3. HYDROGEOLOGICAL ASSESSMENT METHODS

3.1. Investigation approach

The methods and approach to further the conceptual understanding of the hydrogeological functioning of the Limpopo crystalline basement aquifers can be summarised in Figure 3.1.

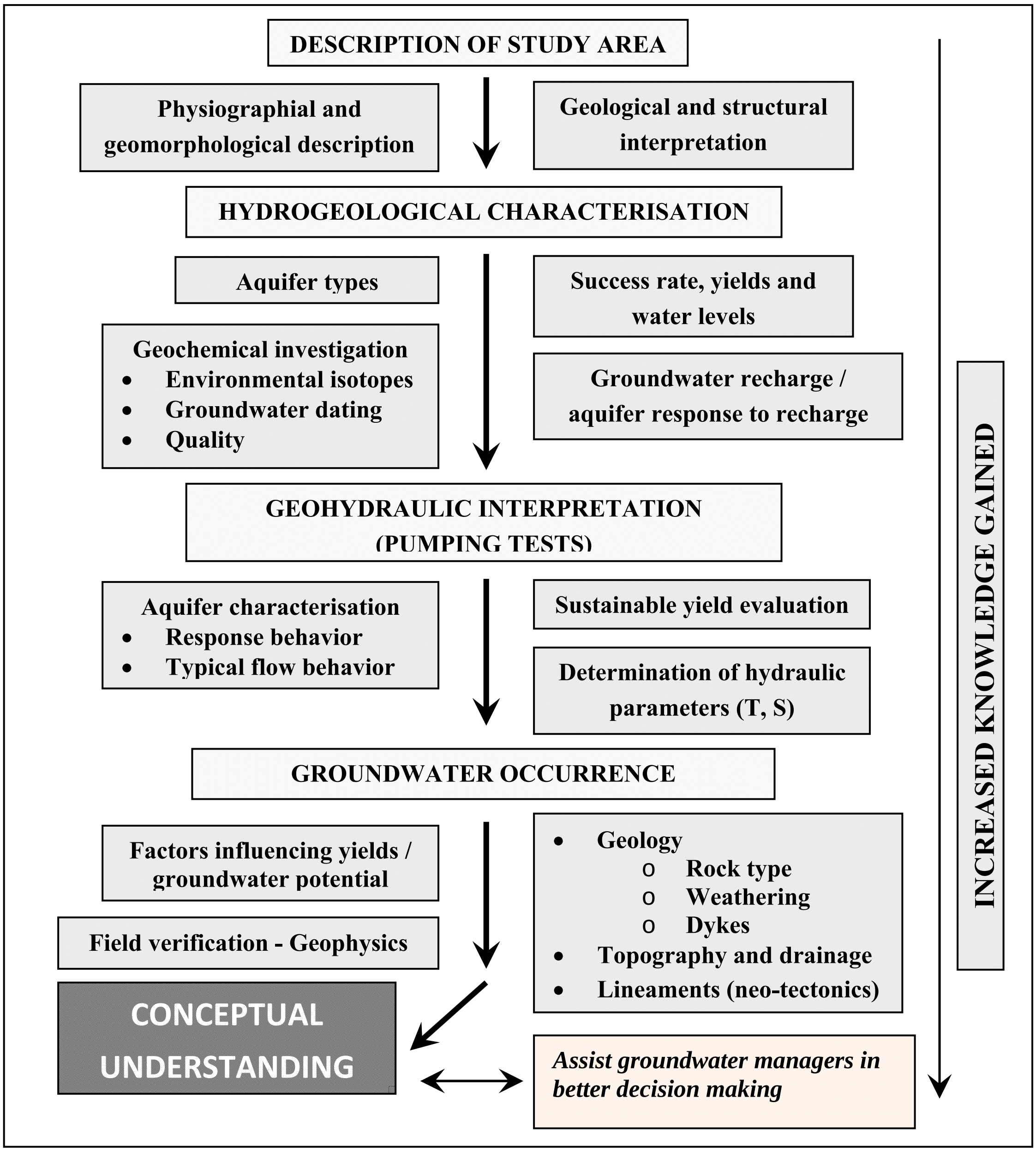

Figure 3.1. Overview of the applied hydrogeological assessment approach and methods.

3.1.1. Hydrogeological overview

The main objective of this phase to establish an understanding of the hydrogeological characteristics of a region based on existing information. In the context of groundwater occurrence (potential) it is important to characterise the physical feasibility of meeting water demands through groundwater. By overlaying the different information layers like geological and structural maps, borehole yields, dry boreholes (!), historic drilling success rates and depth to groundwater and groundwater chemistry using appropriate software (i.e. GIS) will give a first understanding of the aquifer characteristics, structural and geological influences of successful and unsuccessful boreholes as well as potential drilling targets, i.e. a basic conceptual model of the basement aquifer(s) in the area.

Borehole data

Water wells have been a source of water for people, animals and crops since the earliest civilizations in Africa and Asia (Misstear et al., 2006), while boreholes have been in supply since the advent of the drilling machine in the late nineteenth century. In the Limpopo Province alone some 30 boreholes are drilled per day to sustain the ever growing demand for water in the region. In view of the above the Limpopo Province Department of Water Affairs (DWA) initiated and implemented a Groundwater Resource Information Project (GRIP) in 2002 and thus became the first province in South Africa to do so (Botha, 2005). GRIP is a systematic approach to gather, verify, upload and use data to improve management and development of rural groundwater resources in South Africa. As the majority of these boreholes have been verified in the field, the spatial accuracy of borehole positions is within 10 m.

The dataset compiled for the study area consists of over 8 000 boreholes contained in the (GRIP) database. The lithology has been recorded and updated on 1 206 boreholes and approximately 3 000 boreholes have been tested. The majority of the pumping tests were single-well tests, primarily to recommend ‘sustainable’ abstraction rates for rural water supply schemes.It is important to note that these boreholes are not randomly distributed but were limited in many cases to the proximity of rural villages. In some cases the drilling target was chosen based on either geophysical field surveys or geological expertise, so a bias towards lineaments and other anomalies in the dataset may be apparent. Similarly, the pumping test results are biased towards larger transmissivity and yield values since low yielding or ‘dry’ boreholes were excluded from testing.

