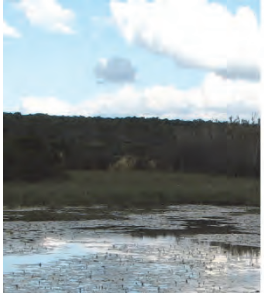


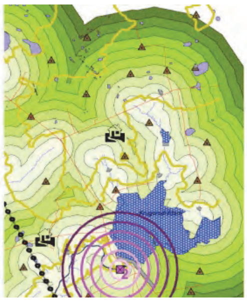


Towards a Guideline for the Delineation of Groundwater Protection Zones in Complex Aquifer Settings

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

INTRODUCTION

Many people from rural communities and towns throughout South Africa are relying on groundwater as a sole source of water supply. Towns like Atlantis, Beaufort West, Mahikeng, Montagu, Prins Albert, Vryburg, and Zeerust are a few of the examples relying on groundwater as their sole water source. The protection of these and other groundwater resources should be regarded as critical. Experience from the last few decades has shown that groundwater is not immune to contamination (For Example: Beaufort West and Delmas) and that once it is contaminated by chemical, biological or radiological agents, etc., it is hard- if not impossible - to clean and very expensive to remediate.

The Department Water and Sanitation (DWS) is currently considering the implementation of an aquifer protection strategy to protect water quality of critical groundwater resources. The implementation of groundwater protection zoning would make use of a combination of the DWS resource directed strategies (protect water quality for basic human needs) and DWS source-directed strategies (regulate and prohibit land-based activities) and will probably be coordinated by the Resource Directed Measures (RDM) directorate.

Choosing the appropriate protection zoning method requires specific procedures that consider the hydrogeological data required, the hydrogeological complexity, the accuracy, time, human resources, the capabilities of the groundwater management agency, and available funding (Miller et al., 2003).

In the South African context it should be recognised that the data and resources to protect the critical water resources would probably not be available and that a phased protection approach need to be adopted. The phased protection approach has been adopted in developing countries like Argentina where a basic protection zoning scheme is implemented and improved over time as more data becomes available (Foster et al., 2002). Monitoring and periodic revision of the protection zones is therefore an important component in the iterative process to ensure the protection of drinking water quality.

High borehole yields in hard rock aquifers - typical South African aquifers - are associated with fractures, faults and bedding planes, complicating the flow of water and contaminants to the boreholes. Protection zones will have to be determined for these types of complex aquifer settings, especially in aquifers like the Table Mountain Group (TMG) and Karoo where faults and dykes are targeted for water supply.

Various international guidelines exist on how to determine protection zones in porous media aquifers. Although fracture rock aquifers can behave like porous media aquifers when used for water supply, the existence of fractures create preferential pathways with much higher local hydraulic conductivity (K) values and also much lower porosity values than primary aquifers. Protection zones can therefore not always be determined using porous aquifer media assumptions, as the actual fracture characteristics must be considered.

SCOPE OF WORK

The overall aim was to develop a guideline to delineate protection zones in complex aquifer settings. This guideline was built on the DWS project (UWC, 2007) to include the latest international best practice, minimum data requirements, the latest data collection methodologies and a risk analysis approach. The components of the guideline were tested at the UWC Rawsonville research site where the fractured Table Mountain Group aquifer is intersected by a fault and a river. Hydraulic properties and water level data for both the upper primary aquifer and the lower fractured aquifer was collected using standard hydrocensus and aquifer test methods. The nearby fault proved to play a significant role in the shape of the capture zones of the lower secondary aquifer, while the perennial river formed a boundary for the capture area in the upper primary aquifer.

GROUNDWATER SOURCE PROTECTION

The risk for contamination of groundwater sources increases with human activity and has a direct link to land use. Aspects of water quality are strongly related to groundwater flow, since the advective motion represents the main process for migration of dissolved substances in groundwater. Groundwater source protection therefore aims to protect sources of drinking water by controlling the land use in the recharge areas and capture zone of the groundwater source.

The extent of groundwater contamination can often be associated with the distribution and nature of land uses in an area. For example, areas of concentrated manufacturing industries are often associated with contamination of heavy metals and organic compounds. Areas of intensive agriculture have been related to excessive pesticide and fertilizer contamination, pit latrines contribute to nitrate and bacteria contamination, while landfills generate leachates, which can result in groundwater contamination from a range of contaminants.

The number of land use zones defined to limit the impact on the underlying aquifers varies between countries, with two to four zones usually delineated to achieve the different levels of protection (Jolly and Reynders, 1993; Chave et al., 2006):

- A *Wellhead Operational Zone* immediately adjacent to the site of the borehole or wellfield to prevent rapid ingress of contaminants or damage to the borehole (also referred to as the '*Accident Prevention Zone*').

- An *Inner Protection Zone* based on the time expected to be needed for a reduction in pathogen presence to an acceptable level (often referred to as the '*Microbial Protection Area*').
- An *Outer Protection Zone* based on the time expected to be needed for dilution and effective attenuation of slowly degrading substances to an acceptable level. A further consideration in the delineation of this zone is sometimes also the time needed to identify and implement remedial intervention for persistent contaminants.
- A further, much larger zone sometimes covering the total catchment area of a particular abstraction borehole/area where all water will eventually reach the abstraction point. This is designed to avoid long term degradation of quality.

It is important to provide guidance on activities which are either acceptable, unacceptable or need to be controlled in various protection zones. The zones should provide a minimum safe distance which separates a water resource and associated abstraction point from a potential contaminant source. This distance ensures that the time taken for the horizontal travel of the contaminant is sufficient to allow degradation of the contaminant (Xu and Braune, 1995). The concept of travel times and minimum safe distances is more applicable to biological and degradable contaminants than non-biodegradable.

In some countries such guideline lists are very extensive and specific. In others, general guidance is issued. With each protection zone comes land use constraints. These constraints are of increasingly stringent moving from the outer protection zone to the wellhead (borehole) operational zone.

Useful legislation for land use management in the Western Cape is the Land Use Planning Ordinance (15 of 1985) (LUPO) which includes sections on structure plans (forward spatial planning), zoning schemes (i.e. the regulation of development), the way in which applications may be made for new development rights, appeal rights, etc.

METHODS AND MEASURES FOR THE PROTECTION OF GROUNDWATER ENVIRONMENTS

The goal of groundwater protection is to ensure the sustainable use of a specific groundwater resource under consideration. This is achieved by specific planning methods and measures. Although many considerations on protection focus particularly on drinking water boreholes, the protection of groundwater resources should in principle be applied to the complete aquifer under consideration, or even the whole drainage basin, as stated in the European Union Water Framework Directive (European Union, 2000). This extension to catchments reflects the frequent interactions between surface and groundwater systems.

The soil zone is part of this interaction and represents the transition from the above land surface to the subsurface environment and therefore plays an important role in the protection planning. In coastal areas and arid/semi-arid areas groundwater protection includes the requirement of avoiding salinization of freshwater.

The protective measures for groundwater systems are usually formulated for different areas in a hierarchical manner. Such areas may be (Stauffer, 2011):

- Parts or even complete river catchment or basin, which include the aquifer under consideration;
- The aquifer itself;
- The catchment (recharge area) of a considered drinking water borehole;
- Protection zones of limited extent, particularly for drinking water boreholes under consideration.

Travel time approaches

International best practice guidelines indicate the time-of-travel should be used whenever possible to identify the area around a borehole that will become the focus of protection efforts. The most commonly used methods to delineate the geographic extent of this area include: 1) the calculated fixed-radius method; 2) hydrologic mapping; and 3) computer modelling. The value of each method depends on the quantity and quality of information available about the individual boreholes, the aquifer involved, and the hydrogeological setting of the area.

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. This may follow the calculated fixed radius or variable shape approach. They may also be supplemented by analytical methods and hydrological modelling, if sufficient scientific expertise and data is available. The delineation of protection zones can then be based on such issues as the recorded or modelled movement of contaminants through the groundwater area. In such cases, zones may not be simple concentric circles around abstraction points, but their boundaries follow the calculated time of travel of chosen parameters. This may be important in heavily developed areas where the imposition of restrictions within a defined area may have economic repercussions.

Selection of Appropriate Method

The methods used to delineate source water protection areas each require increased data to provide reliable estimates of protection areas. It is best to select a delineation method for each public water supply based on the quality and quantity of hydrologic data that is available.

Fixed radius methods are best used for rule of thumb type protection at the accident prevention zone level, preventing short circuit contamination of the aquifer via the borehole itself. This can be implemented at almost no cost to provide protection from contamination immediately around the supply areas like spring outlets, shallow boreholes and dug wells. Much greater accuracy will be required for more vulnerable water supplies and complex aquifer flow paths.

Flow system mapping is recommended as a first step for more complex hydrogeological systems and is relatively easy to implement, producing a total catchment area. The flow system mapping method is one of the recommended methods for aquifers showing conduit flow characteristics. The data required for flow system mapping, also forms the base line data needed for the more advanced methods. The data needed for this method can be obtained from normal national and aquifer level monitoring programmes.

Analytical modelling can be implemented to produce quite advanced two dimensional models. Parameter estimation can be done from literature values or values from local reports. These models give a reasonable estimate of the protection zones and can consider the time of travel for biodegradable contaminants. More importantly they produce cost effective zones where future data collection can be focussed should the importance of the water supply source justify the additional cost. Analytical modelling software (example: WhAEM, GFLOW) is easy to use and can be implemented and updated by local authorities and Water Users Associations.

Numerical models can be implemented in complex geological terrain where the importance of the resource can justify the additional cost of data and modelling expertise. The models should only be updated and implemented by experienced modellers. The data availability and experience of the modeller will directly influence the level of certainty in the results.

The method chosen will depend on (1) the data already available; (2) rhe number of people dependent on the resource; (3) the point in the hydrologic cycle where groundwater is accesses; (4) the hydrogeological conditions; and (4) the financial resources available to implement.

DATA REQUIREMENTS FOR PROTECTION ZONE SIMULATION

Conceptual Model

The conceptual model of hydrogeology integrates geological and hydrological information to describe groundwater occurrence, movement and quality. The conceptual model describes the hydraulic and specific storage/storativity properties of geologic materials, and the boundary conditions that govern groundwater movement under both pumping and non-pumping conditions. For drinking water protection the conceptual model should also describe groundwater quality, particularly when natural or human sources of contamination exist.

The development of a conceptual model is the initial step of modelling. The result should be a computerised database, and simplified electronic maps and cross-sections that would be used in the model design and that could easily be incorporated into the actual electronic model (Kresic, 2007).

A conceptual model should at least be able to answer the following questions (Kresic, 2007):

- In which direction is the water in the aquifer flowing, at approximately what rate, and how does this change with time?
- Where is the water leaving the aquifer, approximately how much of it, and how does this change in time?

Liquid contaminants and contaminants leached by rainfall are sometimes spilled at ground surface, intentionally or by accident. In many cases, once the contaminant reaches the aquifer, the groundwater may be rendered useless for most purposes. Conceptual models for the evaluation of protection zones and associated management must therefore include components of both water quantity and water quality.

Aquifer types in South Africa

In South Africa aquifers are classified into four main types (Jonck and Meyer, 2002), namely:

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

The 1:500 000 maps should be used in conjunction with knowledge of the groundwater occurrence and existence of preferential path ways when applied to groundwater protection. Knowledge of transmissivities for different aquifer types and potential preferential pathways provide a useful link between the borehole yields, contaminant transport and simulation of protection zones.

The subdivision into groups based on primary openings (intergranular) and secondary openings (fractures) is useful to estimate borehole yields from a water bearing point of view (Vegter, 2001) with sustainability of groundwater dependent on the thickness of the weathered zone, usually the uppermost 10-30 m, as borehole as the occurrence of deeper fracture zones (MacDonald et al., 2002).

The type of aquifer plays a significant role when determining the possible pathways contaminants can follow from a contamination source to a potential receptor. The existence of preferential pathways such as fracture or fault zones will allow contaminants to move at much higher rates than suggested by the average borehole yields from the aquifer classification map.

Contaminant Characteristics

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). 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 what phase the contaminant will assume in the groundwater system:

- Aqueous Solubility;
- Inorganic constituents;
- Organic constituents; and
- 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), capable of causing illness in humans. Surface water sources, such as lakes, rivers, and reservoirs, are more likely to contain microorganisms 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 and pit latrines.

DATA COLLECTION METHODS

Characterisation of fractured aquifers at a catchment scale remains problematic largely due to the heterogeneous nature of fractured rock aquifers. Understanding groundwater flow in these fractured rock aquifers requires detailed information. The need to understand flow in fractured rock aquifers has resulted in the development and improvements in available methodologies and practices aimed at enhancing the understanding of the flow dynamics of these aquifer settings. The characteristics of fractured aquifers are highly variable due to varied fracture systems. In order to improve the understanding of the occurrence and dynamics of groundwater, studies need to be done in different climatological and geological settings.

The identification and characterisation of fractures contributing to the flow towards the borehole is one of the main subjects of concern in fractured rock settings. This has led to the adaptation and development of methods and techniques that are best suited to characterise fractures flow including flow of contaminants through them.

The main goal of characterising fracture flow is to understand groundwater flow, transport and fate of contaminant transport in fractured rock aquifers at a scale sufficient to make remedial decisions (Kinner et al., 2005). There are several methods for characterising fractured aquifers. Some of the methods focus on the physical rock characteristics, while others use indirect methods to characterise the flow through the aquifer. These methods are not only able to provide information with regards to the location of fractures in a borehole but they also provide valuable information on the flow characteristics in the aquifer.

RISK ANALYSIS APPROACH

Fracture rock anisotropy

Only in the case where there are large permeability differences between the rock matrix and fracture network do the fractures and their characteristics (aperture, filling, orientation, frequency and connectivity) strongly influence the flow and transport processes. Single, large fractures can have higher flow rates and faster contaminant transport compared to areas with high fracture density. The spread of the plume depends on advective transport in the fracture, sorption, decay and diffusion into the rock matrix.

Knowledge of the characteristics of the fracture network is important for understanding the hydrogeologic character of the bedrock at each site. Anisotropy can be a particularly important characteristic. Anisotropy can be estimated using pump test analysis, and fracture and lineament analysis. Although the direction of anisotropy is usually readily estimated from fracture and lineament analysis, the anisotropy factor is not as definitively established without the data from an extensive pumping test. Usually, the anisotropy factor is estimated from the ratio of the number of fractures orientated in the direction of anisotropy to the number of fractures at a right angle to the direction of anisotropy. The uncertainty in the anisotropy factor is mitigated by including a range of anisotropy factors in the sensitivity analysis (Lipfert et al., 2004).

Sources of Uncertainty

Problems arise for larger capture zones or recharge areas/catchments due to the impact of parameter uncertainty. These problems may lead to uncertain wellhead protection zones. Therefore, the list of parameters and conditions used in the conceptual model should be discussed in a qualitative manner with respect to the associated parameter uncertainty (Stauffer et al., 2005):

- The quality of the overall Information very much depends on the spatial density of the available data. However, due to economic and logistic reasons, the information is often sparse. The location of data sampling is normally restricted to particular regions within the aquifer. Similarly, the temporal frequency of measurements is often limited. Estimates of the order of magnitude of the hydraulic properties can be made based on historic studies and hydrocensus information.
- For small areas a more simplified and intuitive assessment of the uncertainty is often possible, which can be taken into account in the delineation of the protection zone. However, for larger areas the uncertainty can be quite large. Depending on the economic and ecological importance of the protection zone, the implications of the degree of uncertainty associated with its predicted location can be prohibitive.

- Uncertainty of the essential parameters, which determine capture zones or catchments of a production borehole, means that the location of these zones cannot be determined with certainty. Therefore their location can only be defined in a statistical manner. Consequently, the best would consist of offering a probability map, rendering the probability with which a particular location belongs to the capture zone or catchment of a particular borehole. Therefore, the boundary of the capture zone or catchment is presented with its uncertainty bandwidth. Such concepts can be fed directly into a risk assessment of a particular groundwater resource.

Modelling of Fractured Rock Aquifers

A hard rock system has to be fully characterised in order to provide, at catchment scale, the necessary elements for a classical modelling approach (Marechal et al., 2003). Classical distributed models are often not considered adaptable to represent contaminant transport in heterogeneous and anisotropic hard rock aquifers. The connected network is essentially formed where the fracture size is in the order of the distance of the boreholes from each other (Koskinen and Rouhiainen, 2003). Heterogeneity and geometry of the aquifer can be regionalised using airphotos, geological and geophysical investigations (Marechal et al., 2003).

The use of an equivalent porous media model at a fractured bedrock groundwater system can be validated by the nonlinear response of the observation boreholes at distances less than the scale of the delineation (Lipfert et al., 2004). Linear flow to a borehole (to a single fracture) will show as a straight line with a slope of 0.5 on a log-log plot of drawdown versus time (Gringarten, 1982 in Kruseman and De Ridder 1994). When linear flow is not detected beyond a certain distance from the pumping boreholes, generally the presence of discrete fractures in the delineations can be disregarded.

The effect of discontinuity and heterogeneity of the fracture network imposes capture and protection zones strikingly different from those computed using Equivalent Porous Media assumption (Fernandez-Garcia et al., 2002; Carneiro, 2003).

A hybrid approach using a combination of Discreet Fracture Network and Equivalent Continuum Models is recommended by Carneiro (2003) to overcome this problem at catchment scale. The method known as the Statistical Continuum Method (SCM) relies on statistics of movement of particles in a local scale Discreet Finite Network, followed by the use of those statistics to mimic movement in a catchment-scale continuum model. Probabilistic protection zones result from the procedure.

The Statistical Continuum Method provides a useful approach to simulate transport in fractured rocks at the catchment scale, where Discreet Finite Network models may not be practical. The methodology is easy to implement and can be made to work with standard finite difference models. The computational requirements for up-scaling from local to regional scale are not significant and probability contours of protection zones can easily be computed (Carneiro, 2003).

Le Borgne et al. (2003) shows that a continuous approach can be formulated to predict the long term evolution of hydraulic heads in a fractured rock environment. For most regional modelling studies an equivalent porous medium approach can be used, considering that:

(i) A higher value of hydraulic conductivity than those derived from hydraulic tests in boreholes may be required to account for scale dependent fracture distributions (Watkins, 2003).

(ii) Preferential flow paths caused by faults, mineral lodes and dykes must be considered explicitly (Watkins, 2003; Le Borgne et al., 2003).

(iii) For flow perpendicular to the main fracture orientation the average hydraulic conductivity is controlled by the rock matrix portion of the aquifer (Mouri and Halihan, 2003).

Deep discontinuities and fault zones can exist within lower permeability formations, allowing circulation and interaction with the upper zones. These zones can exhibit high local hydraulic conductivities, even at depth (Watkins, 2003).

MONITORING AND VERIFICATION OF PROTECTION ZONES

Although no WHPA (Wellhead Protection Area) is perfect, reasonably accurate delineations are possible when hydraulic and aquifer boundaries are better understood, and when natural and anthropogenic fluctuations and stresses are known.

The evaluation of information available may reveal that the understanding of catchment and aquifer properties is not sufficient, or information from different sources is inconsistent. The information inventory therefore needs to be improved for adequately assessing groundwater pollution potential (Chorus et al., 2006).

Some of the identified information gaps may be fairly readily closed by revisiting specific sites in the catchment or more thorough inspection. If uncertainty is too large to make decisions, then the information gaps need to be closed with specifically targeted groundwater surveys and/or regular groundwater quality monitoring. In some areas of South Africa the desktop level information might be suitable to do preliminary protection zones.

Decisions on investments into improving the information base will depend on the consequences of uncertainty. Such information comes from additional geologic and hydrologic data from boreholes, water-level measurements, aquifer testing, borehole and surficial geophysics, water-quality testing, lineament studies, isotope geochemistry analyses, and tracer tests.

Groundwater protection zones may be a key component of the water security for a given groundwater supply, and protection zones would typically be control measures in this context. This would subject them to operational monitoring for assessing whether or not the required restrictions on land use and controls of human activities are in place, and protect the drinking water sources into the future. Protection zone monitoring would focus on checking whether the required restrictions in land-use and human activities are being adhered to. Groundwater quality monitoring in this context would serve to verify the efficacy of the specific protection zone concept, i.e. both its design and implementation, and can be an important component.

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1 INTRODUCTION

Many people from rural communities and towns throughout South Africa are relying on groundwater as a sole source of water supply. Towns like Atlantis, Beaufort West, Mahikeng, Montagu, Prins Albert, Vryburg, and Zeerust are a few of the examples relying on groundwater as their sole water source. The protection of these and other groundwater resources should be regarded as critical. Experience from the last few decades has shown that groundwater is not immune to contamination (For Example: Beaufort West and Delmas) and that once it is contaminated by chemical, biological or radiological agents, etc., it is hard- if not impossible - to clean and very expensive to remediate.

The Department of Water and Sanitation (DWA) is currently considering the implementation of an aquifer protection strategy to protect water quality of critical groundwater resources. The implementation of groundwater protection zoning would make use of a combination of the DWS resource directed strategies (protect water quality for basic human needs) and DWS source-directed strategies (regulate and prohibit land-based activities), and will probably be coordinated by the RDM-directorate.

In the DWS funded project aquifer protection zoning is recognized as a proactive step towards protecting drinking water by the management of land use, recharge areas and potential contamination sources.

The DWS funded protection zoning initiative produced various products, including:

- A Policy on Protection zoning (UWC, 2007).
- MSc Thesis by Y. Rajkumar, 2009 – The fate of microbial contaminants in the subsurface with a South African case study (University of the Western Cape).
- PhD Thesis by H. Pienaar, 2009 – Institutional arrangements for protection zoning (University of the Western Cape).
- PhD Thesis by J.M. Nel, 2011 – Implementation and benefit of protection zones in fractured rock aquifers (UWC).

According to the US Environmental Protection Agency (1993), the main assessment methods for Well Head Protection Areas can be reduced to six, which can be classified in an ascending order (with regard to complexity and costs) into:

- arbitrary fixed radius;
- calculated fixed radius;
- simplified variables shapes;
- analytical methods;

- hydrogeological mapping; and
- numerical flow and transport models.

Choosing the appropriate method requires specific procedures that consider the amount of hydrogeological data that is necessary, the hydrogeological complexity, the required accuracy of the results, time, human resources, the capabilities of the groundwater management agency, and available funding (Miller et al., 2003).

In the South African context it should be recognised that the data and resources to protect the critical water resources would probably not be available and that a phased protection approach need to be adopted. The phased protection approach has been adopted in developing countries like Argentina where a basic protection zoning scheme is implemented and improved over time as more data becomes available. Monitoring and periodic revision of the protection zones is therefore an important component in the iterative process to ensure the protection of drinking water quality.

High borehole yields in hard rock aquifers - typical South African aquifers - are associated with fractures, faults and bedding planes, complicating the flow of water and contaminants to the boreholes. Protection zones will have to be determined for these types of complex aquifer settings, especially in aquifers like the Table Mountain Group (TMG) and Karoo where faults and dykes are targeted for water supply.

Various international guidelines exist on how to determine protection zones in porous media aquifers. Although fracture rock aquifers can behave like porous media aquifers when used for water supply, the existence of fractures create preferential pathways with much higher local hydraulic conductivity (K) values and also much lower storativity values than expected from primary aquifers. Protection zones can therefore not always be determined using porous aquifer media assumptions, as the actual fracture characteristics must be considered. A guideline to determine groundwater protection zones in local complex fractured aquifers does not exist within the DWS funded project (UWC, 2007).

2 SCOPE OF WORK

The overall aim is to develop a guideline to delineate protection zones in complex aquifer settings. This guideline will build on the DWS project to include the latest international best practice, minimum data requirements, the latest data collection methodologies and a risk analysis approach. This guideline will be tested at the UWC Rawsonville research site where the fractured TMG aquifer is intersected by a fault and a river.

The aims, deliverables and status quo are summarised in Table 2.1 and Table 2.2.

Table 2.1 Project aims and status quo.

Aim	Status quo
Build on DWS project by including international best practice regarding complex aquifer settings	Completed and submitted (Deliverable 1).
Evaluate fractured rock aquifer data collection methodologies	Completed and submitted (Deliverable 1).
Develop initial guideline for complex aquifer systems	Completed and submitted (Deliverable 1).
Test initial guideline at Rawsonville TMG research site	Completed and submitted (Deliverable 4).
Investigate data needs and application of risk analysis modelling software	Completed and submitted (Deliverable 3)
Effect of seasonal variation on protection zones	Completed and submitted (Deliverable 4).

Table 2.2 Project deliverables and status quo.

Deliverable	Description	Target Date	Status quo
UWC Progress report 1	Initial guideline including Part A: Update state of knowledge and international best practice. Part B: Fractured rock data collection methodologies and availability of equipment in SA.	31/07/2011	Del 1 31/07/2011
UWC Progress report 2	Site Data Including: Part A: Hydrocensus and database for study area. Part B: Aquifer tests (Hydraulic, Tracer, Fluid electrical Conductivity (FEC)). Part C: Physical description of fracture characteristics.	31/10/2011	15/12/2011
GCS Progress report 1	Simulated protection zones considering seasonal flow variation. Stochastic model populated using pollution sources and water users from hydrocensus.	31/05/2013	31/05/2013
GCS Progress report 2	Determine minimum requirements for similar systems.	30/08/2013	30/08/2013
Draft final report	Guideline for the Delineation of Protection Zones in a Complex Aquifer Setting.	30/11/2013	9/12/2013
Print ready final report	Guideline for the Delineation of Protection Zones in a Complex Aquifer Setting.	31/01/2014	This Report

3 GROUNDWATER SOURCE PROTECTION

The risk for contamination of groundwater sources increases with human activity and has a direct link to land use. Aspects of water quality are strongly related to groundwater flow, since the advective motion represents the main process for migration of dissolved substances in groundwater. Groundwater source protection therefore aims to protect sources of drinking water by controlling the land use in the capture zone of the groundwater source.

