STATUS GROUNDWATER EXPLORATION IN GEOLOGICALLY COMPLEX AND PROBLEMATIC TERRAIN – GUIDELINES

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Groundwater Exploration In Geologically Complex And Problematic Terrain – Guidelines (Volume 1)

by

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Final Report to the Water Research Commission for the Project "Groundwater Development For Rural Water Supply In Complex And Problematic Terrain: An Assessment Of Geological Controls, Geophysical Exploration Methods And The Quantification Of Exploitation Potential"

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EXECUTIVE SUMMARY

1. Background

The Department of Water Affairs and Forestry has identified the provision of sustainable water and sanitation services to all as being one of its top priorities (DWAF, 1994). The challenge of providing developing rural areas in South Africa with sufficient potable water is substantial, especially where settlement is not densely concentrated and the ability to pay is low. The water requirements of these settlements can be met most cost-effectively from groundwater. The provision of these regions with sufficient potable water is complicated by the large backlog in water delivery, which results in pressure for rapid service delivery at the expense of time-consuming groundwater exploration methods.

Previous studies (King, 1997) have shown that some of the greatest water needs occur in regions underlain by fractured basement aquifers with complex hydrogeology and where the exploitation potential of groundwater has been thought to be low due to historically low drilling success rates or the high frequency of low yielding boreholes. Groundwater exploration success rates in these environments have been relatively low due to inappropriate exploration or interpretation methods resulting from an incomplete understanding of the geohydrology.

The current paradigm of groundwater exploration in South Africa, as well as in many other places in Africa, is based on a geophysical approach, where most boreholes are sited on anomalies identified from magnetic or electromagnetic traverses, often with little or no understanding of the structural geology of the target area. In many areas of complex hydrogeology this technique has proved to be unsuccessful for a variety of reasons. Specific causes that have been identified include:

* an inadequate understanding of the occurrence of groundwater and the factors affecting permeability in these terrains, leading to inappropriate exploration planning;
* siting of boreholes on geophysical anomalies without a conceptual understanding of the geological framework and how it affects the geophysical response, or siting boreholes without an adequate interpretation of the geophysical data;
* the use of only one geophysical method, which makes the interpretation of anomalies difficult or unsubstantiated;
* the use of inappropriate geophysical methods for the specific terrain; and
* inappropriate or insufficient quantification of the sustainable yield of boreholes due to inadequate test pumping procedure or analysis methods.

As the demand for groundwater grows and the more obvious aquifers and target features become increasingly exploited, it can be expected that further development will have to consider alternative targets in such problematic and complex fractured geological environments. Significant savings in exploration and especially drilling costs can be realised if success rates could be improved. However, it is essential not to consider exploration in isolation from resource evaluation. If these complex terrain's are to be developed in a sustainable manner, the importance of quantifying groundwater resources will be magnified due to the their low potential.

To improve the borehole success rate in these terrains, and to develop groundwater resources in a sustainable manner, a multi-disciplinary approach is needed. This approach must incorporate:

1) an understanding of the structural geology and its influence on the occurrence of groundwater so that target features can be identified;
2) the identification of appropriate methods and interpretative techniques to delineate target features in the field;
3) and the use of simple yet effective groundwater resource evaluation methods.

The Council for Geoscience undertook this project to re-evaluate the groundwater resources of some of these regions using a rigorous scientific approach, with the objective of establishing a more successful exploration strategy.

A multidisciplinary approach was followed where structural geological mapping, tectonics, strain analysis, LANDSAT image interpretation and geophysical methods were combined to unravel the geodynamics of a region and to identify geological structures where groundwater could be located. These methods include:

1) the identification and categorisation of lineaments observed on LANDSAT using various digital filtering techniques into strike-frequency and strike-length plots to identify preferential structural orientations;
2) structural mapping on a regional scale to identify tectonic processes given the geological and deformation history;
3) structural mapping of joints on an outcrop scale to identify compressional and extensional orientations through strain analysis; and
4) geophysical exploration of identified potential water bearing structures using magnetics, resistivity and electromagnetics.

Data collection for exploration is often costly and time consuming, hence it is important that any proposed techniques be fully analysed to determine their practical viability. Consequently, a financial analysis of the proposed methodology is presented, demonstrating that, although exploration costs of the adopted approach are higher, the ultimate establishment costs per successful water point and the costs of the water are dramatically reduced compared to conventional methods due to greatly improved success rates and significantly higher yields. These results suggest that it is cost effective to undertake groundwater exploration in a scientific manner, whether only successful points are required for hand pumps, or where high yields are required for reticulated motorised schemes.

From these results, a suggested method for exploration has been formulated to assist with undertaking regional exploration programmes.

2. Research Objectives

The primary objective of this project is to investigate the development potential of groundwater in problematic or complex terrain where the demand for water for rural communities is expected to grow, and to develop guidelines for groundwater exploration and development in these environments. The supporting objectives are to:

- investigate the occurrence of groundwater and the geological and structural controls that distinguish high yielding features from those that have low potential;

- evaluate the ability of currently used geophysical methods to distinguish or delineate target features;
- quantify the exploitation potential of groundwater and evaluate methods for estimating sustainable aquifer and borehole yields;
- and to develop guidelines for groundwater exploitation in these environments.

The geological evaluation of target features and the guidelines for groundwater exploration will assist water practitioners with siting boreholes and interpreting geophysical data. Furthermore it will reduce the use of inappropriate geophysical methods and/or the siting of boreholes based on an incorrect geophysical interpretation. This will reduce the frequency of incorrectly sited boreholes and increase the drilling success rate.

The evaluation of methods to estimate sustainable yield will assist consultants and implementing agents with planning pumping tests and recommending pumping rates so that groundwater abstraction does not exceed sustainable yield of the aquifer.

3. Research Areas

Field data is provided from 4 study areas in South Africa. The four research areas were selected on the basis of the following criteria:

The area is densely populated rural region with underdeveloped infrastructure and services and has been identified as a critical water deficit area by DWAF.

Water scarcity is a serious problem and the area and relies mostly on springs, rivers, hand-dug wells and some boreholes. Groundwater would be a preferred water option in the area because of its generally availability even in drought situations and its relatively good quality.

The areas are underlain by fractured bedrock aquifers where success rates and borehole yields have been historically low, yet high yielding holes are present suggesting that suitable hydrogeological target features do exist.

The areas which have been studied include: the Natal Metamorphic Province of the KwaZulu-Natal south coast in the vicinity of Mapumulo; regions underlain by thick Dwyka Group rocks inland of the south coast in the vicinity of Harding; the greenstone belt of the Barberton Supergroup in the vicinity of Tjakastad, and the basement rocks and greenstones of the Limpopo Mobile Belt in the vicinity of Alldays.

4. Dwyka Group

The area of investigation is situated immediately north of the Transkei border, about 12 km southeast of Harding in KwaZulu-Natal. Water demand in the study area is primarily for domestic purposes and partly for small-scale agricultural activity. Currently, water supply needs are met mostly from upland springs, rivers in the valley bottoms, and boreholes equipped with hand pumps. However, groundwater could play an important role, as it is a reliable water source, even in drought situations, and is generally of good quality compared to other water sources in the area. Water supply provision is complicated by the fact that settlement is concentrated on hill tops and extremely limited access exists to low lying areas, where a more assured water supply could be located. The extreme topography, however, would create static pumping heads of over 300 m; hence, groundwater exploration is predominantly restricted to the hill top regions.

The tillite has a very low permeability and forms a cover of up to 450 m thickness in the area, which prevents drilling through the formation into a more consistent aquifer. This fact is reflected in the very poor historical success rate in the area, with 84 % of the holes being dry.

These unfavourable hydraulic properties explain the relatively low yield of the aquifer. An average blow yield of 0.14 l/s can be expected in wet boreholes; however, this is not sustainable on a continuous basis since fractures in the area are seldom interconnected. Hence long-term sustainability is limited for all but very low pumping rates. The investigations suggest that high yielding boreholes can only be found at sites where several interconnected fractures exist to enlarge the general low permeability of the formation. The massive nature of the rock and the brittle calcite filled fractures suggest that the formation may be a candidate for hydrofracturing to increase yields and fracture connectivity.

The research study showed that successful groundwater exploration for the area is possible, but should be limited to establish hand pump schemes. In addition, the water quality of the Dwyka tillites is suitable for domestic consumption. An evaluation of the structural geology and the hydrogeological conditions of the area together with a suitable geophysical method for the environment pushed the drilling success rate up from a historical 12 % to 50 %. The unfavourable hydraulic properties of the tillite however, limit the yield of holes and median yields of successful holes could not be increased. Therefore, groundwater abstraction in the area will mostly be restricted to exploitation through hand pumps to support small communities. High yielding boreholes are seldom encountered and can only be found at major fault zones where interconnected fracture zones are present to distinctively enlarge the permeability of the subsurface. These are located at the margins of the Dwyka Group.

5. Natal Metamorphic Province

The Natal Metamorphic Province underlies 15% of all rural areas in KwaZulu-Natal and therefore underlies more of the rural areas than any other lithological province. It is also relatively densely settled. The research area is situated in the Mapumulo District of KwaZulu-Natal, about 30 km northwest of Stanger and 75 km north of Durban and extends over approximately 1300 km^2. The area is bounded by steep sandstone cliffs to the east and west, while the Tugela thrust belt forms the northern boundary.

Water in the study area is used for domestic purposes and partly for small-scale agricultural activity. Currently, water supply needs are mostly met from rivers and springs, with boreholes equipped with hand pumps playing a secondary role. However, groundwater could play an important role, as it is a reliable water source, even in drought situations and is generally of good quality compared to other water sources in the area. Settlement varies from dispersed and isolated kraals to dense settlements in communities.

The rocks of the Natal Metamorphic Province are characterised by negligible primary porosity and groundwater movement is primarily within hard rock aquifers and controlled by zones of deep weathering, faulting, fracturing and jointing. Accordingly, water strikes or seepage encountered in the exploration boreholes drilled during the investigations are either associated with the contact between weathered and solid bedrock, or deep-seated fracture zones of low permeability but high confining pressure. There is no evidence of any additional aquifers at contacts between different lithologies, suggesting that tectonic contacts are more relevant than lithological contacts. Lithological variations are more significant in terms of water quality, with poorer water quality having been recorded in schists and granites (King, 1997).

The area exhibits a poor historical success rate with about 46% of the holes being dry. Borehole yields are generally low with only 23% giving a yield greater than 1 l/s, however in this study greater than 75% of boreholes yielded more than 1 l/s. These reported borehole yields are mainly derived from blow tests and seldom from a long duration test. Therefore the percentage of boreholes with a sustainable yield exceeding 1 l/s is likely to be much lower. Dry boreholes as well as high yielding holes have been drilled into all lithologies and are not restricted to any specific rock type; poor and high yielding holes occur within the same lithology and give evidence that structures of tectonic origin are a major factor influencing groundwater occurrence.

