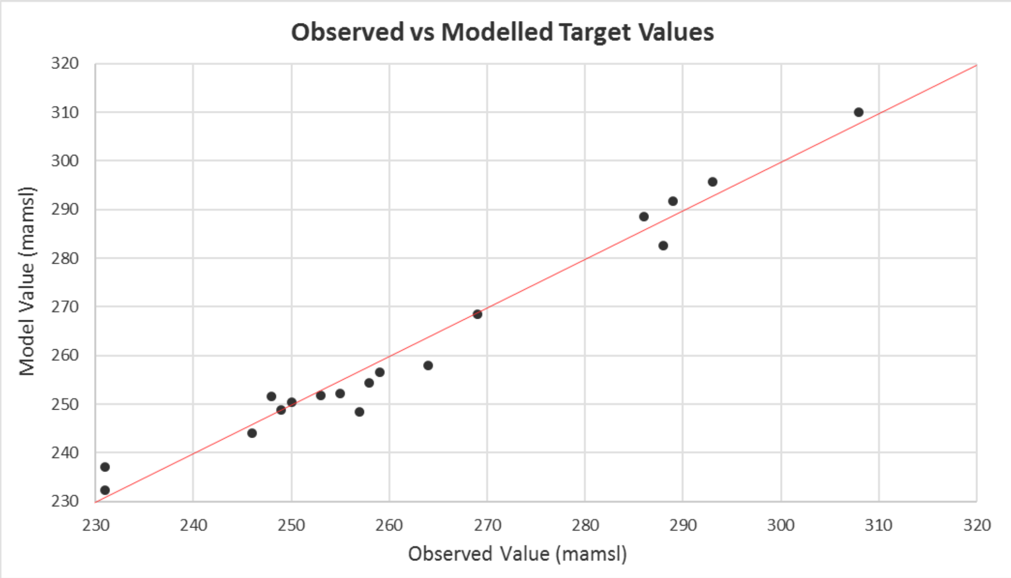

Figure 7.5: Graph showing the observed vs simulated water levels.

In the case of the steady state calibrated model, the mean error is -0.06m, the absolute mean 5.17m and the RMS error 7.82m, all of which are acceptable statistics for a regional model. The Scaled Mean Absolute (SMA) error represents 4.2% of the scaled total head difference measured between the boreholes used for the steady state calibration. The typical SMA and RMS target values for regional models is <10%. Thus the statistics show that the model has been calibrated in steady state with relatively low errors.

7.2.2 Transient Model Calibration Results

The steady state calibrated groundwater flow model properties as well as abstraction and water level data from aquifer tests were used as calibration input for transient conditions. The simulated and observed water level response is shown in Figure 7.6.