Although the determination of aquifer parameters was not a priority in the GRIP framework, pumping tests of over 2000 boreholes within the study area were analyzed using classical analytical models such as Theis (1935) and the Jacob’s approximation (Cooper and Jacob, 1946) method. These methods in additions to methods such as Barker (1988) are collated together with graphical plots (i.e. semi-log, log-log & derivatives) into the Flow Characteristic (FC) excel spreadsheet developed by the Institute for Groundwater studies in South Africa (Van Tonder et al. 2002). As a result, despite the fact that various consultants and contractors were used to conduct and analyze the pumping tests over a number of years within the GRIP project framework, all analysis was conducted using the FC-spreadsheet. Transmissivity estimates are generally based on a late time fit of the time-drawdown curve using i.e. Cooper-Jacob or Theis methods. It should be noted that the pumping test data have been accumulated over a number of years under various conditions and may potentially be influenced by long-term climatic fluctuations, seasonal rainfall and changes in groundwater abstraction by farmers, communities and mines

3.2. Groundwater recharge estimation methods

The assessment on groundwater recharge is not intended to contribute to the literature on the importance of recharge to sustainability, but will provide some insight into recharge rates, process and behaviour that occur in the underlying crystalline basement aquifer.

3.2.1. Chloride Mass Balance (CMB)

For a detailed description of the theory behind the CMB-method the reader is referred to the number of publications available on this subject (i.e. Wood, 1999; Kinzelbach et al., 2002; Adams et al., 2004). The CMB-method can be applied to the saturated zone to estimate a 'true' total recharge originating from both diffuse and preferential flow components through the unsaturated zone. The CMB-method in the saturated zone has been used in basement aquifers throughout southern Africa to estimate recharge (Xu and Beekman, 2003; Adams et al., 2004). This method entails determining the recharge over an entire drainage area by integrating the ratio of average chloride content in rainfall (wet and dry deposition) to that of groundwater over the whole area. The CMB-method can be represented by the equation (Kinzelbach et al., 2002):

$$Rt = \frac{P * Cl_p + D}{Cl_{gw}} \qquad (3\text{-}1)$$

where:
P = precipitation (mm per time)
Rt = total recharge (mm per time)
D = dry deposition (in mg per m^2 and time)
Cl_P = concentration in precipitation (mg/l)
Cl_{gw} = concentration in recharging groundwater (i.e. average over profile) (mg/l)

The Cl_{gw} originates from various flow components in the unsaturated zone. For a regional Rt, Cl_{gw} represents the harmonic mean of chloride concentrations in groundwater:

$$Cl_{gw} = \frac{N}{\sum_{i=1}^{N} \frac{1}{Cl_{gw-1}}} \qquad (3\text{-}2)$$

3.2.2. Cumulative rainfall departure method

The Cumulative Rainfall Departure (CRD) method is a water balance approach and is based on the premise that equilibrium conditions develop in an aquifer over time, i.e. average rate of losses equating to average rate of recharge of the system. In other words groundwater level fluctuations are caused by rainfall events. The method requires monthly rainfall and groundwater level data, as well as information pertaining to aquifer properties (storativity), abstraction and the size of the recharge area. The CRD-method allows aquifer characteristics and components such as i) recharge or storativity, and ii) the impact of abstraction or iii) the natural response of rainfall to be determined. The CRD series is represented by the mathematical relationship (Bredenkamp, et al., 1995):

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

where:

R is rainfall values with subscript "i" indicating i-th month and "av" the average.

$k = 1+(Q_p+Q_{out})/(AR_{av})$.

If, according to the regression k > 1, which indicates that pumping or an external impact has affected the water level, the natural water levels could be simulated from equation (3-3) by setting k = 1.

Xu and Van Tonder (2001) derived a new formula for the CRD-method. The k parameter applied in the Bredenkamp et al., (1995) is important to mimic groundwater flow. Recharge is calculated as (Xu and Beekman, 2003):

$$ CRD_i = \sum_{i=1}^{N} R_i - \left(2 - \frac{1}{R_{av} i}\sum_{i=1}^{N} R_i\right) iR_t \qquad (3\text{-}4)$$

where:

R_t often range from 0 to R_{av}, 0 = aquifer being closed and R_{av} = open aquifer system.

The cumulative rainfall average would conform to R_{av} if R_i does not show a rend ($R_t = k\ R_{av}$). It is assumed that the CRD is the driving force behind the monthly water level changes if the other stress is relatively constant. The groundwater level will rise if the cumaltive deaprtruter is positive and will decline if it is negative. Since:

$$ rCRD_i = S_y[\Delta h_i + \left(Q_{pi} + Q_{out}\right)/\left(AS\right)] \qquad (3\text{-}5)$$

where:

r is that fraction of a CRD which contributes to recharge, S_y is specific yield, Δh_i is water level change during month i (L), Q_{pi} is groundwater abstraction (L^3/T), Q_{out} is natural outflow, A is recharge area (L^2).

3.3. Geochemical investigation methods

The regional geochemical description is based on approximately 2 500 borehole analyses sampled over the last decade as part of the GRIP programme. The analyses included mainly major ions pH and electrical conductivity. Further chemistry data was obtained from the following sources 1) Rossouw (2010), which included 52 groundwater samples for major ions, trace elements, tritium (^3H), stable isotopes (^2H and ^{18}O) and bacterial analysis. A further 7 CFC, radiocarbon and stable isotopes (^2H and ^{18}O) groundwater samples were captured from Talma and Weaver (2003) in addition to radiocarbon data captured from the comprehensive multi-tracer study conducted in by Verhagen et al. (2009). As part of this investigation, 11 samples analysed for Chlorofluorocarbons (CFCs), sulphur hexafluoride (SF6), stable isotopes (^2H and ^{18}O) and major ions, and 5 samples analysed for radiocarbon. The water quality sampling was performed according to SABS/ISO 5667 standards and the samples were analysed in a SANAS accredited laboratory.

Database preparation

A high percentage of trace elements values were below the analytical detection limit (censored data) and therefore not used in the multivariate analysis. Furthermore data with unacceptable errors in the charge balance (> 5%) were excluded from further analysis:

$$\text{E.N.}[\%] = 100\% \cdot \left|(Cations - Anions)/(cations + Anions)\right| < 5\% \tag{3-6}$$

The distribution characteristics of each variable in the database were evaluated by histograms and their measures of location and dispersion. Since most of the applied statistical analysis assumes normally distributed data (Güler et al., 2002), a studentized range test (n > 1 000 valid samples) for normality with a level of significance of 0.01 was performed. The studentized range test compares the ratio of the sample range and standard deviation to tabulated critical values (Pearson and Hartley, 1970). While NO3, Si and HCO3 follow a normal distribution, the following variables were log-transformed so they more closely correspond to a normal distribution: Na, Ca, Mg, K, Cl, Ca, SO4 and EC. These variables were used in the multivariate statistical analysis.