During the Critical Intervention Programme, where only geophysical siting was used, 37% of 27 boreholes drilled in the study area were dry and only 2 had blow yields exceeding 1 l/s. The median yield of successful holes was 0.1 l/s. This study achieved an 89% success rate, with 7 of 9 boreholes exceeding 1 l/s and a median yield of between 1.8-3.3 l/s. This suggests that the aquifer can be reconsidered in terms of reticulated water supply if a scientifically appropriate exploration strategy is adhered to.

The research showed that successful groundwater exploration for the area is possible. An evaluation of the structural geology and the hydrogeological conditions of the area together with a suitable geophysical method for the environment pushed the drilling success rate up from a historical 54% (NGDB) and 63% (Critical Intervention Program) to 89%. Beside the improved success rates, the research did result in significantly improved yields. Whereas the median yield for the NGDB and CIP records is 0.1l/s, a median yield of 1.8l/s was achieved with the applied exploration method, which accordingly lowers water production costs considerably. The average yield of all boreholes was pushed up from a historical 0.96l/s to 2.55l/s.

6. Limpopo Mobile Belt

The research area is situated near the northern border of the Northern Province in the Limpopo River catchment and is underlain by rocks of the Limpopo Mobile Belt (LMB). This geological province is an E-W elongated low lying belt straddling eastern Botswana, southern Zimbabwe and the northern part of the Northern Province in South Africa. Two study areas were selected within the belt, one situated in the northern Bochum District west and southwest of Alldays (study area I), and the other (study area II) is located in Messina District east of Messina (Figure 6-1). Study area I is characteristic of the western part of the LMB, where a quaternary sand cover overlies the metamorphic basement rocks. Rock outcrops are few and the topography is level. Study area II represents the situation in the eastern part of the LMB, where the basement rocks are exposed at surface, with rare occurrences of quaternary cover.

The area exhibits a poor historical success rate with <40%of boreholes yielding water yielding more than 0.1 l/s. Borehole yields fall mainly in the category between 0.01 and 1 l/s (69% study area I and 45% study area II), with the median yield of successful boreholes being only 0.39 l/s. Only 13% of boreholes yield more than 2 l/s. Dry boreholes as well as high yielding boreholes have been drilled in all lithologies and are not restricted to any specific rock type.

The aquifers of the Limpopo Mobile Belt are predominantly structurally controlled and significant water movement is restricted to major fracture and fault zones, primarily related to recent (Post Karoo) geodynamics. These structures can be extremely high yielding and can generate blow yields in excess of 20 l/s. In many instances the distance to streams and rivers is indicative of a fault zone, since many rivers tend to follow structures when they deviate or dogleg from the northerly surface topographic gradient. The highest yielding boreholes are drilled into ENE striking features, the orientation considered as extensional in nature.

However, the scale of the feature shows a strong influence on the yield of the boreholes, with regional scale fault having a far better groundwater potential than local scale structures.

The results suggest that the Limpopo Mobile Belt is a poor aquifer due to marginal to poor water quality (class II-III) related to nitrate levels, low recharge and the extreme heterogeneity in targets. Low success rates exist concurrently with very high yielding features; however, these are restricted to mainly regional scale fault zones. Smaller fault zones and alluvial cover along the streams provide a more limited aquifer. Consequently, water abstraction will have to be reliant on regional abstraction systems from identified structures and reticulation to the point of need. Fortunately, the flat topography does not hinder reticulation.

7. Barberton Greenstone Belt

The study showed that an evaluation of the structural geology and the hydrogeological conditions of the area together with a suitable geophysical method for the environment pushed the drilling success rate up from a historical 50% (NGDB) to 89%. Beside the improved success rates, the proposed methodology resulted in significantly improved yields.

A substantial cut in costs in terms of water production expressed as R/l/s was achieved during this exploration programme. Historic success rates have resulted in an expenditure of approximately R24200 for the establishment of each successful borehole. In comparison, with an exploration budget of about R55000 for the proposed methodology, success rates of 89% can be expected and establishment costs would come down to about R19875 per successful borehole.

Median yields were increased from 0.4 l/s to up to 1.0 l/s, which brings down the costs of water production from 60500 R/l/s in case of random drilling to 18370 R/l/s in this project. The high median yield achieved during this project suggests that water supply systems in the area could involve reticulated systems.

Groundwater is an important resource in the study area, providing a clean, reliable, low cost water source. The geology of the area consists of impermeable granites and meta-basalts metamorphosed at a low-grade amphibolite schist to green schist facies. Fractures in the granites have been intruded by extensive quartz veining, which renders them relatively impermeable and makes them poor targets for groundwater exploration. The meta-basalts are the best targets for groundwater exploration, especially where fracture zones associated with faults and dykes are present.

Dip-slip and strike-slip faults were water bearing and are associated with the formation of deep open cavities that enhance the permeability of the greenstones. The geodynamic and strain analyses suggest that structures having a NNE – SSW strike direction are more likely to be under extension and therefore open, hence they are the primary hydrogeological targets. The E-W striking lineaments are more likely to be strike-slip faults and are also the hydrogeological targets if the target is not a shear zone where gouge material has reduced permeability. The N-S lineaments are expected to have high yielding holes as well, but only if the targeted lineament is a fault, however, this was not proven by the drilling results.

8. Guidelines for Exploration in Complex Terrain

Potential hydrogeological targets are often selected based on a hydrocensus and/or a geological review of existing geological maps. Boreholes are subsequently sited using ground-based geophysics, with the EM-34 and magnetometer being the most widely used methods. This approach has been widely used in the study areas investigated, and has been shown to be relatively unsuccessful and uneconomical when compared to the results that could be achieved by a more integrated and geologically focussed approach. However, using data from the Critical Intervention Programme in KwaZulu-Natal, where the above mentioned geophysical approach was adopted, the geophysical approach has been shown to be more economical than historical success rates, however, median yields were NOT increased. The major disadvantage of this method is that the nature of the hydrogeological targets is rarely understood, neither are the structural and geological stress conditions that control the orientation of structures, which in turn control the distribution of groundwater yield. Consequently, the method is commonly no more than 'anomaly hunting', with geophysical anomalies being attributed to potential weathering profiles, intrusive contacts, or potentially water bearing fracture zones that are assumed to be hydrogeological targets. Often little is known about variations in rock mineralogy, the presence of clay gouge in shears, or the existence of complex folding of the rock fabric, all of which could result in geophysical anomalies. These conditions result in geophysical anomalies over features that are not hydrogeologically significant or even water bearing. In addition, little is known about the regional extensiveness of potential targets or current structural stresses that determine whether the feature is hydrogeologically significant.

The addition of remote sensing to the exploration toolbox allows the regional extensiveness of targets to be identified. LANDSAT TM images or aerial photos assist with identifying potential geological lineaments that are regionally significant so that ground based geophysics can be more intelligently directed towards the location of specific targets. However, such lineaments are not always structurally significant, and the geological stresses responsible for the features are not understood, hence their ultimate water bearing potential is unknown.

A study of the tectonic history and the geodynamics of a region offers the advantage of providing a framework for identifying targets that are hydrogeologically significant based on the understanding of current stress conditions. Consequently, structurally significant lineaments can be identified and geophysical exploration restricted to targets considered to be of greatest potential.

Hydrocensus

Objective

The objective of a hydrocensus is to hydrogeologically characterise a region in terms of the physical and economic feasibility of meeting water demands through groundwater by quantifying:

- Expected borehole yields and their variability by geological domain
- Historic drilling success rates and probabilities of exceeding specific yields
- Proximity of boreholes to geological structures and their yield
- Depth to water strikes
- Static water levels
- Groundwater chemistry
- Potential hydrogeological targets

These investigations should attempt to determine the number of boreholes that will be required to meet water demands, the role of geological structures on yield, the depth to which boreholes should be drilled, and the suitability of water quality for the desired usage.

The location of high yielding boreholes may also assist in identifying targets that are potentially high yielding.

A hydrocensus should ideally also consider geological processes or mineralogies that may negatively impact on groundwater quality in the long term. Critical factors, such as the presence of volcanic massive sulphide deposits, hydrothermal alteration, carbonaceous shales, carbonatites etc., may be indicators of the presence of heavy metals, light metals and non-metals, heavy non-metals, halogens, alkaline earths, rare earths and noble metals that may pose a significant long term health hazard. These elements may be present in the rock but not observed in water samples from recently drilled boreholes; their mobility may be controlled by oxidation-reduction conditions that alter with time. A typical example is arsenic, which is prevalent in South Africa as arsenopyrites, but whose mobility is controlled by oxidation state. Consequently, its presence would only begin to appear in water samples after variations in drawdown due to pumping have introduced oxygen into the formation, resulting in oxidation and weathering.

Methodology

The hydrocensus is conducted by collecting data from the National Groundwater Data Base and previous hydrogeological investigations and subsequently overlaying the data onto existing geological maps using a GIS. The specific processes are:

- Inputting hydrocensus data into a GIS database, such as ARCVIEW, and creating layers for lithology, structures, yield, static water level, water strike depth and water quality
- Characterising domains by using domain boundary polygons to separate borehole data with similar hydrogeological attributes
- Determining the percentage of dry boreholes, and the variability in yield distribution of successful boreholes for each domain
- Determining the optimum drilling depth for each domain based on the depth below which few boreholes encounter water
- Identifying domains where poor water quality precludes water use by categorising median water quality
- Identifying geological indicators of potential geochemical hazards
- Performing a proximity analysis of yield versus distance from known structures to identify important structures and the importance of structures on borehole success.

Tectonics and Geodynamics

Objective

Geodynamic investigations require that the tectonic history of the target be unravelled so that mapped, identified or presumed structures and lineaments can be explained in terms of historic and present day geological strain. Depending on the age of the rocks and the structural complexity, this process may involve extensive literature review on the crustal evolution of the region. Since these processes are of a large scale, investigations often are much broader than the study area. For example, an understanding of the geodynamics of the Natal Metamorphic Province requires a comprehension of Archean craton movement and offshore transform faulting along the Aghulas Transform Fault during the break-up of Gondwanaland. The Limpopo Mobile Belt requires investigation into plate tectonics and craton collision during Archean times, and subsequent shearing during mobile belt emplacement.

Emphasis is given to tectonic events that resulted in brittle deformation, however, in many cases brittle deformation occurs along zones of existing weakness resulting from earlier ductile deformation, such as ENE faulting in the Natal Metamorphic Province along earlier ductile ENE shears.

Geodynamic investigations aim to develop a conceptual model of pre- post- and syntectonic geological evolution that describes historical extension, compression and shear orientations in geological time. The objective is to define a chronologically expected pattern to explain observed faulting by strain analysis using a strain ellipse. The potential rejuvenation of such structures by subsequent tectonic events can then be identified and the present strain on existing structures can be identified. Existing structures considered to be under extension present hydrogeological targets.