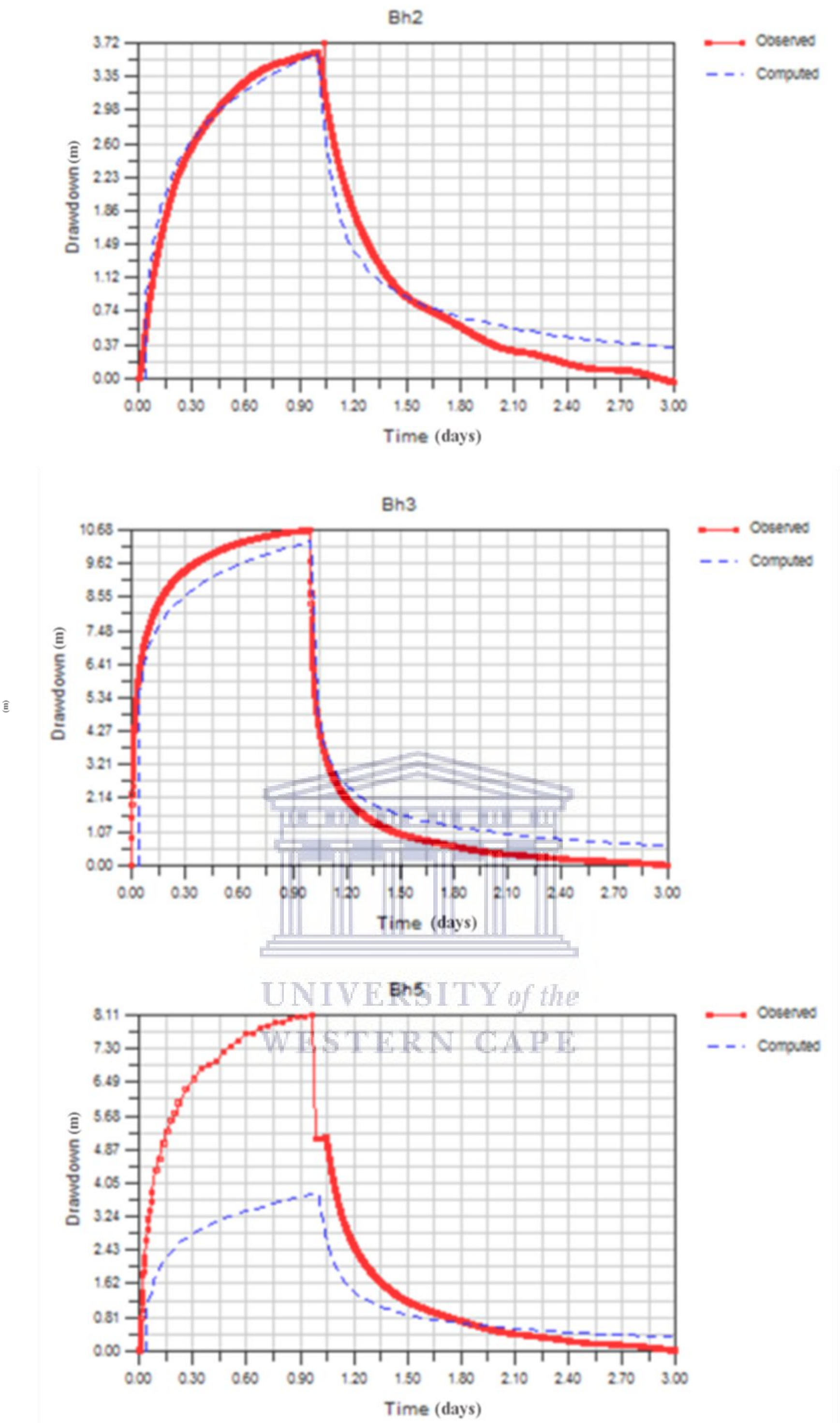

Figure 7.6: Transient calibration graphs for BH2, BH3 and BH5.

It is clear from the simulated results obtained that the hydrogeological flow model is capable of simulating the real aquifer test data sufficiently while allowing confidence in the flow model. During this calibration exercise aquifer specific storage values acquired through aquifer testing were specified (Table 7.2). The model was then calibrated to obtain more accurate results.

Since the graphs of BH2 and BH3 are near perfect matches, it is assumed that the discrepancy observed in the graphs of BH5 can be attributed to the heterogeneous and highly fractured aquifer system. It could be that the borehole is experiencing localised change in flow properties which is why the graphs struggle to align themselves in the manner that BH2 and BH3 have.

7.3 Sensitivity analysis

A sensitivity analysis was carried out on the calibrated steady state model. Groundwater Vistas does this by using zones to assess the importance of the various parameters. Sensitivity analyses were performed on horizontal hydraulic conductivity, vertical hydraulic conductivity and recharge.

The results of the sensitivity analysis presented in Figure 7.7, Figure 7.8 and Figure 7.9 indicate that the highest contribution to the estimate of uncertainty was brought almost exclusively by the Peninsula aquifer (Zone 1), horizontal (*Kx*, *Ky*), vertical (*Kz*), and recharge. Based on these results, it is recommended that groundwater monitoring and characterisation programmes be put into place to provide improved data regarding these parameters. Time series of groundwater level data from the Peninsula aquifer will benefit future model updates the most.