The extent of groundwater contamination can often be associated with the distribution and nature of land uses in an area. For example, areas of concentrated manufacturing industries are often associated with contamination of heavy metals and organic compounds. Areas of intensive horticulture have been related to excessive pesticide and fertilizer contamination, while landfills generate leachates, which can result in groundwater contamination from a range of contaminants. It is therefore possible to assess the land use to determine the environmental and public health significance of potential contamination (NWQMS, 1995; Usher et al., 2004).

The regulation and prohibition of land-based activities are often used to prevent deterioration of the groundwater source. Macro-protection land use management policies include (Schmoll, 2006):

- *No degradation*. The maintenance of the quality of groundwater at no worse than existing levels. Generally, such a policy would only be applied to vital resources, typically a resource that provides the sole source of drinking water.
- *Limited or controlled degradation*. Such a policy acknowledges that existing or proposed land uses will cause a deterioration of groundwater quality, but strives to maintain the quality within the certain specified limits.
- *Differential protection*. Differential protection policies allow for combinations of no degradation and limited degradation. This allows the development of different protection objectives taking into account factors such as present and potential uses of water resources, zoning and uses of land in the locality together with the desires of the communities involved.

The number of land use zones defined to limit the impact on the underlying aquifers varies between countries, with two to four zones usually delineated to achieve the different levels of protection (Jolly and Reynders, 1993; Chave et al., 2006):

- A *Wellhead Operational Zone* immediately adjacent to the site of the borehole or wellfield to prevent rapid ingress of contaminants or damage to the borehole (also referred to as the '*Accident Prevention Zone*').

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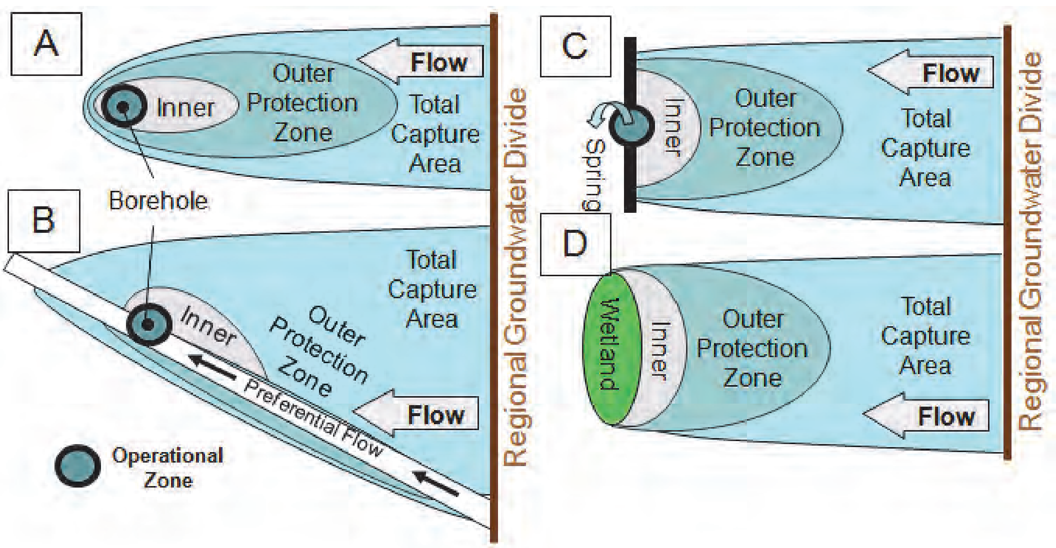

Figure 3.1 **Conceptual protection areas delineated around (A) Homogeneous Aquifer; (B) Aquifer with preferential pathway; (C) Spring water supply; (D) Wetland (Nel et al., 2009).**

Conflicts in land use management can be expected for groundwater quality protection. Restrictions on land use for groundwater protection will always have an economic cost, and decisions must be made how to minimize cost and maximize protection.

It is important to provide guidance on activities which are either acceptable, unacceptable or need to be controlled in various protection zones. The zones should provide a minimum safe distance which separates a water resource from a potential contaminant source. This distance ensures that the time taken for the horizontal travel of the contaminant is sufficient to allow degradation of the contaminant (Xu and Braune, 1995). The concept of travel times and minimum safe distances is more applicable to biological and degradable contaminants than non-biodegradable.

Groundwater contamination resulting from microbial contaminants can pose a significant threat to human health. Microorganisms collectively comprise a major contaminant of concern, second only to nitrate (Xu and Usher, 2006). Microbial contamination tends to have an immediate impact on human health especially in the elderly, infants and people with susceptible immune systems. There have been reports of cases of water borne diseases resulting from microbial contamination of groundwater used for human consumption in South Africa and other parts of Africa resulting in severe illness or in some cases death (Masinga, 2005). Microorganisms can exist naturally in the sub-surface environment or can occur as a result of contamination from human prone incidents like leaking sewer lines or animal faecal waste. Bacteria have contaminated boreholes as far as 170 day time-of-travel (TOT) from boreholes, and viruses have survived in groundwater for up to 270 days.

Generally contamination does not move in a uniform front, so that a TOT represents an average. Significant pollution could reach a borehole before the average TOT. A 2 year TOT provides a reasonable margin of safety beyond the 170 and 270 day figures (NJGS, 2003).

A summary of examples of protection zone dimensions implemented in other countries are provided in Table 3.1.

Table 3.1 Examples of protection zones in other countries.

Country	Wellhead Protection Zone/ Inner Zone	Middle Zone	Outer Zone
Australia	50m	10 years	Whole catchment
Denmark	10m	60 days/ 300m	10-20 years
Germany	10-30m	50 days	Whole catchment
Ghana	10-20m	50 days	Whole catchment
Ireland	100 days or 300m	-	Whole catchment
United Kingdom	50 days and 50m	400 days	Whole catchment

In some countries such guideline lists are very extensive and specific. In others, general guidance is issued. With each protection zone comes land use constraints. These constraints are of increasing strictness moving from the outer protection zone to the wellhead operational zone. Table 3.2 gives a list of typical land use constraints according to each zone.

Useful legislation for land use management in the Western Cape is the Land Use Planning Ordinance (15 of 1985) (LUPO) which includes sections on structure plans (forward spatial planning), zoning schemes (i.e. the regulation of development), the way in which applications may be made for new development rights, appeal rights, etc.

Table 3.2 Typical land use constraints for protection zones (Jolly and Reynders, 1993; Xu and Braune, 1995; Forster *et al.*, 2002).

Zone	Land use constraint
Wellhead Operational Zone	All constraints of inner protection zone and outer protection zone
	Agriculture
	Traffic – both pedestrian and automotive
Inner Protection Zone/ Microbial Protection Zone	All constraints of outer protection zone
	Informal waste disposal
	Cattle kraals/Feedlots
	Sewage sludge
	Small settlements
	Pit latrines
	Mining
	Fuel storage
	Cemeteries
	Workshops
	Farm stables and sheds
	Roads and railways
	Parking lots
Outer protection zone	Hospitals
	Wastewater and sewage treatment facilities
	Solid waste sites
	Mass livestock
	Airports and military facilities
	Oil refineries
	Chemical plants and nuclear reactors
	Large informal settlements using pit latrines
	Storage of hazardous substances underground

4 METHODS AND MEASURES FOR THE PROTECTION OF GROUNDWATER ENVIRONMENTS

The goal of groundwater protection is to ensure the sustainable use of a specific groundwater resource under consideration. This is achieved by specific planning methods and measures. Although many considerations on protection focus particularly on drinking water boreholes, the protection of groundwater resources should in principle be applied to the complete aquifer under consideration, or even the whole catchment, as stated in the EU Water Framework Directive (European Union, 2000). This extension to catchments reflects the frequent tight interactions between surface and groundwater systems. The soil zone is part of this interaction and represents the transition from the above land surface to the subsurface environment and therefore plays an important role in the protection planning. In coastal areas and arid/semi-arid areas groundwater protection includes the requirement of avoiding salinization of freshwater.

The implementation of different methods is based on user expertise, available resources, existing and field collected data, and the desired degree of confidence in meeting protection goals (Figure 4.1).

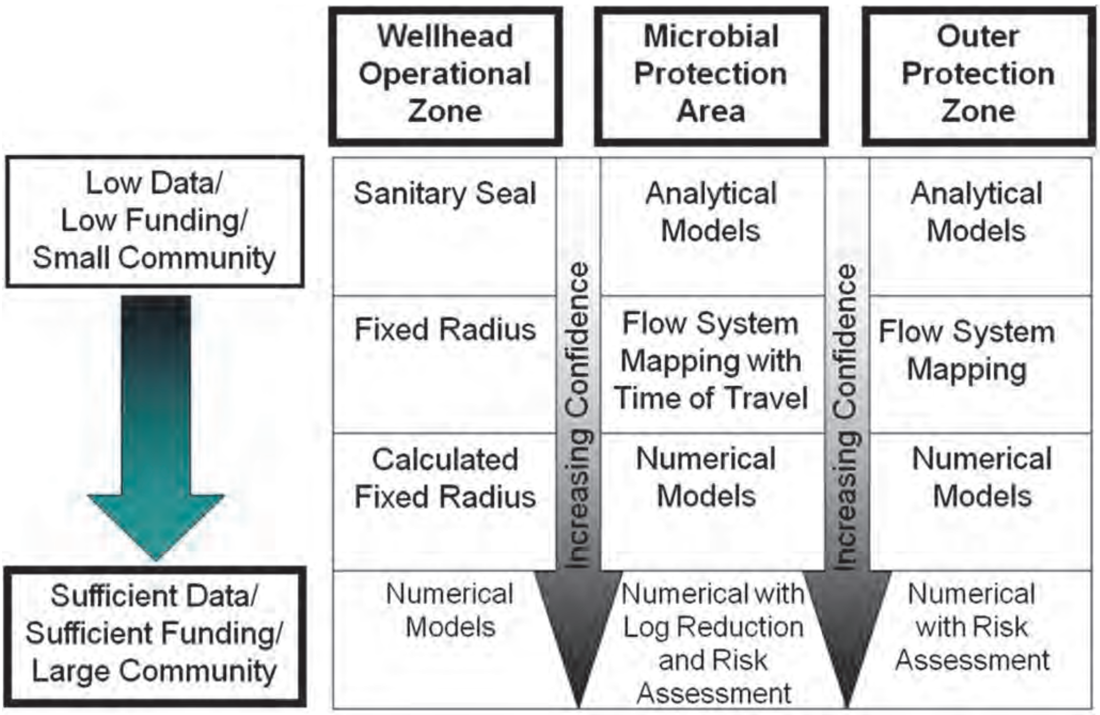

Figure 4.1 Data needs and uncertainty related to the delineation of groundwater protection zones.

The protective measures for groundwater systems are usually formulated for different areas in a hierarchical manner. Such areas may be (Stauffer, 2011):

- parts or even complete river catchment or basin, which include the aquifer under consideration;
- the aquifer itself;
- the catchment (recharge area) of a considered drinking water borehole;
- protection zones of limited extent, particularly for drinking water boreholes under consideration.

Groundwater protection zones have developed historically, using a variety of concepts and principles (Schmoll, 2006). Although some include prioritisation schemes for land-use, all aim at controlling contaminating activities around abstraction points to reduce the potential for contaminants to reach the groundwater that is abstracted.

4.1 Travel time approaches

International best practice guidelines indicate the time-of-travel should be used whenever possible to identify the area around a borehole that will become the focus of protection efforts. The most commonly used methods to delineate the geographic extent of this area include: 1) the calculated fixed-radius method; 2) hydrologic mapping; and 3) computer modelling. The value of each method depends on the quantity and quality of information available about the individual boreholes, the aquifer involved, and the hydrogeologic setting of the area.

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. This may follow the calculated fixed radius or variable shape approach. They may also be supplemented by analytical methods and hydrological modelling, if sufficient scientific expertise and data is available. The delineation of protection zones can then be based on such issues as the recorded or modelled movement of contaminants through the groundwater area. In such cases, zones may not be simple concentric circles around abstraction points, but their boundaries follow the calculated time of travel of chosen parameters. This may be important in heavily developed areas where the imposition of restrictions within a defined area may have economic repercussions.

The methods used to delineate source water protection areas each require increased data to provide reliable estimates of protection areas. It is best to select a delineation method for each public water supply based on the quality and quantity of hydrologic data that is available. For many public supplies, the arbitrary fixed-radius method will be sufficient. Much greater accuracy will be required for more vulnerable water supplies.

4.1.1 *Fixed radius approaches*

The least complicated method for determining a source water protection area is with the calculated fixed-radius method, consisting of a circle drawn around a borehole to delineate a specified time-of-travel. The radius of the circle is defined by the boreholes' pumping rate, the thickness and permeability of the aquifer, and the specified time-of-travel. For multiple boreholes, the calculated circles are merged to define the protection area for the entire wellfield. This method is relatively easy to perform with limited information, but it often results in a larger wellhead management area than other methods. In a narrow alluvial valley for example, this technique may unnecessarily include the surrounding uplands in the protection area.

Another basic approach of zoning employs fixed-distance methods where activities are excluded within a uniformly applied specified distance around abstraction points (Schmoll, 2006). These methods use expert judgement and experience and have been widely applied. There is limited direct scientific evidence to underpin most fixed-distance approaches, as they 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.

Fixed radius approaches are used in a number of countries for defining a protection zone around the immediate vicinity of the wellhead, chiefly designed to protect the boreholes from pollution by short cuts. For example, in Germany this zone is set at a minimum of 10 metres for boreholes, 20 metres for springs and 30 metres for boreholes in karst aquifers. The Swiss, Danish and Austrian protection schemes also use an innermost zone of 10 metres radius. In Australia the wellhead protection zone is a concentric area comprising the operational compound surrounding for the borehole and is often, but not always defined as a 50 metre radius within which the most stringent controls on land use and materials apply (Schmoll, 2006).

Certain conservative elements should be considered during the fixed radius delineation process. These elements are used to make the wellhead protection zone (WHPA) slightly larger than what is likely the actual area of contribution, and help to alleviate the uncertainties of mapping bedrock fracture flow at the wellfield. These are, as follows (adapted from Heath 1995):

1. Peak daily discharges (instead of average rates) should be used in capture zone modelling.
2. Boreholes should be pumped for a full 24-hour period in the model, rather than the fraction of a day that might be observed.

3. Capture-zone modelling should be performed under confined instead of unconfined aquifer conditions with recharge. Capture zones in a confined setting are generally larger than aquifers recharged from infiltration.

4. Land use in the vicinity of the wellfield should consist only of low risk activities and should not change in the near future.

4.1.2 Hydrogeologic Mapping approaches

A second method uses the physical and hydrologic characteristics of the area to map the protection zone. With this method, the protection area around a borehole is governed by the presence of groundwater flow boundaries which are based on rock and soil characteristics, the extent and thickness of the aquifer, and surface and groundwater drainage divides. In the example, boundaries are established to the east by lateral extent of the alluvium and low permeability of the valley walls, and on the west by a river that acts as a constant recharge boundary (constant supply of water). Because groundwater flow within alluvial aquifers usually parallels the direction of river flow, in this case northeast to southwest, the delineated protection area is primarily along the river. One difficulty in using this method is the accurate determination of the upstream and downstream boundaries that correspond to the selected TOT distance.

Flow system mapping is recommended as a first step for more complex hydrogeological systems and is relatively easy to implement, producing a total catchment area. The flow system mapping method is one of the recommended methods for aquifers showing conduit flow characteristics. The data required for flow system mapping, also forms the base line data needed for the more advanced methods. The data needed for this method can be obtained from normal national and aquifer level monitoring programmes.

The hydrogeologic mapping approach requires a conceptual model from the aquifer geometry and contacts, depth to water table, the presence of anisotropy in the aquifer, and any recharge and barrier boundaries that may influence a pumping borehole in the aquifer including possible losing stream conditions. The hydrogeologic characteristics of surficial materials can be gathered from a combination of the hydrocensus, existing hydrogeologic reports and additional field investigations. The water table surface can be estimated from measured water levels, the topographic slope, or non-pumping model simulations. The anisotropy can be estimated from bedrock characteristics from the field work and lineament analysis. The presence of recharge or barrier boundaries can be conducted by field inspection.

4.1.3 Modelling Approaches

A third method of delineating a protection area relies on a computer program to model the groundwater flow system. Computer models typically require large inputs of data describing the dimensions and hydrogeologic properties of the aquifer materials in order to simulate the aquifer's behaviour. Information is also needed about borehole construction, pumping rates, river conductance (how much water flows through the base of the river channel), recharge and evapotranspiration rates. Models can be either two- or three-dimensional representations of groundwater systems. Water flow paths are determined in the model by placing "particles" at the boreholes and instructing the computer to trace their routes backward for the specified TOT, here ten years. The area bounded by the flow paths then becomes the source water protection area. Although the results of modelling often imply a high level of accuracy, one of the fundamental principles of groundwater modelling is that without sufficient data to properly formulate a model, the results may be no closer to reality than the arbitrary fixed-radius method.

The Analytical Model approach uses well established hydrologic equations to model groundwater flow and pollutant transport. It uses computer codes to solve the analytical equations for two- dimensional flow to a borehole considering various combinations of parameters. A linked particle-tracking code delineates the zone of contribution for the borehole (Muldoon and Payton, 1993). Analytical models require knowledge of the hydrogeologic setting including: aquifer thickness, hydraulic conductivity, aquifer porosity, pumping rate of borehole, and some experience with computer modelling methods.

Numerical models use computer code to approximate three-dimensional 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 may be important in heavily developed areas where the imposition of restrictions within a defined area may have economic repercussions (Chave et al., 2006). Numerical models can be implemented in complex geological terrain where the importance of the resource can justify the additional cost of data and modelling expertise. The models should only be updated and implemented by experienced modellers. The data availability and experience of the modeller will directly influence the level of certainty in the results.

Advanced delineation of aquifer protection zones is based on two principles: 1) In cases where more data is available, an advanced delineation will likely be more accurate. 2) When a water user requires a high level of certainty regarding the protection of the water source.

Complex aquifer settings like situations where a borehole receives a portion of its water from a nearby river that has good hydraulic connection to the aquifer, or a wellfield that is affected by borehole interference are also good candidates for advanced delineation.

4.1.3.1 Data Requirements

Resources and efforts need to focus in particular on the following top 10 data sets:

- land cover/land use
- surface water quality monitoring
- groundwater quality and –quantity monitoring
- stream flow monitoring
- water supply boreholes and springs, volumes and positions
- identification of abandoned boreholes
- potential contaminant sources
- water use registration and licensing (WARMS)
- topo cadastral data
- tile/municipal drain mapping.

The time-of-travel (TOT) zones using a computer model requires certain input data, some of which can be estimated or assumed. The technical details are summarized below:

1. Positions of water supply boreholes/springs and pumping/flow rate.
2. Aquifer description: Nature of flow conditions, saturated thickness (maximum depth of water strikes), cross sections and spatial extent of aquifers.
3. Aquifer properties: transmissivity, effective porosity, hydraulic tests at different investigation scales; fracture set orientation, length and density; positions of large discrete fractures/faults, vertical and horizontal distribution of properties.
4. Natural groundwater flow directions (from hydrocensus), vertical flow conditions (flow meter or FEC), deep circulating water (hot springs with discharge points not necessarily at lowest altitude). The slope of the water table, recharge processes, recharge areas, discharge areas, interaction with surface water systems, surface water runoff contributing to focused aquifer recharge.
5. Boundaries of aquifer.
6. Time series water and salt budget: calibration targets, steady state, transient, heads, fluxes, contaminants.

4.2 Vulnerability assessments

A number of countries (e.g. the United Kingdom, Australia and Ireland) have introduced vulnerability assessment of groundwater 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. Such systems are also useful outside of drinking-water protection zones for long term planning of the protection of groundwater resources. They also provide guidance to organisations concerned with major works activities that could cause problems of groundwater contamination, such as the siting of new industrial or urban developments.

The example of Ireland highlights how vulnerability assessments have been included in protection plans. The Irish Environmental Protection Agency (1999) has proposed a protection zone identification scheme based upon the division of the entire land surface according to the vulnerability of the underlying groundwater to contamination. In this system vulnerability depends upon the time of travel of contaminants through the strata, the relative quantity of contaminants which can reach the groundwater and the attenuation capacity of the local geology. These factors are dependent upon the subsoil characteristics, whether the contamination source is point or diffuse source and the thickness of the unsaturated zone. Assessing these factors results in classification of the vulnerability of a given area as extreme, high, moderate, or low (Schmoll, 2006). Such ratings are based on judgement, experience and available scientific information. The resultant map shows the vulnerability of groundwater to contamination from contaminants released at 1-2 metres below the surface. Where deeper discharges are made, site-specific local conditions would have to be taken into account. The characteristics of the contaminants are not considered. This vulnerability classification is not only used for drinking-water resources, but also applied to the whole land surface of the country.

Figure 4.2 illustrates the concept of delineation of protection zones around a public water supply borehole from the integration of a source protection area map and a vulnerability map.

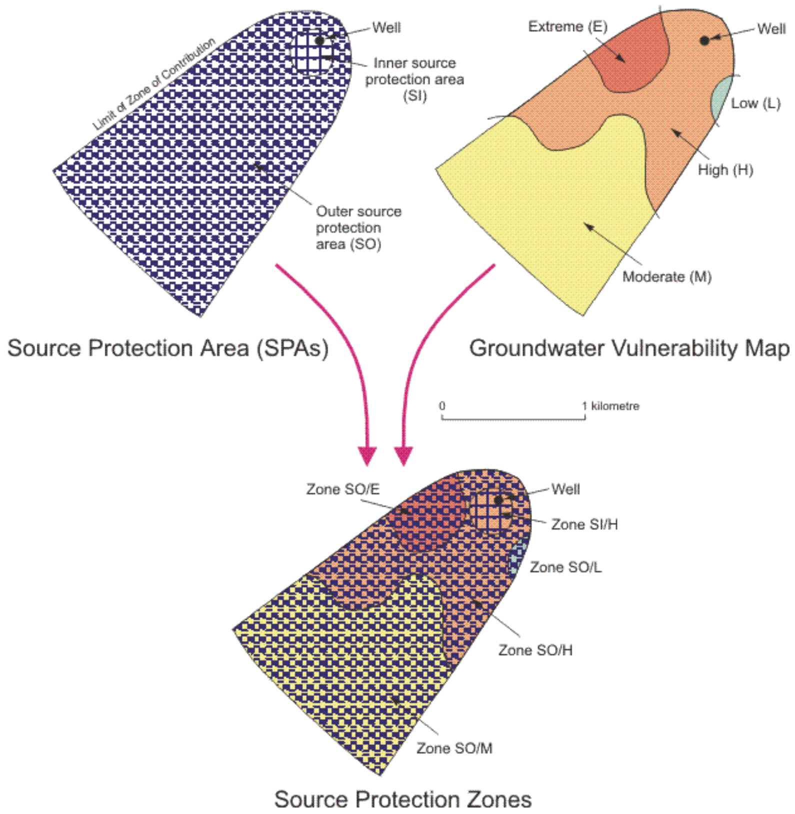

Figure 4.2 **Example of vulnerability assessment by Geological Survey of Ireland: Groundwater Protection Schemes (DoELG, 1999).**

4.3 Susceptibility Analysis

Susceptibility is a relative measure of risk. The relative risk is based upon:

1. The general potential for different classes of facilities or land uses to release "environmentally mobile contaminants";
2. The time-of-travel (TOT) zone the facility is located in; and
3. The vulnerability of the aquifer to contamination.

The overall or "Cumulative Risk" is the result of adding these three factors. Scores can range for example from 3 to 12; potential contaminant sources with a score of 3 would have a relatively low chance of reaching the wellfield, while contaminants with a score of 12 would have a relatively high risk of impacting the system's boreholes.

The goal of the susceptibility analysis is to provide systems with a list to help them in prioritizing potential risks so they can be addressed through management strategies. During the development of a source water protection plan, though, it is up to the local community to decide which potential contaminant sources carry the most risk since many potential contaminant sources use some form of best management practice to reduce the possible risk of contamination.

4.4 Selection of appropriate method

Fixed radius methods are best used for rule of thumb type protection at the accident prevention zone level, preventing short circuit contamination of the aquifer via the borehole itself. This can be implemented at almost no cost to provide protection from contamination immediately around the supply areas like spring outlets, shallow boreholes and dug wells.

Flow system mapping is recommended as a first step for more complex hydrogeological systems and is relatively easy to implement, producing a total catchment area. The flow system mapping method is one of the recommended methods for aquifers showing conduit flow characteristics. The data required for flow system mapping, also forms the base line data needed for the more advanced methods. The data needed for this method can be obtained from normal national and aquifer level monitoring programmes.

Analytical modelling can be implemented to produce quite advanced two dimensional models. Parameter estimates can be obtained from literature values or from local reports. These models give a reasonable estimate of the protection zones and can consider the time of travel for biodegradable contaminants. More importantly they produce cost effective zones where future data collection can be focussed should the importance of the water supply source justify the additional cost. Analytical modelling software is easy to use and can be implemented and updated by local authorities and Water Users Associations (WhAEM, GFLOW).

Numerical models can be implemented in complex geological terrain where the importance of the resource can justify the additional cost of data and modelling expertise. The models should only be updated and implemented by experienced modellers. The data availability and experience of the modeller will directly influence the level of certainty in the results.

The method chosen will depend on (1) the data already available; (2) The number of people dependent on the resource; (3) the point in the hydrologic cycle where groundwater is accesses; (4) the hydrogeological conditions; and (4) the financial resources available to implement. Figure 4.3 shows a flow chart designed to assist with the selection of protection methodology to use.

