2 LITERATURE REVIEW

2.1 GIS AND GROUND WATER

The aim of a Geographical Information System(GIS) is to store geographically referenced data as different layers. These different data layers may be manipulated and visually accessed as output data. The usefulness of the output data, however is determined by the quality of the input data.

Using a GIS in the modelling of small watersheds is not a new concept. Cavallin and Giuliano (1992) used GIS's on a regional scale to evaluate aquifer vulnerability. Data was digitized with ARC/INFO (ESRI) and processed in raster format using ILWIS (ITC). The procedure can only be applied on a regional scale where free surface aquifers with mainly vertical recharge are found. They state that both dynamic and static conditions must be considered and therefore proposed that depth to water table, recharge, aquifer media, soil media, topography, impact of the vadose zone and conductivity of the aquifer should all be included in a GIS. Suwanwerakamtron (1994) stated that the use of hydrological models makes it possible to predict hydrological processes and watershed behaviour. He also concluded that a GIS can provide essential input data for a hydrological model, in both time and space.

Prior to incorporating a GIS into a geohydrological study, the role of the GIS and the input data which will be used must be defined. Van Riet and Slabbert (1994) used ENPAT (Environmental Potential Atlas) to compile a 1: 250 000 / 1: 1 000 000 map of South Africa incorporating the following data sets:

- groundwater
- surface water
- population

The information obtained was used to identify areas with constraints regarding water demand. It was also suggested that the following input data sets were necessary in a GIS for use during modelling (Suwanwerakamtron, 1994):

- Topographical maps - scale 1: 50 000
- Geological maps - scale 1:250 000
- Soil maps; Land use maps (1: 250 000 / 1:50 000)
- Satellite imagery (LandSatTM data)
- Climatological and daily rainfall data

Yaser and Radwin (1995) suggested that a best management practice (BMP) approach is essential for accurate modelling. Therefore the initial setting up of a GIS must incorporate all the existing data sets, followed by addition of the field data after which the data can then be manipulated. Suwanwerakamtron (1994) divided his study into three phases:

Phase I - Pre-field work (desk study), data collection.

Phase II - Field work and measurement of weather conditions
Phase III - Post-fieldwork

A GIS serves as a tool in various fields of study. According to Croukamp (1996) an integrated GIS is an ideal tool for management of geotechnical data and other related data through its unique ability to store the spatial relationship of all information on a site and the spatial relationship with similar information at different sites. Croukamp used a GIS for land use planning and suggested the following as input data:

- Geology
- Structural geology
- Land forms
- Instability features
- Land use
- Outcrop nature (soil depth and rock outcrop)
- Geotechnical properties
- Construction materials
- Soils
- Cadastral data
- Slope grade
- Infrastructure

It was also suggested that remotely sensed data, such as LandSat TM and SPOT images, climatic and hydrological data could be used successfully in a GIS.

Wolff-Piggott (1995), as Suwanwerakamtron (1994), investigated the integration of GIS into a hydrological model. According to Wolff-Piggott, a GIS should rather be used as a pre- or post-processor for hydrological modelling for it lacks the ability to handle time-varying data structures, lineage and product quality information. GIS should therefore be used as an enduring spatial database that can be used over and over again. Wolff-Piggott also praised GIS for its map capabilities and for the assessment it gives in detecting configuration errors. GIS can be used in a weighted map overlay procedure for mapping ground water pollution potential, providing a statistical snapshot rather than a dynamic model. GIS therefor has a weaknesses with data that varies in time and space, eg. seasonal fluctuations in ground water levels. GIS, however is an excellent tool for water resource management, addressing management issues rather than scientific and technical questions.

Donker (1992) used a digital terrain model (DTM) to explain the main principles applied in the automatic extraction of catchment properties. Calculations were done from four data categories, *viz*:

- Elevation
- Flow directions
- Ranked elevation
- Flow accumulation

Yaser and Radwan (1995) recognized that several previous attempts to evaluate hydrological systems with the aid of a GIS used the following data:

- Relief
- Land cover
- Hydrology
- Soil
- Climate base data
- Socio-economical constrains.