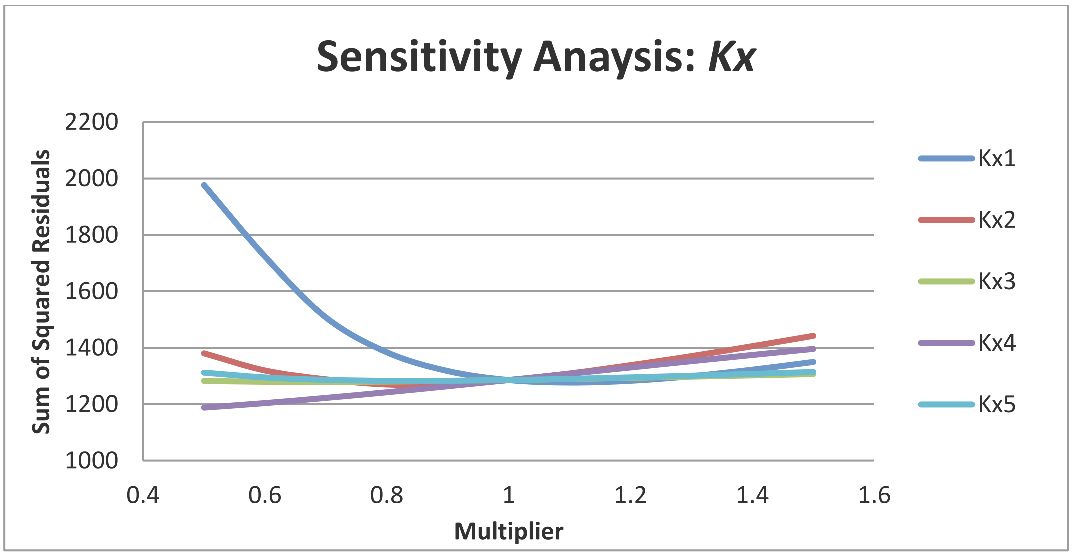

Figure 7.7: Sensitivity analyses for horizontal hydraulic conductivity.

From the above graph it can be seen that *Kx*1 (Peninsula Formation) is most sensitive to a decrease in horizontal conductivity. The rest of the zone lines are fairly stable as the lines are nearly flat which means that there will be a minimal change in residual if the values were adjusted within the model.

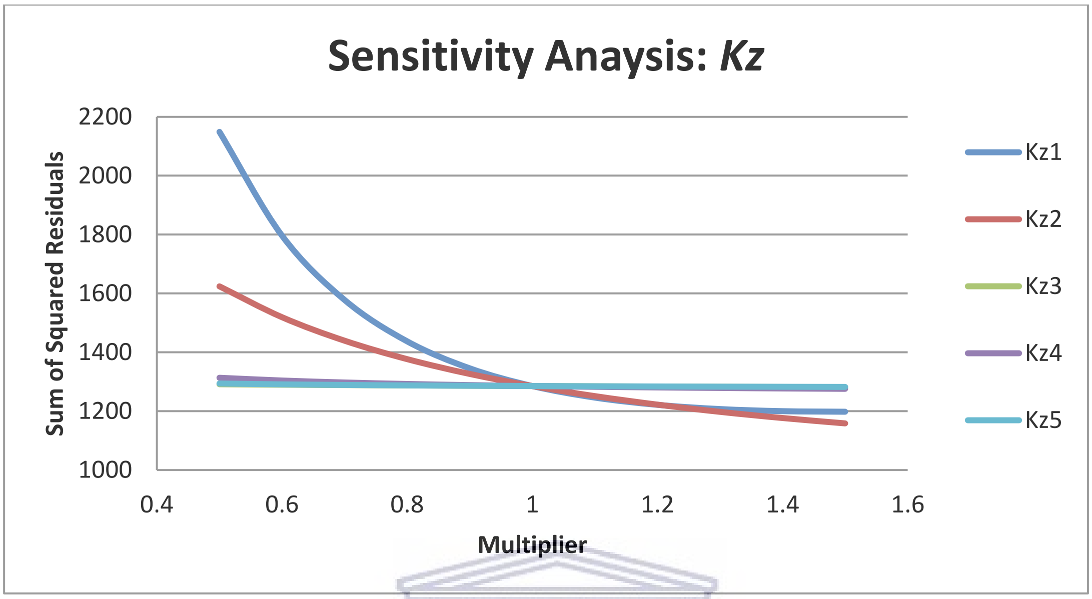

Figure 7.8: Vertical hydraulic conductivity sensitivity analyses.

From the above graph it can be seen that *Kz*1and *Kz*2 are most sensitive to a change in vertical conductivity whereas the others seem to be unaffected by changes in vertical conductivity.