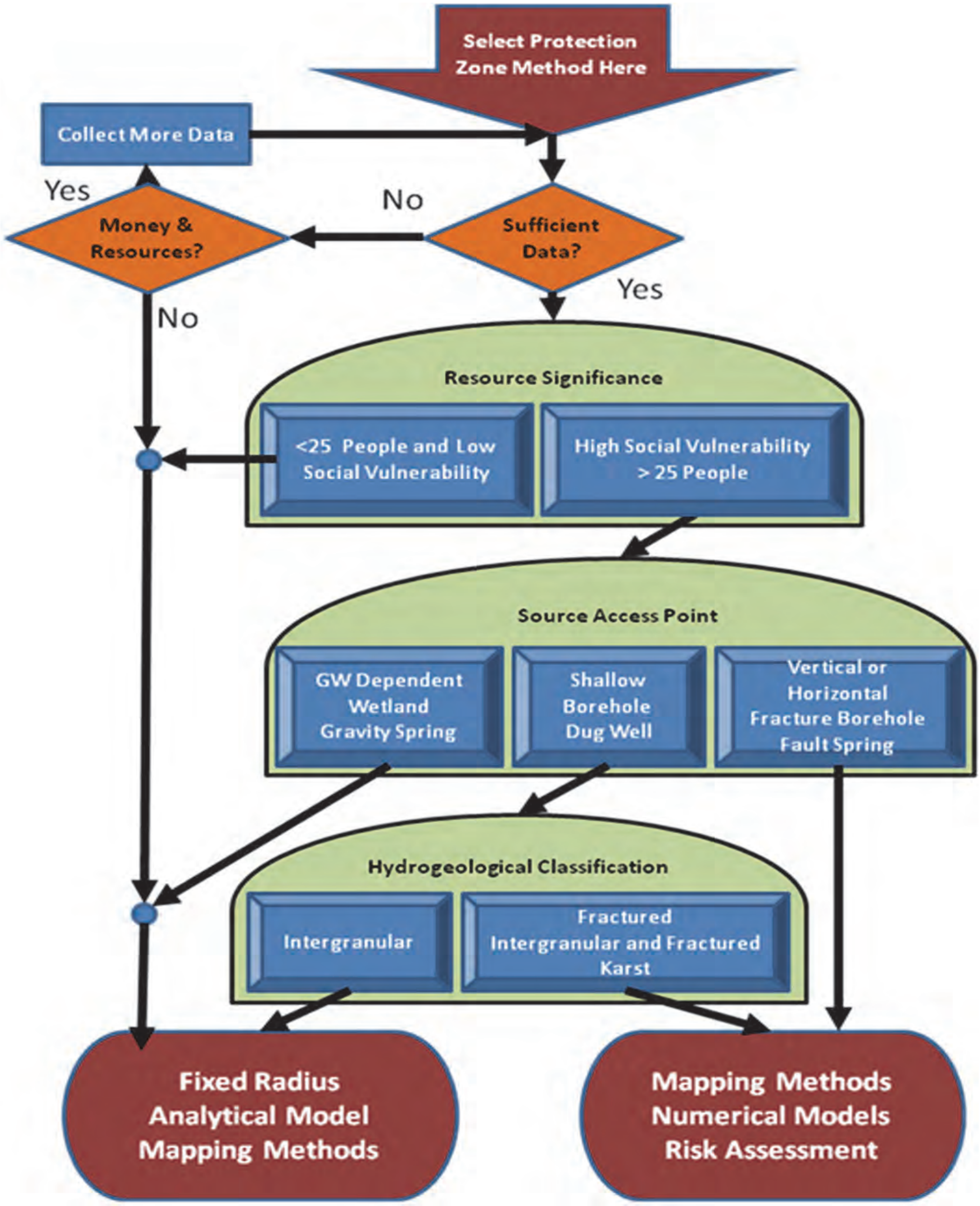

Figure 4.3 **Flow chart for selection of the appropriate method to delineate capture zones for different data availability, aquifer characteristics and water access points.**

5 DATA REQUIREMENTS FOR PROTECTION ZONE SIMULATION

5.1 Conceptual Model

The conceptual model of hydrogeology integrates geological and hydrological information to describe ground-water occurrence, movement and quality of the wellhead protection area/protection zone. The conceptual model describes the hydraulic and storage properties of geologic materials, and the boundary conditions that govern ground-water movement under both pumping and non-pumping conditions. In some cases, the conceptual model should also describe groundwater quality, particularly when natural or human sources of contamination exist.

5.1.1 Components of a conceptual model

According to Kresic (2007): “The art of modelling is to simplify the description of the system (aquifer) and its behaviour to a degree that will be useful for the purpose of planning and making management decisions in specific cases”.

The development of a modelling concept is the initial step of modelling. The result should be a computerised database, and simplified electronic maps and cross-sections that would be used in the model design and that could easily be incorporated into the actual electronic model Kresic (2007).

A conceptual model should at least be able to answer the following questions:

- In which direction is the water in the aquifer flowing, at approximately what rate, and how does this change with time?
- Where is the water leaving the aquifer, approximately how much of it, and how does this change in time? (Kresic, 2007)

In order to answer the above questions ideally the following steps should be taken:

- Seasonal synoptic measurements of water levels should be acquired;
- Aquifer pumping tests should be conducted;
- Borehole logs should be examined to facilitate the designing of a multilayer model;
- Examine land cover and land use in the aquifer area to better estimate potential aquifer recharge;
- Continuously and simultaneously measure precipitation and water level fluctuations in several strategically located monitoring boreholes (Kresic, 2007).

Some examples of assumption characteristics according to Bear et al. (2009) are:

- The domain's hydrogeology, stratigraphy, etc.;
- The dimensionality of the model (one, two, or three dimensions), and the geometry of the boundary of the domain of interest;

- The kind of soil and rock materials comprising the domain, as well as heterogeneity, anisotropy, and deformability of these materials;
- The relevant transport mechanisms within the domain;
- The flow regimes of the involved fluids (e g., laminar or non-laminar);
- The presence of assumed sharp macroscopic fluid-fluid boundaries, such as a phreatic surface;
- The presence of sources and sinks of fluids and contaminants within the domain, and their nature (spatial distribution and temporal variation);
- The initial conditions within the domain and conditions on its boundaries.

5.1.2 Impact of a specific activity

Natural quality of groundwater varies from one rock type to another and also within aquifers along groundwater flow paths (Schmoll, 2006). It is important for those with the responsibility for protecting groundwater quality to be aware of the geological environments in which naturally-occurring substances are likely to exceed drinking water criteria so that groundwater is properly tested for those natural substances.

These natural groundwater qualities together with added substances from the surface/adjacent aquifers will result in a different – and most times harmful – quality.

Liquid contaminants, whether as toxic liquid or as a solution of a toxic chemical species dissolved in water, are sometimes spilled at ground surface, intentionally or by accident. In many cases, once the contaminant reaches the aquifer, the groundwater may be rendered useless for most purposes. Management of aquifers must therefore include management of both water quantity and water quality.

The following are all potential groundwater contaminant hazards:

- Septic tanks: These are used as a means of disposal of domestic sewage ill many especially rural) areas. In general, a properly designed and maintained septic tank should be regarded as an efficient and economical means of domestic sewage disposal. However, even when each unit in itself is well designed and maintained, a high density of septic tanks may exceed the natural ability of the subsurface environment to absorb and purify effluents, thus causing a degradation of groundwater quality due to release of bacteria, organic contaminants and nitrates.
- Storage tanks. In terms of the number of incidents (e.g., gasoline tanks/service stations), this is probably the major source of subsurface contamination in the USA and other industrialized Countries. The tanks may contain hydrocarbons, organic compounds, and inorganic liquid chemicals. The main cause of leakage from steel tanks is corrosion.

- Transportation accidents. Spills may take place as a result of accidents that occur in the process of transporting toxic liquids by trucks or trains even if the quantity is not large, and spilled liquid migration stops after a certain volume of soil has been contaminated, subsequent percolating water will dissolve and carry the contaminants to underlying groundwater, unless the contaminated soil has been removed. If the chemical is volatile, its vapour will diffuse and may contaminate an increasingly larger soil volume.
- Agriculture. Many agricultural activities produce potential sources of groundwater contamination. Among such sources, we may mention pesticides and herbicides, fertilizers, animal feed and waste, irrigation, and plant residues. Fertilizers (chemical and manure) constitute a serious danger to the subsurface, both at the handling stage (transportation and storage) and when applied in the field. Irrigation, especially excessive irrigation, may leach and transport significant quantities of nitrogen fertilizers, in the form of nitrate, to underlying groundwater.
- Animal raising activities produce contaminants that include nitrogen compounds, phosphates, chlorides, bacteria, and sometimes heavy metals (Ba, Cd, Cr, Cu, Pb, Ag, and Zn) (Bear, 2010).
- Mining and Industry. Potential contaminants include leachate from return water dams, tailings, etc.

5.1.3 Typical data requirement

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

1) The spatial dimension of the flow domain: this information is obtained from hydrogeological investigations. The prevailing flow field can often be approximated by a horizontal two-dimensional (2D) flow and transport model. 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) The pumping rate of the borehole and all further water abstraction rates in the domain: the given or planned schedule of the abstraction should be taken into account.

3) The groundwater recharge rate: the rate can be estimated on the basis of hydrological considerations. In the case of confining low-permeability layers their effectiveness and areal extent has to be assessed by hydrogeological and hydraulic investigations.

4) 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.

5) The levels of the bottom and of the top of the aquifer form this information is generally obtained from borehole and/or geophysical investigations.

6) The piezometric head of the aquifer or the level of the groundwater table: this Information is generally obtained from boreholes and/or geophysical investigations.

7) The location of the boundary of the flow domain to be investigated: this information is obtained from a regional hydrogeological and hydrological investigation. The boundaries are often chosen in such a manner that a feasible formulation of the boundary conditions (fixed head or streamline) can be obtained.

8) The boundary conditions consist of the piezometric heads at the boundary (or portions of it) or of the water flux through the boundary (or portions of it): this information can be obtained from hydrological and hydrogeological investigations.

9) The hydraulic conductivity (or transmissivity) of the aquifer: this information can be obtained from pumping or slug test evaluation or other procedures.

10) The effective porosity of the aquifer (effective with respect to solute transport): this information is relevant for proper isochrones prediction and can be deduced, for instance, from tracer tests.

5.2 Aquifer types in South Africa

In South Africa aquifers are classified into four main types (Jonck and Meyer, 2002), namely:

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

This classification is used in the published 1: 500 000 hydrogeological map series (Jonck and Meyer, 2002) of South Africa that is available to all water resource managers and can be used to identify typical borehole yields for water supply. Figure 5.1 shows a simplified national hydrogeologic map.

To use the 1:500 000 maps for groundwater protection it should be used in conjunction with knowledge of the groundwater occurrence and existence of preferential path ways. Knowledge of transmissivities for different aquifer types and potential preferential pathways provide a useful link between the borehole yields, contaminant transport and simulation of protection zones.

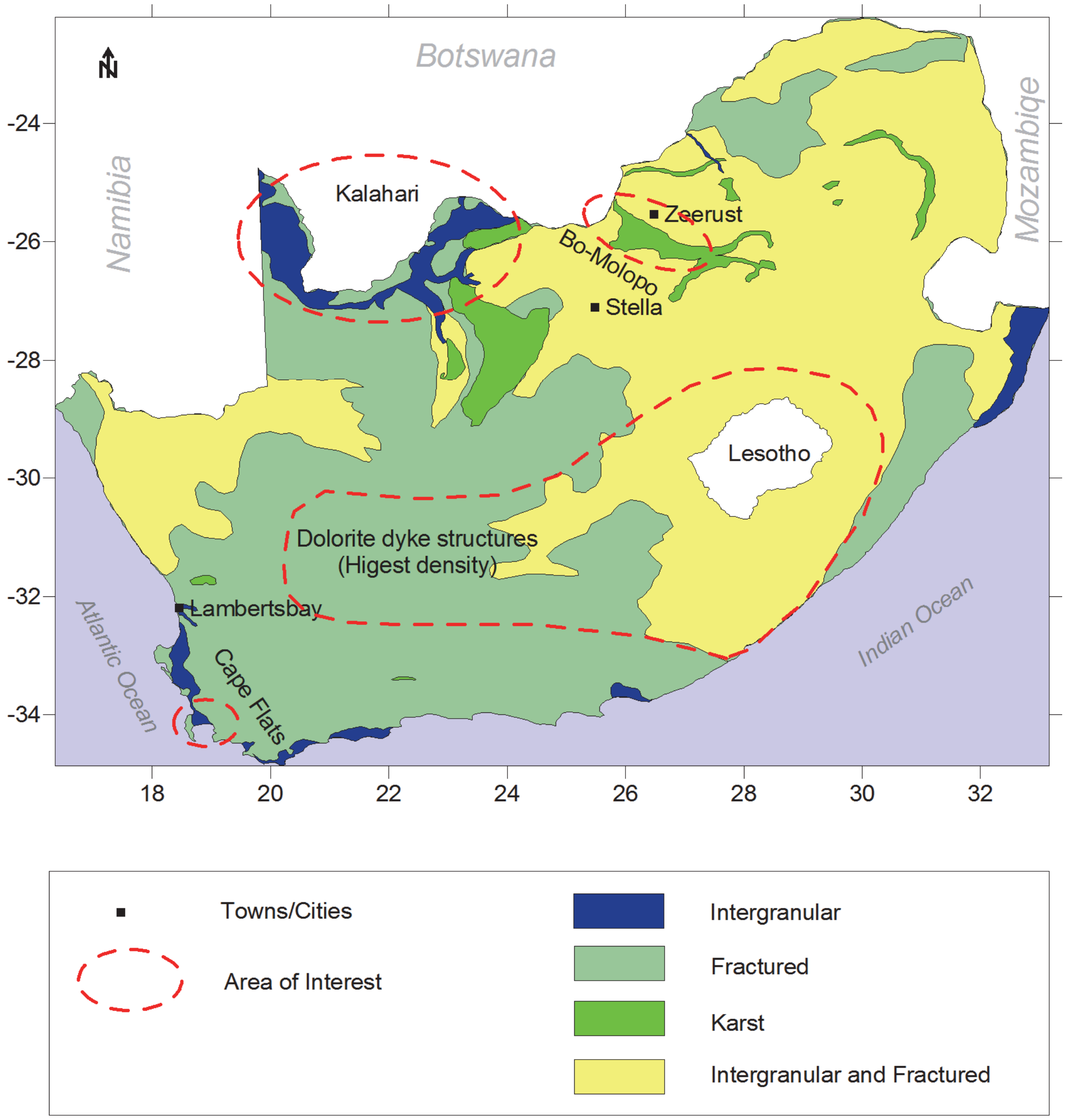

Figure 5.1 Simplified hydrogeological map of South Africa showing the different aquifer types, with areas highlighted due to their data availability and characteristics in terms of the type groundwater occurrence.

5.2.1 Intergranular Aquifers

Intergranular aquifers in South Africa comprises of different combinations of unconsolidated to semi-consolidated material ranging from boulders through sand to clay size particles. Extensive primary water bearing strata are mostly confined to the coastal belt and the Kalahari region (Figure 5.1). Some patchy occurrence of narrow strips of alluvial deposits is also found along rivers and paleo channels (Vegter, 2001; Baran and Dziembowski, 2003).

Typical yields for intergranular aquifers depend on particle size and sorting. Conglomerate layers provide borehole yields of between 0.5 and 5 l/s, while course sands associated with alluvial deposits provide borehole yield above 2l/s. In the fine grained coastal sand most of the boreholes provide yields of between 0.5 and 5 l/s (Meyer, 1999; Barnard, 2000). Transmissivity values of between 4 and 70 m^2/day with average of 25 m^2/day and storage coefficient of between 7% and 25% with an average of 15% is reported by King (2003).

Work by the author on coastal sand in the Lamberts Bay area provided transmissivity estimates of about 10 m^2/day for 10 m saturated sand and up to 100 m^2/day for 40 m saturated aquifer. Aquifer tests on Cape Flats coastal sand at the University of Western Cape campus research site provide and a transmissivity estimate of 25 m^2/day for 18 m saturated thickness and a storage coefficient of 10%.

Shallow intergranular aquifers are vulnerable to contamination from surface activity and pit latrines. Since groundwater flow is through pores rather than fractures the contamination risk is generally more of a chemical nature (e.g. elevated nitrate) than microbiological (MacDonald and Davies, 2000). Water movement can in general be described as porous flow, with contaminant retardation a function of the porous matrix, contaminant chemistry and surface area (Vance, 2002).

5.2.2 Fractured Aquifers

Pure fractured aquifers are found within hard rock aquifers throughout South Africa (Figure 5.1) and are characterised by negligible primary porosity with groundwater movement controlled by zones of faulting, fracturing and jointing. In general little or no decomposition of the rock mass has taken place. The storage volume of groundwater found in this type of aquifer is therefore limited and much lower than in other aquifer types. Transmissivity values of between 7 and 1320 m^2/day and storage coefficient values of between 0.0002 % and 2% is reported by Meyer (2003).

Conduit flow conditions can be expected in individual fractures. Individual fractures are however not infinite in extent. Therefore where flow is supported, fracture density must be high enough to assure connectivity through the system. With an increase in fracture density the system becomes increasingly pervious (Vance, 2002). Work by the author on fractured Malmesbury Shale Formation underlying the Cape Flats on the University of the Western Cape campus research site provide an fracture transmissivity of 100 m^2/day using early time constant rate discharge tests data, while the host rock matrix provide a transmissivity estimate of 22 m^2/day using late time data. Storage coefficient of 1% is estimated from observation borehole analysis.

In many cases the micro-fissures store most of the water, which gets transmitted by the large fractures. This fractures and fissures serve as hydraulic conduits. High yielding features are normally associated with regional fault zones. As a result, regional groundwater abstraction schemes from identified structures are preferable.

Characterisation of these resources has however been limited (Pieterson, 2004). Ideally, data should be gathered on fracture length, orientation, aperture, and density. Additionally, information on hydraulic head, the porosity and hydraulic characteristics of the bulk matrix, the type of contaminants, and potential interactions between contaminants and the matrix are also important (Vance, 2002). As an estimate, a block of fractured media will have a surface area 1,000 to 100,000 times smaller than a similar block of intergranular media. Contaminant retardation will be roughly proportional (Vance, 2002).

5.2.3 Intergranular and Fractured Aquifers

Intergranular and fractured aquifers, like weathered granite, dolorite and sandstone formations are found throughout the central regions of South Africa (Figure 5.1) and represent a multi-porous medium that essentially consists of two major components (Baran and Dziembowski, 2003; Woodford and Chevallier, 2002), namely:

(a) Fractures; and

(b) Inter-fracture blocks or rock matrix.

The intrusion of dolorite into shale and sandstone host rock formations created zones of local metamorphism at the contact zones. This intrusion can also create fractures on both sides of the dolorite body. The weathering of these zones is an important process that enhances the permeability, with the depth of weathering relative to the water levels also important. With boreholes these zones of fracturing can become a natural underground drainage system of groundwater stored in the weathered rock (Baran and Dziembowski, 2003). Yields of up to 70 l/s were intersected at the contacts with dykes at depths of 200 m (Chevallier et al., 2000).

Transmissivity values for fractured and intergranular aquifers of between 0.5 and 150 m^2/day can be expected (King, 2003) with values of up to 3 797 m^2/day in weathered contacts between formations (Meyer, 2003). Storage coefficient values of between 0.003% and 7 % are reported by Meyer (2003).

Work by the author on fractured and intergranular granite in the Stella district provided storage coefficient values of 0.5%, fracture transmissivity estimates of 2000 m^2/day and matrix transmissivity of between 100 and 200 m^2/day (Nel, 2001). Fractured and intergranular quartzites associated with faults in the West Coast near Lamberts Bay are estimated to be between 500 and 1000 m^2/day based on blowout yield during drilling.

Intergranular and fractured aquifers are generally considered to form dual-porosity fractured rock aquifer systems, where it is difficult to simultaneously quantify the groundwater flow within fractures and the rock matrix (Woodford and Chevallier, 2002). Both diffuse and conduit flow can be found in intergranular and fractured aquifers and depends on fracture density and interconnectivity as in fractured aquifers. Water flowing through the fracture in an intergranular and fractured medium may result in dissolved contaminants, e.g. chemicals, travelling slower than water flow through the fracture alone, due to mixing of fracture water with the intergranular matrix. This mixing may occur via diffusion, even if the matrix permeability is low. With an increase in fracture density the system becomes increasingly pervious and can display porous flow characteristics (Vance, 2002). Larger particles like microbiological contaminants are not able to enter the small pores of the matrix and hence travel faster through the fracture flow.

5.2.4 Karstic Aquifers

In South Africa the karstic aquifers (Figure 5.1) mainly comprise of dolomite with variations in the chert content, where the chert rich dolomite provide the highest yields. The continuity of the dolomite aquifer is interrupted by vertical and sub-vertical intrusive dykes. The intrusive dykes create low permeability barriers to movement of water, creating compartments with springs at the outflow of the compartments.

Local karstic features are formed around springs by the dissolution of a carbonate rock by circulating groundwater containing carbonic acid. The process takes place along fractures and cracks in these formations enabling the solution of the solid rock, resulting in large solution cavities, sinkholes and even cave forming (Baran and Dziembowski, 2003; McCarthy and Rubidge, 2005).

Fracture aperture can increase with time due to chemical solution or physical erosion (Vance, 2002; Bloomfield et al., 2005). High yields can also be found in fractured and karstic limestone (MacDonald and Davies, 2000). Classic groundwater flow equations are however invalid for conduit flow characterized by turbulent and fast groundwater flow, making the simulation of these aquifers complex and expensive (Bradbury et al., 1991).

Estimates of transmissivity obtained by the author from the modelling of dolomitic aquifers near Zeerust provided transmissivity estimates of between 50 and 80 m^2/day for the chert poor zones and 800 to 8000 m^2/day for the chert rich zones (Bredenkamp and Nel, 1996; Nel, 2000). Storage coefficient values of between 1% for the chert poor and 25% for the chert rich dolomites was estimated.

The key challenge for the dolomite aquifer system relates to the management of the resource, which is threatened by various land use impacts and the protection of aquifer integrity. Since these aquifers are in part overlain by areas of intensive land use and urbanisation, they are potentially susceptible to water quality deterioration. However, groundwater contamination by substances such as oil, fertilizer nitrate and other sources of pollution does not seem to be serious in the dolomite areas (Stephens and Bredenkamp, 2002). This is probably due to the large volumes of water stored underground in relation to localised infiltration of contaminants (Stephens and Bredenkamp, 2002). The groundwater quality of Bo-Molopo dolomite aquifers seems to be generally good, with the springs in general not extensively contaminated.

5.2.5 Comparative Transmissivities

The above subdivision into groups based on primary openings (intergranular) and secondary openings (fractures) is useful to estimate borehole yields from a water bearing point of view (Vegter, 2001) with sustainability of groundwater dependent on the thickness of the weathered zone, usually the uppermost 10-30 m, as well as the occurrence of deeper fracture zones (MacDonald et al., 2002).

As seen above the type of aquifer plays a significant role when determining the possible pathways contaminants can follow from a contamination source to a potential receptor. The existence of preferential pathways such as fracture or fault zones will allow contaminants to move at much higher rates than suggested by the average borehole yields from the aquifer classification map.

Figure 5.2 shows a summary of the transmissivities discussed in the preceding sections to provide comparative values for the aquifer types relative to each other and more importantly a comparison between the host rock and preferential pathways like fracture and fault zones. These relative transmissivities of each aquifer type must be considered to recommend appropriate groundwater protection zones.

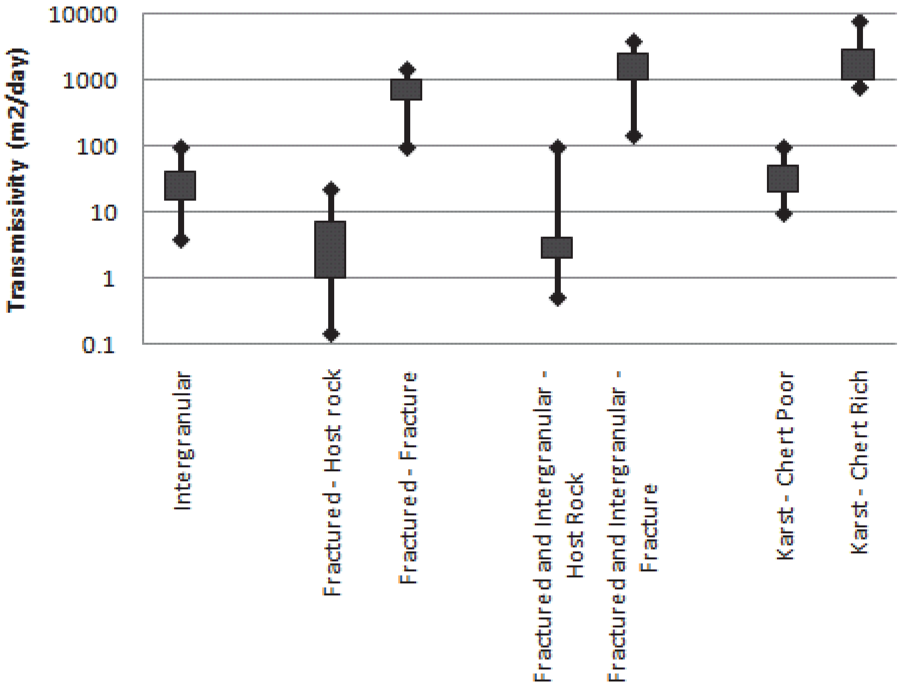

Figure 5.2 Transmissivity ranges for the different aquifer types in South Africa to be considered when evaluating transport distances.

5.3 Contaminant Characteristics

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). 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 what phase the contaminant will assume in the groundwater system:

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

5.3.1 Aqueous Solubility

The aqueous solubility of a contaminant compound and its ability to stay in solution through its pathway will influence the transport, 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.

5.3.1.1 Sorption to Solids

Compounds present in groundwater systems will in general have the opportunity to associate with either the solid or the aqueous phase(s). The partitioning of a constituent among these phases will depend on the constituent and the phases themselves. Both adsorption and absorption processes play a role in the association among aqueous and solid phases. As it is almost impossible to distinguish, which of the processes is at work and therefore the term sorption is often used (Blatchley and Thompson, 2007).

Sorption involves the formation of bonds between the constituent and the solid phase. Three types of sorption can be distinguished, namely: Physisorption, chemisorptions and ion exchange. It is important to recognize the difference in bond strength between these sorption processes. In chemisorption the bond strength between a solute and solid surface may approach that of a covalent bond and would not be reversible. Physisorption and ion exchange tend to be readily reversible processes, as the forces that are responsible for the attraction of a solute to the solid are relatively week (Blatchley and Thompson, 2007). Compounds demobilised due to physisorption or ion exchange can therefore be released to the groundwater flow path if changes in conditions like pH occurred.