Multivariate statistical analysis

Hierarchical cluster analysis (HCA) has been proven to be an extremely powerful grouping mechanism (Güler et al., 2002 Lambrakis et al., 2004). Groundwater is classified into groups, which is a different grouping from conventional geochemical graphical techniques (e.g. Piper, Schoeller and Stiff diagrams). This different grouping is mainly due to the use of a much greater combination of chemical and physical parameters (e.g. temperature) to classify water samples.
Ward's linkage rule was used to analyse the distances among linkages for the entire group of observations and the squared Euclidean distances were used to determine the distance between observations. An HCA results in a graphical representation of the hierarchical grouping along with the corresponding rescaled distance to achieve the linkage (dendrogram). The clusters with the greatest increase in the rescaled distance are usually chosen as the final number of clusters. Cluster membership is then saved for each observation and group averages compared to the sample population average. Mapping of cluster membership is used to spatially interpret the identified structures in the geochemical dataset (chemical signatures).

3.3.1. Environmental and radiogenic isotopes

The use of environmental isotope techniques may, in addition to conventional investigation methods, provide further insight into the storage properties of the natural hydrological system and has become a routine in most hydrogeological studies in the last few decades. Isotopes act as natural occurring tracers in groundwater (commonly referred to as environmental tracers) which can provide valuable information on aquifer characteristics and groundwater flow paths to the hydrogeologist that would otherwise be difficult, if not impossible, to establish (Verhagen et al, 1991). A detailed discussion on the application of environmental isotopes in hydrogeology is available in Clark and Fritz (1997) and more recently in a special issue of *Environmental Geology* (Thomas and Rose, 2003).

Stable isotopes (deuterium (^2H), oxygen-18 (^{18}O))

During phase changes of water between liquid and gas, the heavier water molecules tend to concentrate in the liquid phase, which fractionates the hydrogen and oxygen isotopes. Water that evaporates from the ocean is isotopically lighter than the water remaining behind and precipitation is isotopically heavier; that it contains more ^{2}H and ^{18}O than the vapour left behind in the atmosphere. These isotopic ratios from an environmental sample can be compared with the isotopic ratio of standard mean ocean water (SMOW) (Hiscock, 2005). When δ^2H is plotted as a function of δ^{18}O for water found in continental precipitation, an experimental linear relationship is found that can be described by the equation (Craig, 1961):

$$\delta^2 H = 8\delta^{18} O + 10 \qquad (3\text{-}7)$$

This is known as the global meteoric water line (GMWL). The position of any pair of δ^2H and δ^{18}O values on this line for rainwater worldwide will depend on local climatological conditions (temperature, latitude, altitude, and rainfall amount effects) (Figure 3.2). After the infiltration of precipitation only physical processes such as diffusion, dispersion, mixing and evaporation alter the groundwater isotopic condition. Oxygen-18 (^{18}O) stable isotope is utilised to identify the recharge process and mixing of groundwater from different sources. Surface waters contain a distinct composition of stable isotopes due to enrichment caused by evaporation.

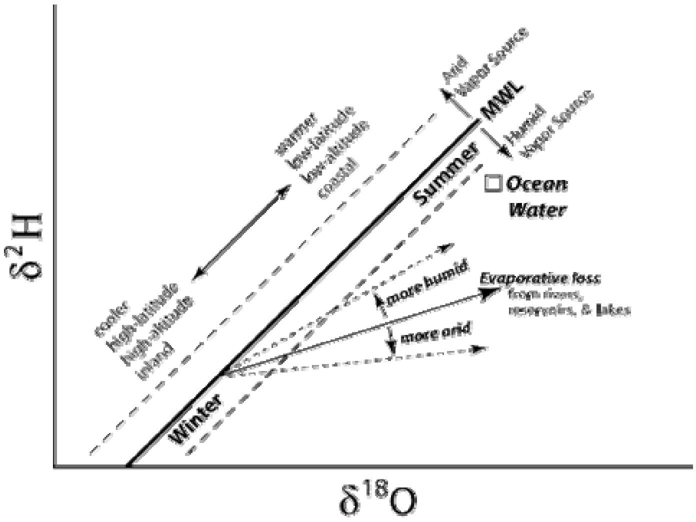

Figure 3.2. Summary diagram of the stable isotope composition from precipitation to percolation.

Radioactive Isotopes (tritium (^3H), radiocarbon (^{14}C) and carbon $\delta^{13}C$

Tritium (^{3}H) occurs as a result of man-made (thermonuclear devices) processes is a radioactive isotope of hydrogen having mass 3 and half-life of 12.38 years (Hiscock, 2005). The unit of measurement is the tritium unit (TU) defined as 1 atom of tritium occurring in 10^{18} atoms of H and equal to 3.19 pCi L^{-1}. Tritium in the atmosphere is typically in the form of the molecule H^1H^3O and enters the groundwater as recharging precipitation. When rainwater is isolated from the atmospheric source, i.e. during groundwater recharge, no new tritium is added and the tritium concentration will decrease with this characteristic half-life. The changes in atmospheric ^{3}H are monitored by the International Atomic Energy Agency (IAEA) through a global monitoring network. In Southern Africa, tritium levels in rainfall rose from initial (natural) values of about 5 TU to 60 – 80 TU as a result of fall-out of nuclear weapon testing in the early 1960's. Due to this tritium is an ideal isotope to be used for age dating of groundwater that recharged after 1952 (Pannatier *et al*, 2000). According to Weaver *et al*., (1999) tritium studies can provide semi-quantitative age determinations of groundwater:

- Water with zero tritium (< 0.5 TU) has a pre-1952 age.
- Water with significant tritium concentrations (> 5 TU in the southern hemisphere) is of post-1952 age.
- Water with little, but measurable, tritium (between 0.5 and 5 TU) seems to be a mixture of pre- and post-1952 water.

However, with half-life of 12.32 years and a decay rate of 5.626% per year have been reduced by a factor of 8 in the period from (1963 to 2000) (Mook and de Vries, 2001). With no further atmospheric nuclear weapons testing, tritium will continue to drop to near natural background levels. Therefore, usage of tritium for age dating groundwater recharge is reaching its limit and alternative tools, such as chlorofluorocarbons (CFCs) (discussion to follow) were devised over the last decade or so for quantifying modern groundwater recharge.