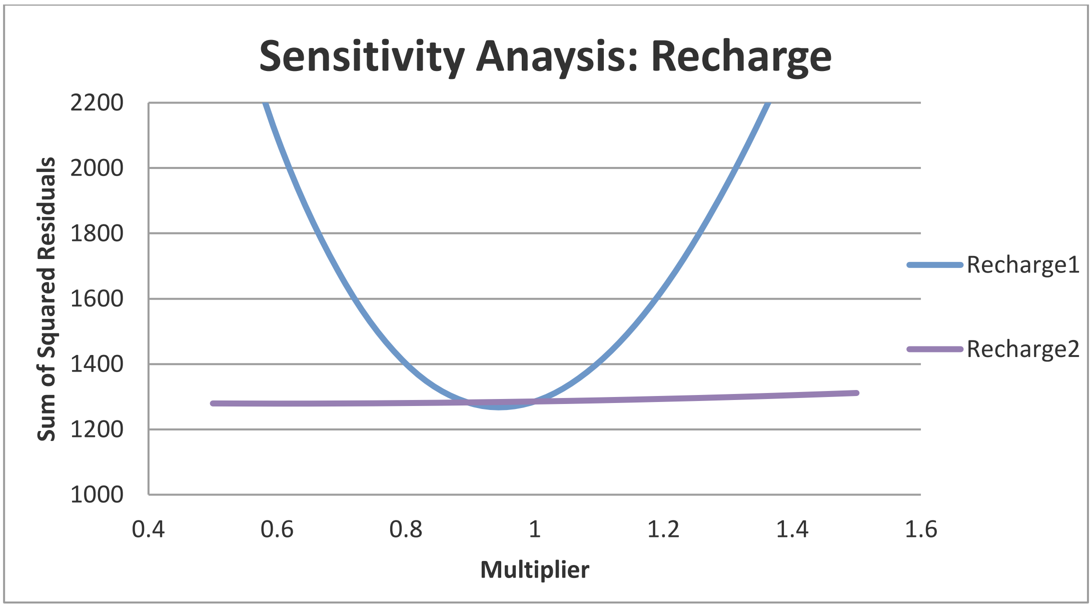

Figure 7.9: Sensitivity results for the effective recharge of the Peninsula (Recharge 1) and Primary (Recharge 2) aquifers.

Figure 7.9 shows that the Peninsula Formation is most sensitive to changes in recharge while the primary aquifer remains relatively stable.

7.4 Predictive Scenarios

Various possible scenarios have been modelled using particle tracking to identify capture zones of abstraction boreholes pumping at 250 m^3/d. Hydraulic properties were adjusted higher and lower by 20% as mentioned in Section 4.5.5 to account for variability in bulk hydraulic property. The combined results of the modelled scenarios are presented as groundwater protection zones (Figure 7.10).

Changes in hydraulic property values showed slight horizontal shifts in flow fields; however, the general direction/origin of the particles remained the same. Results show that water flows along the fault line from the mountain where recharge is assumed to be occurring. The one year contributing area is localised to the borehole (Figure 7.10), with the additional flow conduit existing along the eastern side of the fault line. The fault line seems to play a significant contribution to the local flow field around the borehole.

Over a ten year period, the flow field characteristics change. At this point, the overlying unconsolidated primary aquifer starts contributing to the borehole water supply, with path lines reaching the Molenaars River. In the fractured Peninsula Formation the flow field expands to the east of the pumping well and to the south of the fault. Water is additionally contributed from the western side of the fault.

Over a one hundred year period, the flow field has extended to the south west mountain ridges with little or no change towards the Molenaars River. This suggests that the river could be feeding the aquifer system, with any contamination in the river expected to influence the water quality in the production borehole. The river would therefore need to be adequately monitored and protected.