5.3.1.2 Chemical Composition

No single factor plays a more universal role in defining the characteristics of an aqueous system than pH (Blatchley and Thompson, 2007). The solution pH has a dramatic effect on the solubility of compounds that can donate or accept protons while also determining the speciation of all acids and bases in solution. Equilibria within the system are affected when H^+ is added or removed, and redistribution of the H^+ among all these other reactions adds to buffering effects. The observed pH of natural water is, in this sense, a convenient indicator of the status of these equilibria and the pH buffering capacity related to H^+ in solution to participate in chemical reactions (Hem, 1985). Various metals and pesticides demonstrate a strong dependence on pH with high percentages of sorption occurring at pH above 8 (Sposito, 1998; Dzombak and Morel, 1990; Roy and Dzombak, 1997). The role of pH in determining the surface charge is significant in all these processes and must be considered in an evaluation of the fate and transport of ionic contaminants and micro-organisms (Blatchley and Thompson, 2007).

In South Africa the pH of natural groundwater varies between 7 and 8 (Figure 5.3) for most of the country. Slightly lower pHs of between 5 and 6 are displayed in the TMG areas, while and high pHs of around 9 are recorded for individual points in the Eastern Cape and Swaziland areas. Limited sorption is expected for the areas with pH below 6 and would it be beneficial to increase travel times between potential pollution sources and drinking water sources.

The data to produce this map is obtained from the field measurements of the Department Water and Sanitation National Background Quality Monitoring Network (ZQM) and was recorded at existing production boreholes after purging and pH readings stabilised between 5 minute intervals.

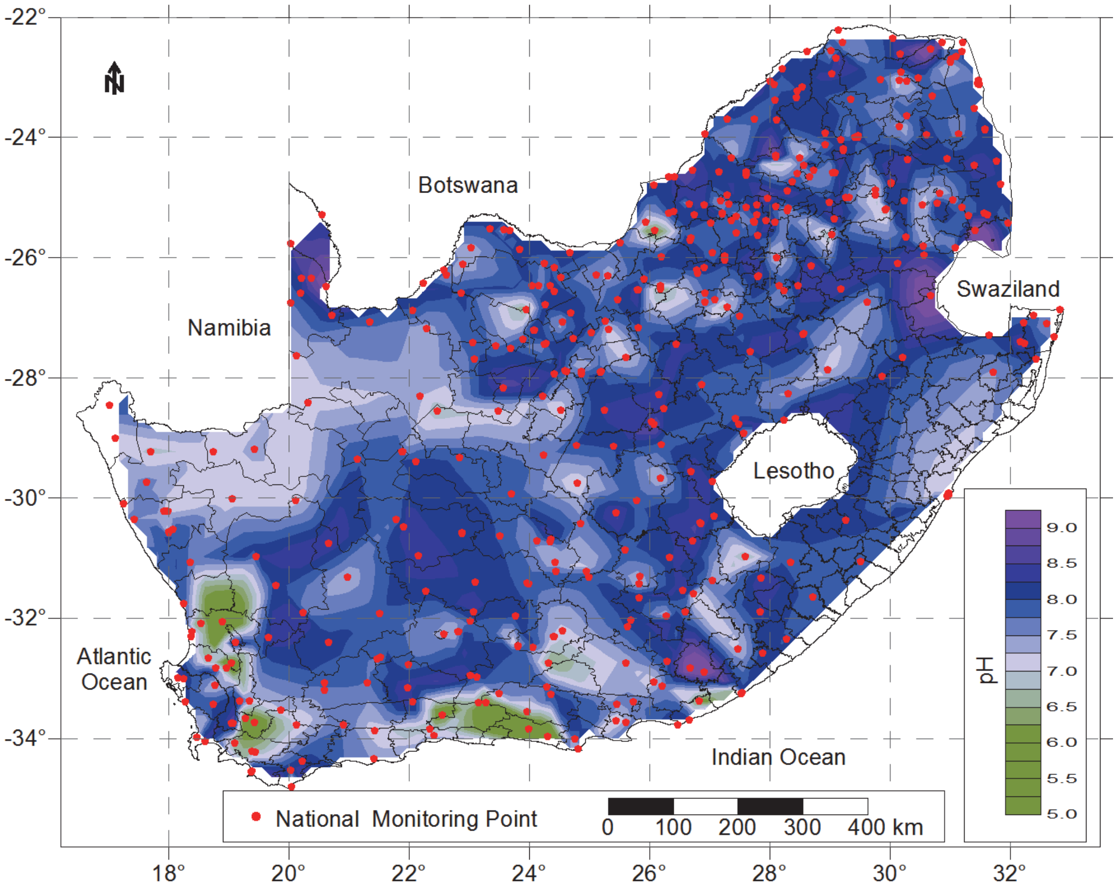

Figure 5.3 **Ambient groundwater pH distribution across South Africa, compiled using field data from Department of Water and Sanitation national water quality monitoring programme.**

5.3.1.3 Temperature

Thermodynamic considerations play an important role in evaluating the rates and equilibria of chemical reactions. In South Africa the groundwater temperature varies between 18 and 24 (Figure 5.4) for most of the country with slightly warmer water in areas like Western Cape, Aliwal North and Lesotho where hot springs are found. The data used to compile the map was obtained from field parameters for the Department of Water and Saniatation National Water Quality monitoring programme, recorded after purging of the sample points.

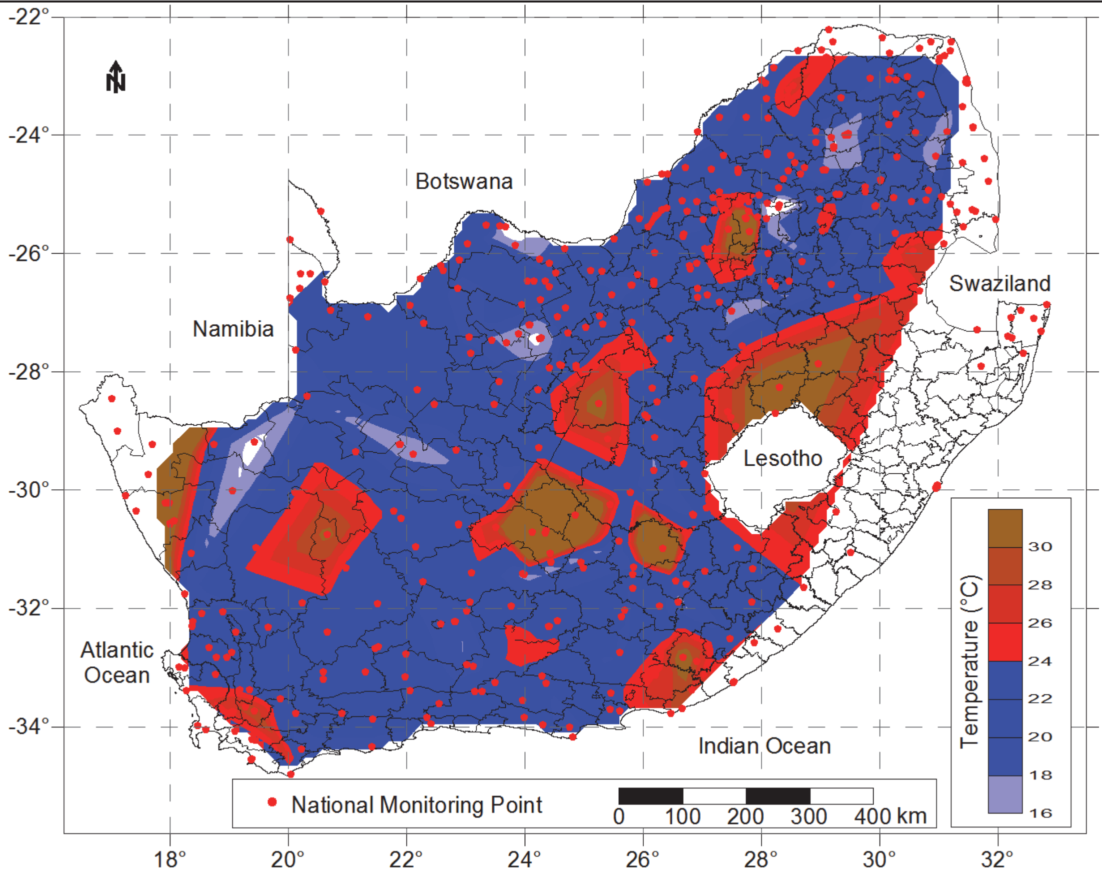

Figure 5.4 Ambient groundwater temperature distribution across South Africa, compiled using field data from Department of Water and Sanitation national water quality monitoring programme.

In general, reaction rates will increase with temperature due to the increased availability of thermal energy. This energy will promote collisions between molecules by increasing rates of diffusion and will reduce energy barriers to reaction progress. Examples of the effects of heat on groundwater contaminants include changes in equilibria and kinetics of precipitation and dissolution of minerals, and changes in the rates by which biological transformation processes proceed (Blatchley and Thompson, 2007).

5.3.2 Inorganic Constituents

A number of factors can contribute to the changes in solution chemistry in groundwater systems. These include changes in atmospheric composition, changes in soil chemistry, and human activities that directly alter the physical and chemical conditions of a soil matrix (Blatchley and Thompson, 2007). Atmospheric particulate matter such as dust and salt will control the quality of the local rainfall entering the aquifer. As water moves through the geologic medium, further chemical reactions between the geology and water will change the composition of both phases. The compounds that comprise the inorganic fraction of groundwater are heavily influenced by interactions between rain water and geologic environment.

Inorganic groundwater contaminants may come in the form of (a) increases in the concentration of the natural constituents, above their natural occurring concentrations, or (b) the introduction of constituent that would not be expected at all.

Some of the biggest 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. In South Africa large scale acid mine drainage problems are associated with coal and gold mines in the Mpumalanga and Gauteng regions.

Protecting groundwater used for drinking water in these mining areas is important due to the potential negative effect of mining on the quality of local ground and regional surface water. Mining will further change the aquifer hydraulic characteristics, affect recharge processes and increase salt loads, complicating the protection of drinking water.

5.3.3 Organic Constituents

Contaminant compounds that display extremely low aqueous solubility can exist as a separate liquid phase in groundwater systems, if present in sufficient quantities. In groundwater systems these contaminant phases are referred to as nonaqueous phase liquids (NAPLs) and their behaviour will be fundamentally different from that of the bulk aqueous phase. In the case of a NAPL with density less than the surrounding water, the nonaqueous 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. Their behaviour in the subsurface environment is fundamentally different from that of LNAPLs. DNAPL compounds, because of their high density, 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.

5.3.4 Particulate Matter

Microorganisms 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), capable of causing illness in humans. Surface water sources, such as lakes, rivers, and reservoirs, are more likely to contain microorganisms 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 and pit latrines.

Because microbes are living organisms, their transport in groundwater is more complex than is the case for abiotic colloids. This complexity is partly responsible for the lack of understanding of transport processes of microorganisms in groundwater (Flynn et al., 2004). Not only are they subject to the same physicochemical phenomena as are colloids, but there are also a number of strictly biological processes that affect their transport e.g., temporal changes in surface properties due to changes in metabolic state and predation by other subsurface organisms (Ginn et al., 2002; Taylor, 2004).

Viruses in groundwater are thought to pose a greater health risk than bacteria due to their small size, which enables them to move more effectively than larger microorganisms like bacteria and protozoan cysts. Viruses also have a high infectivity rate and prolonged persistence in the environment (Jiwan and Gates, 1998; Schijven and Hassanizadeh, 2000). Bradbury et al. (2006) and Borchardt et al. (2007) have further shown that enteric viruses have the potential to move deep into the subsurface environment, even penetrating a confined aquifer system.

Bacterial pathogens frequently contaminating groundwater systems include *Vibrio cholerae, Shigella dysenteriae, Escherichia coli, Campylobacter spp., Salmonella paratyphi* and *Salmonella typhi* (Dzeda et al., 1997; Stanley et al., 1998) and *Arcobacter butzleri* (Rice et al., 1999). Due to the relatively large sizes of bacteria (compared to viruses), they are removed much more efficiently by soil filtration (Schijven and Hassanizadeh, 2000; Blatchley and Thompson, 2007). Very little is however known about their transport and fate in fractured rock environments.

The potential health risk associated with protozoa is the high level of persistence of their dormant stages, such as spores and oocysts (Schijven, 2001). It is thought that the processes involved in the removal processes of viruses in soil also apply to protozoa (Schijven, 2001).

6 DATA COLLECTION METHODS

Characterising of fractured aquifers at a catchment scale remains problematic largely due to the heterogeneous nature of fractured rock aquifers. Understanding groundwater flow in these fractured rock aquifers requires detailed information. The need to understand flow in fractured rock aquifers has resulted in the development and improvements in available methodologies and practices aimed at enhancing the understanding of the flow dynamics of these aquifer settings. The characteristics of fractured aquifers are highly variable due to varied fracture systems. In order to improve the understanding of the occurrence and dynamics of groundwater, studies need to be done in different climatological and geological settings.

The identification and characterisation of hydraulically active fractures is one of the main subjects of concern in fractured rock settings. This has led to the adaptation and development of methods and techniques that are best suited to characterise fractures flow including flow of contaminants through them.

The main goal of characterising fracture flow is to understand groundwater flow, transport and fate of contaminant transport in fractured rock aquifers at a scale sufficient to make remedial decisions (Kinner et al., 2005). There are several methods for characterising fractures. These methods are not only able to provide information with regards to the location of fractures in a borehole but they also provide valuable information on the flow characteristics in the aquifer. Of the many methods that can be used in characterising these aquifers, conceptual and numerical models are most widely used at both regional and local (discrete fracture) scale.

6.1 Application of geophysical methods in characterisation of fractured aquifers

Borehole geophysics refers to a wide range of methods used to establish lithological/stratigraphic properties and infer fluid and rock properties as a function of depth (Morin et al., 1997). In fractured rock aquifers, borehole geophysics enables characterisation of fluid flow and transport properties of fractured rocks. Geophysical logs provide an indication of trends and anomalous responses that reveal the lithologic variability as well as stress history of rocks (Morin et al., 1997). Traditional geophysical logging utilise wire line logging methods like electrical resistivity, calliper, and fluid logs. The wire line methods are usually used in conjunction with core logging, optical and acoustic imaging methods to assist in mapping of fracture zones (Morin et al., 1988). The most popular geophysical method used in groundwater studies is the electrical resistivity method (Krulc and Mladenovic, 1968).

6.2 Electrical resistivity

Electrical resistivity logging utilises the difference in electrical resistance of different geologic units to identify different layers traversed by a borehole as well as water bearing zones (Pretorius, 2007). Fractures without water have a very high resistance to flow of electric current, while fractured rock bearing free water have low resistivities (Bernard, 2003). The resistivity of fractured basement rocks with water is less than 1500-300 ohm.m (David, 1988; Hazell et al., 1992), while those without water will have resistivities higher than 3000 ohm.m.

In fractured aquifers, flow paths can be identified from the measured potential and calculated resistivities of the aquifer medium which are a result of the interaction of the current introduced into the subsurface and the electrical resistivity of the flow path along which the electric current has travelled (Loke, 2001; Loke and Barker, 1996). Fractures have successfully been studied using electrical resistivity measurements in crystalline basement environments based on the significant contrasts in the geoelectric parameters of the in-situ weathered material, fractured and fresh crystalline rocks (McDowell, 1979; Koefoed, 1979; Ako and Olorunfemi, 1989; Olasehinde, 1989; Olayinka, 1996).

6.3 Fluid logging

Fluid logging is commonly used in hydrogeology to determine the water quality within boreholes in different aquifer types. Information that is obtained from fluid logging includes temperature of the fluid, pH, electrical conductivity (EC), and dissolved oxygen. Over the years, fluid logging in form of fluid electrical conductivity (FEC) logging has evolved into an important tool in the characterisation of preferential flow paths in fractured aquifers (Keys, 1989; Aquilina et al., 1996; Ward et al., 1998).

FEC logging is used to identify conductive fractures in hard rock environments based on the assumption that the presence of water bearing fractures in a borehole or aquifer produces anomalous electrical conductivity logs (Dhakate and Singh, 2008). This assumption has been proven in numerous studies for identifying inflow and outflow points, flow directions as well as transmissive zones in fractured aquifers (Pedler et al., 1990; Tsang et al., 1990; Doughty and Tsang, 2000; 2002; 2004; Lasher, 2012).

Doughty and Tsang, (2004), argue that FEC logs exhibit different signatures such as peaks at different depths where fractures are located. The peaks of FEC logs tend to be skewed towards the direction of the groundwater flow. Successive FEC logs can therefore yield information about the flow rate of groundwater inflows from the hydraulically active fractures (Doughty and Tsang, 2004). Figure 2.1 shows some of the signatures expected in FEC logs indicating inflows and flow directions (Doughty and Tsang, 2004).

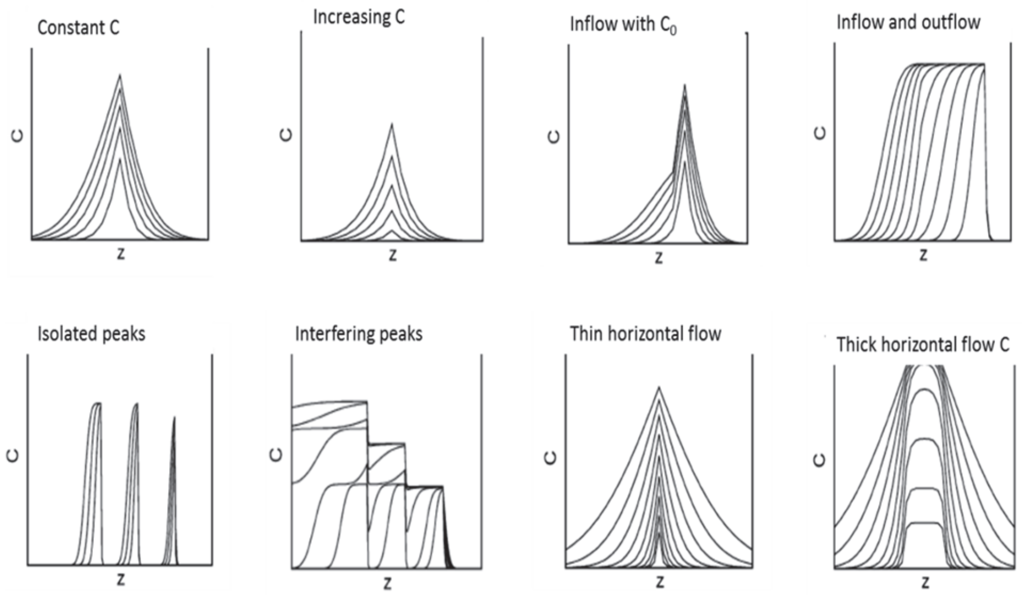

Figure 2.1 Expected FEC logging signatures in boreholes (C = concentration, Z=depth) (adapted from Doughty and Tsang, 2004)

In South Africa, FEC logging has been used in the mapping of fractures (Nel, 2011; Lasher, 2012). The Use of FEC logging has proved to be advantageous as it is relatively simple to use and works well in characterising heterogeneities in the subsurface environment such as those in fractured hard rock terrain (Keys, 1989; Aquilina et al., 1996; Ward et al., 1998; Doughty and Tsang, 2004). FEC logging when used in collaboration with tracer tests provides information regarding the connectivity of the fractures and also characterises the transport processes (flow velocities, dispersion e.tc) within the fractured aquifer (Vandenbohede and Lebbe, 2003).

6.4 Borehole video logging

Borehole video logging is an optical geophysical method that in fractured rock environments can be used to identify fractures and joints. Borehole video logging is widely used in fractured terrain to depict in situ conditions within a borehole because it is not affected by incomplete core recovery which is a common problem in fractured rock aquifers (Williams, 2011).

6.5 Application of stable isotopes in fractured environments

According to Sukhija et al., (2005), the challenge of characterising groundwater flow and flow paths in fractured rock is a result of discontinuities in fractured rocks which make the flow within discontinuities multifaceted in comparison to those in porous media. Similarly, characterisation of recharge processes in fractured rock environments has proved problematic (Sukhija et al., 2005).

To understand recharge processes and flow dynamics in fractured rock environments, the application of environmental isotopes and geochemical tracers has proved to be useful (Cook et al., 1996: Sukhija et al., 2005). Isotopes are suitable geochemical tracers in fractured aquifers because their individual signatures are not affected by interactions with the aquifer material (UNESCO, 1973; Dávila-Olmo, 2011). Any changes in the isotopic signatures will be a result of groundwater mixing in the aquifer (Clark and Fritz, 1997). Among the most commonly used stable isotopes in hydrogeological studies are deuterium and oxygen-18 (Clark and Fritz, 1997). Literature indicates that deuterium and oxygen-18 are used to identify the occurrence of mixing two or more water types (waters from different sources that is, groundwater, precipitation or surface water) and to provide groundwater residence time estimates in aquifers (Cook et al., 1996; Clark and Fritz, 1997; Sukhija et al., 2005). Groundwater residence time refers to the time elapsed since groundwater had its last contact with the atmosphere. This is important because it indicates how rapidly an aquifer is recharged (Cook et al., 1996).

7 RISK ANALYSIS APPROACH

7.1 Fracture rock anisotropy

Only in the case where there are large permeability differences between the rock matrix and fracture network do the fractures and their characteristics (aperture, filling, orientation, frequency and connectivity) influence the flow and transport processes strongly. Single large fractures can have higher flow rates and faster contaminant transport compared to areas with high fracture density. The spread of the plume depends on both the advective transport in the fracture and diffusion into the rock matrix. The spread of the plume depends on the diffusion into the rock matrix as well as the fracture orientation and the lengths of the intersecting fractures (Fahrenholz et al., 2003).

Knowledge of the characteristics of the fracture network is important for understanding the hydrogeologic character of the bedrock at each site. Anisotropy can be a particularly important characteristic. Anisotropy was estimated using pump test analysis (from only a few sites), and fracture and lineament analysis. Although the direction of anisotropy is usually readily estimated from fracture and lineament analysis, the anisotropy factor is not as definitively established without the data from an extensive pump test. Usually, the anisotropy factor was estimated from the ratio of the number of fractures orientated in the direction of anisotropy to the number of fractures at a right angle to the direction of anisotropy. The uncertainty in the anisotropy factor was mitigated by including a range of anisotropy factors in the sensitivity analysis (Lipfert et al., 2004).

7.2 Sources of Uncertainty

Problems arise for larger capture zones or recharge areas/catchments due to the impact of parameter uncertainty. These problems may lead to uncertain wellhead protection zones. Therefore, the list of parameters and conditions used in the conceptual model should be discussed in a qualitative manner with respect to the associated parameter uncertainty (Stauffer et al., 2005):

1. The extent of the flow domain is subject to uncertainty, mainly due to the extrapolation and interpolation of data.
2. The pumping rate of the borehole is probably the least uncertain of all information, provided that it is measured. Often, long term averaged pumping rates can be used. However, the pumping schedule can affect the capturing mechanism of the borehole by the time-dependent velocity field.

3. The groundwater recharge rate can, in general, only be determined indirectly. It depends on the rainfall rate, on the evaporation and transpiration rate, and on the subsequent flow processes in the unsaturated zone. The latter are present as a more or less distinct delay between infiltration and recharge at the groundwater table. Overall, the recharge rate is time dependent and more or less spatially variable. Often these effects can hardly be assessed precisely. Even the temporally and spatially averaged recharge rate may show considerable uncertainty. Both effects hold true also for the confining low permeability layers.

4. The infiltration rate from rivers, streams, lakes and wetlands is usually difficult to assess since in general it cannot be measured directly, but depends on the local infiltration conditions which can be affected by clogging of the never bed. The rate is in general time dependent and spatially variable.

5. The level of the bottom and the top of the aquifer are usually based on local borehole information and can be obtained by interpolation. Consequently, some uncertainty remains. The situation may be improved by a combination with geophysical techniques.

6. The piezometric head of the aquifer or the level of the groundwater table is based on local borehole measurements and represents valuable data used for a calibration of the flow model. The piezometric head essentially dominates the flow directions. Consequently, transient effects in the head field can be of utmost importance. In shallow aquifers it is usually vertically averaged information while in some cases it can be known at different intervals along a vertical.

7. The location of the boundary of the aquifer is based on a regional hydrogeological assessment and is always subject to uncertainty.

8. Fixed head boundary conditions are subject to uncertainty caused by data interpretation and interpolation. The transient behaviour of these conditions can hardly be assessed in detail. Flux boundary conditions are also difficult to estimate. They can often be determined in a satisfactory manner with the help of flow models, provided that reliable data of hydraulic conductivity and piezometric head are available. Nevertheless, some uncertainty inevitably remains. The averaged value and the transient behaviour of both types of boundary conditions can be important for the flow field, and, therefore, for the location of the capture zone or catchment.

9. Hydraulic conductivity of the aquifer always shows a more or less pronounced spatial variability due to the heterogeneous nature of aquifers. Therefore a thorough investigation of the field scale hydraulic conductivity is advisable. The local values can never be known in detail everywhere. Spatial variability can considerably affect the uncertainty of the location of the capture zone or catchment. In addition, the scale at which the measurements have been taken has to be carefully considered in the evaluation of the measurement.

10. The effective porosity of the aquifer directly affects the flow velocity and therefore the residence times, which subsequently determine the location of the capture zone. Moreover, a spatial variability of field scale and local porosity may exist also in unconsolidated aquifers. However, the effect of a spatial variability can be smaller than that of the hydraulic conductivity.

11. Uncertainty may also be present in water quality data. These parameters may also show a considerable spatial variability, and a temporal variability. Moreover, it much depends on the standard of the technology used for the analyses.

Since several of the above listed items concern local information, which is typically measured in boreholes, the quality of the overall Information very much depends on the spatial density of the available data. However, due to economic and logistic reasons, the information is often sparse. The location of data sampling is normally restricted to particular regions within the aquifer. Similarly, the temporal frequency of measurements is often limited.