According to their experience the above mentioned parameters make output data subjective and that experience, preferences, intuition, judgement and the expertise of various specialist fields should be combined with a GIS, to arrive at a better answer.

A GIS can also be used to incorporate sosio-economic issues like sanitation, education and housing in a water management program.

2.2 GROUND WATER EXPLORATION METHODS IN HARD CRYSTALLINE ROCK AQUIFERS

2.2.1 Siting

Ground water exploration and development in hard crystalline rock areas is a difficult task and several perspectives on how to find suitable ground water resources have been devéloped. Taylor, Roy and Sett (1955) made a few suggestions, including the following:

- Study the geology, structure and groundwater conditions.
- Study aerial photographs; identifying possible lineaments.
- Verification of lineaments in the field.
- Demarcating suitable areas and delineating traverse lines for geophysical surveys.
- Employ suitable geophysical methods.

Dijon (1984) found that in Precambrian rocks major fractures associated with faults weather along strike, forming deep basins. These weathered zones correspond with topographic lows and drainage systems. The topographical lows serve as water recharge areas and most successful wells are located in these areas.

Taylor (1984) did work in the northwest of India on middle Precambrian granitic rocks, situated in a hot, semi-arid, Savannah-type climate. He found that borehole yield depends on the number, width and spacing of fractures and/or the relative thickness and permeability of the weathered layers.

Larsson (1981) did some hydro-geological work on the Sardina granites in Italy, and concluded that hydrological investigations at Santa Margherita must follow a certain pattern, including the following:

- Supplementary land surveying - Contour mapping using aerial photographs and stereo plotter.
- Calculate possible recharge - Setting up of rainfall gauges and constructing runoff stations.
- Regional geological mapping
  - Petrology of the main rocks
  - Tectonic studies
- Investigation of soils and weathered rocks
- Establishing a general working criteria for the geological environment.
- Planning of drilling- and testing programme, including observation wells.

Many countries do not have the necessary financial resources or qualified personnel to follow the prescribed methods or programmes. Larsson (1984), suggested that the strategy for groundwater exploration and development in hard-rock areas should be effective and economical. Some of the most important issues are:

- Defining and assessing the parameters which determine the storage capacity of hard rock aquifers.
- Making proper use of ground water exploration methods and using them in a step-like manner, starting with simple methods initially and proceeding to more sophisticated ones as the need arises.
- Finding short cuts in the process of determining favourable sites for wells. Making use of satellite imagery and air photos, focussing on structural and geomorphological features.

A methodology developed by Baweja and Raju (1988) suggested that groundwater development programmes should make use of geology, structure and groundwater conditions expected in the area. They also suggested a systematic hydrological survey making use of air photographs and LandSat imagery. They suggest that lineaments identified during the desk study should be investigated making use of both geology and geophysics.

Yaser and Radwan (1995) suggested that a watershed management project should be an integrated programme involving experience, preferences, intuition, judgement and expertise of various fields. They decided to involve a whole spectrum of disciplines when dealing with community water supply programmes.

It is therefore essential that all available methods and tools such as GIS, geophysics, structural geology, engineering geology and hydrology (water modelling) are used when dealing with geohydrological investigations. While using all these methods one must always follow the BATNEEC principle (Best Available Technology Not Exceeding Excessive Cost).

However, Schoeman (1997) summarized an approach to research being bedded in understanding the multi-dimensional nature of the problem. This approach forces an inevitable realization that research in this field, as well as the interventions based thereon, can never be regarded as offering a final answer or the ultimate solution.

2.2.2 Drilling

The most common method used for the sinking of water supply wells is rotary air percussion drilling, employing a down-the-hole hammer (DTH). This drilling technique is ideally suited for hard rock formations. In some instances where site specific circumstances require specialized techniques, other methods such as odex drilling are used.

Cuttings from percussion drilling are brought to the surface via air return from the bottom of the borehole and are collected and described at one metre intervals to record the lithology in the borehole. Depths of water intersections are recorded, and blow lift yields measured with the aid of a V-notch weir.