Strain analysis conducted during geodynamic investigations also permits an understanding or classification of observed lineaments and joint patterns in terms of their origin and present strain conditions, hence allowing the identification of preferred structures.

Methodology

The process involves investigations into:

- Identification of geological domains based on lithology, geochronology and structural setting
- Pre-depositional environment to identify aquifer boundaries and their nature (depositional-lithological versus post depositional or tectonic)
- Plate tectonics and its impact on geological strain in the region
- Metamorphism and ductile deformation episodes and their expression in the lithologies
- Intrusive and volcanic history
- Recent tectonic history and processes
- Mapping of faults and shears
- Application of strain analysis based on historic strain and stress to derive a pattern of faulting, folding, thrusting and shearing
- Verification of predicted faulting against observed fault pattern

Structural Analysis

Objective

A structural analysis attempts to identify strain conditions in rocks by identifying compressional and tensional orientations by mapping the strike and dip of joints and plotting the data on stereonets. The objective is to identify the orientation that is extensional, so that geological structures aligned perpendicular to extension can be identified. These targets are then assumed to be open and are targeted as preferential targets.

The risk of using this methodology is that in many cases rocks have been exposed to several tectonic events, perhaps with different stress orientations, hence jointing from several generations may be superimposed in joint patterns. Consequently, joints may be aligned in many orientations and the resulting structural analysis would be meaningless unless conducted on subsets related to a specific event. Identifying joint patterns from specific events requires a geodynamic analysis to identify stresses originating at various periods in time. A specific example can be observed in the Limpopo Mobile Belt, where joints are the result of late Archean shear, with post Karoo extension superimposed. For this reason, it is often necessary to conduct joint mapping in the most recent lithological formation present, even if outside the study area, to identify stresses originating from the most recent tectonic event. This process allows coarse dating of joint sets.

Methodology

The investigations conducted include:

- Identifying the age relationship of various formations present in the region

- Mapping of the strike and dip of joint sets in the various lithologies post-dating the study area, as identified at road cuttings and stream beds
- Plotting joint lineation and bedding data on stereonets
- Classification of joints by age relationship or by dip to categorise features by tectonic origin
- Derivation of compressional and extensional relationships by structural analysis

Remote Sensing
Objectives
The objective of using remote sensing methods is to identify structures that may be of hydrogeological significance and that are not noticeable in the field, or that have not already been mapped. These can be identified by satellite images using variations in surface reflectance, by aerial photos using variations in tone and contrast, or by airborne geophysics, which is based on variations in rock physical properties. Often digital filters are used to enhance features considered to be of interest, such as vegetation, structure, soil moisture, clay content, magnetic field etc.

Identified lineaments are presumed to have a hydrogeological significance, and are presumed to be related to lithological variations, faults, variations in saturation, topographical depressions are linear vegetation trends. However, field proofing is necessary to verify the nature of the identified lineament.

Unless a geodynamic analysis has been undertaken, it is usually not possible to identify the stress regime of a lineament or its structural significance. To some extent this is overcome by an analysis of lineament orientation and length so that the predominant regional scale features can be identified.

The usefulness of remote sensing is hindered where:

- disturbance of the land surface hinders lineament identification
- surface cover such as sands prevents identification of subsurface structures
- lineaments are related to non-structural features such as lithological variations of non-hydrogeological significance
- rock physical properties are not sufficiently distinct to permit geophysical delineation
- features are too narrow to be delineated at the scale of the image

Methodology
Remote sensing investigations ideally require the following steps:

- Selection of applicable digital features to highlight features of interest
- Identification of lineaments and overlaying onto topographic and geological maps using a GIS
- Preparation of strike-frequency rose diagrams to identify dominant orientations
- Preparation of strike-total length plots to identify regional orientations and trends
- Preparation of strike-maximum length plots to identify regional structures
- Identification of target lineament orientations based on geodynamics, structural analysis, and lineament strike analysis

Field Verification Investigations
Objective

Field proofing investigations are required to identify the nature of target lineaments to determine their nature and origin, and to pinpoint the lineaments in the field using observation or geophysics, with due consideration being given to constraints on siting. The objective is to identify drilling sites on structural features identified as being of hydrogeological significance at locations where drilling and water abstraction are physically, economically, socially and legally acceptable.

A field survey is also required to evaluate the effect of constraints on target site selection. These constraints may include:

- topographic and access constraints affecting drilling rig mobilisation
- water demand location and topographical constraints on reticulation or distribution
- quantitative water demand and its impact on target location in terms of large regional structures versus smaller local structures
- access to properties and water rights
- contamination potential and vulnerability
- Acceptance of drilling site by stakeholders

These constraints impact on the point at which specific linear targets may be targeted and ultimately determine where the boreholes can be sited.

Methodology
Field investigations include:

- Observation of land use and geology to identify the nature of lineaments and ensure that they are structurally significant
- Observation and evaluation of constraints in terms of drilling rig accessibility, topographic constraints between source and demand location, distance from demand points, contamination
- Field geophysics to pinpoint the structure in the field at potential target points

9. Conclusions and Recommendations

The results obtained in the 4 selected study areas show that the methodology employed results in increased borehole success rates compared to previous drilling, as recorded in the National Groundwater Database and the Critical Intervention Programme, which utilised a geophysical approach:

Borehole Success Indicators

Geology	Success Rate			Median Yield		
	1	2	3	1	2	3
Dwyka Tillite	12%	27%	50%	0.16 l/s	0.1 l/s	0.1 l/s
NMP	50%	63%	89%	0.1 l/s	0.1 l/s	1.8 l/s
LMB	40%	38%	66%	0.39 l/s	0.1 l/s	3.9 l/s
BGB	50%		89%	0.4 l/s		1.2 l/s

Financial Indicators

Geology	R/successful borehole			R/l/s		
	1	2	3	1	2	3
Dwyka	99473	52100	28600	621706	521000	286000
NMP	22990	20710	18370	229900	207100	10206
LMB	30250	34855	24390	77564	348550	6254
BGB	24200		19875	60500		18370

The project indicates that groundwater exploration is significantly more cost effective when structural controls on groundwater occurrence are considered so that only potentially significant targets are considered for field investigation. However, groundwater exploration exhibits a significant economy of scale and unit costs per borehole decrease with the number of boreholes drilled. In the Dwyka Tillites exploration costs as a proportion of total borehole establishment costs were shown to drop from 27% for 3 boreholes to 14% for 20 boreholes to 12% for 50 boreholes. Consequently, such an approach is warranted only when the exploration costs can be distributed over several boreholes. Based on financial analyses for establishing 10 boreholes, the proposed methodology proved to be cost-effective in all the geological provinces investigated. Cost-effectiveness would subsequently increase with the number of boreholes required in each study area.

Consequently, cost effective groundwater exploration should:

- Have a regional focus and be based on identifying target features for a region rather than be locally demand driven, where boreholes are sited only for a few specific communities. This will minimise the exploration cost overhead per borehole due to the economy of scale principle. However, subsequent drilling of targets can be locally demand driven according to priorities.
- Consider the expertise required rather than the expertise locally available. Borehole siting is commonly undertaken by a local consultant using the tools and skills he has available. This often results in the repetition of poor practice and the use of instrumentation that cannot achieve the required results. This was seen to be the case in KwaZulu-Natal, where the EM-34 was consistently applied in spite of poor results resulting from its limited depth of penetration and a lack of understanding of the nature of structurally significant targets.
- In complex structural environments, exploration should be guided by a hydrogeologist with an understanding of the tectonic setting and geodynamics, together with the water bearing properties of identified targets, rather than be restricted to 'divining' using a variety for instrumentation.
- Consider the geological nature of targets prior to geophysical investigation. Some of the high yielding targets identified and drilled during this study did not exhibit any geophysical anomalies using magnetics or electromagnetics, yet were considered to be of structural significance and proved to be high yielding. Conversely, some geophysical anomalies yielded dry boreholes on targets that were drilled in spite of not being structurally relevant (compressional lineaments, compressional dykes, lithological variations etc.).
- Consider the nature of the geological environment, hence no fixed methodology is applicable. Not all the methodologies adopted proved to be successful in all areas. For example, a quaternary cover may limit the usefulness of remote sensing, or several generations of tectonic events super imposed on a lithology may limit structural analysis unless a younger formation is present.
- Groundwater exploration should be tendered on a per successful site or R/l/s basis. *Define Outputs Rather than Inputs.* The current practice of sub-contracting borehole siting to geohydrological consultants purely on cost or a per borehole sited basis does not promote incentive to increase success rates. In fact, the opposite may be the case, with consultants' income increasing with the number of boreholes sited and the number of boreholes where drilling supervision is provided, regardless of success. The sub-contracting of borehole siting independent of drilling success also reduces the responsibility of the Implementing Agent, who carries the drilling budget. An incentive to increase success rates could be achieved by tendering groundwater exploration on a per successful site or a per R/l/s basis, placing the onus for success on the tenderer. This approach would also encourage consultants to use the most appropriate methodology for exploration, as opposed to the current approach adopted

by DWAF where the approach is prescribed and standard rates are defined, as occurred during the Critical Intervention Programme as well as subsequent programmes such as BOTT.

The above-mentioned conclusions suggest that there is a significant need for a fundamental paradigm shift in groundwater exploration in South Africa. All of the above lessons can be considered as being opposed or contradictory to the current practice of groundwater exploration for rural water supply.