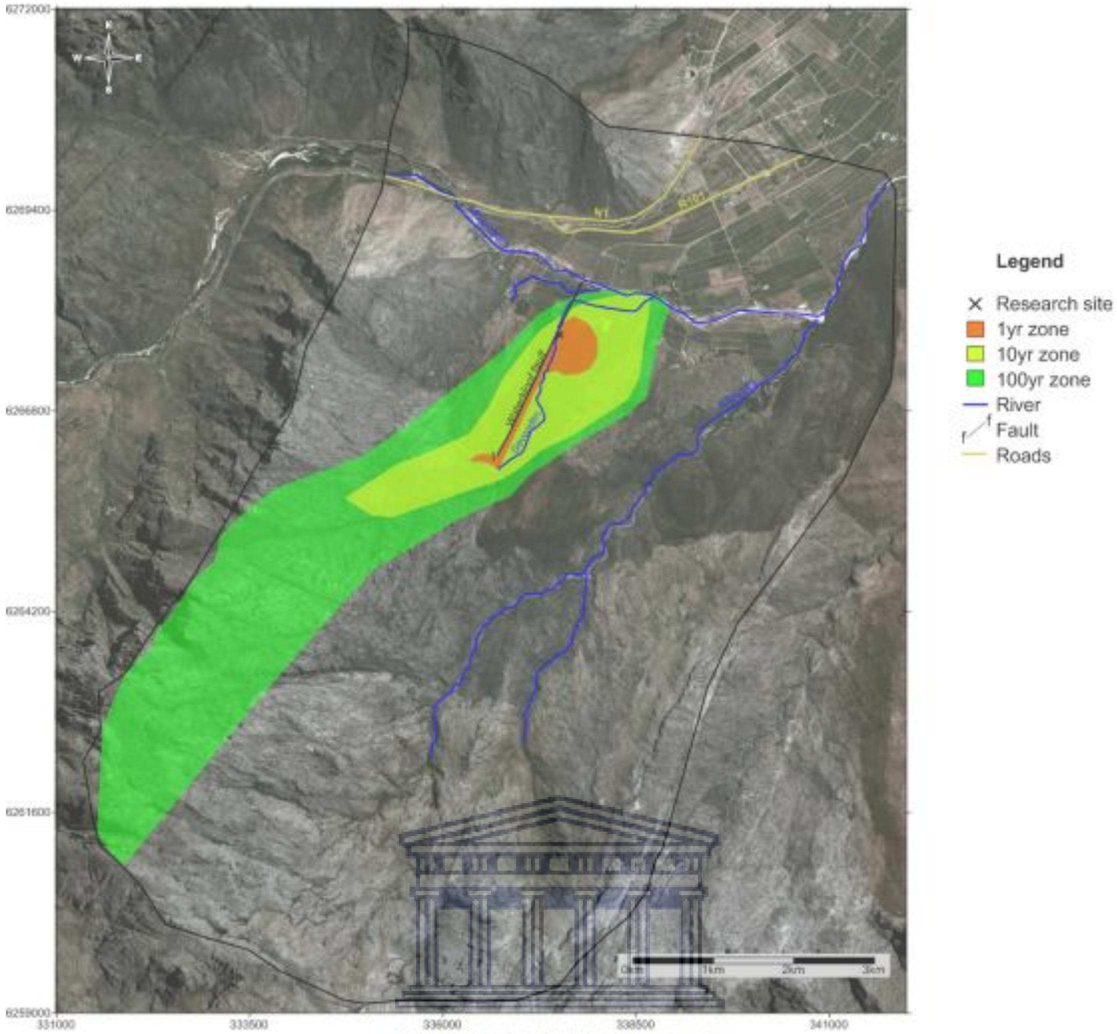

Figure 7.10: Combined delineated protection zones derived from 20% uncertainties for the 1yr, 10yr and 100yr flow fields. Base map taken from Google Earth

CHAPTER 8

MONITORING AND PROTECTION OF DRINKING WATER

8.1 Updating the Conceptual Model

Given the complexity of the site and the results of the sensitivity analysis, more information is needed on particularly the Peninsula aquifer and fault properties in order to increase the reliability of the model. Ongoing monitoring in the area is needed to update the conceptual model which in its turn will improve the numerical model.

The hydrogeological conceptual model and extent of the connection between the fault and the aquifer must be updated during aquifer production conditions to improve the understanding of the processes that governs groundwater flow. The water level, water quality and water balance data collected during the monitoring programme will be essential for the updating of the conceptual model.

It is recommended that the conceptual model be updated and the numerical flow model calibrated every two years with on-going monitoring data. A better understanding of the local aquifer conditions will be developed through the use of the data and more reliable long-term predictions can be made.

8.2 Groundwater protection measures

Restricted activities within the capture zones were chosen specifically for the site. Typical activities in the area and incidents most likely to occur were also taken into account. Both regulatory and non-regulatory approaches can be followed to protect the drinking water. Things to avoid include:

Zone 1:

- Inorganic farming;
- Recreational use and servicing of vehicles;
- Feedlots; and
- Pit latrines.

Zone 2:

- Inorganic farming;
- Servicing of vehicles;
- Pit latrines; and
- Waste discharge into the Gevonden River and upstream of the Molenaars River.

Zone 3:

- Inorganic farming;
- Servicing of vehicles;
- Waste discharge into the Gevonden River and upstream of the Molenaars River.

8.3 Improved Monitoring

Monitoring for the Gevonden research site will include water level and water quality monitoring of the local groundwater system as well as the surface water system (Table 8.1). Key monitoring points were selected using existing boreholes as well as rivers in the area (Figure 8.1). Isotope analyses of the Molenaars River as well as the Gevonden River should be done quarterly to ensure proper understanding of surface water/groundwater interaction. Due to the site topography, monitoring along the full extent of the protection zones is not possible. However, best efforts should be made to improve the extent of sampling points along the protection zones.