The extreme diverse nature of subsurface conditions, over very short distances, renders it virtually impossible to standardize borehole construction specifications. The majority of the boreholes presently being drilled for community water supply in the Northern Province, South Africa have a diameter of 165 mm with a steel casing having a wall thickness of 4 mm. Casing is installed from surface, through unstable, unconsolidated or fractured material down into solid bedrock. Perforated casing sections are extended across water bearing horizons to allow groundwater to flow into the borehole (DWAF, 1997).

2.3 GROUND WATER ASSESSMENT

To reliably assess the groundwater potential in a hard rock aquifer, a well prepared pump test programme should be executed. The pump testing should be adequately planned and organized, using approved equipment. It is important to use the appropriate calculation methods for boreholes that are situated in hard rock aquifers.

2.3.1 Pump testing

The correct operation and utilization of boreholes are dependent on the assessment of the productive capacity (yield potential) of the borehole obtained from calculating the storage capacity (S) and the transmissivity (T) of the aquifer. This information is obtained from pump test results. Prior to performing a pump test, information on the purpose for which the borehole is to be used and the amount of the water required are needed. All the boreholes drilled during the research project will be utilized as drinking water resources and the volumes required are dependent on the size of the different villages.

According to Kirchner and Van Tonder (1995) the most important information needed to analyse pump test results are:

- Information regarding the test hole
  Hole number, locality, depth , diameter, water depth level, yield and type of equipment used to test the borehole.
- Information regarding the observation wells

Hole number, locality, depth, diameter, water depth level and equipment.

- Information regarding test procedures.

Number of steps, duration of main test and yield, duration of recovery data, time intervals, temperature and electrical conductivity must be measured and when water samples are collected.

A pump test can only be executed correctly when the above parameters are taken into account. It is important to record water levels in all the observation boreholes prior to conducting the pump test. The regional influence of the pump test on the aquifer can only be evaluated if the ground water levels are known.

The decision to pump test a borehole is based on the airlift yield recorded during the drilling phase. Initially a **calibration test** is done, with short pumping periods, not exceeding 20 minutes. After each step the recovery of the borehole is recorded. Secondly, a **step draw down test** is conducted, followed by a **constant draw down test**. Each test must be followed by a recovery period, preferably not exceeding the total pumping time.

The **calibration test** is performed to assess the efficiency of the borehole from which the final pumping rate yield for the *step draw down test* is determined.

The **step draw down test** or variable-rate test provides information on the hydraulic conditions in the immediate vicinity of the borehole (Kirchner *et al*, 1995). It entails pumping the borehole at three or more sequentially increasing pumping yields, each maintained for an equal length of time (eg.100 minutes). Water levels are measured and recorded in accordance with a prescribed time schedule. On completion of all steps recovery is allowed, preferably not exceeding twice the pumping time. A **multi-rate test** (short duration) can also be conducted and it is basically the same as a **step test** except that recovery is allowed after each individual step. Both methods may be used to estimate the best yield for the constant discharge test.

The **constant discharge test** is performed to determine aquifer parameter values (transmissivity and storativity) and to determine the possible existence of groundwater barrier boundaries. The test entails pumping the borehole at a single pumping rate, which is kept constant for the entire duration of the test. Boreholes tested are pumped for at least 24 hours, with the higher yielding boreholes being pumped for 96 hours. During the course of the test the draw down in the pumped borehole, as well as in the specified observation boreholes are recorded. After completion of the **constant discharge test**, the recovery in all the affected boreholes must be recorded. Preferably recovery is measured until 100% recovery is achieved.

The data obtained from the constant discharge tests permit the calculation of the specific capacity of the borehole at the set-pumping rate. A comparison of this value with those obtained from the step draw down tests offers a means of calculating a more realistic production yield value.

Although test pumping cannot be considered as the ideal way of evaluating the long-term sustainability of a groundwater resource, it does provide a quick and simple way of evaluating the short to medium term performance characteristics of a borehole in an aquifer. It must be emphasized that the calculations done from test pumping data are only representative of the aquifer characteristics in the immediate vicinity of the specific site. Factors such as aquifer transmissivity as well as the duration of the test, will determine the influence on the aquifer during the test (the longer the test, the greater the influence).