Radiocarbon occurs in the environment as a result of natural (cosmic radiation) and as with tritium; thermonuclear tests increased the atmospheric level of radiocarbon to peak in the early 1960's. Carbon dioxide CO_2 from the air is trapped in rain and snow and labelled with environmental ^{14}C. As this water infiltrates into the subsurface recharging groundwater it becomes isolated from the atmosphere. Radioactive decay causes the ^{14}C content in the dissolved inorganic carbon to gradually decline. Radiocarbon has a half-life of 8 270 years, making it a useful tool for "dating" groundwater up to an age of 50 000 years. In contrast to ^{3}H, ^{14}C is not strictly a conservative tracer of water, as numerous chemical processes can alter the ^{14}C / ^{12}C ratio (i.e. the dissolution of carbonate minerals). Based on the hydrochemistry and δ^{13}C values these unrealistic old radiocarbon ages can be corrected (Verhagen et al., 1991; Plummer and Sprinkle, 2001). The unadjusted age of groundwater can be determined by:

$$t = -8270 \ln\left(\frac{A}{A_0}\right) \qquad (3\text{-}8)$$

where:

t = the decay of the carbon isotope (years)
A = the activity per unit mass of sample
A_0 = the specific capacity (disintegration per unit time per unit mass of sample) of ^{14}C

Vogel (1970) suggested a rule of thumb initial ^{14}C recharge value of about 85% for many aquifers. In principle however, this initial value may be as low as 50% in carbonate aquifers, approach 100% in purely crystalline terrain and has to be assessed for each area. During the early sixties, atmospheric ^{14}C concentrations rose due to thermonuclear fallout and declined since. In qualitative terms, groundwater radiocarbon values of > 100 pMC can be interpreted as falling in the thermonuclear era, i.e. recharged over the past four decades. Mean residence times (MRT) can then be estimated on the assumption of the exponential model weighting function by considering observed ^3H or ^{14}C concentrations (Verhagen, 2000).

3.3.2. Chlorofluorocarbon (CFC) and sulphur hexafluoride (SF6)

Groundwater dating with chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF_6) is based on historical data for the atmospheric mixing ratios of these compounds over the past 50 years, their Henry's Law solubility in water, and measurement of CFC and SF_6 concentration in water samples (IAEA, 2006). The apparent age of a groundwater is then dependent on the Henry's Law constant calculated at the recharge temperature, which is generally taken to be equivalent to the annual average air temperature. Figure 3.3 shows concentrations of CFC-11, CFC-12 and SF_6 in pptV, respectively, expected in southern hemisphere (USGS, 2009).

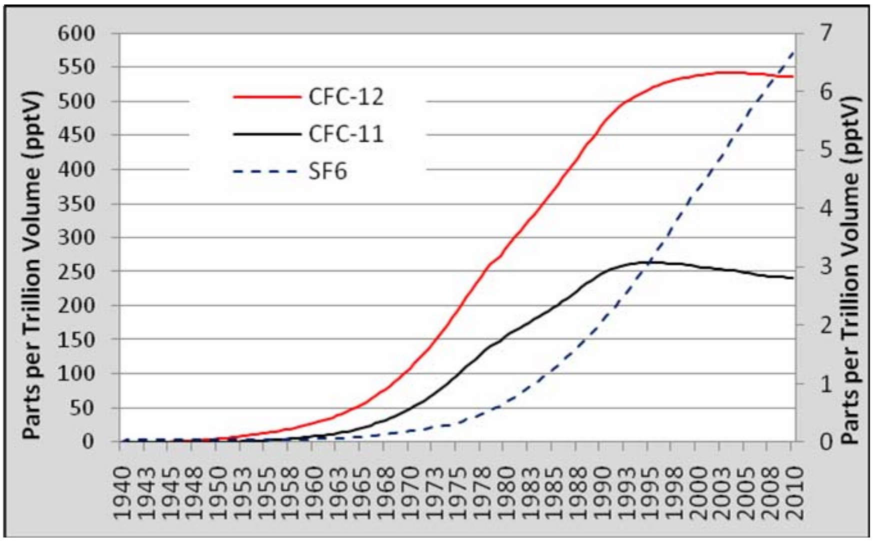

Figure 3.3. Atmospheric mixing ratios of CFC-11, CFC-12, and SF_6 for the southern hemisphere.

The International Atomic Energy Agency (IAEA) provides a detailed guidebook on the use of chlorofluorocarbons in hydrology (IAEA, 2006). The ratios of any two CFCs can provide useful information on the date of recharge of groundwater because the three CFCs of interest were introduced at different times and have different atmospheric growth rates. However, several assumptions are necessary in assigning an apparent groundwater age and are described in detail in the IAEA guidebook (IAEA, 2006). Contamination of groundwater with chlorofluorocarbons appears to be the greatest limitation on CFC dating (Gooddy et al., 2006). Some commonly recognized sources of CFC contamination include seepage from septic tanks, landfills infiltration or disposal of industrial wastes, and recharge from rivers contaminated with CFCs. One criterion for rejection of apparent CFC ages is that calculated CFC concentrations in air (in pptv) are greater than that possible for water in solubility equilibrium with air at the time of the peak in atmospheric concentration (IAEA, 2006).

Another important factor when considering the dating of groundwater with CFCs is to collect and analyse a water sample for CFCs that is representative of the aquifer at a given location. It is then assumed that the water sample was in solubility equilibrium with the unsaturated zone air at the time of recharge. Groundwater temperature may not be a reliable indicator of the recharge temperature and recharge temperatures are more precisely estimated from measurements of other dissolved gases, such as nitrogen and argon (Gooddy et al., 2006). However, nearly all groundwater samples have concentrations of noble gases in excess of Henry's Law solubility at the recharge temperature. The source of this excess has been attributed to 'excess air' and is probably a result of the forcible solution of air bubbles trapped in soil or rock as water infiltrates (Gooddy et al., 2006). Typically, the amount of excess air is determined by analysis of the concentrations of different noble gases or from the nitrogen/argon ratio in the sample (IAEA, 2006). When such measurements are available, it is possible to correct CFC ages for the presence of excess air. The content of "excess air" is often less than 2 cm^3/kg of water, but can be substantially higher in samples recharged along floodplains of rivers, or arroyos, or where recharge occurs through fractured rocks (Böhlke, 2006). As a result an excess air of between 1 and 5 cm^3/kg was assumed for samples collected.