For small areas a more simplified and intuitive assessment of the uncertainty is often possible, which can be taken into account in the delineation of the protection zone. However, for larger areas the uncertainty can be quite large. Depending on the economic and ecological importance of the protection zone, the implications of the degree of uncertainty associated with its predicted location can be prohibitive.

Uncertainty of the essential parameters, which determine capture zones or catchments of a pumping borehole, lead to the consequence that the location of these zones cannot be determined with certainty. Therefore their location can only be defined in a statistical manner. Consequently, the best would consist of offering a probability map, rendering the probability with which a particular location belongs to the capture zone or catchment of a particular borehole. Therefore, the boundary of the capture zone or catchment is presented with its uncertainty bandwidth. Such concepts can be fed directly into a risk assessment of a particular groundwater resource.

7.3 Reducing uncertainty

Uncertainty is likely to be an issue in all elements of catchment analysis and groundwater pollution potential assessment. The information base on hydrogeological conditions and on the scale and range of human activities in the catchment are only rarely sufficiently comprehensive to allow a fully qualitative determination or prediction of the pollution potential or contaminant concentrations. For example (Adapted from Chorus et al., 2006):

- Data about the populations water needs may be incomplete;
- Information on human activities in the catchment is likely to be incomplete;
- Information regarding the aquifer properties and flow paths is not fully understood;
- The meaning of data gained from groundwater monitoring is dependent on the representativeness of sites for observation boreholes, and cost for their installation constrained by the number of sites that can be sampled.

The modeller should have a thorough understanding of hydrogeology, hydrology and dynamics of groundwater flow in and around the area of interest. It is very important that a conceptual model makes hydrogeological sense, and that all uncertainties be fully documented. In the real, non-idealistic environment, every conceptual model will have a certain amount of uncertainty. There are however, ways to minimise the level of uncertainty within a model. These uncertainties may include model uncertainty, parameter uncertainty, boundary uncertainty and initial uncertainty. There are however ways to reduce uncertainty within a model e.g. conducting a sensitivity analysis or a Monte Carlo simulation (Kresic, 2007; Bear et al., 2010).

7.4 Modeling of Fractured Rock Aquifers

Classical distributed models are often not considered adaptable to represent contaminant transport in heterogeneous and anisotropic hard rock aquifers. A hard rock system has to be fully characterised in order to provide, at watershed scale, the necessary elements for a classical modelling approach (Marechal et al., 2003). The connected network is essentially formed by fractures whose size is in the order of the distance of the boreholes from each other (Koskinen and Rouhiainen, 2003). Heterogeneity and geometry of the aquifer are regionalised using geological and geophysical investigations (Marechal et al., 2003).

The use of an equivalent porous media model at a fractured bedrock groundwater system can be validated by the nonlinear response of the observation boreholes at distances less than the scale of the delineation (Lipfert et al., 2004). Linear flow to a borehole (to a single fracture) will show as a straight line with a slope of 0.5 on a log-log plot of drawdown versus time (Gringarten, 1982 in Kruseman and De Ridder 1994). When linear flow is not detected beyond a certain distance from the pumping boreholes, generally the presence of discrete fractures in the delineations can be disregarded.

The specific features of solute transport in fractured rock environments may result in considerable deviations in the shape and size of groundwater protection zones that one would establish using the Equivalent Porous Media (EPM) assumption. A hybrid approach using a combination of Discreet Fracture Network and Equivalent Continuum Models is recommended by Carneiro (2003) to overcome this problem at catchment scale. The method known as the Statistical Continuum Method (SCM) relies on statistics of movement of particles in a local scale DFN, followed by the use of those statistics to mimic movement in a catchment-scale continuum model. Probabilistic protection zones result from the procedure.

The effect of discontinuity and heterogeneity of the fracture network imposes capture and protection zones strikingly different from those computed using EPM assumption (Fernandez-Garcia et al., 2002; Carneiro, 2003). The SCM provides a useful approach to simulate transport in fractured rocks at the catchment scale, where DFN models may not be practical. The methodology is easy to implement and can be made to work with standard finite difference models. The computational requirements for up-scaling from local to regional scale are not significant and probability contours of protection zones can easily be computed (Carneiro, 2003).

Le Borgne et al. (2003) shows that a continuous approach can be formulated to predict the long term evolution of hydraulic heads in a fractured rock environment. For most regional modelling studies an equivalent porous medium approach can be used, considering that:

(i) A higher value of hydraulic conductivity than those derived from hydraulic tests in boreholes may be required to account for scale dependent fracture distributions (Watkins, 2003)

(ii) Preferential flow paths caused by faults, mineral lodes and dykes must be considered explicitly (Watkins, 2003; Le Borgne et al., 2003)

(iii) For flow perpendicular to the main fracture orientation the average hydraulic conductivity is controlled by the rock matrix portion of the aquifer (Mouri and Halihan, 2003).

Deep discontinuities and fault zones can exist within lower permeability formations, allowing circulation and interaction with the upper zones. These zones can exhibit high local hydraulic conductivities, even at depth (Watkins, 2003).

7.4.1 Code Selection

There is a constant battle between the users of finite element and finite difference codes. For relatively simple conceptual models these codes would be similar, with both codes providing similar grid capabilities, boundary conditions and particle tracking as one of the output options. Finite element has traditionally had an advantage of being able to better define the geological contacts.

The main consideration in selecting a code for complex aquifer settings would be whether:

- The grid could represent the most important features of the conceptual model in sufficient high detail. For example accommodating preferential flow paths like fractures or surface water channelling – if required as distinct features;
- Evaluate uncertainty using Monte Carlo techniques (Or similar).

8 MONITORING AND VERIFICATION OF PROTECTION ZONES

An essential component of any groundwater protection programme is water level and - quality monitoring. This is required to assess the initial conditions and to confirm the effectiveness of the protection measures.

A monitoring strategy for an aquifer protection zone is generally designed to perform three functions - source release detection, ambient trend monitoring, and early warning detection (Carter et al., 1987). Verification monitoring is needed to quantify uncertainties in many of the more complex aquifers, especially fractured aquifers (Bradbury, 1991; Xu and Van Tonder, 2002).

The function that a monitoring device performs depends, in part, on its position along the flow path from the potential source to the borehole (US-EPA, 2004).

- The *source release detection* function determines if contamination has started migrating from the contamination source. Monitoring devices would be situated below or immediately down-gradient of the potential contamination source.
- The *ambient trend monitoring* function assesses the temporal and spatial trends in ground-water quality in the bulk of the aquifer protection area between the source area and the borehole. A dispersed array of monitoring devices situated along flow paths is required for this purpose.
- The *early warning detection* function provides advance notice of the need to implement contingency response plans to prevent public exposure to contaminants. This function is performed by monitoring devices a relative short distance up-gradient of the borehole.

Although no WHPA is perfect, reasonably accurate delineations are possible when hydraulic and aquifer boundaries are better understood, and when natural and anthropogenic fluctuations and stresses are known.

The evaluation of information available may reveal that the understanding of catchment and aquifer properties is not sufficient, or information from different sources is inconsistent. The information inventory therefore needs to be improved for adequately assessing groundwater contamination potential (Chorus et al., 2006).

Some of the identified information gaps may be fairly readily closed by revisiting specific sites in the catchment or more thorough inspection. If uncertainty is too large to make decisions, then the information gaps need to be closed with specifically targeted groundwater surveys and or regular groundwater quality monitoring. In many cases this can be limited to selected localities and/or polluting activities in the catchment.

Decisions on investments into improving the information base will depend on the consequences of uncertainty. Such information comes from additional geologic and hydrologic data from boreholes, water-level measurements, aquifer testing, borehole and surficial geophysics, water-quality testing, lineament studies, isotope geochemistry analyses, and tracer tests.

Recommended tasks to refine the wellfield WHPA are (Heath, 1995):

1) Install hour meters on all production boreholes to obtain more accurate abstraction rates and volumes (Hour reading x Pump yield);
2) Perform individual long-term, constant-rate aquifer tests on each borehole until drawdowns stabilize to determine transmissivity and storage coefficients, and the configuration of zones of influence;
3) Inject specific tracers in observation boreholes and monitor their arrival times in the supply boreholes to measure fracture-flow velocities and connectivity;
4) Revise the water table map of the wellfield and vicinity using accurate non-pumping water altitudes in boreholes and ponds;
5) Perform radio-isotope studies in the aquifers to age-date groundwater and quantify relative residence times; and
6) Simulate transient production borehole capture zones with a three-dimensional numerical model, reverse particle tracking and conservative assumptions.

Refinement of the existing WHPA with new information accomplishes two objectives: 1) a better estimate of the actual recharge area to the wellfield augments more effective land-use management options to protect ground-water quality and human health; and 2) the water management authorities will have information about the potential risk the land use imposes on ground-water resources, especially those in the WHPA itself (Heath 1995).

Groundwater protection zones can play a key component of the water security for a given groundwater supply. This would subject them to operational monitoring for assessing whether or not the required restrictions on land use and controls of human activities are in place, and verification for checking whether they are indeed effectively protecting groundwater at the point of abstraction. Protection zone monitoring would focus on checking whether the required restrictions in land-use and human activities are being adhered to. Groundwater quality monitoring in this context would serve to verify the efficacy of the specific protection zone concept, i.e. both its design and implementation, and can be an important component.

9 CONCLUSIONS

Aquifer protection zoning is feasible in South Africa and well established in developed countries to protect valuable groundwater and surface water resources.

Ecosystem benefits, health benefits to the users and financial savings to the management institutions are some of the benefits of properly implemented protection zoning. These benefits enable the recovery of implementation cost and strengthen the urgency and importance of the implementation of protection zoning.

Still, zoning measures need local understanding, acceptance and control to be able to be meaningful. Appropriate participation of the key stakeholders and the general public is a requisite for sustainable development of a scarce resource. This is valid particularly for groundwater, because it is invisible and often poorly understood but is very vulnerable to pollution and is often the only source of water for a community.

Resource classification can highlight the significance of aquifers used for drinking water and those where groundwater is also important for aquatic and terrestrial ecosystems. Aquifer protection zoning is feasible in South Africa and can form a complementary protection measure to protect important water resources.

Common principles are needed in order to coordinate efforts from CMAs to improve the protection of drinking water in terms of quality and quantity. In the same breath, the promotion of sustainable water use to protect aquatic ecosystems, terrestrial ecosystems and wetlands directly depending on these water resources also need to be enforced.

The implementation of protection zones ensures early action and stable long-term planning of important resources considering the natural time lag in the resource renewal.

The establishment of protection zones generally will be a compromise between what is desirable and what is feasible. Zoning regulations could have adverse economic effects on a community if an inappropriate amount of land were to be placed in an area zoned for stringent protection. When considering public health, however, the delineated area should not result in under protection. The implementation of resource protection strategies like protection zoning is not visible and benefits difficult to measure, but provides benefits to communities, water supply companies, ecosystems and policy makers. These benefits must be communicated to the stakeholders to start the implementation at all management levels.

The management techniques that can be used in source protection zones can be a mix of regulatory and non-regulatory approaches. Regulatory approaches involve placing a system of legal constraints on land use or on particular activities that have a potential to contaminate the groundwater. This could include wellfield design and operating standards or source prohibitions. Non-regulatory tools, which can complement regulations, include public education, voluntary-based management practices, government coordination and training programmes (Xu et al., 1995).

Protection zoning methods should take into cognisance the sub-surface media conditions, as movement in porous media differs greatly from that in fractured rock. Flow in fractured aquifers pose a special problem as the flow cannot be assumed to follow average flow velocities.

Various protection zoning techniques are available with different levels of data availability and different levels of protection. In order to address some of the fundamental weaknesses in fixed distance approaches, more sophisticated protection zones can be defined based flow path mapping in combination with travel time of water through the saturated zone. Travel time approaches are more realistic in that they attempt to incorporate more empirical evidence, usually related to expected die-off of microbes or dilution of chemicals in defining the land area to be protected. Commonly time criteria are established that provide confidence that the concentration of contaminants will have been reduced to an acceptable level.

Reasonably accurate protection zone delineations are possible with a good understanding of hydraulic and aquifer boundaries, natural and anthropogenic fluctuations, and stresses are known. The evaluation of the information available may reveal that the understanding of catchment and aquifer properties is not sufficient, or information from different sources is inconsistent.

Some of the identified information gaps may be fairly readily closed by revisiting specific sites in the catchment or more thorough investigations. Decisions on investments into improving the information base will depend on the consequences of uncertainty. Such information comes from additional geologic and hydrologic data from boreholes, water-level measurements, aquifer testing, borehole and surficial geophysics, water-quality testing, lineament studies, isotope geochemistry analyses, and tracer tests.

Initial protection zones can be updated and refined as new information becomes available. The targeted collection of additional information would provide a better estimate of the actual contributing area to the wellfield, as well as improve the understanding of the potential risk the various land use imposes on ground-water resources.

10 WAY FORWARD

The proposed source water protection methodology in this thesis now needs to be implemented.

All groundwater users can benefit from aquifer protection zoning. The implementation of aquifer protection zones must be prioritized in areas where groundwater is used by a large number of people as primary water supply and where users have a high social vulnerability.

Better assurance of protection and contamination response plans can be provided for drinking water by delineation and implementation of a protection zoning strategy. The benefit of application of protection zones can take into account the need to balance economic development and resource protection in a differentiated approach.

Enforcement of land use limitations to implement aquifer protection zones must be a combined activity between DWS, National and Local departments authorising land use as well as Water Users Associations. Land use authorisation must consider the possible impacts on users and must consult with DWS and local users before authorisation. A committee should be established between DWS and the relevant land use authorities to ensure the implementation of this combined authorisation process.

User buy-in and institutional capacity are important components to ensure the successful implementation of aquifer protection zones. The aquifer protection zoning must therefore be combined with user education and institutional capacity and training.

It is envisaged that the nation's water resources can be managed, protected and controlled in a manner that ensures clean drinking water and meeting Reserve requirements by regulating the land use affecting aquifer water quality based on sound principles and objectives relating to-

- Geological environment constraints and opportunities;
- Community and user needs and requirements;
- Sound business practice;
- A clear understanding of both the manner, purpose and extent of this use; and
- Co-operative governance processes,

Groundwater source protection can be implemented at numerous groundwater access points by using the principles described in this document. Significant drinking water sources in South Africa can be protected to provide socio-economic, political and environmental benefits. Protection zoning will help to focus the limited financial and human resources through the selective protection of water flow paths contributing to the most significant drinking water access points.

Health benefits to the users, financial savings to the management institutions and ecosystem benefits enable the recovery of implementation cost and strengthen the feasibility of implementation of protection zoning in South(ern) Africa.

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12 APPENDIX A: CONCEPTUAL MODEL FOR GEVONDEN RESEARCH SITE

12.1 Introduction

The research site is located approximately 6 km west of the town called Rawsonville, has the N1 highway running along the northern side of the site and forms part of the Breede Overberg Catchment Management Agency. Geographically, the area lays approximately S33.718188º and E19.245913º (WGS84) in the Tygerskloof. The farm is bounded by the Du Toits Mountains which range from 280 m at the base i.e. where the research site is situated, and 1900 m at the peaks further south.

Figure 12.1 is a topographical map of the study area relative to the town of Rawsonville (Lasher, 2012)

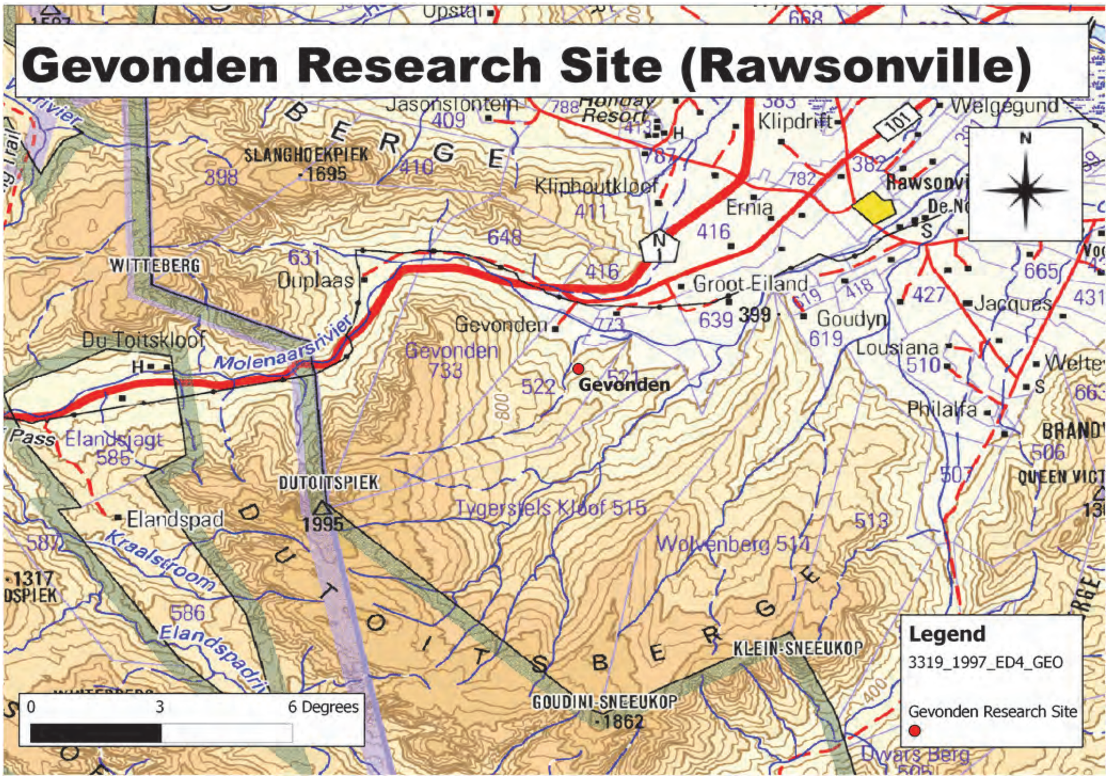

Figure 12.1 Geographic location of Gevonden showing nearest town, river and mountain ranges (Lasher, 2012).

Five boreholes form a network for a fractured rock research site. Core drilling was used for BH1 (270 m at a 60º angle) and BH2 (200 m) which gave insight into the underlying fractured rock geology, and percussion drilling for BH3 (200 m) and BH4 (8 m). BH5 (175 m), which is situated on the neighbouring property was also drilled using the percussion method, this borehole was an existing borehole. Drilling and hydrocensus information suggest two distinct types of aquifers. A sand primary upper aquifer (0-30 m thick) and a fractured sandstone lower aquifer (>200 m thick).

12.2 Topography

On a regional scale the natural directions of groundwater flow can be related to surface topography (Kresic and Mikszewski, 2013). Groundwater is expected to flow from pronounced topographic highs to pronounced topographic lows, with the exception of confined aquifers found in parts of the Gevonden study site.

The specific landforms at the site are closely related to the underlying geology, (geology, folds, faults).

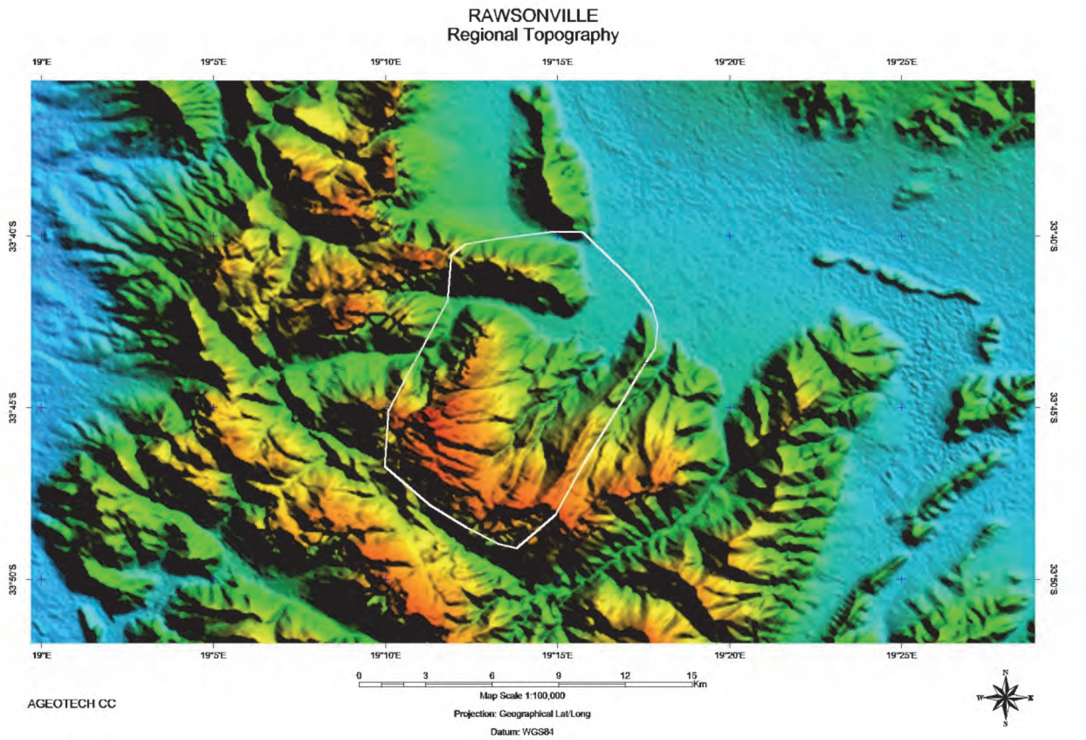

Figure 12.2 Regional topography interpreted from remote sensing data.

12.3 Climate

The climate in the Rawsonville area is typically Mediterranean with some possible oceanic influences. It is characterized by the occurrence of warm, dry summers and mild and wet winters (occurrence of winter rainfall). Sometimes winters are frosty with heavy snowfalls at high altitudes. The average annual rainfall in Rawsonville varies from 200 mm/year in the low lying areas and 1595 mm/year in the mountainous areas (Lasher, 2012). The highest rainfall is recorded during the months of July and August with the least rainfall occurring during the months of January and February (Figure 12.2).

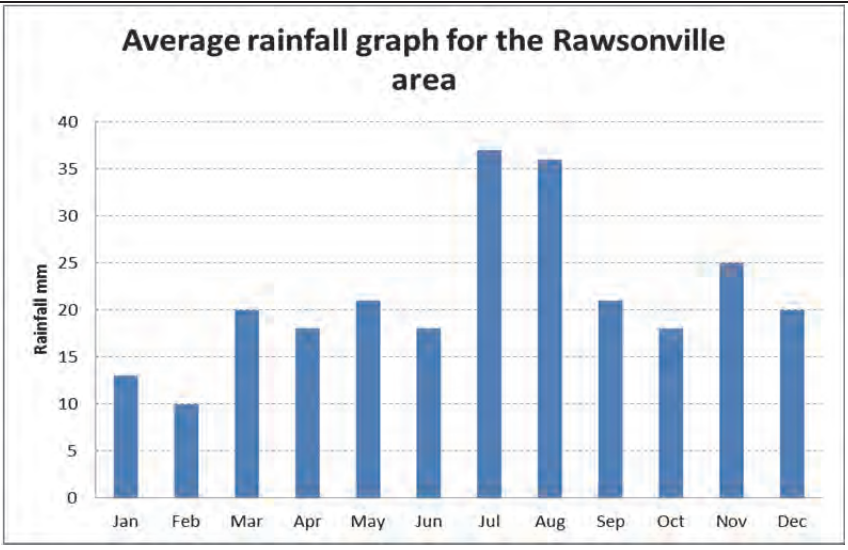

Figure 12.3 Average monthly rainfall for the Rawsonville area

The highest temperatures are experienced during the summer months of January to February and the coolest period is from June to August (Figure 12.3). Daily maximum temperatures vary from 20°C in winter to 35°C in the summer (Figure 12.3). Daily minimum temperatures are 6°C to 7°C in winter and 15°C to 18°C in summer (Figure 12.3). The climate favours the growth of natural vegetation such as the *Proteaceae* (proteas) and *Elytropappus rhynocerotis* (renosterbos) which are abundant in the area. These plants are susceptible to wild fires which are common in the area during the hot dry summer periods. The climate experienced in the study area is likely to have an impact on the isotopic compositions of the groundwater and surface water which will be used to characterise recharge sources in the area. However, the extent of the impact of the climate on groundwater recharge mechanisms in the area is not known and will be explored in this study.

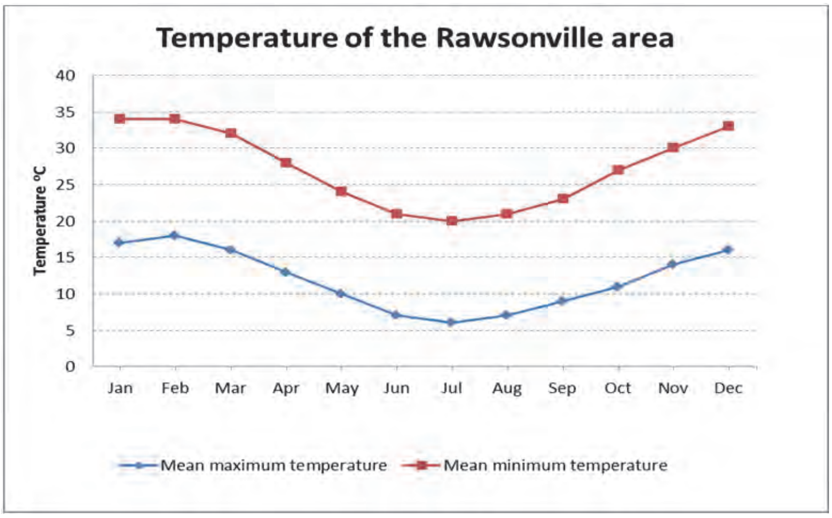

Figure 12.4 Average monthly temperature in the Rawsonville area

12.4 Geology

The geology of Rawsonville comprises rocks from the Cape super group with the main group being the Table Mountain group (TMG). The TMG is divided into the Nardouw subgroup with further geological subdivisions being the Peninsula, Cedarberg, Pakhuis, and Goudini formations as described below. These stratigraphic units are fully represented at the research site (Figure 12.4).