2.3.2 Pump test analysis

Data obtained during the pump test allows the **transmissivity (T)** of the aquifer to be calculated. This parameter quantifies the ability of the aquifer to transmit water, thereby describing the conduit function of the aquifer. Quantification of the second function of an aquifer, namely its water **storage coefficient (storativity)** (Bredenkamp *et al*), is also determined (Bear, 1979). The storativity is defined as the amount of water that a permeable unit will absorb or discharge from storage per unit surface area per unit change in head, whilst the aquifer remain fully saturated. The aim of the whole exercise is to determine the sustainable yield.

Several methods were developed to analyse and evaluate pump tests. Kruseman and de Ridder (1991) discuss most of these methods. However, before proceeding with the analysis of an aquifer the type of aquifer must be determined and it is most important to have accurate drilling logs. From the drilling logs an appropriate aquifer can be chosen (Van Tonder, 1999 *pers. comm.*). There are basically seven aquifer types (Kruseman and de Ridder, 1991):

- Confined aquifers
- Leaky aquifers
- Unconfined aquifers
- Bounded aquifers
- Un-bounded aquifers
- Wedge-shaped and sloping aquifers
- Anisotropic aquifers
- Multi-layered aquifers

For every hydrological model certain assumptions must be made and each model has an unique list of assumptions, which is detailed by Kruseman and de Ridder (1991).

According to Kruseman and de Ridder there are three basic porosity systems (Figure 3).

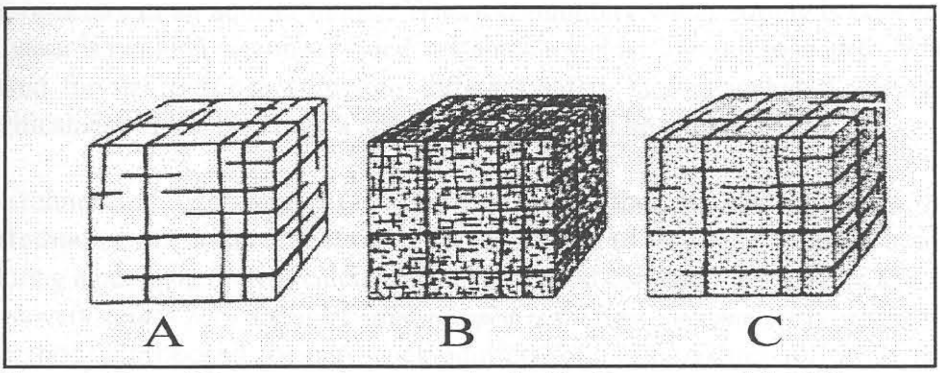

Figure 3. Three different porosity systems decribed by Kruseman and de Ridder.

A- Single porosity - *Only the fracture system*
B- Micro-fissures - *Fracture system with micro fissures*
C- Double-porosity - *Fractures in a porous medium.*

Kirchner and Van Tonder (1995) discussed fractured aquifers in a broad sense and took most parameters into account. They described the fractured media as follows:

"Fractures are cracks, fissures, joints and faults caused by any geological activity. A fractured rock mass consists of two components: matrix and fracture. The fracture serves as a conduit for water flow and the matrix as a less permeable to impermeable medium having a high storage capacity."

Kruseman and de Ridder (1991) indicated that the draw down in a single fracture system is similar to the Theis curve for porous confined media. They also concluded that a double-porosity fractured system draw down curve follows the same path of the water-table aquifer discussed by Neuman(1972). Van Tonder (1999, *pers. comm.*) suggested that a well-known method known as the Cooper-Jacob method may be used in a fractured media to calculate the **S**- & **T**-values. Van Tonder and Yongxin Xu (1999) suggested a Flow Regime Characteristics method know as the FC_Method. This method was developed to interpret pumping tests and to estimate sustainable yields of boreholes in fractured-rock aquifers. Van Tonder (1999, *pers. comm.*) also suggested that a method know as RPTSOLV may be use to calculated realistic **S-values** and manipulating the FC_Method so that the same S-value is applicable.