Groundwater mixtures

CFC ages are generally based on absolute concentrations. As a result, when waters of different ages mix, the CFC concentration changes and so does the apparent age. When used together, CFCs and SF_6 can help to resolve the extent to which groundwater mixing occurs, and therefore provide indications of the likely groundwater flow mechanisms (Gooddy et al., 2006). Plots of one tracer against another can be useful in distinguishing hypothetical mixing processes. According to Cook and Böhlke (2000) four hypothetical mixing models can be typically used to describe some of the variation seen in groundwater mixtures: piston flow (PFM), exponential piston flow (EPM), exponential mixing (EMM) and binary mixing (BMM). Binary mixing of young water with old (pre-tracer) water is one of the simplest models to consider. The two principal geohydraulic conditions of groundwater flow are schematically shown in Figure 3.4.

In some cases, water reaching the open interval of a borehole or discharging from a spring is nearly uniform and can be approximated with a piston-flow model, analogous to water flowing through a pipe from the point of recharge to the point of discharge without mixing during transit. Exponential mixing can be used to describe discharge from an unconfined aquifer receiving uniform areal recharge. According to Gooddy et al. (2006) the exponential- piston model corresponds to a situation in which an aquifer receives distributed recharge in an up-gradient unconfined area, and then continues beneath a down-gradient confined area.

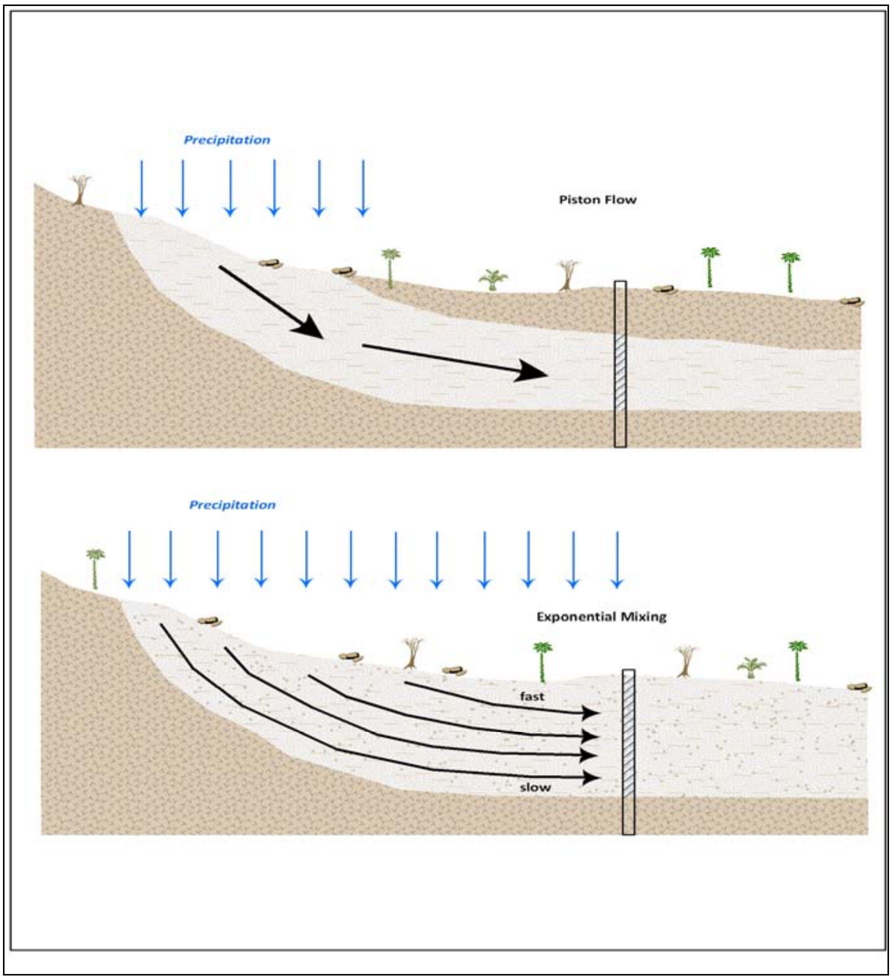

Figure 3.4. Two cases of groundwater movement by piston-flow in confined aquifers and flow in an open aquifer where different fast flowing water is mixed in the well or spring.

CFC sampling

The sampling procedure for CFCs is complicated and requires special sampling equipment to avoid atmospheric contact. CFC and SF_6 samples were collected unfiltered and without atmospheric contact in glass bottles contained within metal cans. The apparatus used ensured the sample is protected from possible atmospheric contamination by a jacket of the same water. Groundwater samples were collected from 11 boreholes in January 2004 using a submersible pump, with each purged for roughly 3 to 5 well volumes prior to the sample being taken (Photo 1). Samples were shipped to the British Geological Survey groundwater laboratory (Wallingford, UK) for CFC and SF_6 analysis.

Photo 1. Photograph of discharge hose, canisters and glass bottles used for the CFC sampling.

3.4. Hydraulic testing

By means of the pumping test, the hydraulic response to pumping is measured and analyzed with the objective to 1) characterise an aquifer, 2) quantify its hydraulic properties, and 3) determine the efficiency and sustainable yield. The type and duration of a pumping test depends on the planned usage of the borehole, but typical tests include a multiple discharge test (step-drawdown test), a constant discharge test and a recovery test. In crystalline aquifers short-term pumping tests (i.e. 24 hrs) may be adequate to predict the sustainability of an abstraction if the abstraction rate is small and the aquifer relatively uniform. However, the sustainability at higher abstraction rates can generally not be reliably assessed using short-term tests. The heterogeneous and discontinuous nature of crystalline basement aquifers requires generally long term testing (i.e. 1 to 10 days) preferably with a comprehensive monitoring network to determine whether groundwater levels will stabilize during abstraction.