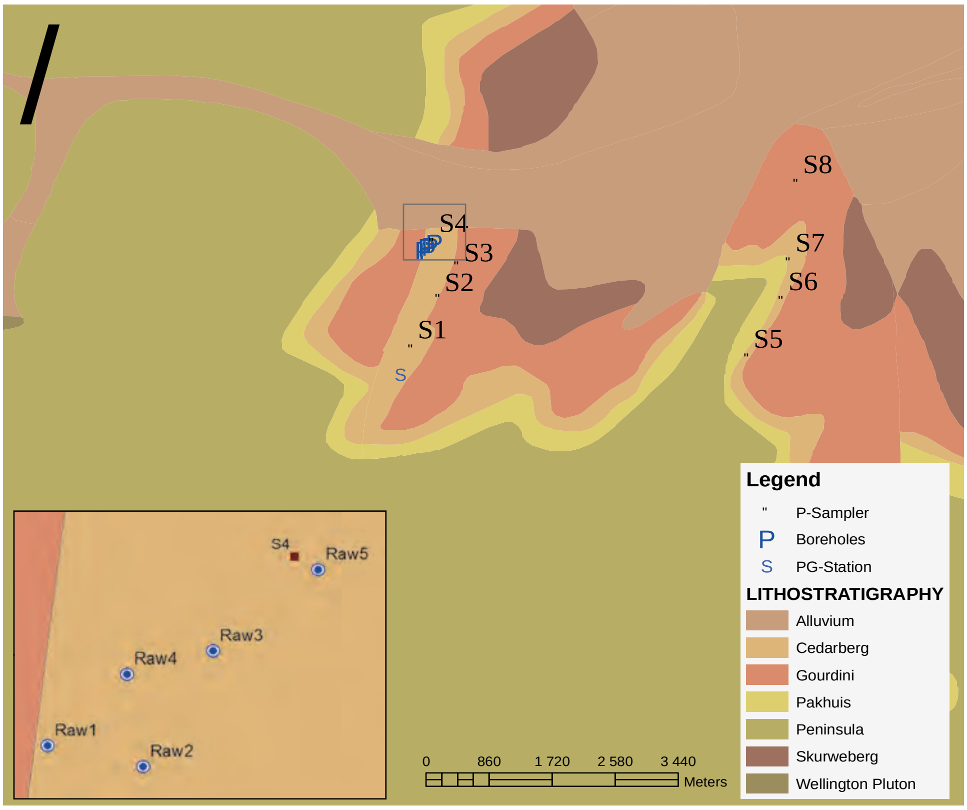

Figure 12.5 Lithostratigraphy map of Rawsonville indicating geological units intercepted at the study site

12.4.1 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.

12.4.2 Goudini Formation

The Goudini Formation in the Rawsonville area is characterised by the occurrence of reddish brown weathering thin beds of fine to medium grained quartzitic sandstones. 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).

12.4.3 Pakhuis Formation

The Pakhuis Formation consists of quartz rich diamicite and is representative of glacial deposition that occurred following the deposition of the Peninsula formation (Blignault, 1981; Rust, 1981). The Pakhuis formation is easily identified in the Rawsonville area (Gevonden) by the sharp, narrow cuspate anticlinal folds that alternate with broad bottomed synclines with near vertical or even over folded flanks (Gresse and Theron, 1992).

12.4.4 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).

The manner in which the formations described above are layered is illustrated in a geological transect of the study area (Figure 12.5). With reference to Figure 12.5, the Kliprivier Formation and the intruded Cape Granite Suite is found in the west and southwest of Gevonden. The high areas predominantly consist of Peninsula Formation, overlain by the Pakhuis, Cedarberg and Nardouw formations. The aforementioned formations are overlain by quaternary sands. The Waterkloof Fault as mapped on the geological transect of the research site, intersecting Gevonden is approximately 80 m wide (Lin, 2008).

From the geological description of the study area, it can be generalised that the area is dominated by sandstone, quartzite, shale and siltstones. In relation to this study, the described geology bears a significant impact on groundwater flow through fractures. The shale layers in the area have the potential to act as groundwater flow impeding layers while the sandstones and quartzites are likely to be the most fractured and storage matrix for groundwater flow in the area (Telford et al., 1990).

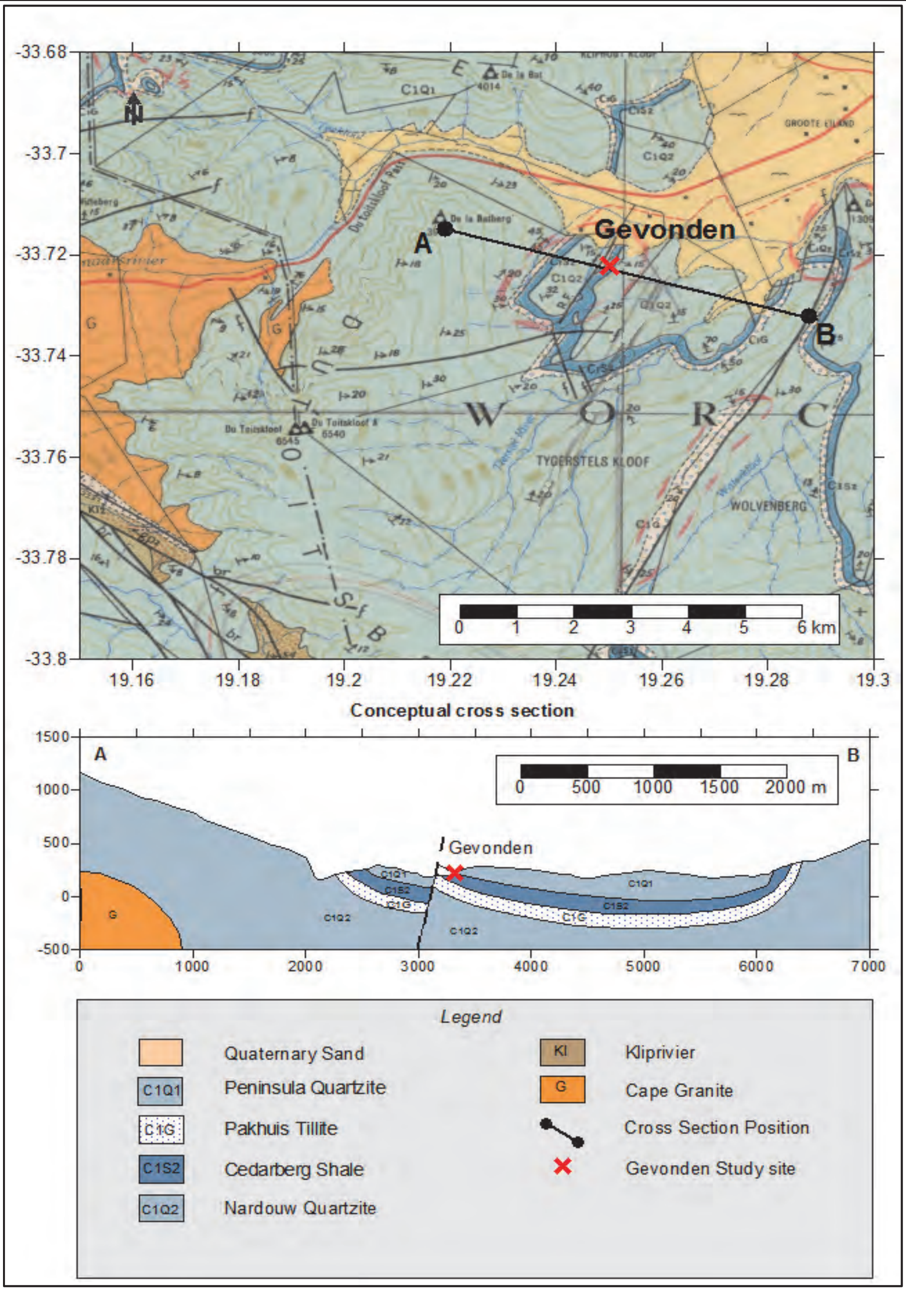

Figure 12.6 Geological map and transect of the Rawsonville study area represented as Gevonden showing different geological formations and structural features (Lasher, 2012)

12.5 Recharge Areas

The primary aquifer is recharged by direct precipitation and runoff from the mountains.

The fractured rock aquifer receives its recharge from direct precipitation and snowmelt along the rock outcrop areas. Preferential recharge is expected along surface exposed faults and geological contacts. Recharge induced by minor topographic variations is also important at a local scale. The topography of recharge areas of the TMG aquifer is controlled by lithology and structure (Wu, 2005).

A regional fault is normally a structural boundary as well as a hydrogeological boundary. Most of the regional faults are impermeable boundaries, but fault branches are tensile faults, which are excellent infiltration paths (Wu, 2005).

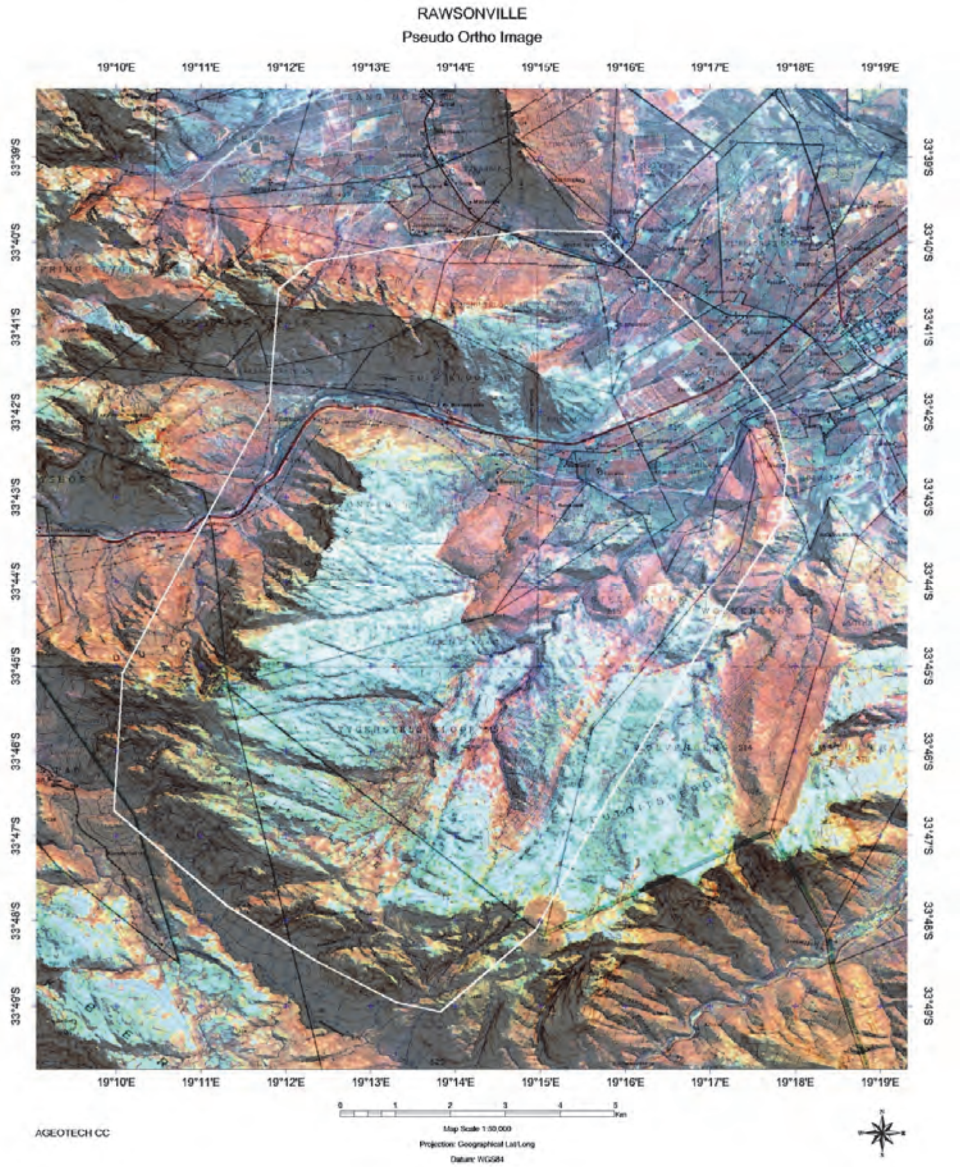

Figure 12.7 A pseudo ortho image of the study site.

12.6 Flow paths

12.6.1 Surface water

Surface water flow paths at the research site is characterised by rivers which have sections that flow all year round and sections which seasonal flow (Gevonden River and Molenaars River). The Gevonden River originates from springs in the high altitude mountains at the Gevonden farm, flows along the fault line and passes alongside the borehole network of the research site. During the dry summer season the Gevonden River seeps into the primary aquifer just after it passes the research site. During the wet winter season the river flows up to the Molenaars River, draining water from both surface water runoff and groundwater.

Like the Gevonden River, sections of the Molenaars also dry up during the dry seasons. There is however evidence of base flow within the Molenaars River based on DWS river flow measurements upstream of the research site. This section has water present all year round without any surface water feeding it. Surface water in the area flows in a NE direction.

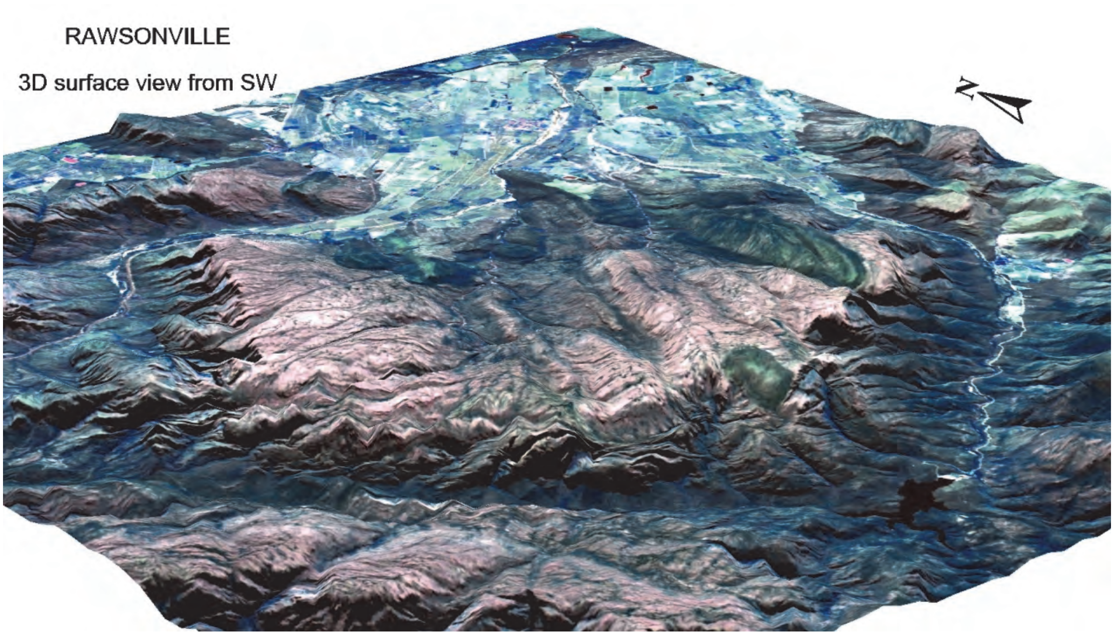

Figure 12.8 A 3D surface view from the study site from a south-west direction.

12.6.2 Groundwater

Groundwater flow in the upper unconsolidated primary aquifer is likely to follow the topographic gradient of the area with the possibility of groundwater feeding parts of the Molenaars River. Flow in the underlying fractured rock aquifer follows a heterogeneic path controlled by fractures, faults and confining layers.

Ambient conditions fluid logging done in both the wet and dry seasons showed variations in flow rate and flow direction within the fractured rock aquifer. Flow within the boreholes responds relatively quickly to rainfall events with fracture flow showing a clear increase in flow velocity. Flow also slows down as soon as two days after a rainfall event has stopped.

Pumping changes the local fracture flow directions to the pumping borehole with work done by Nel (2011) showing the response of the fracture flow direction under different pumping rates. Some flow directions within the borehole changed when the pumping rate was increased where as others stayed the same.

Artesian conditions in BH1 suggest that the fractured aquifer can contribute groundwater to the primary aquifer and rivers.

Table 12.1 Gevonden BH3 fracture positions, flow rates and quality using BORE II software to simulate Ambient FEC and Flowing FEC data.

DEPTH(m)	Ambient FEC Q(L/min)		Flowing FEC 0.3l/s Q(L/min)		Flowing FEC 0.5l/s Q(L/min)	EC(mS/cm)
36	0.05	⇨	0.05	⇧	3.00	0.10
44	0.20	⇨	0.20	⇨	0.20	0.10
49	-9.00	⇧	4.30	⇧	9.00	0.10
70	2.1	⇨	2.1	⇨	2.1	0.05
74	4.50	⇧	6.00	⇨	6.00	0.05
90	1	⇨	1	⇨	1	0.05
95	1.50	⇧	2.00	⇨	2.00	0.05
110	0.80	⇧	1.00	⇨	1.00	0.05
122	0.30	⇧	0.50	⇧	0.80	0.05
133		⇧	0.2	⇨	0.2	0.05
137		⇧	0.50	⇧	0.80	0.05
139		⇧	0.4	⇨	0.4	0.05
142	-1.40	⇧	0.40	⇧	0.50	0.05
144	0.05	⇧	0.60	⇧	1.00	0.05
146		⇧	0.06	⇧	0.10	0.05
150		⇧	0.06	⇧	0.40	0.20
165	-0.45	⇧	-0.20	⇧	0.07	0.20
181	0.10	⇨	0.10	⇨	0.10	0.20
181	-0.30	⇨	-0.30	⇧	-0.20	0.20
186	0.05	⇧	0.10	⇧	0.15	0.20
194	0.50	⇨	0.50	⇨	0.50	0.50

Legend
Outflow points = Negative value
⇨ No Change in fracture flow due to increase in pumping rate
⇧ Increase in fracture flow due to increase in pumping rate

12.7 Surface Water/Groundwater Interaction

Several springs and seeps originate from the high altitude fractured rock mountain aquifers, contributing surface runoff to small streams from the mountain. Several of these springs are perennial and contribute to surface flow throughout the dry summer season.

Very high flow rates in fractures were measured during winter recharge periods. These flow rates seem to reduce in summer (ongoing research). This results in a reduction in groundwater contribution to the surface water in summer.

The streams flowing from the mountains recharge the primary aquifers of the valley aquifers. In summer the flow from these streams disappear into the subsurface after flowing short distances over the primary aquifer.

There is also some isotopic and chemical evidence that the underlying fractured rock aquifers contribute water to the primary aquifer, which then discharges to the rivers. The Molenaars River is the lowest topographical elevation at the site and therefore acts as a discharge point to the aquifers, draining water from the valley aquifers.

12.8 Land Use

Land use in the area is dominated by agriculture although some farm housing is present. The main income of the area comes from wine farming. The research site is adjacent to the N1 national road and the R101 which is used by a weigh bridge. 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.

12.9 Aquifer Vulnerability

ASTER data lineament interpretation suggests that the secondary aquifer is highly fractured with several faults cross-cutting the study area. These fractures and faults could act as preferential pathways for any contaminant infiltration. The unsaturated zone will provide little protection for the secondary aquifer should development take place in these areas. Fortunately access to the mountain areas at the study site is limited.

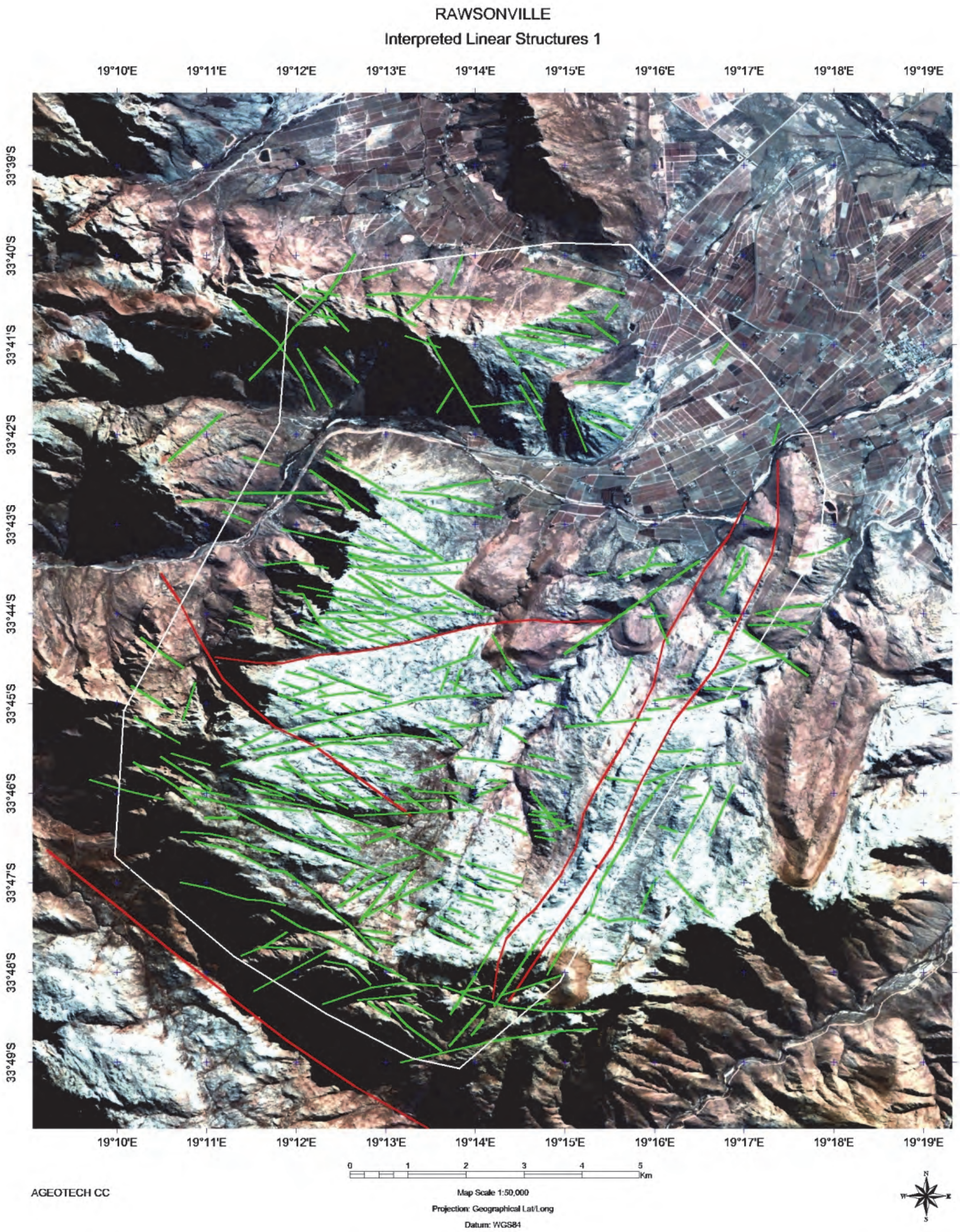

Figure 12.9 Interpreted linear structures of the study site.

12.9.1 Primary upper aquifer

The upper unconfined aquifer consists of quaternary sands and has an average water level of 2 mbc. This aquifer is highly vulnerable to contamination at the ground surface due to the infiltrative properties of the quaternary sands and the very shallow water table. The area is dominated by agricultural activity such as wine farming, distilleries and the keeping of livestock. These activities have a high contamination potential.

12.9.2 Secondary lower aquifer

This aquifer is characterised by fractured rock of the Peninsula Formation. The upper limit is 8 m below the surface on average. Late time pump test data of the site suggest that a) the cone of depression has reached a recharge boundary or b) the upper aquifer is starting to feed the lower aquifer.

12.10 Social Vulnerability

12.10.1 Groundwater used for primary school at Lorraine

Groundwater is used to supply a primary school north of the research site. This water is pumped from the upper aquifer. Contamination of this water will have major negative effects on the children attending the school. Because these children come from poor households, proper medical care might be too expensive.

12.10.2 Rural settlement at the Molenaars river in Rawsonville

Contamination leached from the agricultural activities or from the roads in the area have a high potential of reaching the river system in Rawsonville. The informal settlement further downstream of the Molenaars River uses the river water (domestic, recreational, etc.). This informal settlement is home to many labourers that are hired to work on the farms in the area. If they should fall ill due to upstream contamination, they would lose precious income. Loss of income can be devastating to a community such as Rawsonville and the overall incident costs can easily escalate e.g. Delmas 2005.

12.10.3 Surface water used for artificial recharge

Surface water is also used as a means of artificial recharge. Contaminated surface water which is injected into an aquifer will contaminate the aquifer’s water. This water is used for crops as well as domestic use. Using contaminated water domestically and to irrigate crops will have major negative effects on the income derived from crops and on the health of the people using or ingesting the water as household water filters will not kill all bacteria and/or salts that may exist in the contaminated water. Evidence of base flow is also present during the drier seasons in both the Gevonden River and Molenaars River. These rivers are linked and flow through the town of Rawsonville. Any contamination in the aquifer therefore has the potential to enter the river system.

12.10.4 Shared resources

It is not unusual for a water source to be shared between farmers. Pipelines are laid which capture spring or river water. These pipelines then split up and feed farms with water. Should one of these water sources be compromised, more than one will be affected. This will have a negative snowball effect on crops, sales, work and income.

12.11 Groundwater Access Points

Groundwater is primarily accessed by means of boreholes. Most farmers have boreholes drilled into the upper primary aquifer from which they pump water for irrigation however, water from the deeper aquifer is also used in some cases.

Some farmers utilize water from springs. Water from springs is transported up to 3km via pipelines. This water is then either used to artificially recharge the upper aquifer or fill dams.

12.12 Water Use

Groundwater in the area is mainly used for irrigation on farmland. Borehole water is used mostly during the dry seasons however it is not unusual for farmers to irrigate with borehole water during other parts of the year. Some boreholes are assigned for domestic use as well. Groundwater in the area is also used to supply some residents with water. Boreholes are used to fill farm dams which act as reserves for the dry seasons. However, there are instances where the aquifers tapped by the boreholes are artificially recharged with surface water during the wet seasons and then pumped during the drier parts of the year.