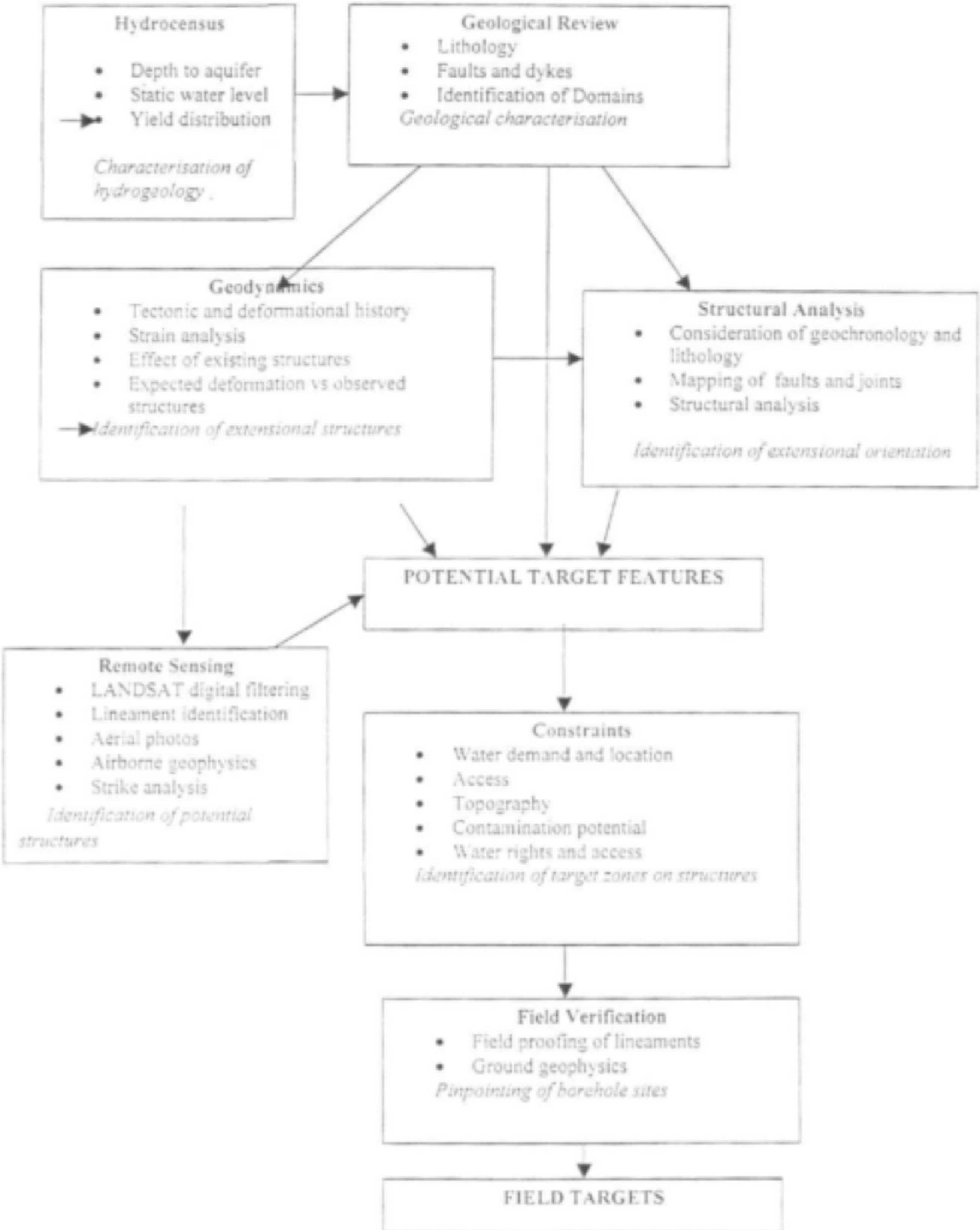
10. Recommendations for Future Research

The major shortcoming encountered during the project was that the current situation in South Africa has resulted in a fundamental split between geological mapping and groundwater exploration. Geological mapping has been lithologically and petrologically oriented, with little attention being paid to structures other than mapping the location of major faults. Little or no attention has been paid to joint mapping to permit a structural analysis. In addition, tectonic evolution, where it has been considered, has often ignored more recent post-deposition deformation. For example, resulting strain and stresses on Archean rocks resulting from the break-up of Gondwanaland is rarely described and the geological community has concentrated on Archean tectonics and unravelling the complexities related to the ages of metamorphic episodes. As a result, a hydrogeologist considering a structural analysis of target features must go through a mapping exercise. This project has shown that structural analysis usually requires 2 days to complete 4 1:50 000 sheets. however, a tectonic interpretation may require extensive literature review and the application of strain analyses to an observed fault set since the required information on recent tectonics is rarely available. This shortcoming requires that the scope of geological mapping be broadened if the results are to be of greater value to the hydrogeological community. A programme of structural mapping is urgently required if groundwater targets are to be regionally identified.

In contrast, the hydrogeological community has paid scant if any attention to the importance of geodynamics and structural analysis in groundwater exploration. Consequently, exploration has not been focussed and has been relegated to an exercise in anomaly hunting that adds little to the identification of future targets. A structural understanding of the aquifer is rarely built up and mistakes are commonly repeated. This shortcoming may reflect a lack of training in structural geology in South Africa, which is fundamental to groundwater exploration in fractured aquifers. This lack of awareness has resulted in minimal attention being given to structural models in hydrogeological investigations.

Urgent attention also needs to be given to cost-benefit analyses of past and current groundwater exploration strategies, as it is only by using the language of economics that the voice of hydrogeologists calling for a revision in exploration strategy will be heard.

Figure 1. Flow Chart of the Groundwater Exploration process



ACKNOWLEDGEMENTS

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Groundwater development for rural water supply in complex and problematic terrain: an assessment of geological controls, geophysical exploration methods and the quantification of exploitation potential

The Steering Committee responsible for this project, consisted of the following persons:

Mr. K. Pietersen	Water Research Commission (Chairperson)
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1. INTRODUCTION

1.1 Background

The Department of Water Affairs and Forestry has identified the provision of sustainable water and sanitation services to all as being one of its top priorities (DWAF, 1994). The challenge of providing developing rural areas in South Africa with sufficient potable water is substantial, especially where settlement is not densely concentrated and the ability to pay is low. The water requirements of these settlements can be met most cost-effectively from groundwater. The provision of these regions with sufficient potable water is complicated by the large backlog in water delivery, which results in pressure for rapid service delivery at the expense of time-consuming groundwater exploration methods.

Previous studies (King, 1997) have shown that some of the greatest water needs occur in regions underlain by fractured basement aquifers with complex hydrogeology and where the exploitation potential of groundwater has been thought to be low due to historically low drilling success rates or the high frequency of low yielding boreholes. Groundwater exploration success rates in these environments have been relatively low due to inappropriate exploration or interpretation methods resulting from an incomplete understanding of the geohydrology.

The current paradigm of groundwater exploration in South Africa, as well as in many other places in Africa, is based on a geophysical approach, where most boreholes are sited on anomalies identified from magnetic or electromagnetic traverses, often with little or no understanding of the structural geology of the target area. In many areas of complex hydrogeology this technique has proved to be unsuccessful for a variety of reasons. Specific causes that have been identified include:

* an inadequate understanding of the occurrence of groundwater and the factors affecting permeability in these terrains, leading to inappropriate exploration planning;

* siting of boreholes on geophysical anomalies without a conceptual understanding of the geological framework and how it affects the geophysical response, or siting boreholes without
an adequate interpretation of the geophysical data;

* the use of only one geophysical method, which makes the interpretation of anomalies difficult or unsubstantiated;

* the use of inappropriate geophysical methods for the specific terrain; and

* inappropriate or insufficient quantification of the sustainable yield of boreholes due to inadequate test pumping procedure or analysis methods.

As the demand for groundwater grows and the more obvious aquifers and target features become increasingly exploited, it can be expected that further development will have to consider alternative targets in such problematic and complex fractured geological environments. Significant savings in exploration and especially drilling costs can be realised if success rates could be improved. However, it is essential not to consider exploration in isolation from resource evaluation. If these complex terrain's are to be developed in a sustainable manner, the importance of quantifying groundwater resources will be magnified due to the their low potential.

To improve the borehole success rate in these terrains, and to develop groundwater resources in a sustainable manner, a multi-disciplinary approach is needed. This approach must incorporate: 1) an understanding of the structural geology and its influence on the occurrence of groundwater so that target features can be identified; 2) the identification of appropriate methods and interpretative techniques to delineate target features in the field; 3) and the use of simple yet effective groundwater resource evaluation methods. The Council for Geoscience undertook this project to re-evaluate the groundwater resources of some of these regions using a rigorous scientific approach, with the objective of establishing a more successful exploration strategy.

A multidisciplinary approach was followed where structural geological mapping, tectonics, strain analysis, LANDSAT image interpretation and geophysical methods were combined to unravel the geodynamics of a region and to identify geological structures where groundwater could be located. These methods include: 1) the identification and categorisation of lineaments observed on LANDSAT using various digital filtering techniques into strike-frequency and strike-length plots to identify preferential structural orientations; 2) structural mapping on a regional scale to identify tectonic processes given the geological and deformation history; 3) structural mapping of joints on an outcrop scale to identify compressional and extensional orientations through strain analysis; and 4) geophysical exploration of identified potential water bearing structures using magnetics, resistivity and electromagnetics.

Data collection for exploration is often costly and time consuming, hence it is important that any proposed techniques be fully analysed to determine their practical viability. Consequently, a financial analysis of the proposed methodology is presented, demonstrating that, although exploration costs of the adopted approach are higher, the ultimate establishment costs per successful water point and the costs of the water are dramatically reduced compared to conventional methods due to greatly improved success rates and significantly higher yields. These results suggest that it is cost effective to undertake groundwater exploration in a scientific manner, whether only successful points are required for hand pumps, or where high yields are required for reticulated motorised schemes.

From these results, a suggested method for exploration has been formulated to assist with undertaking regional exploration programmes.

1.2 Research Objectives

The primary objective of this project is to investigate the development potential of groundwater in problematic or complex terrain where the demand for water for rural communities is expected to grow, and to develop guidelines for groundwater exploration and development in these environments. The supporting objectives are to:

- investigate the occurrence of groundwater and the geological and structural controls that distinguish high yielding features from those that have low potential;
- evaluate the ability of currently used geophysical methods to distinguish or delineate target features;
- quantify the exploitation potential of groundwater and evaluate methods for estimating sustainable aquifer and borehole yields;
- and to develop guidelines for groundwater exploitation in these environments.

The geological evaluation of target features and the guidelines for groundwater exploration will assist water practitioners with siting boreholes and interpreting geophysical data. Furthermore it will reduce the use of inappropriate geophysical methods and/or the siting of boreholes based on an incorrect geophysical interpretation. This will reduce the frequency of incorrectly sited boreholes and increase the drilling success rate.

The evaluation of methods to estimate sustainable yield will assist consultants and implementing agents with planning pumping tests and recommending pumping rates so that groundwater abstraction does not exceed sustainable yield of the aquifer.

1.3 Selection of Research Areas

Field data is provided from 4 study areas in South Africa. The four research areas were selected on the basis of the following criteria:

- The area is densely populated rural region with underdeveloped infrastructure and services and has been identified as a critical water deficit area by DWAF.
- Water scarcity is a serious problem and the area and relies mostly on springs, rivers, hand-dug wells and some boreholes. Groundwater would be a preferred water option in the area because of its generally availability even in drought situations and its relatively good quality.
- The areas are underlain by fractured bedrock aquifers where success rates and borehole yields have been historically low, yet high yielding holes are present suggesting that suitable hydrogeological target features do exist.

The areas which have been studied include: the Natal Metamorphic Province of the KwaZulu-Natal south coast in the vicinity of Mapumulo; regions underlain by thick Dwyka Group rocks inland of the south coast in the vicinity of Harding; the greenstone belt of the Barberton Supergroup in the vicinity of Tjakastad, and the basement rocks and greenstones of the Limpopo Mobile Belt in the vicinity of Alldays.