Other methods mentioned by Kirchner and Van Tonder (1995) to calculate or estimate the aquifer parameters are:

- Rock sampling and laboratory measurements.
- Analysis of natural variations of water levels (water balance).
- Inverse modelling.
- Correlation with other parameters, eg electrical resistance or grain size.
- Use of environmental tracers.
- Packer and double packer borehole tests.

Tests are done to evaluate the aquifer, either to estimate a production yield or to use the parameters in an aquifer model. Where community water supply is concerned, a quick answer is required, bearing in mind sustainable yields. The proposed FC_Method may be used for this purpose with four different safety factors included. Depending on the criticalness of the borehole a sustainable yield can be chosen.

Kirchner and Van Tonder (1995) proposed another method known as the **Recovery Method** in which the time it takes for a borehole to recover if pumped at a specific rate during a pumping cycle is calculated. The method can however only be applied when the recovery equals zero and if t/t' (***time pumped +total time /time pumped***) is greater than 1. The method is proposed for hard rock aquifers, but when values for t/t' is greater than 2 (inflection point) then the method may result in incorrect high production values. The method is commonly used in practice for pump test recommendations.

2.4 GROUND WATER CHEMISTRY IN HARD CRYSTALLINE ROCK

2.4.1 Inorganic assessment

It is known that the hydro-chemistry of fractured aquifers in hard rock areas is related to the minerals found in the fracture. However, if the recharge and discharge cycle is rapid the ground water chemistry is less likely to correspond to the chemistry of the dissolving minerals. During an investigation conducted by Banwart, Gustaffsson, Nilsson, Tullborg and Wallin (1994) in Switzerland, a large volume of water was released into a vertical fracture in crystalline bedrock. Using Cl^- as a conservative tracer, mixing between the diluted shallow ground water and the saline native ground water was recorded. The 80% dilution front measured in the native water proofs that the fracture zone serves as a hydraulic conduit bringing "fresh" water into the aquifer and serves as a pathway for element transport. If this then serves as a conduit bringing in near surface water, the environment should change from anaerobic to more aerobic. However, input of organic carbon provides a possible energy source for microbial respiration within the fracture zone consuming all additional oxygen. If this is true the ground water in the fracture may have higher NH_4 and NO_3 levels than suspected due to nitrification.

If a granite intrusion is 'wet' then the fluoride will move into the hydrothermal fluids and crystalize as fluorite in the hydrothermal vents. Hydrothermal deposits may also be found in faults or fractures (Lapidus, 1990). During their work in Rajasthan, India, Vanish and Gyani (1998) concluded that the heavy withdraw of ground water, and poor recharge cause an increase in the fluoride content. Weathering of rocks containing fluoride rich minerals (eg. CaF_2)[1] leads to the release of fluoride into the ground water, therefore if recharge and discharge fluctuate the fluoride level will fluctuate.

1 CaF_2 or fluorite is a mineral preferring a hydrothermal environment, therefore fluorite is a fairly common mineral in granites which also exhibit hydrothermal conditions.

2.4.2 Sanitation and microbial assessment

Improved water supply and sanitation may improve the quality of life, it may even facilitate other development activities, but the main achievement is improvement of community health. When waste water move through the soil into the aquifer it is subjected to flow through the vadose zone (unsaturated) and the saturated zone. Contamination travels primarily in a thin sheet at the surface of the saturated zone and little evidence can be found of dispersion and therefor the benefit of drawing water from great depth from a screen well. Fourie and van Reyneveld (1994) also concluded that the rate of subsurface water flow is not the controlling factor of pollution, but physical movement of contaminants, microbial growth and degradation play a major role in the mobility of contaminants. Apart from micro-organisms, chemical contaminants could also be derived from bad sanitation and it is therefore essential that good sanitation practices are promoted (Fourie, van Renyeveld, 1995). Human waste is rich in organic matter and carbon, with a meaningful amount of nitrogen, phosphate, calcium and potassium (Table 1). It is therefore possible that due to domestic sewage effluent, excess nitrate may enter the ground water system, tipping the Nitrate-cycle (Terblance, 1991).