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13 APPENDIX B: SIMULATED PROTECTION ZONES FOR GEVONDEN RESEARCH SITE

13.1 Introduction

This report provides a description of the Rawsonville UWC Research Site Model. The model was designed to simulate the travel time of water to an abstraction borehole in order to delineate groundwater protection zones for that borehole.

The conceptual model, numerical model construction and model calibration is presented below. Predicted capture zone scenarios were undertaken with the calibrated model, considering uncertainty in parameter values.

13.2 Hydrogeological conceptual model

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.

Local shallow groundwater system

The local shallow groundwater system incorporates unconsolidated sedimentary units originating from a Quaternary drainage and depositional environment, namely:

- Alluvial deposits;
- Organic deposits; and
- Boulders.

Groundwater flow within the shallow groundwater system consists of intergranular flow through unconsolidated sediments. Flow follows the river channel in a NE direction.

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 formation acts as an aquitard due to the shale have such low hydraulic conductivity.

The hydrogeological system is composed of a number of geological units:

- Nardouw Quartzite formation
- Pakhuis Tillite formation
- Cedarburg Shale formation
- Peninsula Quartzite formation
- Waterkloof fault

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 acts as a flow boundary which can account for the flowing artesian conditions experienced at BH1. A brecciated zone also exists on either side of the fault. Most groundwater flow is likely to be restricted to any open fractures with the fault assumed to be a boundary for cross-flow.

Aquifer tests have shown that three boreholes (BH2, BH3, and BH5) are connected through the Peninsula fracture network. BH3 was pumped at a rate of 1.6l/s for 24hrs. The pre-pumping static water level was at 3.39 mbc and the pumping caused a total drawdown of 10.57 m. Flow to the borehole was principally via fractures, identified during fluid electrical conductivity logging and borehole video logging. The locations of these active fractures vary depending on the borehole. 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 as previously discussed in Deliverable 2.

Available literature suggests that the bulk rock hydraulic conductivities of the Peninsula formation ranges from 0.21 to 3.6 (Lin, 2007) and 3 to 15 for sandstone (Kresic, 2007). Hydraulic conductivities calculated from aquifer test data was then calibrated during transient simulations.

The average annual precipitation in the Rawsonville area is estimated to be 1595 mm (WR2005). It is assumed that recharge to the bedrock occurs through precipitation and snow melt coming from the mountain ridges.

Recharge of the primary aquifers occurs through direct and indirect recharge mechanisms. Direct rainfall and runoff from the steep mountain slopes and side channels contribute to recharge of the primary unconsolidated aquifer during the winter season.

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.

13.3 Model construction

13.3.1 Governing Equations

The numerical model for the project was constructed using Groundwater Vistas (GV6), a pre- and post- processing package for the modelling code MODFLOW. MODFLOW is a modular three dimensional groundwater flow model developed by the United States Geological Survey (Harbaugh *et al.*, 2000). MODFLOW uses 3D finite difference discretisation and flow codes to solve the governing equations of groundwater flow. MODFLOW NWT (Niswonger *et al.*, 2011) was used in the simulation of the WE&M groundwater flow model. Both are widely used simulation codes and are well documented. The numerical model was based on the conceptual model developed from the findings of the desktop and the baseline investigations.

The simulation model used in this modelling study simulates groundwater flow based on a three-dimensional cell-centred grid and may be described by the following partial differential equation:

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) \pm W = 0 \quad (1)$$

where:

K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the *x*, *y*, and *z* coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T);

h is the potentiometric head (L);

W is a volumetric flux per unit volume representing sources and/or sinks of water, with
W < 0.0 for flow out of the ground-water system, and *W*>0.0 for flow in (T^{-1});

S_s is the specific storage of the porous material (L^{-1}); and

t is time (T).

Equation 1, when combined with boundary and initial conditions, describes transient three-dimensional ground-water flow in a heterogeneous and anisotropic medium, provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions (Harbaugh *et al.*, 2000).

13.3.2 Boundary conditions

Boundary conditions express the way in which the considered domain interacts with its environment. In other words, they express the conditions of known water flux, or known variables, such as the hydraulic head. Different boundary conditions result in different solutions, hence the importance of stating the correct boundary conditions. Boundary condition options in MODFLOW can be specified either as:

- specified head or Dirichlet; or
- specified flux or Neumann; or
- mixed or Cauchy boundary conditions.

From the conceptual point of view, it was essential to meet two criteria to the maximum extent possible:

1. The modelled area should be defined by natural geological and hydrogeological boundary conditions, i.e. the model domain should preferably encompass entire hydrogeological structure; and
2. The mesh size of model grid has to correspond to the nature of the problem being addressed with the model.

Local hydraulic boundaries were identified for model boundaries. They were represented by local watershed boundaries and delineated 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 by rivers and drains. The Gevonden and Klipvoet Rivers are represented by the MODFLOW Drain package and the Molenaars River as River cells.

13.3.3 Model Domain, Mesh and Layers

The model domain is defined by topography and surface water catchment boundaries. It covers the area between coordinates 330000, 625700 and 342500, 6272500.

Compilation of the finite difference grid using the Groundwater Vistas graphic user interface facilitated the construction of a rectangular horizontal grid, as well as vertical geometry provided for each of the layers. The rectangular grid consisted of 7 layers with a total of 283 185 cells (155 x 261 x 7 layers). The positions of the different geological boundaries are incorporated in the modelling grid. A grid of 100 m x 100 m refined to a 6.25 m cell size around the borehole network was allocated to the model Figure 13.1.

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. Cell size refinement across the model domain did not exceed 0.5 times the neighbouring cells.

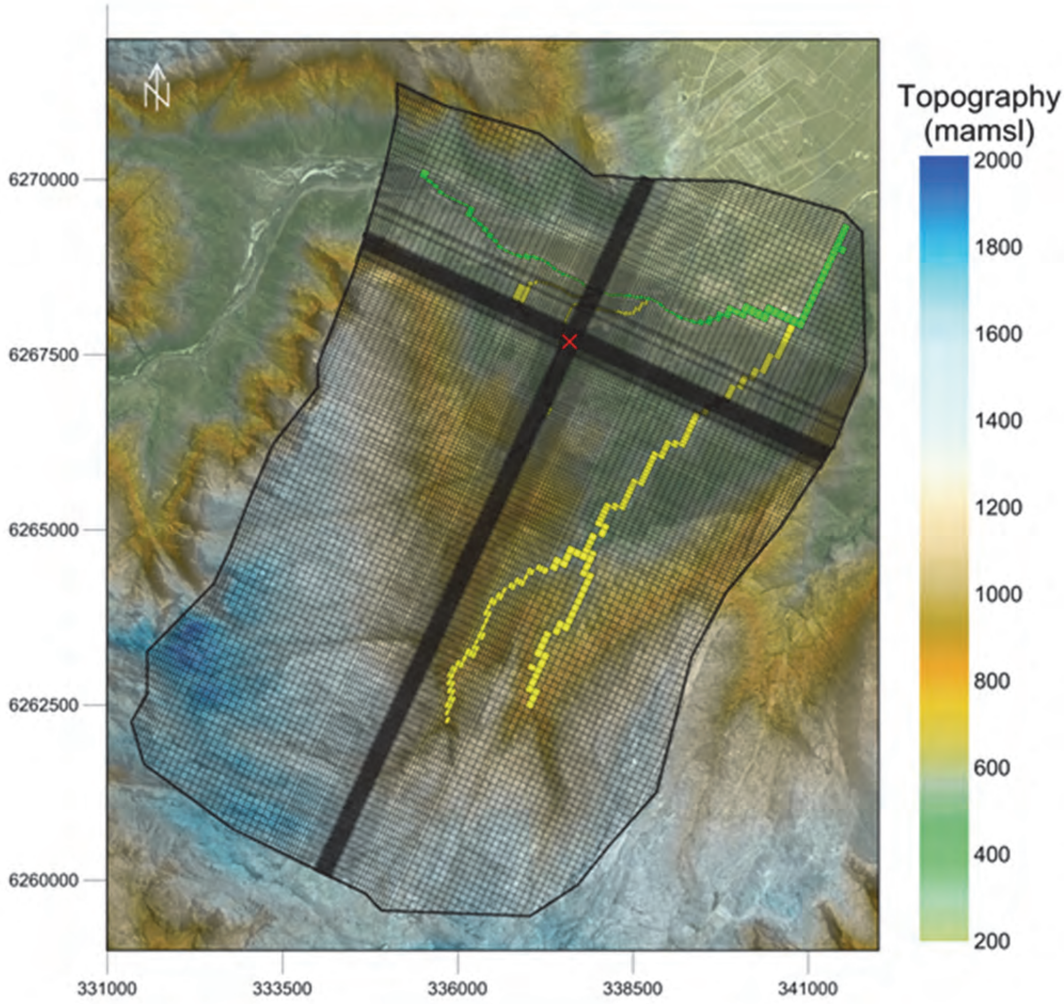

Figure 13.1 The model grid overlain onto the model domain. Model drains are represented in yellow with rivers represented in green. The site is marked with a red cross.

A 7-layer, MODFLOW finite difference grid is applied to the model area as shown in Figure 13.2. The grid is more refined around the borehole network to achieve a more accurate numerical solution.

Along the vertical direction, the steady state hydrogeological model is structured in 7 model layers (Figure 13.2). The layer positions were selected to best incorporate the conceptual model.

The model layers are broadly defined by hydrogeological units, based on the site conceptual model (see Figure 13.2).

Table 13.1 indicates the layer elevations and thicknesses represented in the model. Geologic formations within the layers are listed below:

- Layer 1: Shallow valley groundwater system, i.e. alluvium and sedimentary and boulder cover, and exposed bedrock lithologies on the mountain slopes; and

- Layer 2 – Layer 7: Peninsula quartzite formation and Waterkloof fault.

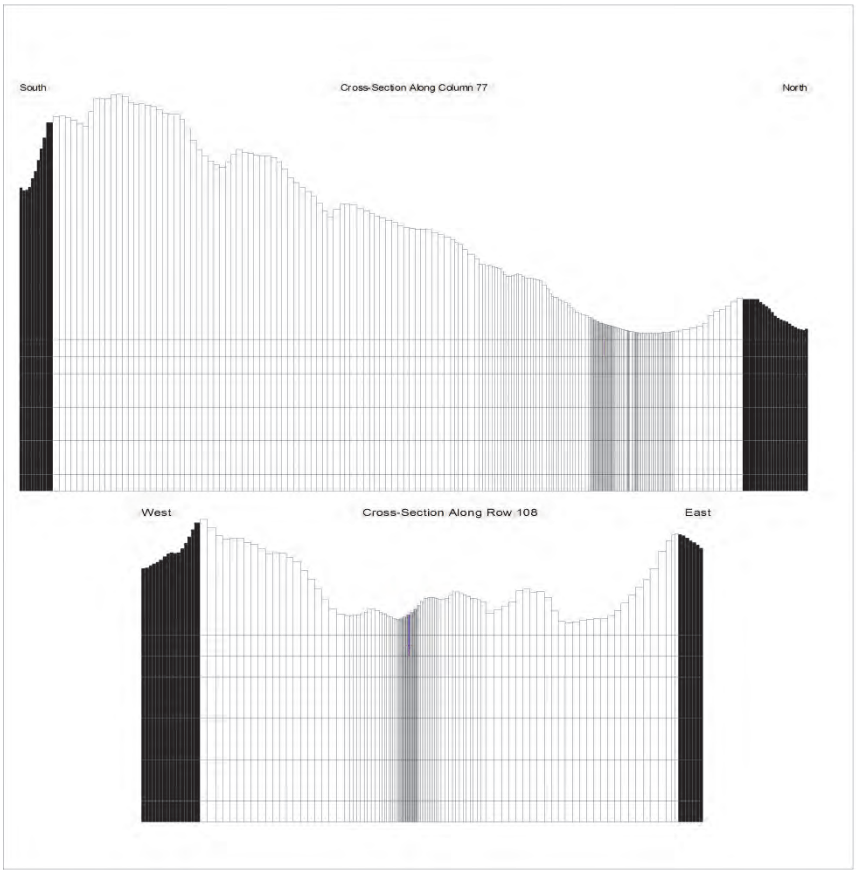

Figure 13.2 The vertical cross-sections of the model.

Table 13.1 Model layer elevations and thicknesses

Model Layer	Hydro-lithological unit	Layer top elevation	Layer bottom elevation	Thickness (m)
1	Unconsolidated alluvium	Topographic map	Base of alluvium	Topography minus base elevation
	Peninsula formation			
	Gevonden River		Topographic surface minus 40 m	
	Klipvoet River			1
	Molenaars River			
2-8	Peninsula formation	Bottom of upper layer	Layers 2-6: Base of upper layer minus 100 m	100
	Waterkloof fault			
	Waterkloof fault buffer zone		Layers 7-8: Base of upper elevation minus 200 m	200
	Klipvoet fault			

13.3.4 Time Discretization

Time parameters are relevant when modelling transient (time-dependent) conditions. They include time unit, the length and number of time periods and the number of time steps within each time period. All model parameters associated with boundary conditions and various stresses remain constant during one time period. Having more time periods allows these parameters to change in time more often (Kresic, 2007).

The steady state groundwater flow model was used for sensitivity analysis.

For the purpose of simulation of capture zones of the borehole the steady state water levels were used.

13.3.5 Recharge

Effective precipitation is represented in the model as distributed recharge into the saturated groundwater system (Figure 13.3). The percentage of precipitation reaching the alluvium and sedimentary cover and bedrock as recharge was adjusted during model calibration and a percentage infiltration of 6% for alluvium, 4% for the bedrock, and negligible for the shale layer was found to be optimum.

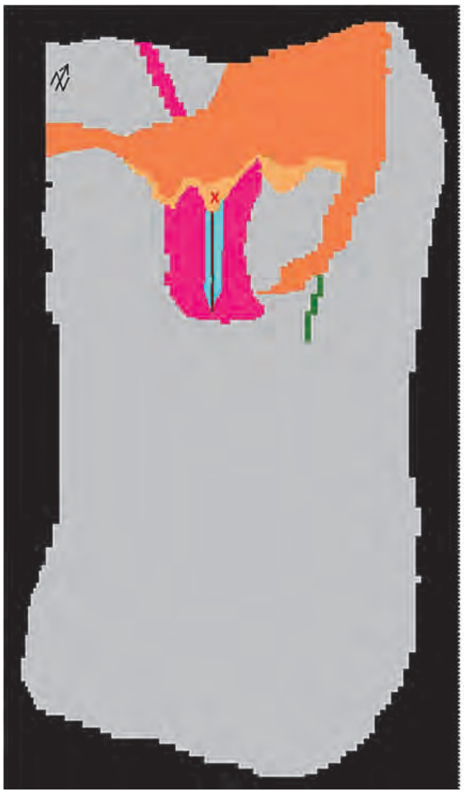
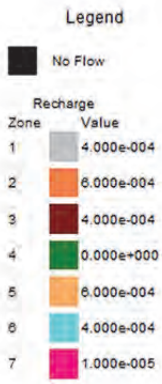

Figure 13.3 Recharge properties for the model domain with the research site represented with a cross.

13.3.6 Hydraulic properties

Average hydraulic properties were used as initial values in the model. These properties were modified during calibration within realistic ranges.

Figure 12.4 present the spatial distribution of hydraulic properties for the different hydrogeological units. Table 12.2 shows the calibrated values obtaind.

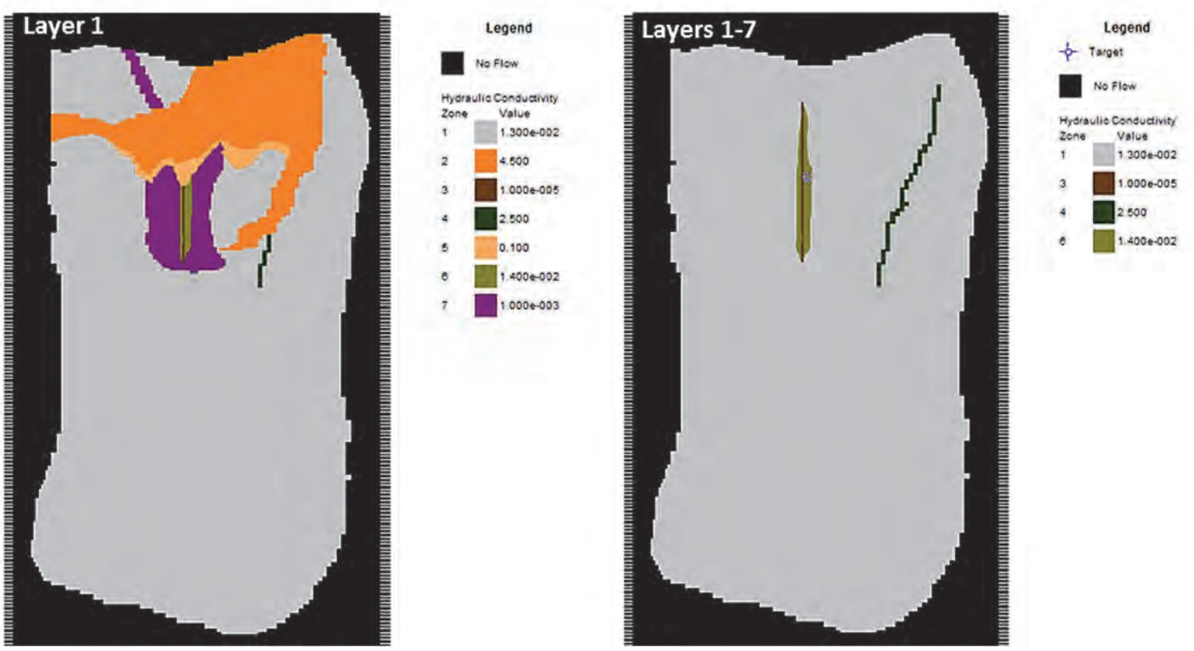

Figure 13.4 ` Hydraulic properties assigned to the model layer

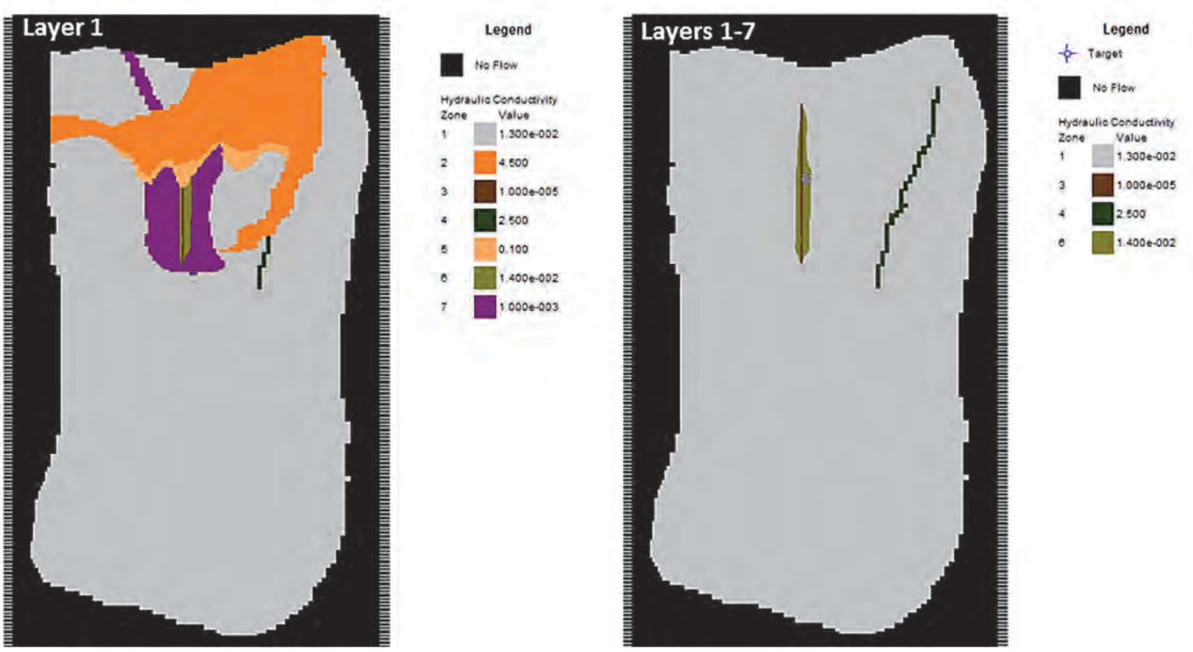

Figure 13.4 ` Hydraulic properties assigned to the model layer.

Table 13.2 Calibrated model property values

Hydrolithological unit	Kx	Ky	Kz	Ss	Sy	Porosity
Peninsula formation	0.013	0.01	0.013	1e-007	5e-005	0.002
Unconsolidated alluvium	4.5	4.5	2	0.007	0.02	0.2
Waterkloof fault	1e-007	1e-007	1e-007	1e-006	0.001	0.0002
Klipvoet Fault	2.5	5	10	0.0002	0.001	0.0002
Alluvium buffer zone	0.1	0.1	0.053	0.2	0.15	0.2
Waterkloof fault buffer zone	0.014	0.014	0.01	0.005	5e-005	0.006
Cederburg formation	0.001	0.001	0.0001	1e-008	5e-006	0.03

13.4 Model calibration

The aim of the Steady State calibration is to simulate the undisturbed state of the groundwater system (baseline conditions). Undertaking a steady state simulation has the dual benefit of testing the conceptual model without the complication of time variant behaviour, and of providing numerically stable starting conditions for time variant simulations. Water level data collected from the hydrocensus was imported as groundwater elevation targets and used to calibrate the model. The transient model was calibrated using aquifer test data.

13.4.1 Steady State Model calibration results

For steady state conditions the groundwater flow equation (1) reduces to the following equation:

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z})\pm W=0 \qquad (2)$$

The numerical model calculated head distribution ($h_{x,y,z}$) is dependent upon the recharge from rainfall, hydraulic conductivity and boundary conditions. For a given set of boundary conditions the head distribution across the aquifer can be obtained for a given set of hydraulic conductivity values (or transmissivity value) and specified recharge values. This simulated head distribution can then be compared to the measured head distribution and the hydraulic conductivity or recharge values can be altered until an acceptable correspondence between measured and simulated heads is obtained.

Steady state calibrated water levels shows the steady state groundwater elevation contours. Water level contours within the alluvium and sedimentary cover (Layer 1) are largely influenced by recharge zones.

Water levels measured in bedrock boreholes indicate an apparent hydraulic disconnection between water in the primary aquifers and that in the bedrock. The bedrock borehole water levels seem to be controlled by hydraulic conductivity of the Peninsula aquifer unit.

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 calculated as the observed water level minus the modelled:

Residual = Observed – Modelled

The graph in Figure 13.5 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.

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

The success rate of the calibration process is usually assessed by the following statistical quantities:

Mean Error $$ME = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i \quad ;$$

Mean Absolute Error $$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|h_m - h_s\right|_i \quad ;$$

Root Mean Square $$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(h_m - h_s\right)_i^2} \quad ;$$

Normalized RMS $$RN = \frac{RMS}{H_{\max} - H_{\min}} \quad ;$$

where h_m represents measured head, h_s represents simulated head, n is the number of calibration targets, H_{max} represents maximum measured head and H_{min} represents minimum measured head.

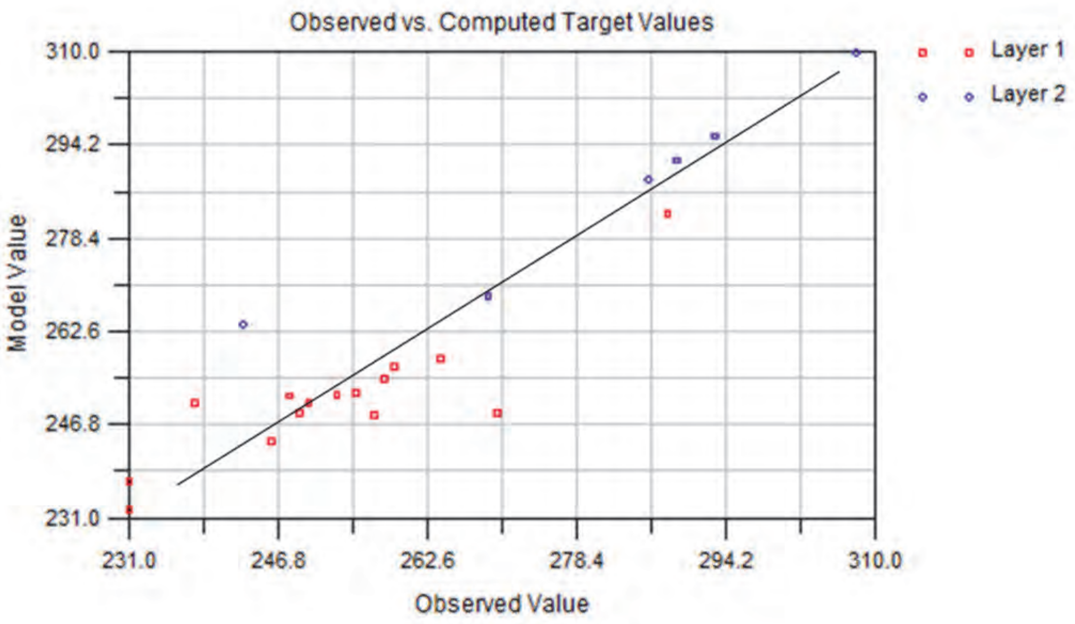

Figure 13.5 Graph showing the observed vs simulated water levels with the line indicating the positions for an ideal fit.