1.4 Developing A Conceptual Hydrogeological Model of Terrains

Groundwater exploration in fractured rock environments is directed towards finding fracture zones, bedding planes or contact zones where permeability is enhanced. These zones are primarily structurally controlled; consequently, an understanding of regional tectonics and its structural expression is essential. Tensile and shear fractures caused by brittle deformation are the most hydrogeologically significant types of structural expression in response to tectonic stress. Boreholes located in tensional zones often have a significantly higher median specific capacity than those in shears since shears can be subjected to intense weathering, which reduces their yield potential.

Successful exploration consequently requires the development of a hydro-tectonic model based on the original stress regime, from which promising structural azimuths can be identified. Since stress forces can change several times over geological history, complex fracture patterns are often seen in complex geological terrains that have been subjected to several deformational episodes. This process can result in the reactivation of existing fracture systems under new stress conditions, which may change their compressive or tensile character. Consequently, the commonly used simplistic approach of identifying target features from lineaments using LANDSAT imagery or aerial photographs needs to be treated with caution. An understanding of the tectonic history of the region, and the accompanying stresses resulting in brittle deformation, can be considered as the fundamental basis of deriving a hydro-tectonic model for assessing and classifying potential target features.

1.5 Report Structure

The report is structured into two volumes. Volume 1 consists of: Chapter 1 describes the objectives of the report; Chapter 2 outlines the investigative procedure adopted by the study. Chapter 3 provides the theoretical basis of the interpretative techniques utilised by the project team; Chapter 4 provides a conclusion pertaining to the findings in each of the 4 study areas; and Chapter 5 provides a synthesis of the investigation procedure and is designed to provide a guideline for groundwater exploration in similar environments. Volume 2 consists of 4 chapters, each of which describes investigation results in one of the 4 study areas. These chapters can also be viewed as stand alone hydrogeological investigations of each study area and can be read independently. An executive summary of the whole project is duplicated in each volume to provide a comprehensive overview of the results and the proposed guidelines for hydrogeological exploration.

1.6 References

King, G. (1997): The development potential of KwaZulu-Natal aquifers for rural water supply. Unpubl. M.Sc. thesis, Rhodes University, South Africa.

2. INVESTIGATION PROCEDURE

2.1 Literature Review

In each study area a literature review of existing information regarding geology, structural geology and hydrogeology areas has been undertaken on the basis of the following data:

- Published and unpublished geological maps at 1:250 000 and 1:50 000 with associated memoirs
- Topographical maps at 1:50 000
- Publications, articles, theses and reports available for the areas

The objective was to gain an understanding of the geological environment, including lithological descriptions, structural geology, deformational and metamorphic features. The results were interpreted to determine how the tectonic history of the region produced the observed structural features, and to hypothesise as to the orientation of compressional and extensional forces using strain analysis.

2.2 Hydrocensus

To gather existing hydrogeological data, the Council for Geoscience undertook a detailed hydrocensus for every study area. An inventory of all boreholes within the research area was compiled from the National Groundwater Database (NGDB), the Critical Intervention Program (CIP) of the middle 1990s, and from databases of various consulting companies. These data were used to characterise the spatial distribution of high and low yielding boreholes. All available information regarding groundwater usage, quality, yield, borehole depth and geology, water levels and water strike depth and geophysical data from these sources was compiled as individual layers in an ARCVIEW database. In order to gain a visual understanding of the data, borehole distribution, geology and structural geology were presented in terms of ARCVIEW maps.

2.3 LANDSAT Image Interpretation

LANDSAT TM imagery was used to map visible lineaments that could act as groundwater indicators in the area. Lineaments interpreted as fracture zones are assumed to be associated with brittle deformation in the uppermost region of the earth. The interpretations of the LANDSAT TM data were performed with an image processing system called ER Mapper 5.1. The data were analysed at a 1:150 000, 1:100 000 and 1:50 000 scale on-screen. To ensure objectivity, lineament mapping was undertaken manually using a third person not having a structural knowledge of the area. Consequently, derived lineaments were purely observational, and not related to a bias towards looking for certain orientations. Different enhancement techniques were employed to detect groundwater-controlling features. The digital outputs of the following products were found to be the most useful for extracting the parameters required for groundwater studies in a hard rock terrain:

1. Normalized band 4 (black and white)
2. False colour composite (FCC) of normalized bands 3,5, and 7
3. FCC of the first three principle components
4. Composite of the vertical filtered band 7, the diagonal filtered band 5, and the horizontal filtered band 7
5. Product of bands 4 and 3.

Lineaments identified by each of these enhancements were assessed individually and combined to form an integrated lineament map of the study area.

Lineaments were subsequently interpreted in terms of:

1. Strike-frequency rose diagrams
2. Strike-maximum length rose diagrams
3. Length-frequency histograms
4. Strike-length rose diagrams
5. Strike-total length rose diagrams

ARCVIEW software was used to investigate the correlation between the location of high yielding boreholes and lineaments and proximity analyses between high yielding boreholes and lineaments were undertaken.

2.4 *Geological and Structural Geological Mapping*

Field and photogeological mapping of geology and structure to identify any possible preferential groundwater flow paths in the study areas was undertaken. Field structural geology mapping consisted of mapping the strike and dip of observed faults and joint sets at an outcrop scale. These data sets were interpreted using stereonets and rose diagrams to identify the tectonic setting of joint sets using stress analysis, and to identify the orientation of extension. A geodynamic analysis was also undertaken to understand the tectonic and deformational history in each region. This procedure involved developing conceptual models of how identified tectonic events resulted in tectonic stresses that would be expressed in regional structures such as faults. A strain ellipse was subsequently oriented according to identified tectonic stresses to predict extensional, compressional and shear stress conditions prevailing in existing structures. The geodynamic analyses were used to identify the orientation of structures and lineaments considered as extensional in nature and hence preferred target features.

2.5 Ground-based Geophysics

To avoid that large sums of money are being spent on drilling "dry" holes the application of appropriate geophysical techniques is vital under the difficult hydrogeological conditions encountered in all areas. Different exploration techniques were used to locate water bearing features and to identify the most promising drilling sites.

Under the given hydrogeological conditions, the applicable geophysical methods for the research areas need to provide information about the subsurface conditions to a reasonable depth but remain within economical drilling limits, which are approximately 100m. Furthermore, the method must be able to locate relatively narrow structural zones, as it is assumed that groundwater flow in the study area takes place mostly in fracture zones. Therefore the electromagnetic technique chosen was the Max-Min (HLEM) technique, as it has a greater depth penetration than the EM-34 and is suitable for locating fractured aquifers (Botha et al. 1992) as long as the conductivity thickness product of the conductive zone increases with depth. Electrical sounding was also applied, to determine the depth of weathering. Additionally, magnetics was applied during investigations to locate dykes or sills.

Magnetic and electromagnetic profiles, as well as vertical electrical soundings, were undertaken across prominent observed lineaments and faults to characterise the geophysical responses of structures considered to be water bearing and poor target features. Although the selection of drilling sites was based on structural geological criteria in order to investigate structures under various predicted stress conditions, the geophysical exploration results formed the basis of locating boreholes on identified structures in the field.

2.6 Drilling

Percussion-drilled exploration boreholes were drilled to evaluate the groundwater potential of some of the target features delineated during the research study and to characterise the geology, and to provide sites where hydraulic testing could be performed to identify boundary conditions and characterise flow in the structures. From the drilling and the geophysical data, the occurrence of groundwater was conceptualised to differentiate typical regions of potentially high and low yields and to define geophysical signatures that could be expected from various structures.

2.7 Test-pumping

Test pumping of the percussion-drilled boreholes were carried out to quantify hydraulic properties of the penetrated lithologies, interpret aquifer hydraulic characteristics, and to determine the exploitation potential of the aquifer. Additionally, samples were obtained and analysed to determine the groundwater quality in the study areas in terms of potability.

2.8 Down-the-hole Geophysics

Down-the-hole geophysical logging was carried out to delineate hydrogeologically significant features in the formation penetrated. Apparent resistivity and spontaneous self-potential logs as well as gamma logs were obtained from newly drilled yielding boreholes and correlated to the geological logs.

2.9 References

Botha, W.J., Wiegmans, F.E., van der Walt, J.J. and Fourie, C.J.S. (1992): Evaluation of electromagnetic exploration techniques in groundwater exploration. WRC Report No. 212/1/92, 214 p.

3. THEORY AND METHODOLOGY

3.1 LANDSAT Imagery

The interpretation of satellite imagery can help in the extraction of features that possibly act as groundwater indicators and therefore is part of the investigation procedure applied in this project.

Rock types, fracture zones, fault zones, drainage patterns, and various types of unconsolidated deposits or different vegetation patterns can be identified using satellite images. Satellite data is especially useful in hard rock areas with limited regolith cover. Here, potential fracture or fault systems, or magnetic structures like dykes and sills can show up as linear features, commonly referred as lineaments.

Although satellite data provide little information on the nature or origin or the lineament, it is a means of finding possible targets, which can be then investigated through field visits or geophysical surveys.

The basic concept for remote sensing is that information about an object is contained in the electromagnetic radiation passing from the object to the observer (Lo 1987). For geological materials the prime natural source, providing the energy is the sun. Subsequently the absorbed energy is emitted as electromagnetic energy by the object. Reflection, absorption or emission of energy by the object leads to either a subtraction or addition of the intensity at specific wavelength from or to the original radiation. Therefore the wavelength-intensity relationship of an object can be used to characterise variations in the subsurface by collecting the electromagnetic radiation leaving the object at a specific wavelength and measuring its intensity. Every object imposes its characteristic imprint on the wavelength-intensity relationship and spatial variations can be used to detect for instants variations in geology, soil, vegetation and land use. A sensor detects the electromagnetic energy. For the study areas the specific LANDSAT TM scenes were obtained, which cover swaths of 185 x 185 km.

The electromagnetic spectrum is divided into wavelength bands. They range from the short wavelength UV band to the long wavelength microwave and radio bands. Table 3-1 gives a list of spectral divisions used by LANDSAT TM and their applications for geological features. The resolution of the bands is 30 m, except for band 6, which is 120 m.