3.4.1. Step drawdown test and well efficiency

Step-drawdown tests are basically made with the purpose to establish a relation between the yield and the corresponding drawdown in a well. In this regard the test is conducted to estimate the greatest flow rate that may be sustained by the pump well for the duration of the constant discharge. More importantly the efficiency and the realistic yield of a borehole can be assessed using a step-drawdown test in which the discharge rate Q is increased in a series of steps each lasting one to two hours; the drawdown in the well S_w at the end of each step is recorded. If there are no well losses, the drawdown increases linearly with discharge rate, but in most practical situations the drawdowns for higher discharge rates are greater than predicted by a linear relationship. Jacob (1947) proposed the non-linear relationship:

$$S_w = BQ+CQ^2 \qquad (3\text{-}9)$$

where:

B is the formation loss and *C* is the well loss coefficient. The values of B and C can be found directly from the diagnostic plot of S_w/Q versus *Q* itself; it will yield a straight line whose slope is equal to *C*; the value of *B* can be found by extending the straight line until it intercepts the Q = 0 axis. Under best conditions, an efficiency of about 80 % is the maximum that is normally achievable in most cased boreholes, while under less than ideal conditions, an en efficiency of 60 % is probably more realistic (Heath, 1983).

3.4.2. Identification of characteristic flow regimes (constant discharge test)

In pumping test analyses, the effects of different factors in the well, its immediate vicinity, in the aquifer and at the aquifer boundaries on the responses should be distinguished (Figure 3.5).

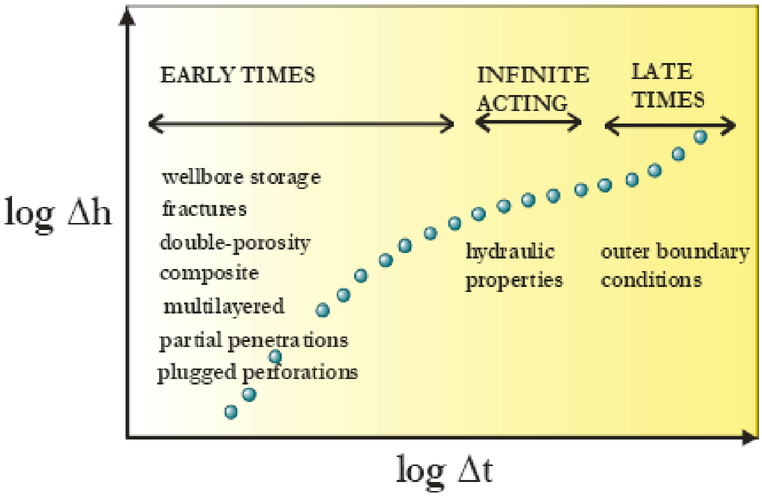

Figure 3.5. Illustration of early, intermediate and late periods of pump tests responses (Gringarten 1982 in Leveinen, 2001).

The distinction can be attempted made by applying a number of diagnostic plots. Diagnostic plots include:

- the drawdown s versus time t in a log-log plot (log s vs. log t),
- the drawdown versus the logarithm of time (semi-log plot: s vs. log t),
- the drawdown versus the square root of time (s vs. $t^{1/2}$),
- the drawdown versus the fourth root of time (s vs. $t^{1/4}$), and
- the time derivative of the drawdown versus the time in a log-log.

Plotting the observed drawdown from the dataset simultaneously with the log derivative can greatly enhance the identification of certain flow regimes and facilitates the selection of an appropriate model (Renard et al., 2009). The type of flow regime is not an intrinsic property of a fractured hard rock aquifer because it usually changes in time during a pumping test, which is reflected in the time drawdown behaviour at the pumped well and observation wells. A useful diagram presented by Ehlig-Economides et al. (1994) developed primarily for well tests in the petroleum shows in a synthetic way the behaviour of the derivative as a function of the main type of flow behaviour within a log-log plot (Figure 3.6). The diagram can be superposed to the data and shifted to identify visually and rapidly the type of flow that occurs during a certain period of the test.

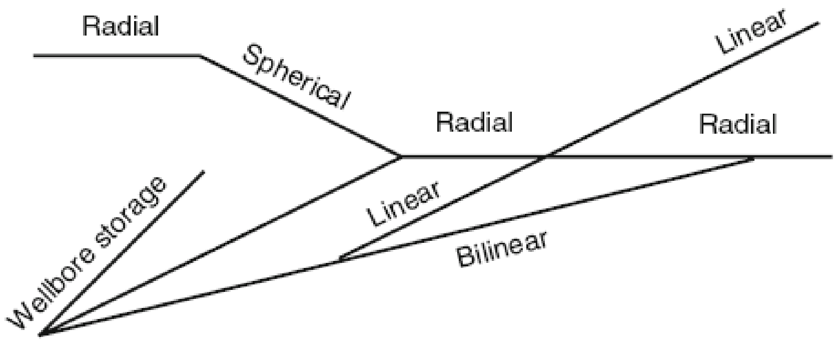

Figure 3.6. Flow regime identification tool representing schematically the log-derivative of drawdown as a function of logarithmic time (Ehlig-Economides et al., 1994 in Renard et al., 2009).

Another useful illustration to identify the characteristics that can be obtained from the derivative graph was developed by Van Tonder et al. (2001) (Figure 3.7).

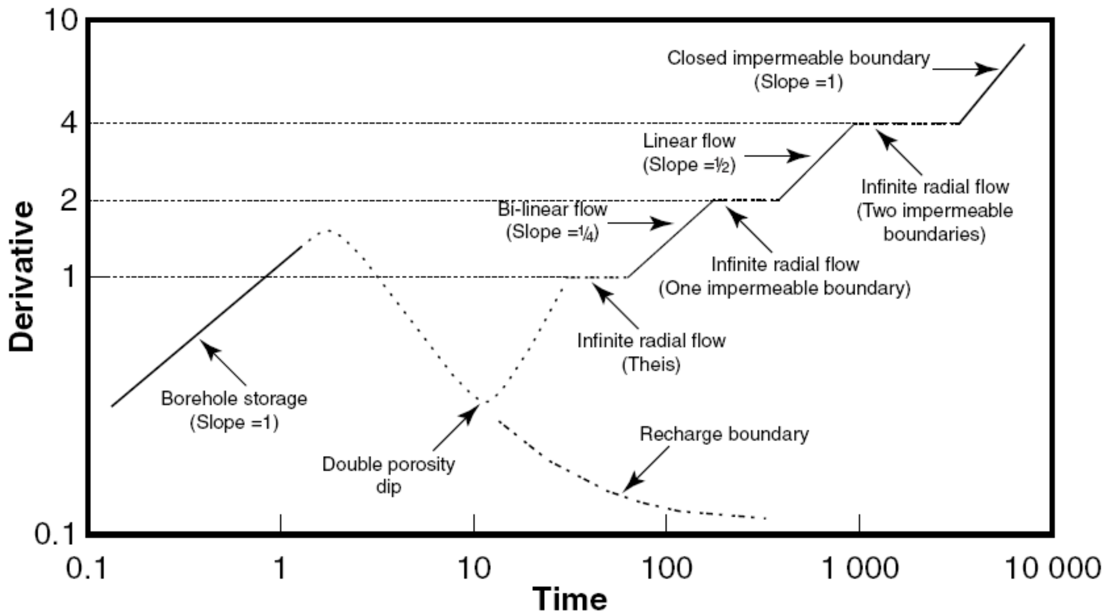

Figure 3.7. Graphs of the first logarithmic derivative of the drawdown in a borehole for a few types of geometries and boundaries (Van Tonder et al., 2001).