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

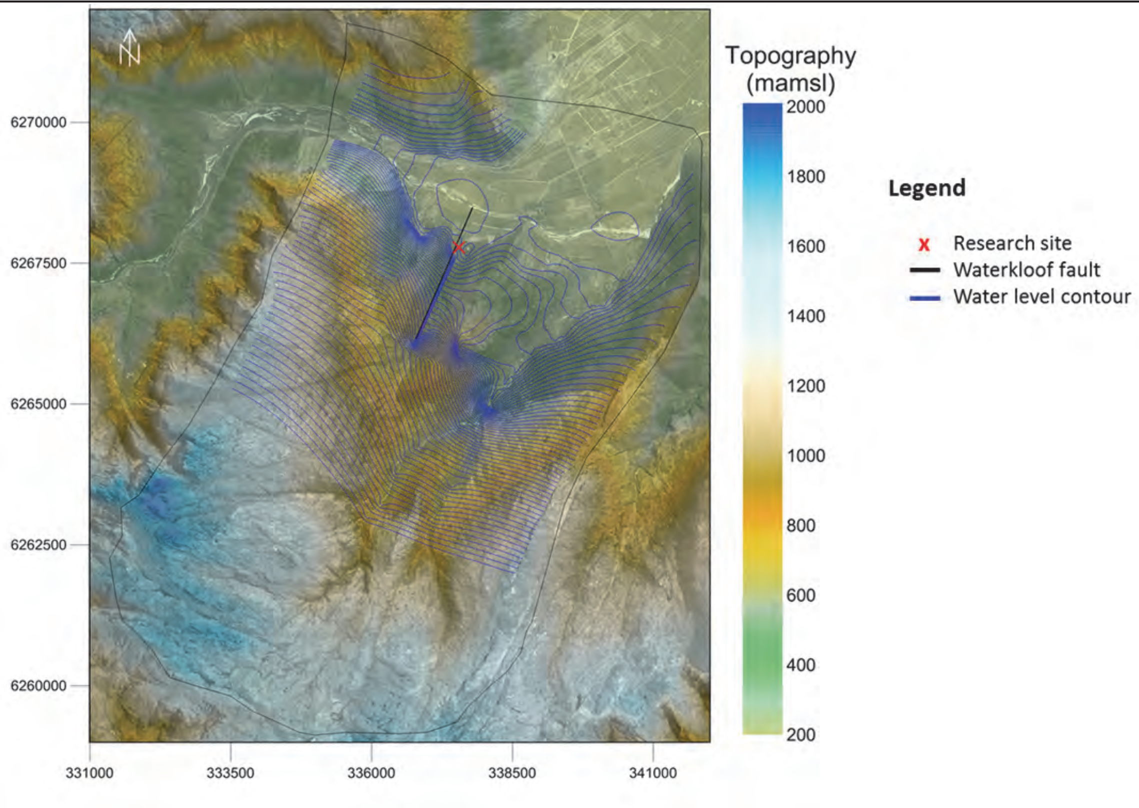

Figure 13.6 Water level contours after steady calibration

13.4.2 Transient Model calibration

The steady state calibrated groundwater flow model was calibrated under transient conditions using abstraction and water level data obtained from an aquifer test conducted at the wellfield. This calibration was performed in order to ensure that the model is sufficiently calibrated on a small scale around the boreholes to enable predictions regarding overall wellfield behaviour. The simulated and observed water level response is shown in Figure 13.7.

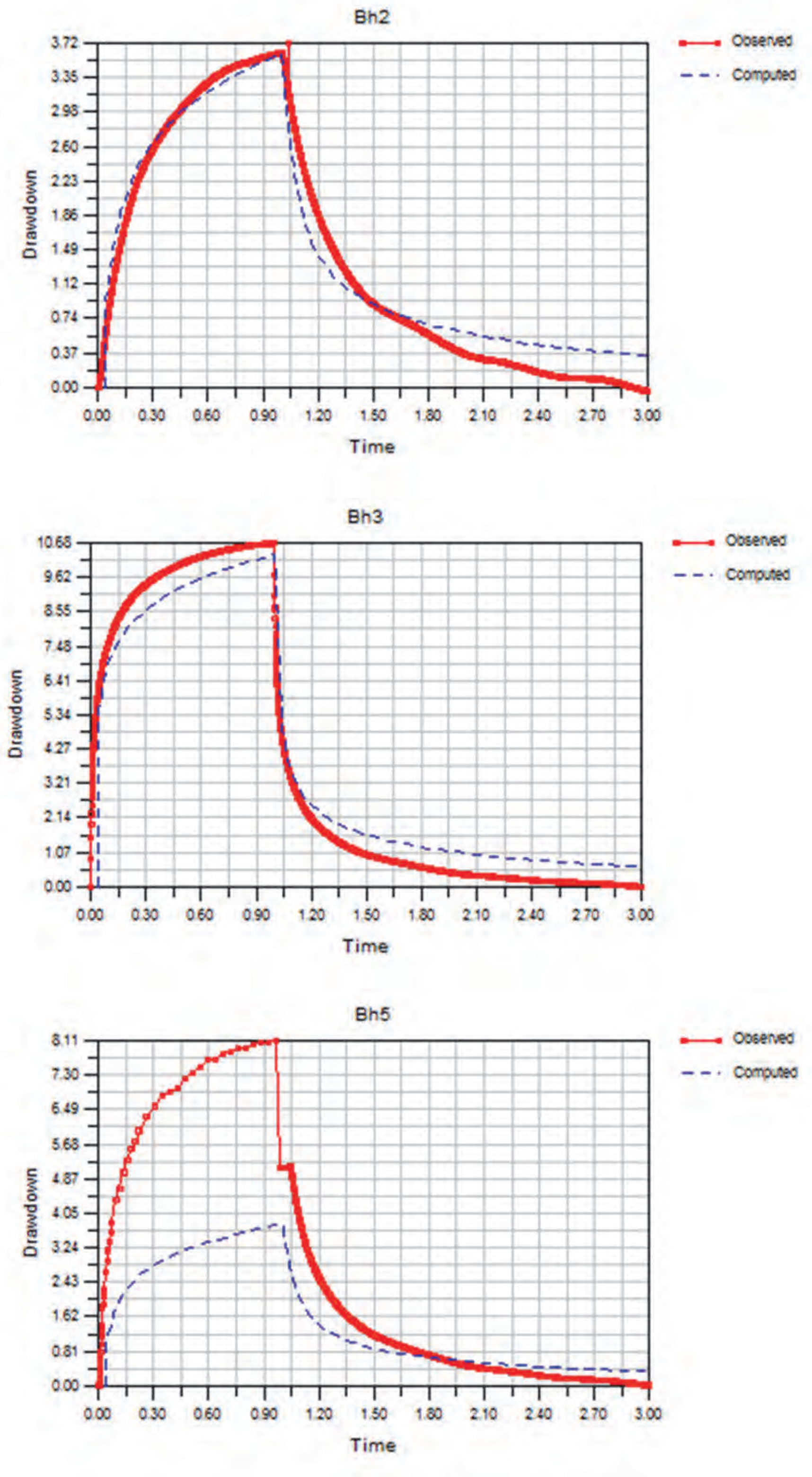

Figure 13.7 Transient calibration graphs for BH2, BH3 and BH5.

It is clear from the simulated results obtained that the hydrogeological flow model is capable of simulating the real aquifer test data sufficiently well allowing confidence in the flow model. During this calibration exercise specific aquifer storage values were specified (**Table 13.2**) for the different aquifers in order to obtain good results.

13.5 Sensitivity analysis

A sensitivity analysis was carried out on the calibrated steady state model using zones to assess the importance of the various parameters. This 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. The sensitivity analysis was carried out by varying one input parameter and keeping all others constant and then observing the resulting changes in the calibration. Sensitivity analyses were performed on horizontal hydraulic conductivity, vertical hydraulic conductivity and recharge.

The results of the sensitivity analysis presented in Figure 13.8, 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 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.

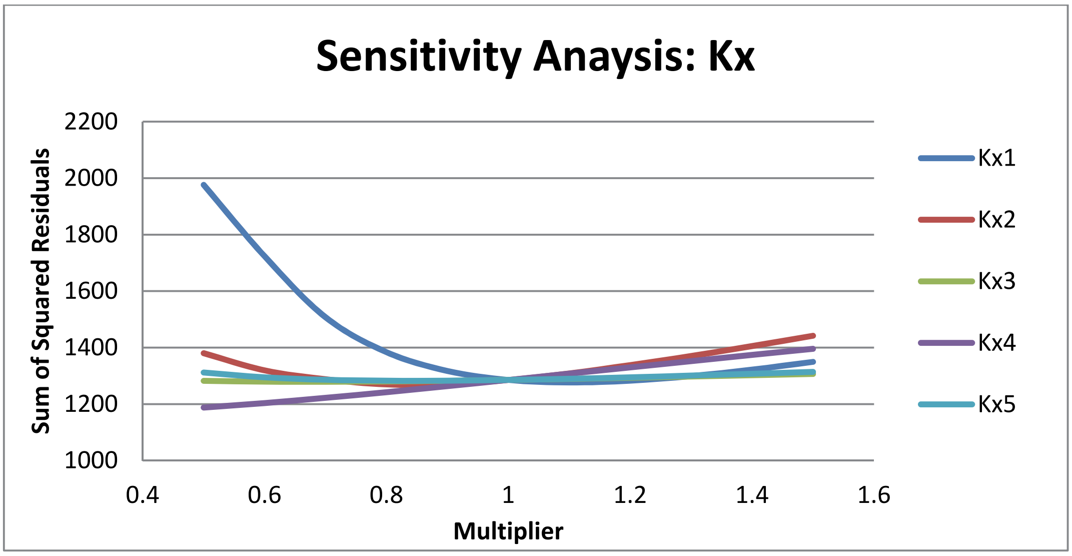

Figure 13.8 Sensitivity analyses for horizontal hydraulic conductivity.

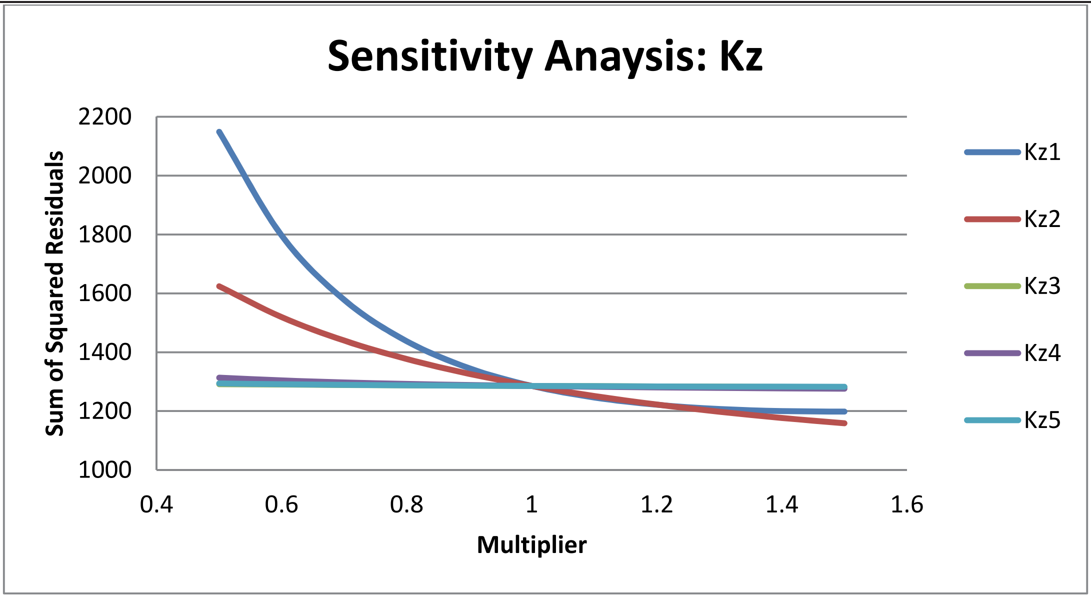

Figure 13.9 **Vertical hydraulic conductivity sensitivity analyses.**

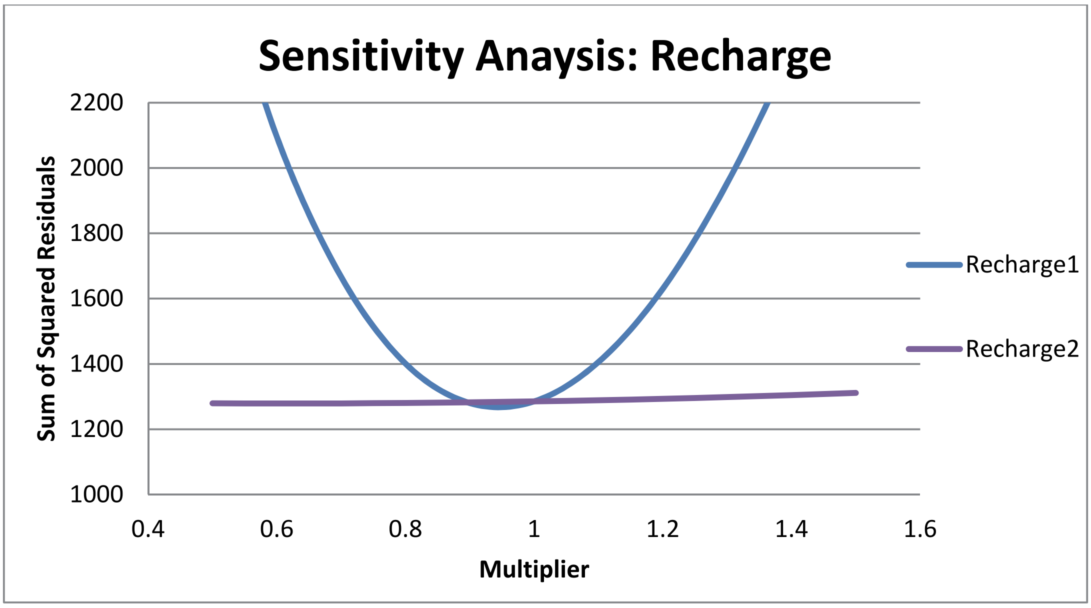

Figure 13.10 **Sensitivity results for the effective recharge of the Peninsula (Recharge 1) and Primary (Recharge 2) aquifers.**

13.6 Predictive Scenarios

13.6.1 Simulations

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 model scenarios have been realized. Properties such as hydraulic conductivity, porosity, recharge and storage were increased and decreased by 20% and their capture zones recorded. 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. The combined outer boundary of all of the capture zones put together were then 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.

The following zones were delineated for illustrative purposes:

- Zone 1: Simulates the 1 year capture zone;
- Zone 2: Simulates the 10 year capture zone; and
- Zone 3: Simulates the 100 year capture zone.

13.6.2 Results

The results of the modelled scenarios are presented as groundwater protection zones (Figure 13.11). These zones were modelled and delineated using the 20% hydraulic property deviation described in Section 13.6.1.

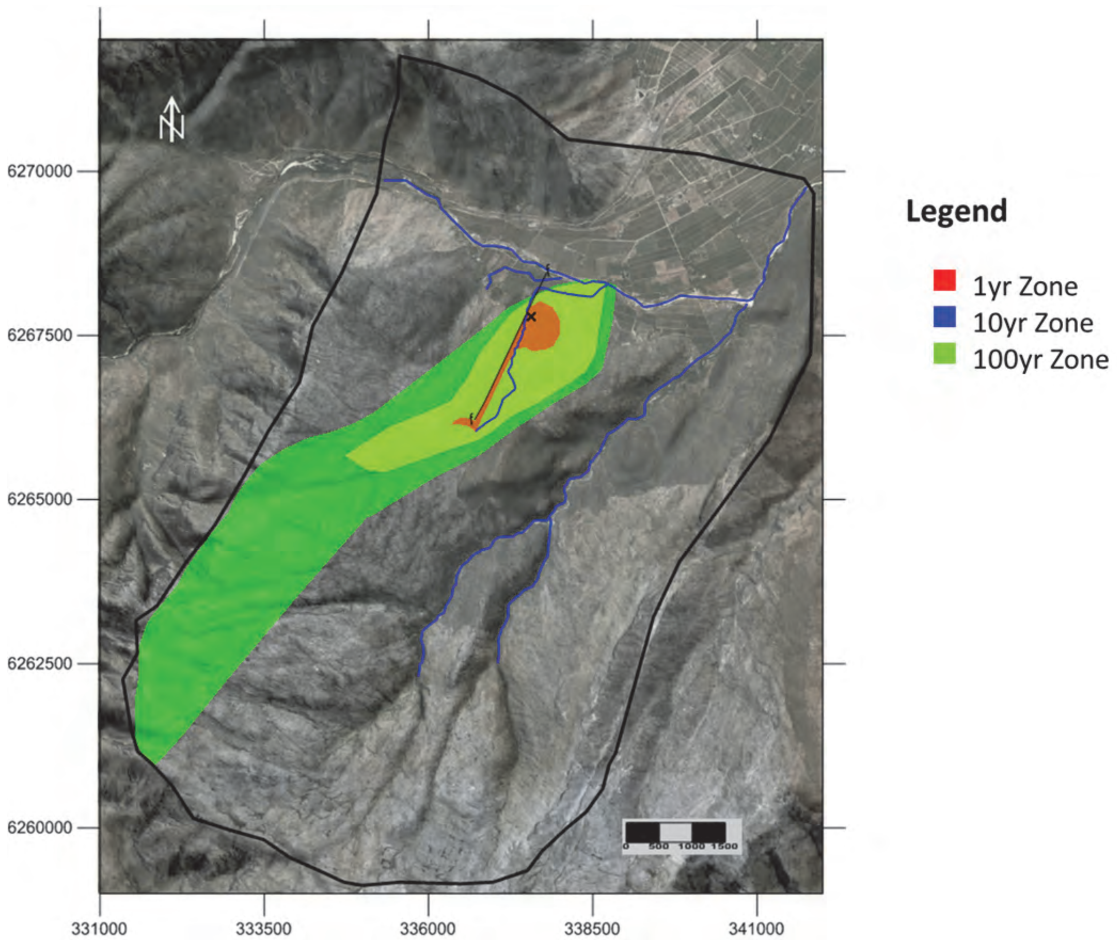

Figure 13.11 Delineated protection zones for the 1yr, 10yr and 100yr flow fields.

Changes in hydraulic property values showed slight horizontal shifts in flow fields, however, the general direction/origin of the particles remained the same. A more obvious effect on the flow field could be seen in the vertical direction.

As expected, flow is along the fault line from the mountain where recharge is assumed to be occurring. 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 flow field characteristics change. At this point, the overlying unconsolidated primary aquifer starts contributing to the borehole water supply, with pathlines reaching the Molenaars River. In the fractured Peninsula the flow field expands radially 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, 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. Changes in the flow field on the western side of the fault mainly occur as a result of a change in capture zone to the fault.

13.6.3 Knowledge gaps identified

Data used in modelling the influence of the Gevonden capture zones is based on the hydrocensus and site specific wellfield results. This data represents 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 history of boreholes from the primary or secondary aquifer (Some of t*he monitoring boreholes showed depressed groundwater levels assumed to be due to localized pumping*.)
- The monitoring borehole elevations were not surveyed. (*The boreholes elevations used in the model were derived from ASTER GDEM v2 grid by taking the uncertainties related to such approach into the consideration*.)

- Groundwater calibration data were mostly only available in the primary aquifer with fractured rock aquifer data limited to the site scale. (*Groundwater model fractured rock properties were not calibrated in distant areas*.)
- Borehole construction and depths for the hydrocensus 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 model layer 1 and 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 of the fault is approximately of 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*.)

13.7 Protection of drinking water

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 (**Figure 13.12**). Both regulatory and non-regulatory approaches can be followed to protect the drinking water. These include:

- The French drain toilet should be changed to tanks and disposed of off-site;
- Farm land falling within the protection zones should limit fertilizer and pesticide use. 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 Hugenote tunnel and can be contaminated accidental/purposeful 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.

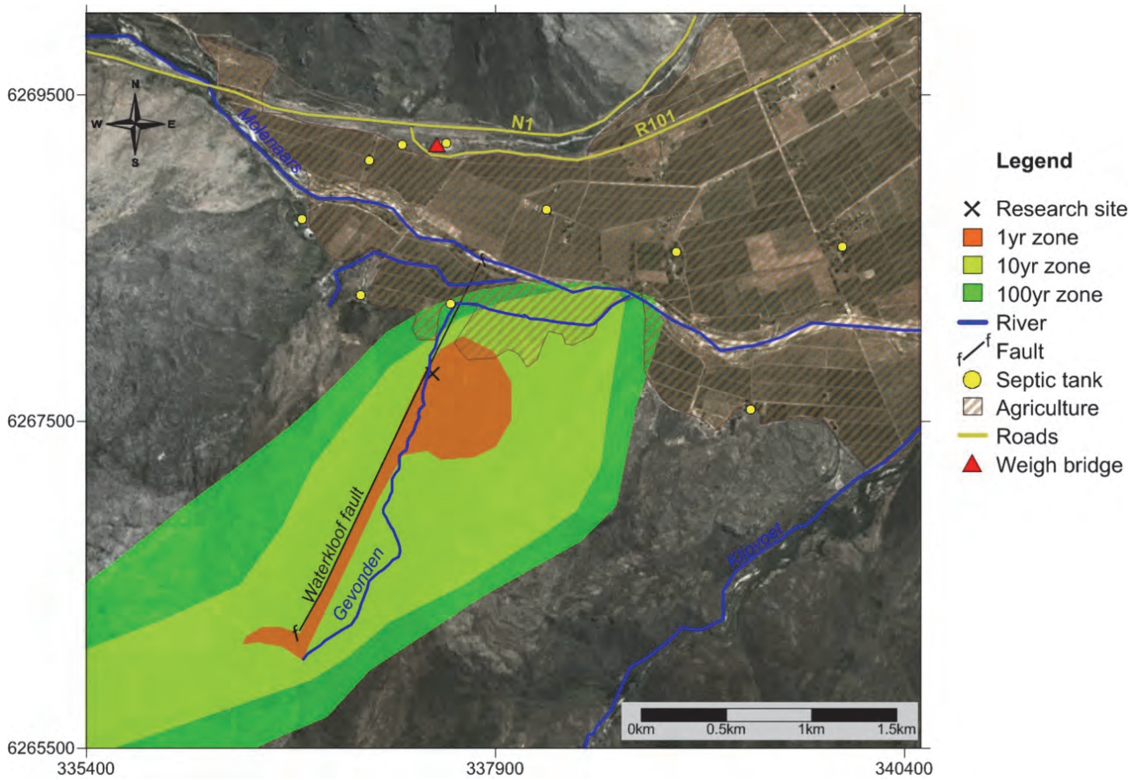

Figure 13.12 Possible contamination sources within the delineated protection zones.

13.8 Monitoring Recommendations

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 update of the conceptual model.

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 13.3). Key monitoring points were selected using existing boreholes as well as rivers in the area (Figure 13.13). 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.

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.

Table 13.3 Suggested monitoring to improve conceptual model at the Gevonden site.

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, 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, 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 within the 10yr zone	Monthly
MP7	337619	6267835	Borehole + Isotope sampler	Groundwater and precipitation monitoring and 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	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

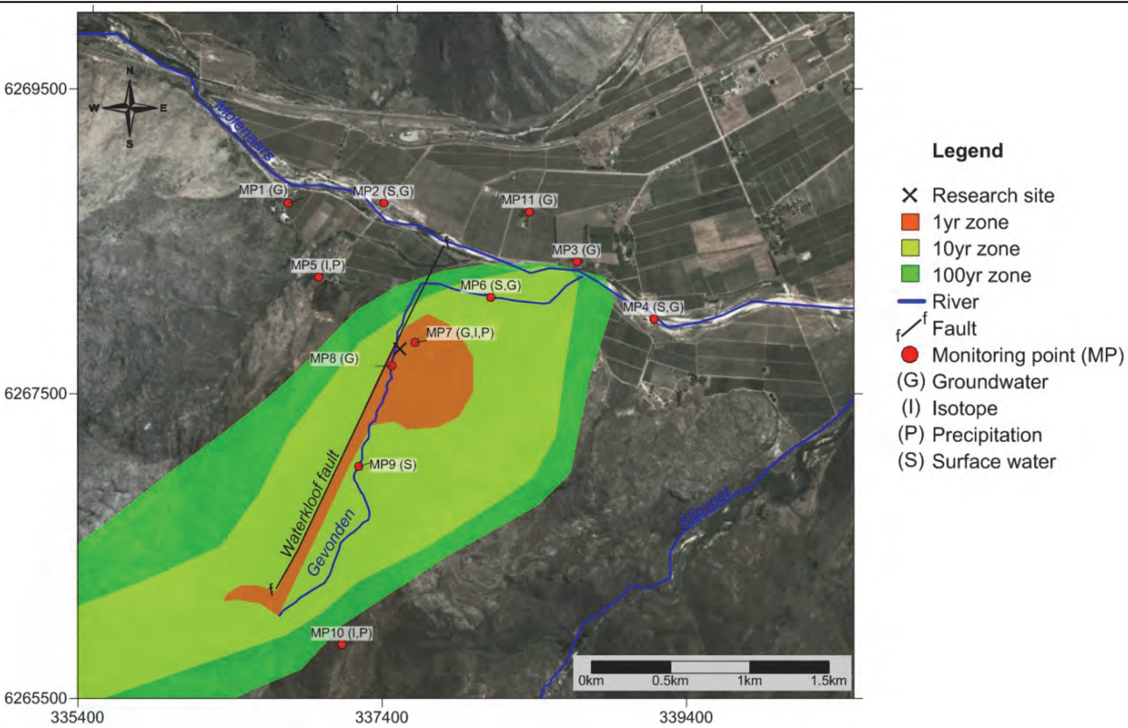

Figure 13.13 Spatial presentation of suggested monitoring for the management of the protection zones.

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.

13.9 Database

Establishing a groundwater protection database will ensure that the data for protection of the water supplies are available. The data can also be considered for water use licensing and the protection of surface and groundwater, and/or the conservation of habitats and species directly depending on these aquifers.

This protection zone delineation must be available to local users and water managers to ensure protection of the Gevonden groundwater supplies. The change in water levels and the impact on the zone of contribution must be monitored and used to update the management plan.

13.10 Case Study Conclusion

The methodology was successfully applied to provide a protection zone in which water managers and local users can negotiate with one another on the management of the groundwater resources. The water users can participate in the management of the local resource and impacts can be managed by them.

Maps of the protection zones will focus the human and financial resources and allow insight to the effect of competing water users. The understanding between these interactions can be updated as more data becomes available from the monitoring programme.

13.11 References

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