Table 3-1 Spectral divisions used by LANDSAT TM and their applications for geological features

Visible Region (0.4-0.7 µm)	Band 1 (0.45-0.52 µm)	Designed for water body penetration- useful for coastal water mapping Differentiation of soil from vegetation and deciduous from coniferous flora
	Band 2 (0.52-0.6 µm)	Designed to measure visible green reflectance peak of vegetation for vigor assessment
	Band 3 (0.63-0.69 µm)	A chlorophyll absorption band important for vegetation discrimination
Reflected Infrared (0.7-3 µm)	Band 4 (0.76-0.90 µm)	Determining biomass content Delineation of water bodies Tectonic analysis
	Band 5 (1.55-1.75 µm)	Vegetation moisture content Soil moisture content Differentiation of snow from clouds
	Band 7 (2.08-2.35 µm)	Discriminating rock types Hydrothermal mapping
Thermal Infrared (3-5µm and 8-14µm)	Band 6 (10.40-12.50 µm)	Useful in vegetation stress analysis Soil moisture discrimination Thermal mapping

The objective of lineament mapping is to accurately trace all linear features that might reflect a tectonic structure. Several different enhancement techniques can be employed to highlight groundwater-controlling features. Those considered of relevance to groundwater investigations are listed in Table 3-2.

Table 3-2 Purposes of different digital techniques.

Digital technique	Purposes
Linear stretching	Normalisation of raw data
False colour composite	Extraction of geology, Hydrogeomorphic features
Band combination	Extraction of vegetation distribution within valley zones and lineaments
Principal component analysis	Extraction of hydrogeomorphic features
Filtering	Extraction of linear features like fractures, faults, dykes, joints using algorithms

The digital outputs for the following image processing techniques were found to be the most useful for extracting groundwater-controlling features in the study areas:

- Normalized band 4 (black and white)-linear stretching
- False colour composite (FCC) of normalized bands 3,5 and 7
- FCC of the first three principle components as red green blue
- Composite of the vertical filtered band 7, the diagonal filtered band 5 and the horizontal filtered band 7
- Product of band 4 and band 3

3.2 Structural Geology

Geometry of brittle deformation structures

Faults can be divided into normal-slip (extension), thrust-slip (compression) and strike-slip categories (Suppe, 1985; Davis and Reynolds, 1996) (Figure 3-1). There is a dynamic basis for the fact that on average strike-slip faults are vertical, normal faults dip at ~60° and thrust-slip faults dip at ~30°. The dynamic analysis of faulting is concerned both with the stress conditions under which rocks break and with the orientation of faults relative to stress patterns. The properties of principal stress directions, in combination with the Coulomb law of failure implies that only brittle deformation structures, which are strike-slip, thrust-slip and dip-slip faults, will form near the surface of the earth.

Therefore, if we know the orientation of fractures and the slip directions, we can infer the orientations of the principal stresses. The three major orientations of the conjugated fracture sets are displayed in Figure 3-1 with typical data on the fault- and slickenslide orientation plotted on stereonets. Figure 3-1 shows that σ_2 (neutral force) is parallel to the intersection line of the conjugated fracture sets. The acute angle of the conjugated fracture set indicates the orientation of σ_1 (maximum compression) and the obtuse angle σ_3 (maximum extension). If compression (σ_1) is vertical and extension (σ_3) horizontal then dip-slip faulting conditions prevail (Figure 3-1a). If both compression ($\sigma 1$) and extension (σ_3) are horizontal thrust-slip conditions will occur (Figure 3-1b). Where compression (σ_1) is horizontal and neutral force (σ_2) is vertical conditions will favour strike-slip faulting (Figure 3-1c).

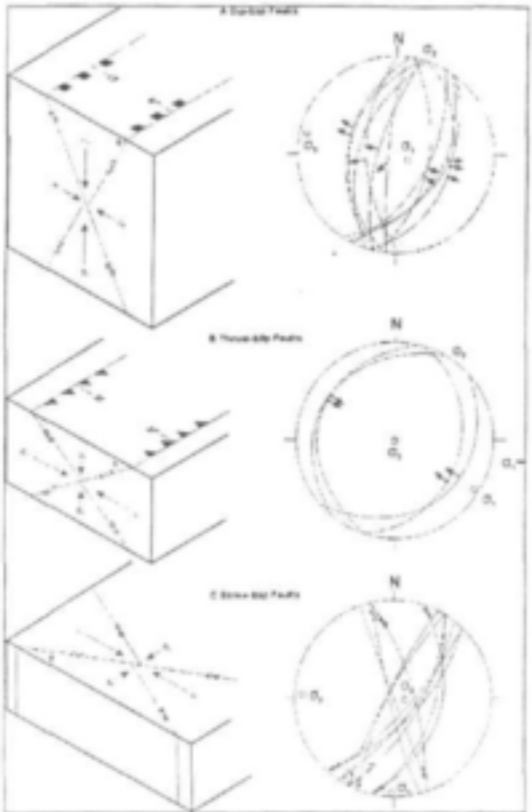

Figure 3-1 Schematic presentation of (A) thrust-slip faults, (B) dip-slip faults and (C) strike-slip faults (Davis & Reynolds, 1996).

Although the joint sets and displacement may occur parallel to the conjugated planes, secondary joint and fault sets develop frequently (known as Mode1 tension joints) parallel to the direction of greatest principal stress (σ_1) and perpendicular to the direction of minimum principal stress (Figure 3-2). For the dip-slip and strike-slip settings the Mode 1 tension joints are sub-vertical and for the thrust-slip settings sub horizontal. Fracturing along one stress field can occur in two dimensions, as shown in Figure 3-1, but in nature the features are mostly observed in three dimensions. The fracture and displacement patterns for that are illustrated in Figure 3-3.

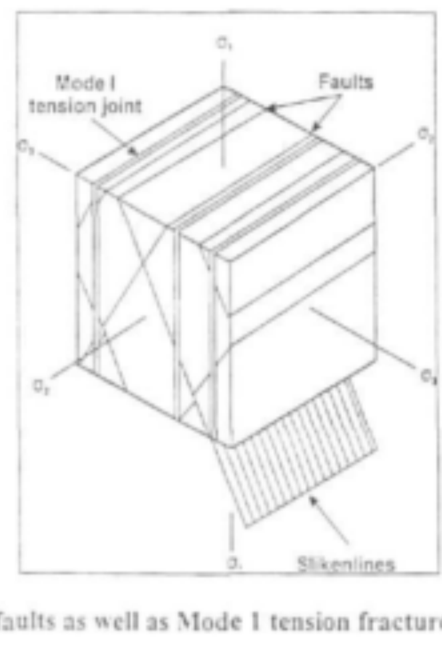

Figure 3-2 Conjugate faults as well as Mode 1 tension fractures in a block of rock that has

been subjected to length-parallel shortening (Davis & Reynolds, 1996).

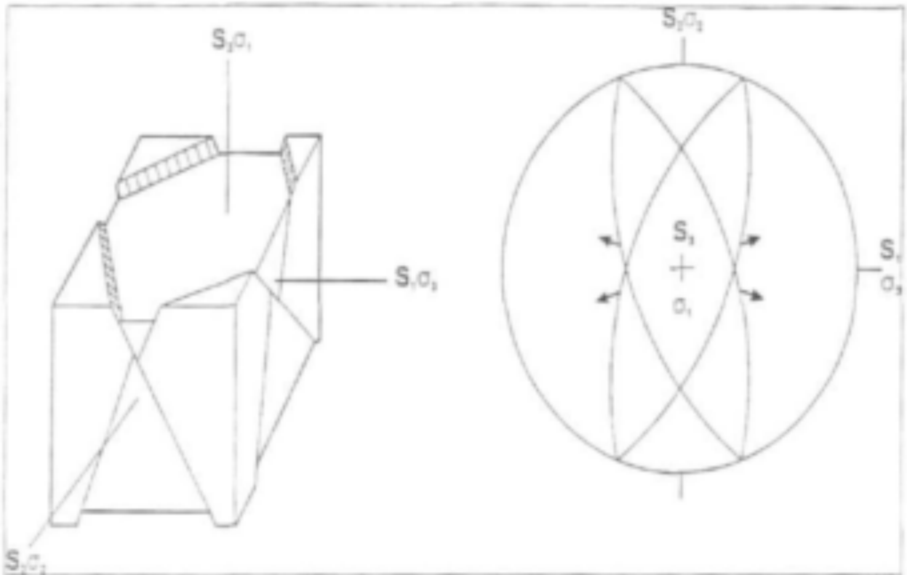

Figure 3-3 Relation of conjugate faults with the stereographic representation of conjugate faults produced in a three-dimensional strain field (Davis & Reynolds, 1996).

However, in nature rocks are anisotropic due to primary or secondary characteristics and fracture patterns deviate substantially from patterns discussed so far. According to the work done by Handin (1969) and Donath (1961) the orientation of existing planar features influences the orientations of fractures and faults that develop in response to stresses. When foliation is nearly perpendicular to the compression (inclined more than 45° to σ_1) the fracturing will occur with little deviation. If the foliation is between 25° and 45° to the compression the orientation of the fracturing will deviate and commonly develop sub parallel to the foliation. When the foliation is parallel to the compression, the angles of fracturing will be very small, in the order of 10° to 20°.

3.3 Ground-based Geophysics

3.3.1 The electromagnetic technique

Electromagnetic techniques can be subdivided into time domain (TDEM) and frequency domain (FDEM) techniques. Only the FDEM technique was applied during the research project.

The electromagnetic technique measures the electrical conductivity of the ground by utilizing a source and a receiver. The transmitter, as being the artificial source, creates an alternating magnetic field by passing varying current through a coil, which causes currents to flow in the subsurface by induction. If a conductive zone is present stronger secondary currents are induced in these zones. These induced currents, which are dependent on the conductivity, size and geometry of the conductor, will have their own secondary magnetic field. The receiver then measures the magnetic field strength of this induced field. By comparing the actual measured field and the calculated field at the receiver, against the transmitter field the presence of a conductive zone can be deduced (Van Zijl & Kostlin, 1986).

The conductivity depends on the clay content, the porosity, the dissolved mineral content and the water saturation of the rocks (Palacky, 1994). Therefore conductivity zones are often linked to weathered zones, lineaments, faults and fracture zones, or water with a high total dissolved solids content. Weathering of the host rock results in water-saturated clays, which are among the most common geologic conductors (Palacky, 1994). What makes lineaments, faults and fracture zones more conductive is the presence of water in discrete fracture zones or water-saturated clays. Since these are zones of fragile host rock, the weathering process advances faster along these lines and can thus be detected by electromagnetic techniques. Therefore the whereabouts of lineaments and fracture zones is important information with regards to groundwater exploration. However, the electromagnetic method cannot directly distinguish between permeable fracture zones and zones of water saturated clay where the yield is usually low to moderate (Palacky 1994).

The APEX Max-Min HLEM

The instrument used for the electromagnetic investigations was the APEX Max-Min horizontal loop electromagnetic technique (HLEM), a frequency-domain EM method. The APEX Max-Min HLEM is a moving source – moving receiver system, where both, the transmitter and receiver are moved along the survey line with a constant coil separation. The coils are held coplanar and horizontally and the traverses were carried out perpendicular to the strike of the zone of interest. This Max-Min system can be operated at frequencies ranging from 110 to 56320 Hz while coil separations could be selected between 10 and 400 m. The choice of coil separation is dependent on the expected target depth. For the investigations during this project a separation of a 100 m was chosen resulting in a penetration depth of at least 50 m, which is half the coil spacing. Conductors at greater depth may still be recognizable, if geological conditions are favorable (Van Zijl & Kostlin, 1986). Only where infrastructure or topography did not allow spacious investigations, a 50m-coil separation was used. The depth penetration can be controlled qualitatively by varying the frequency.