Bacteria and viruses find bad sanitary conditions excellent breeding places and certain health risks are therefore associated with these practices (Table 2). Genthe and Seager (1996), found that there are high levels of food and water contamination in the home environment even when clean water is used. They suggest that improvement of water quality alone seems to have little effect on handling practices and subsequent contamination of stored water takes place. It is therefore necessary to develop programs in reducing the risk to a minimum. According to a WRC report (1993) the best technologies to use in rural areas are VIP[2] and SanPlat[3] sanitation systems. These are economical and feasible systems which may improve on-site sanitation.

Table 1. General composition of human excreta.

Minerals	% of dry weight (Faeces)	% of dry weight (Urine)
Calcium(CaO)	4.5	4.5 -6.0
Carbon	44-55	36480
Nitrogen	5 - 7	15 - 19
Organic matter	88 - 97	65 - 85
Phosphorus (P_2O_3)	3.0 - 5.4	2.5 - 5.0
Potassium (K_2O)	1.0 - 2.5	3.0 - 4.5

2 VIP - Ventilated improved pitlatrine.

3 SanPlat - Sanitation Platform.

Table 2. Bacteria and Viruses and their associated with illnesses (After Fourie, 1993).

Micro-organism	Associated illness	Virus	Associated illness
Vibrio cholera	Cholera	Echovirus	Meningitis, diarrhea
Salmonella typhi	Typhoid	Polivirus	Paralysis
Shigella spp.	Bacillary	Coxsackievirus A&B	Herpectic agina
E.coli	Diarrheal diseases	Hepatitis A	Infectious hepatitis
		Norwalk virus	Vomiting, fever, diarrhea
		Rota virus	Vomiting, diarrhea

2.4.3 Health classification

The Department of Water Affairs and Forestry (DWAF) worked closely together with the Department of Health in developing a quality classification system. This classification system is documented in the *Quality of Domestic Water Supplies, Volume 1: Assessment Guide* (1998) and classifies drinking water into five colour categories or classes.

CLASS 0 - Blue - Water of ideal quality.
CLASS 1 - Green - Good water quality.
CLASS 2 - Yellow - Marginal water quality.
CLASS 3 - Red - Poor water quality.
CLASS 4 - Purple - Unacceptable water quality.

During pump testing successive samples are taken to evaluate the water quality due to variability of the quality with time as the water move from the aquifer towards the borehole. At least two water samples are taken per borehole and tested according to the standards set by the Department of Water Affairs and Forestry.

2.4.4 Age classification

When evaluating the aquifer recharge it is important to establish the age of the groundwater. Natural isotopes such as Deuterium and Tritium are usually used in water dating.

2.5 COMMUNITY WATER SUPPLY

Rural water supply is presently one of the main concerns in South Africa. The South African government has therefore launched the so-called Reconstruction and Development Programme to especially develop rural areas. Van Schalkwyk (1996) developed guidelines for the estimation of water demand in developing communities in the Northern Province, South Africa. According to Van Schalkwyk some of the factors influencing water demand are population density, household size, housing type, gardening type, income, education, agricultural activity, water supply systems, sanitation facilities, water tariff, water quality, people per abstraction point and water user type. Assuming that water is not restricted by access and no other inhibitors are present, he concluded that:

- Water use = f(living conditions, access, tariff, inhibitors), and
- Water demand = f(living conditions, tariff)

Palmer and Eberhard (1995) stated that the water access level and land acceptance (responsibility of the people) by communities are two major factors influencing water supply within rural communities. They proposed that areas should rather be classified according to water access and the socio-economical structure of the various communities. Classified groups should therefore be identified and all communities grouped together should be treated equal.

Community water supply schemes are only successful if the communities also get involved. Davis, Garvey and Wood (1993) developed a strategy for community involvement where each community elect a *water committee*, to monitor and evaluate the performance of their own water supplies. Successful programs, as proposed by Davis *et al*, are running in Dalmot Gale, Ethiopia at present.