All characteristics of the log-log time-drawdown straight line slopes remain the same, and provide the following information. A summary of the theoretical methods applicable to weathered-fractured rock systems is presented in Table 3.1.

Table 3.1. Methods of recognizing observed flow character[illegible]ystalline basement aquifers.

Aquifer Type/*Characteristic*	Flow regime	Diagnostic plots			Typical theoretical model (see section 2.4.3)
		Semi-log	*Log-log*	*Derivative {special }*	
Homogenous, isotropic	radial	straight	(Theis-type)	stabilises	Theis (1935) / Cooper and Jacob (1946)
Leaky		*	*	decrease	Hantush and Jacob (1955) Moench (1985)
Unconfined		*	typical S-shape	slight dip (early times) stabilises	Neuman (1972, 1974).
Double porosity	linear or Bi-linear (early times) radial	two parallel straight-line sections	typical S-shape	characteristic dip stabilises	Warren & Root (1963) Moench (1984)
Single vertical fracture or dyke	linear flow (fracture)	reverse C-shape	straight line, slope 0.5	straight line, slope 0.5	Cinco-Ley and Samaniego (1981) Boonstra & Boehmer (1986)
	bilinear		straight line, slope 0.25	straight line, slope 0.25 {**s vs t**$^{1/4}$: straight}	
	linear (formation)		straight line, slope 0.5	straight line, slope 0.5 {**s vs t**$^{1/2}$: straight}	Gringarten et al. (1974)
	pseudo-radial	straight line		stabilises	Theis (1935) / Cooper & Jacob (1946)
Single horizontal fracture	storage	*	straight line with 1 slope	*	Gringarten and Ramey (1974)
	linear		straight line with 0.5 slope	straight line with 0.5 slope	
	pseudo-radial	straight line	*	stabilises	
General radial flow	n < 2 (linear)	*	*	positive slope	Barker (1988)
	n > 2 (spherical)			negative slope	
Fracture dewatering	-	flattening at fracture position		characteristic hump(s) (intermediate to late)	
Closed no flow boundary		tripling of slope	-		Kruseman and de Ridder (1990)
Recharge boundary		Decrease in slope		strong downward trend	

* - Refer to Figure 2.4 in section 2.4.1 for the typical drawdown behaviour observed for these models.

3.4.3. Pumping test interpretation

To advance the conceptual understanding of basement aquifers behaviour in response to pumping, over 2 359 semi-log, log-log and derivative plots from the GRIP dataset were visually interpreted with the aim of establishing the various conceptual aquifer models observed in the region. The data were analyzed with the software package AQTESOLV Pro version 4.5 using automatic curve fitting or manual fitting of late time data with the appropriate analytical solution/conceptual model (i.e. confined, unconfined, leaky and fractured aquifers). The aquifer and well parameters were obtained from the inverse curve-fitting procedure. The following procedure for the analysis of pumping test data is proposed for the Limpopo crystalline aquifers (modified after Bäumle, 2003):

- Ensure proper planning and execution of a pumping test (i.e. ensure constant pumping rates, insufficient drawdown, poor monitoring) to obtain representative results
- Develop a conceptual understanding of the geological setting (use geological map etc. if no field visit is done) of the test
- Create the diagnostic plots from pumping test data and define the flow regime according to 1) the summary provided in Table 3.1, 2) the type-curves in Figure 2.4 (see section 2.4.1), and 3) the graphical illustrations in Figure 3.6 and Figure 3.7).
- Choose the appropriate analysis method(s) and determine the aquifer and well parameters from the curve fitting of the drawdown and the recovery data. In principle, the best match of the measured time-drawdown data to an analytical solution has to be found by either a graphical or computer-operated method.
- If different flow regimes can be identified during a test, each section can be evaluated using the corresponding analysis method (i.e. stabilising of the derivative can indicate the state of infinite acting radial flow (IRF) and the late time data can be evaluated with traditional methods such as Theis (1935).
- The analytical solutions for fractured aquifer systems contain two fitting parameters 1) representing the aquifer matrix, and 2) the fracture (conduit).
    - The geometric properties of the fracture such as the fracture half-length can be obtained or verified from geological or geophysical investigations.
    - The hydraulic parameters of the aquifer matrix can be evaluated from hydraulic tests which are not influenced by the lineament (i.e. IRF phase).
    - By inserting these values, the equation describing the fracture type flow regime can be solved for the remaining parameters.
- Drawdown influenced by fluctuating pumping rates should rely on an accurate description of the recovery data. The recovery of a pumped aquifer can be interpreted in the same way as the drawdown by using diagnostic plots. Through a simple transformation of the time variable, Agarwal (1980) devised a procedure that uses solutions developed for drawdown analysis (i.e. the Theis type-curve) to analyze recovery data.

3.4.4. Recommending a long term yield for a single borehole

Although Van Tonder et al., (2001) recommend a very conservative approach for the estimation of recommended yields (i.e. assuming no recharge), the use and application of the FC-spreadsheet is often not understood. The inspection of the diagnostic plots to assess the drawdown behaviour and to identify the theoretical model needed in the analyses, should supplement the recommend borehole yield estimate. All of these conventional time drawdown analysis is accessible in the FC-spreadsheet. As discussed in the beginning of this chapter (see section 3.1.1) the GRIP dataset is an existing dataset and no attempt was made to re-analyse the over 2000 pumping test analysis.
Another major shortcoming identified in the GRIP dataset is the lack of observation monitoring conducted during pumping tests. Single borehole tests generally will not identify impermeable boundaries, recharge boundaries, or interconnection between other groundwater and surface water unless these conditions exist in very close proximity to the well being tested.