Station spacing was chosen between 10 and 25 m to ensure a well-defined anomaly profile with a sufficient number of data points. The results are recorded as occurring midway between the transmitter and receiver stations.

The measurements are taken by comparing the receiver signal with the primary signal and by further separation of the receiver signal into the in-phase and the out-of-phase values. The receiver then displays the in-phase and out-of-phase components of the secondary magnetic field as a percentage of the primary field strength.

Interpretation of HLEM data

A typical electromagnetic response over a vertical narrow sheet conductor is shown in Figure 3-4.

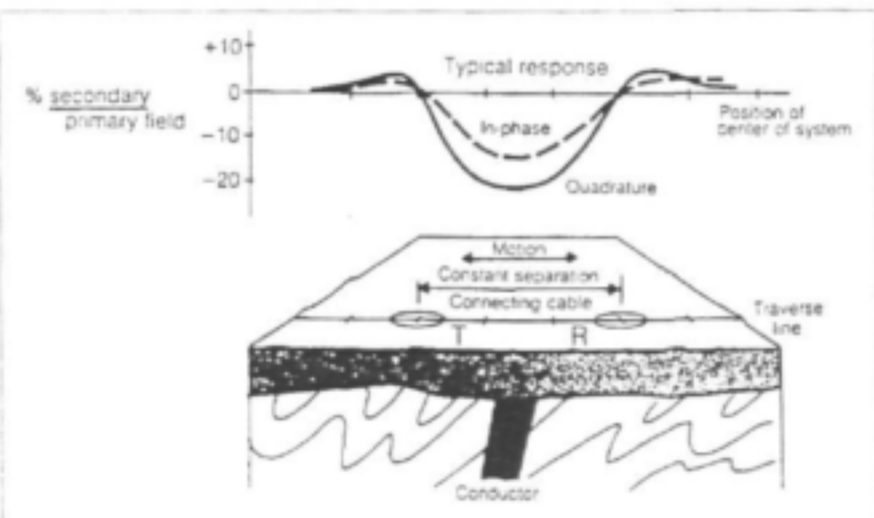

Figure 3-4 HLEM response for a vertical thin sheet conductor (van Zijl and Kostlin, 1986).

The response profile is symmetric with negative in- and out-of-phase values over the conductor, flanked by two positive shoulders. The distance between the zero points of the anomaly profile is approximately equal to the coil spacing.

The ratio of the in-phase value to the out-of-phase value is an indicator for the relative conductivity of the source. High amplitude ratios indicate good conductivities, whereas the opposite is true for poor conductors.

The depth of the conductor is related to the relative amplitudes of the response as shown in Figure 3-5.

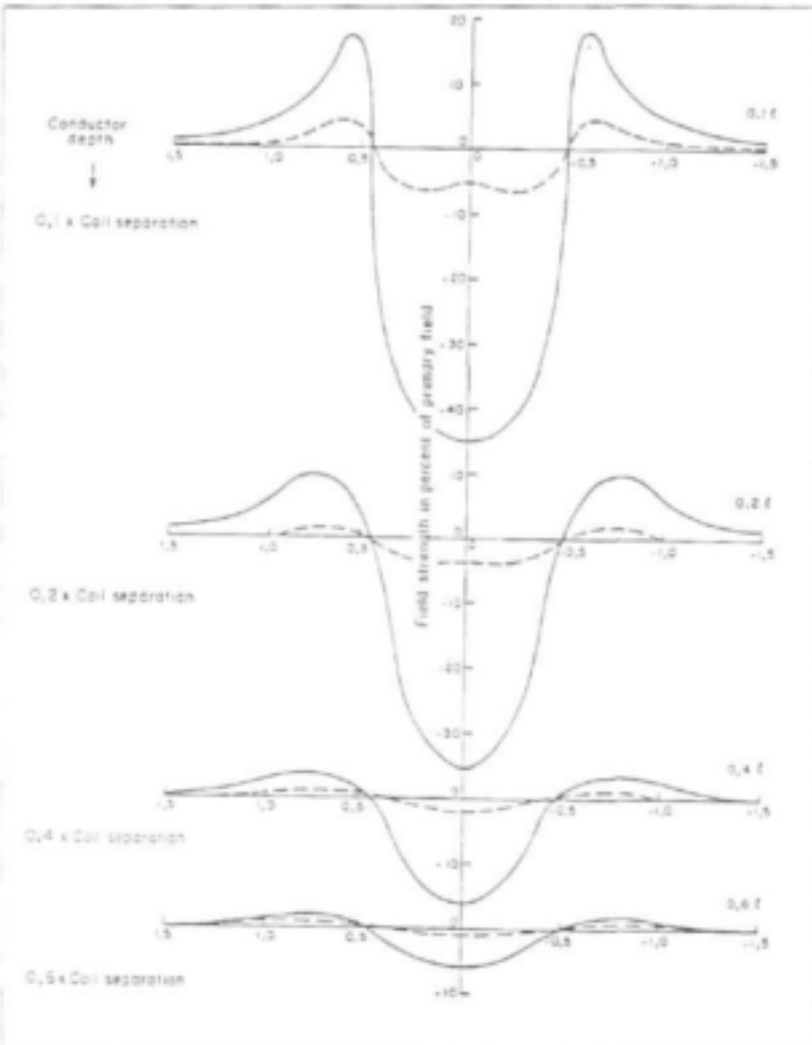

Figure 3-5 Effect of depth of conductor (vertical sheet) on HLEM response relative to coil separation (van Zijl and Kostlin, 1986).

Low amplitude anomalies suggest a deep source, whereas a shallow good conductor is indicated by a high amplitude anomaly.

A dipping conductor results in an asymmetrical shape of the EM profile (Figure 3-6), where the higher shoulder indicates the down dip side of the conductor. Additionally, the negative in-phase peak shifts down dip and increases in value with increasing depth.

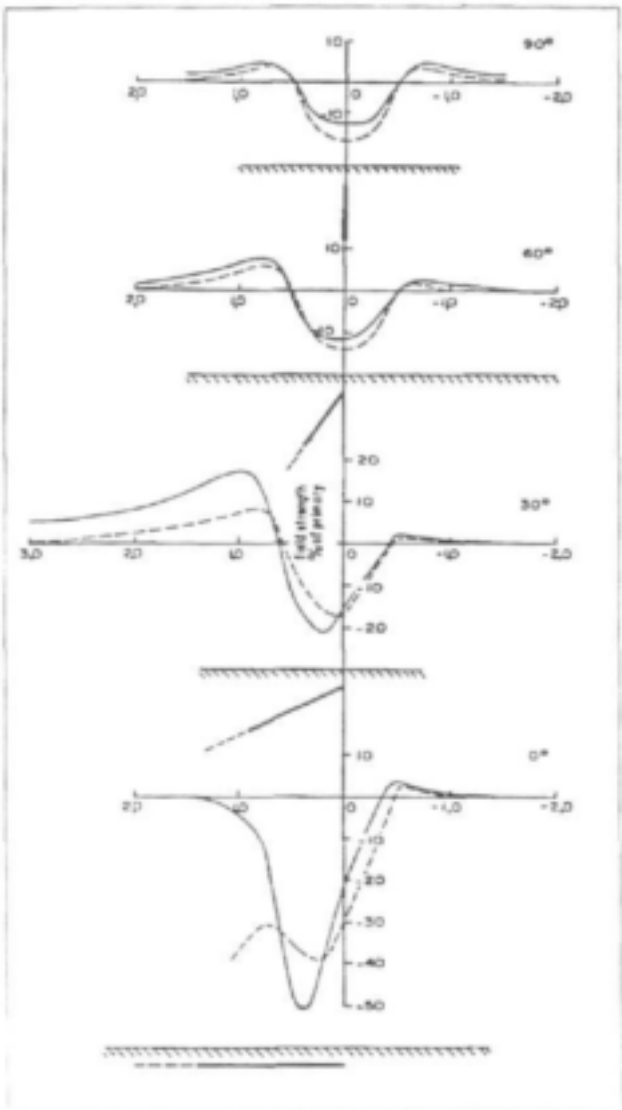

Figure 3-6 Effect of dip of a medium conductor on HLEM response at a constant depth of 0.2 times coil separation (van Zijl and Kostlin, 1985).

Up to now we assumed the absence of a conductive overburden. But targets in groundwater exploration are often found beneath some thickness of overburden (Botha et al. 1992). These deep weathered zones are sufficiently conductive to cause electromagnetic anomalies due to their higher water content (Villegas-Garcia, 1979). This is especially the case if the overburden is inhomogeneous as commonly found in fractured environments.

Villegas-Garcia (1979) investigated the electromagnetic responses of these overburden heterogeneities by means of scale model experiments. Three shapes of discontinuities were studied: Step, ridge and valley overburden discontinuities.

Each of these cases is illustrated in Figure 3-7. All other possible shape of heterogeneities can be considered as a combination of these three.

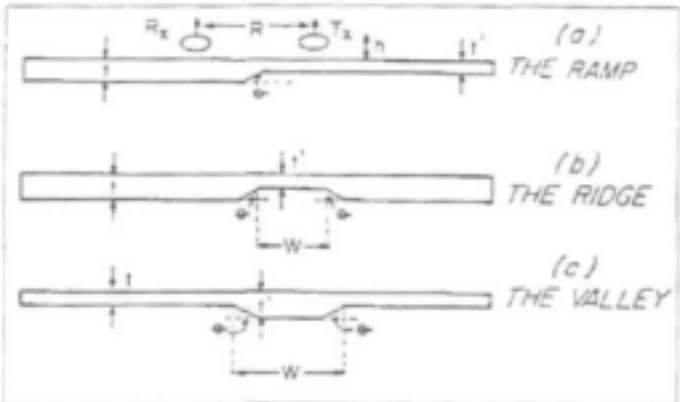

Figure 3-7 Models of the different overburden discontinuities. The angle θ was kept constant with 30 degrees throughout the experiment (after Villegas-Garcia, 1979).

Variations in the HLEM response can be due to variations in the:

- geometrical size (t'/t)
- coil separation (L)
- the skin-depth/overburden thickness ratio (δ/t)
- ratio between coil separation and thickness of the overburden

Response of the step-discontinuity in the overburden

The general response of the step-discontinuity is shown in Figure 3-8 to Figure 3-10. The anomaly consists of a minimum and then a maximum in the in-phase and the out-of-phase component, as the transmitter-receiver coils pass from the thicker to the thinner side of the overburden.