Table 8.1: Suggested monitoring to improve conceptual model

Name	X	Y	Type	Monitoring Objective	Recommended Frequency
MP1	336781	6268750	Borehole	Aquifer water balance: Groundwater monitoring	Bi-Annual, wet and dry season
MP2	337409	6268750	River + Primary + Secondary Borehole	Surface water and groundwater interaction and water quality upstream of site	Monthly
MP3	338677	6268364	Borehole	Groundwater monitoring at the 100yr zone limit	Monthly
MP4	339184	6267990	River + Primary + Secondary Borehole	Surface water and groundwater interaction and water quality, downstream of site	Monthly
MP5	336980	6268265	Isotope Sampler	Isotope sampling and precipitation monitoring	Precipitation: Daily Isotope: Monthly
MP6	338115	6268133	River + Borehole	Surface water and groundwater interaction and water quality within the 10yr zone	Monthly
MP7	337619	6267835	Borehole + Isotope sampler	Groundwater and precipitation monitoring. Isotope sampling	Isotopes: Monthly Groundwater: Weekly Precipitation: Daily
MP8	337465	6267681	Borehole	Groundwater monitoring up-gradient of site	Daily (Data Loggers)
MP9	337244	6267020	River	Upstream river monitoring within the 10yr zone and at the 1yr zone limit	Daily (Data Loggers)
MP10	337134	6265852	Isotope sampler	Isotope sampling and precipitation monitoring	Monthly
MP11	338368	6268693	Borehole	Aquifer water balance: Groundwater monitoring	Bi-Annual, wet and dry season

Isotope samples taken from MP5 and MP10 should be used to update recharge values for the area. These are initial monitoring points chosen using existing facilities on site. The monitoring plan can however be upgraded in time by increasing the frequency of monitoring rounds and adding new monitoring points such as boreholes or isotope samplers.

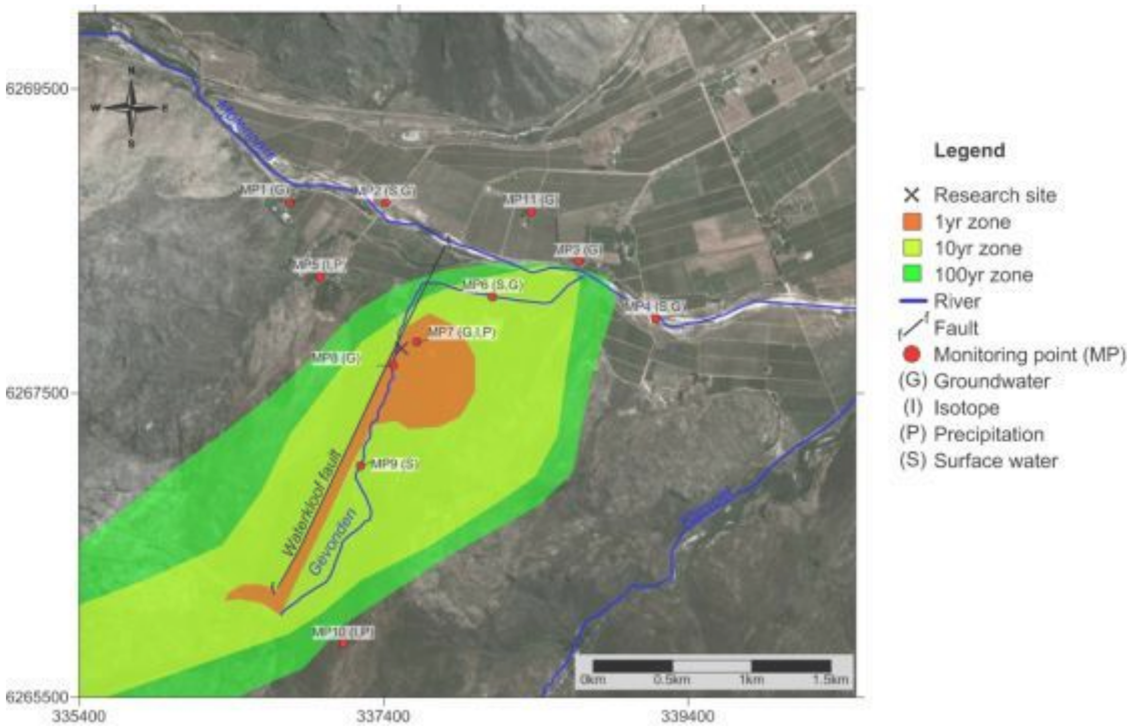

Figure 8.1: Spatial presentation of suggested monitoring for the management of the protection zones. Base map taken from Google Earth