3.5. Assessment of factors controlling the occurrence of groundwater

Statistical evaluations are commonly used to identify correlations between borehole yields and physical features which can be observed. These features (or factors) can be divided into the following components:

- Geological or lithological (comparison of yields obtained from various rock types and geological settings).
    - Regolith thickness (correlation of borehole yields with thickness of weathering).
- Terrain, geomorphological or hydrological features (includes correlations of borehole yields with respect to relief, erosion surfaces and surface water drainages).
- Structural correlations (asses the relationship between yields and proximity to lineament in addition to the lineament azimuth).

Cumulative frequency plots of borehole yield and transmissivity (or specific capacity) are able to characterise the regional occurrence of groundwater. With the advances of Geographical Information Systems (GIS) techniques, an integrated and conjunctive analysis of large datasets (spatial and non-spatial) over vast areas is possible.

3.5.1. GIS analysis

Analysis of large datasets in regional studies requires the application of Geographical Information Systems (GIS). The visual representation of the associated geographic phenomena together with their spatial dimensions and their associated attributes provides a rapid, integrated and cost effective tool in any groundwater investigation. To study the influence of different factors like the topographical setting on transmissivities and borehole yields, a hydrogeological database was created in ArcGIS using the 1:250 000 geological and 1:50 000 topographic vector files as well as borehole coordinates. With this approach it is possible to extract spatial information based on the location of a borehole (i.e. geology, proximity to a lineament, dyke or river course etc.) (Holland and Witthüser, 2009). Boreholes were then grouped according to their location and the corresponding arithmetic mean values of transmissivity and yield calculated. The level of confidence (significance) that a mean of a sub-group deviates from the total population mean is based on a one-sample Student t-test. In testing the null hypothesis that the population mean is equal to a specified value μ_0, one uses the statistic

$$t = \frac{\bar{x} - \mu_0}{s / \sqrt{n}} \qquad (3\text{-}10)$$

where s is the sample standard deviation of the sample and n is the sample size.

Boreholes within a 100 m buffer zone along major river courses were regarded as representing alluvial aquifers. Similarly a 500 m buffer (in- and outside of the mapped features) was used to present the metamorphic aureole that developed during the granite intrusion of the batholiths. The topographic setting of a borehole (along river, valley, flat surface, slope and mountain) was based on drillers' reports and the depth of weathering was derived from almost 600 boreholes with detailed geological logs. These logs are based on the drill chips captured at 1 m intervals during drilling. The logs were also used to indicate whether diabase or dolerite was encountered during drilling, representing the intersection of a dyke. Dykes were furthermore inferred from the interpretation of aeromagnetic data from the South African Council for Geoscience (CGS). The magnetic nature of the dykes makes aeromagnetic data ideal for mapping these features and most magnetic lineaments identified on aeromagnetic maps are therefore associated with dyke swarms (Stettler et al., 1989).

3.5.2. Lineament analysis

The use of lineament mapping, especially in crystalline lithologies with poor primary porosity, is of major importance for groundwater exploration and was incorporated into the GRIP framework by the Department of Water Affairs (DWA) for the Limpopo Province. The mapping and interpretation of lineaments is conducted by geological remote sensing consultants on behalf the DWA Limpopo regional office. The satellite imagery used for the capturing of lineaments is from the medium resolution ASTER (Advanced Spaceborne Thermal Emission and Reflectance) missions. ASTER data is a good choice for groundwater development projects, due to their large spectral resolution, reasonably high spatial resolution, ability to derive DEMs and low cost of acquiring the imagery (Sander, 2007). The mapping of lineaments in the Limpopo Province takes place in a digital environment using GIS and is mapped at a scale of 1:50 000. These interpreted lineaments may reflect a number of features such as faults, fracture zones, joints, foliations, dykes (not interpreted as dykes), lithological contacts and linear branches of the drainage systems. According to Braathen and Gabrielson (1998) a large lineament can enhance fracturing up to 300 m away while Clark (1985) suggested that the area of influence might be less than 150 m and Fernandes and Rudolph (2001) reduced it further to 70 m in their studies. Considering the spatial margin, all boreholes within 150 m of a lineament were considered to be targeting a lineament in this study.

It is recognized that lineament mapping is often subjective (Mabee et al., 1994, Sander, 2007) and that a two-dimensional lineament of geological origin, mapped on remote-sensing imagery, provides little direct information on the type of feature, its depth, dip or potential infilling (Sander 2007). However, the extent to which these lineaments influence or relate to borehole productivity in the Limpopo Province has not yet been assessed. In this regard this investigation can be regarded as an initial regional assessment of the potential relationship between mapped lineaments and borehole productivities from which future studies could improve on.

3.5.3. Geophysical methods

Individual boreholes will still need to be sited carefully, and this is usually done by means of geophysical techniques. Three basic principle surface geophysical methods were used to confirm regional lineaments and to pinpoint drilling targets, which include electrical resistivity, electromagnetic and magnetic methods. One way to improve a geophysical interpretation and the confidence in borehole siting is to combine the use of maps, field observations and geophysics in a method known as geological triangulation (MacDonald et al., 2005) (Figure 3.8).

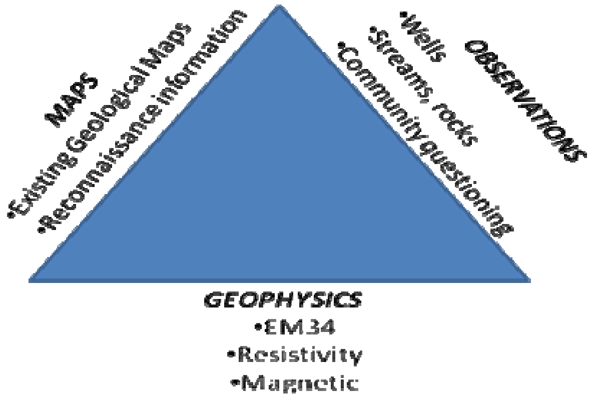

Figure 3.8. The geological triangle method (MacDonald et al., 2005).

3.6. Development of a regional conceptual model

The development of a conceptual hydrogeological model is the single most important step in managing an aquifer. The knowledge obtained from the hydrogeological assessments described in this chapter provides us with a conceptual understanding of the occurrence of groundwater and the typical behaviour of the aquifer to pumping in the crystalline aquifers in the Limpopo Province. In return this could assist groundwater managers with better decision making on groundwater exploration targets, improved aquifer parameter estimation and higher confidence in borehole yield recommendations. The development of a conceptual understanding should be an iterative process, being updated as new data become available or as the understanding of the system is improved.