Contamination sources potentially contributing to the Gevonden wellfield capture zone include at least one French drain toilet system (100yr zone), agricultural land (all zones) as well as the Molenaars River (10yr and 100yr zones) as can be seen in Figure 8.2. The French drain toilet (septic tank) should be changed to tanks and disposed of off-site;

- Farm land falling within the protection zones should use organic fertalizers and pestacides. The land owners should be guided regarding best practice guidelines focused on groundwater contamination prevention.
- The Molenaars River section upstream of the protection zone intersection with the river will contribute to the capture zone of the Gevonden wellfield. The river flows close to the road up to the Huggenote tunnel and can be contaminated by spillages along this section of the river. A key aspect of groundwater protection along this section of river is public awareness. Notices should be put up along the river with emergency numbers to inform motorists/trucks that it is a water protection area. Emergency responses will depend on the river flow rate and the type of contaminant. In extreme cases it might be necessary to reduce the pumping for a few weeks to change the

capture zone of the wellfield in such a manner that the river contamination do not contribute to the wellfield.

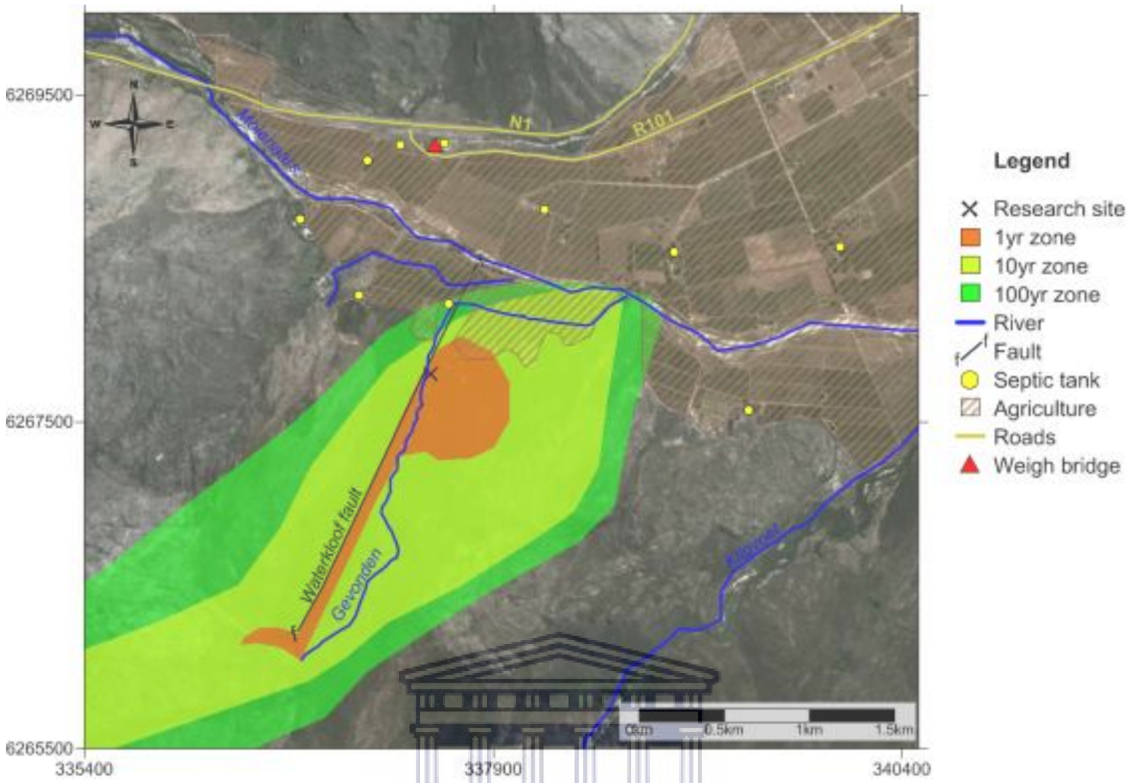

Figure 8.2: Possible contamination sources within the delineated protection zones. Base map taken from Google Earth

CHAPTER 9

CONCLUSIONS

9.1 Groundwater Use and Possible Contamination Sources

Identifying and understanding how groundwater is being accessed and used is required in determining the level and type of groundwater protection needed. Groundwater in the study area is mainly used for agricultural irrigation; however, it is also used domestically, to fill farm dams for irrigation during the dry season.

Groundwater access points were identified as (Figure 6.3):

- Boreholes
- Springs
- Rivers.

Rawsonville is an area that thrives on wine farming. This has many implications with regards to groundwater contamination. A few potential contamination sources were identified at the site. Leachate from fertilizers and pesticides may reach the groundwater used by the farmers for domestic water supply as well as irrigation.

The Molenaars River runs through the densely farmed area and is vulnerable to agricultural leachate. Groundwater contribution to the river could cause the river to carry contaminants to the town of Rawsonville where the water is consumed by many people living next to the river. If any contamination should occur upstream of the research site and the river gets contaminated, the river will become a contaminant carrier.

Initially, the N1 and R101 roads were thought to both be possible contaminant sources. However, numerical modelling suggests that the R101 does not pose a threat to the groundwater supply of the study area. Numerical modelling also suggests that the N1 is not a direct threat to the groundwater system. Since the N1 runs along and in some cases across the Molenaars River, it can be considered as an indirect potential contaminant.

9.2 Aquifer properties

The geological setting of the site resulted in the Formation of two aquifer systems. Understanding these aquifer systems is important as this information will help in understanding the flow processes in the aquifer. The quaternary sands form the primary aquifer and the TMG fractured rock forms the lower secondary aquifer. Groundwater flow within the shallow groundwater system consists of intergranular flow through unconsolidated sediments. Flow follows the river channel in a NE direction.

The regional groundwater system is associated with fractured bedrock units. Groundwater flow within the aquifer is controlled by the presence of non-continuous open fractures and joints. The Cedarberg Formation acts as an aquitard due to the shale having such low hydraulic conductivity.

Pumping tests were conducted at the research site to establish aquifer properties. Data plots suggest that early time data shows fracture flow feeding the borehole where as late time data suggests that the aquifer matrix is feeding the borehole. Pumping test data was inserted into the FC programme and the data was analyzed. This gave transmissivity values ranging between of $4m^2/d$ and $14.8m^2/d$ and storativity values ranging between. The data analysis showed storativity values of 1.27x10-7 and 4.6x10-5.

9.3 Delineate groundwater protection zones

Due to the complexity of the site, a 3D numerical model was found to be optimum.
Various scenarios were modelled to provide conservative results for each protection zone.

The one year contributing area is localised to the borehole, with the additional flow conduit along the eastern side of the fault line. The fault line plays a significant contribution to the local flow field around the borehole.

Over a ten year period, the overlying unconsolidated primary aquifer starts contributing to the borehole water supply, with path lines reaching the Molenaars River. In the Peninsula aquifer, the flow field expands to the east of the pumping well and to the south of the fault in the shape of a tail. Water is additionally contributed from the western side of the fault.

Over the one hundred year period, the flow field "tail" has extended to the south west mountain ridges with little or no change towards the Molenaars River. This suggests that the river could be feeding the aquifer system.

CHAPTER 10

RECOMMENDATIONS

- Fertilizers, pesticides and herbicides are constantly used. This creates a need for continuous monitoring. Monitoring data should include water level and water quality data of the local groundwater system as well as the surface water system. This type of monitoring will also act as an "early warning" system should contamination occur. Isotope analyses of the Molenaars River as well as the Gevonden River should also be done in order to ensure proper understanding of surface water/groundwater interaction.

- Contamination sources potentially contributing to the Gevonden wellfield capture zone include at least one French drain toilet system, agricultural land as well as the Molenaars River. Both regulatory and non-regulatory approaches can be followed to protect the drinking water. These include:

    - The French drain toilet (septic tank) should be changed to tanks and disposed of off-site;
    - Farm land falling within the protection zones should limit fertilizer and pesticide use.
    - Notices should be put up along the Molenaars River with emergency numbers to inform motorists/trucks that it is a water protection area. In extreme cases it might be necessary to reduce the pumping for a few weeks to change the capture zone of the wellfield in such a manner that the river contamination does not contribute to the wellfield.

- The groundwater system should be adequately monitored and both the conceptual model, numerical model and zone restrictions should be periodically updated to ensure proper protection of the groundwater system.
- The inclusion of any freshwater sources in the study area may assist in obtaining more accurate results for future research.

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APPENDIX CD

Appendix A: Hydro Census Survey Forms
Appendix B: CD Pumping Test Data
Appendix C: Tracer Test Data