The response is highly controlled by the ration δ/t and the coil separation, as Figure 3-8 and Figure 3-9 indicate.

Response of the ridge discontinuity in the overburden

The general shape of the ridge discontinuity is illustrated in Figure 3-11 to 3-14 and is a combination of the response of two step discontinuities in the overburden. The anomaly is characterized by two minima in both the in-phase and out-of-phase, located on either side of the ridge and a maximum in both phases situated above the ridge. This response can be possibly mistaken for two parallel vertical plate-like conductors.

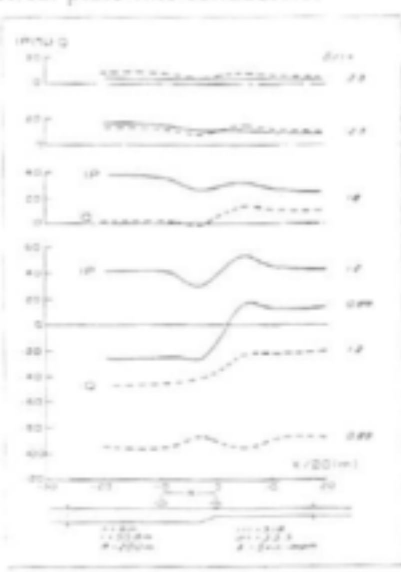

Figure 3-8 HLEM response of the ramp discontinuity in the overburden to various δ/t ratios (after Villegas-Garcia, 1979).

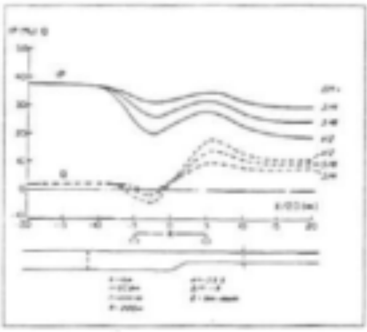

Figure 3-9 HLEM response of the ramp discontinuity in the overburden to different coil separations (after Villegas-Garcia, 1979).

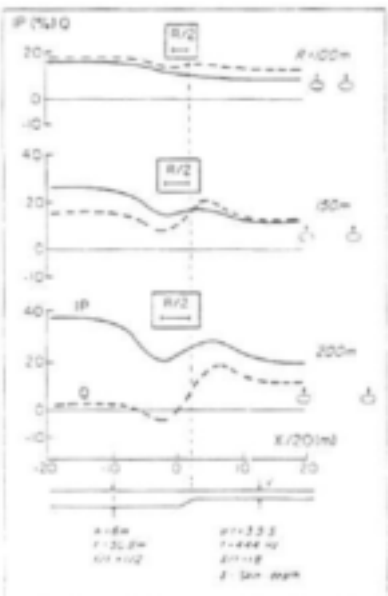

Figure 3-10 HLEM response of ramp discontinuities of different size (after Villegas-Garcia, 1979).

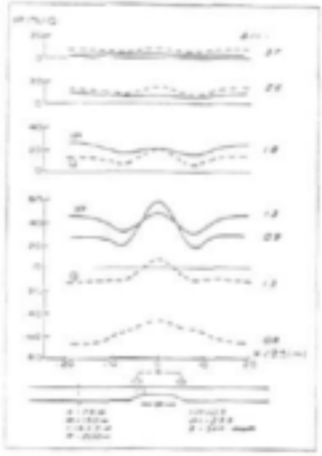

Figure 3-11 HLEM response of the ridge discontinuity in the overburden to different δ/t ratios (after Villegas-Garcia, 1979).

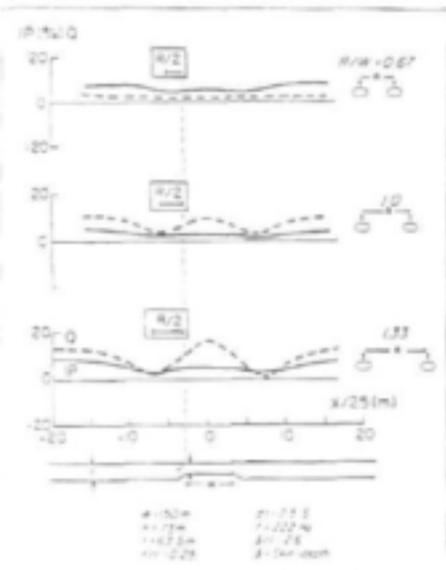

Figure 3-12 HLEM response of the ridge discontinuity in the overburden to different coil separations (after Villegas-Garcia, 1979).

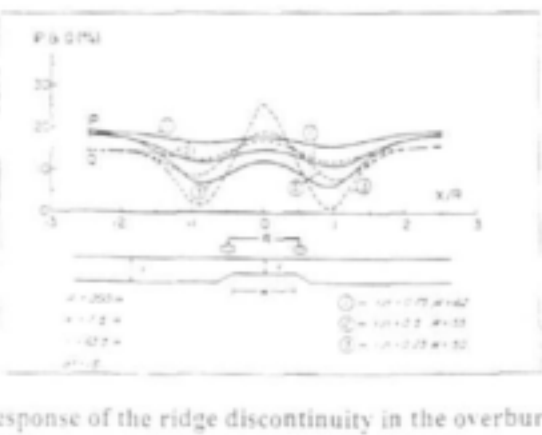

Figure 3-13 HLEM response of the ridge discontinuity in the overburden to different sizes (after Villegas-Garcia, 1979).

The maximum value in the in-phase and out-of-phase components is determined by the width of the ridge and the coil separation (Figure 3-12 and 3-13.

Response of the valley-discontinuity in the overburden

The electromagnetic response on a valley-discontinuity is shown in Figure 3-14. The shape of the anomaly consists of two shoulders in both the in-phase and the out-of phase flanking a minimum right above the valley discontinuity. Therefore the response of a vertical plate conductor is very similar to the valley discontinuity.

To differentiate between these two geological features one has to consider the following:

- the prominent amplitude of the shoulders in the case of the valley discontinuity makes a pronounced difference
- in case of a vertical plate the distance between the crossovers of the anomaly is approximately equal to the coil separation.

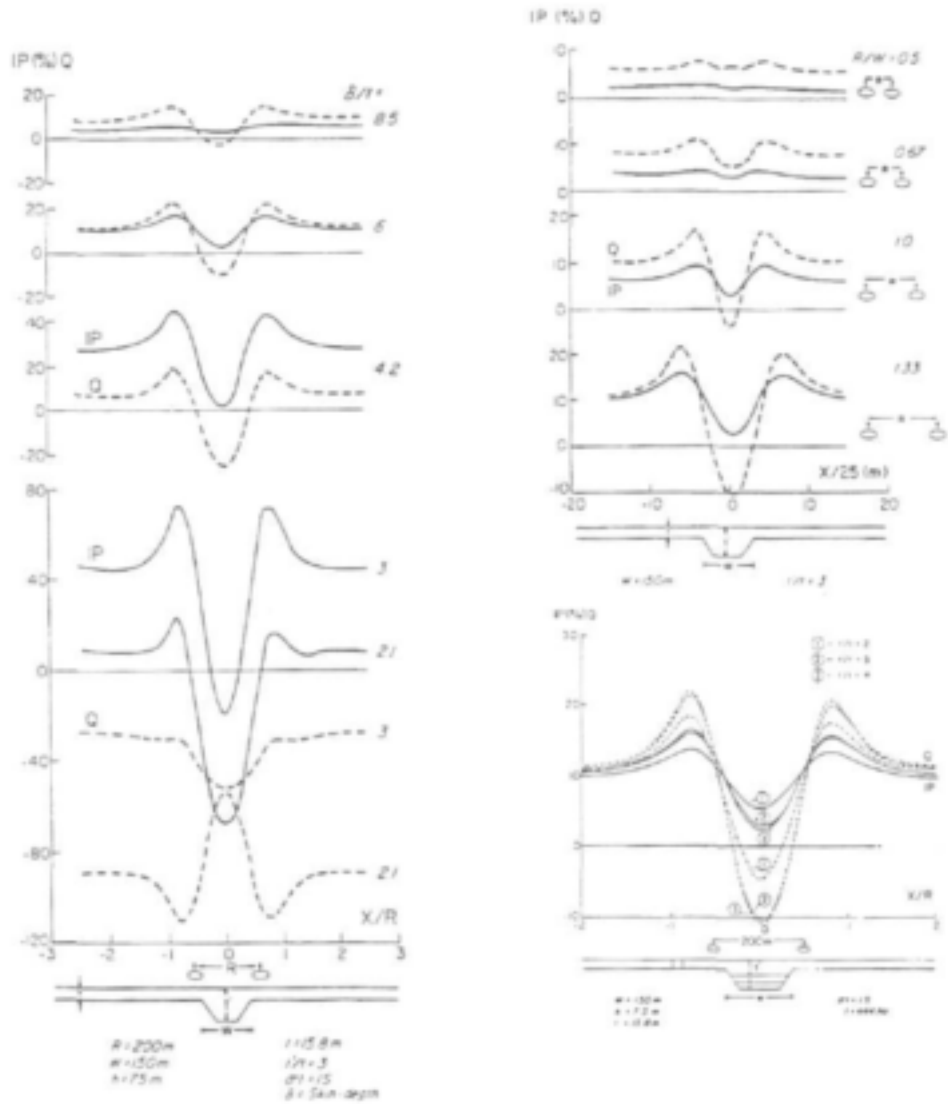

Figure 3-14 Responses for different δ/t ratios, different coil separations and different sizes of the valley discontinuity (after Villegas-Garcia, 1979).

3.3.2 The resistivity technique

The electrical resistivity method is based on the response of earth materials to the flow of electrical current at low frequencies. Electrical conduction in the subsurface is largely electrolytic and takes place in connected pore spaces, along grain boundaries, in fractures, fault lines and joints. The majority of earth materials conduct electricity due to the mineralised water that they contain in pores and fissures (Van Zijl, 1985). The resistivity of different rock types depends on:

- the conductivity of the contained water, e.g. amount of dissolved solids in the water
- the amount of water in the formation, e.g. the degree of saturation
- the way the water is distributed in the formation, e.g. the porosity.

This implies that weathering, faulting, shearing and dissolution lower the resistivity of a formation by increasing porosity and fluid permeability. On the other hand will cementation, unconnected pore space in a formation, compaction and metamorphism of a formation result in an increase in resistivity due to the reduction in fluid permeability.

It is important to note that the resistivity of earth materials varies largely as it is mainly controlled by the amount of dissolved solids in the occurring water. The resistivity of naturally occurring water may vary from a few tenth of an Ωm for seawater to up to more than a hundred Ωm in the case of fresh mountain water (Van Zijl, 1985). Figure 3-15 gives typical ranges for resistivities of different rock types.

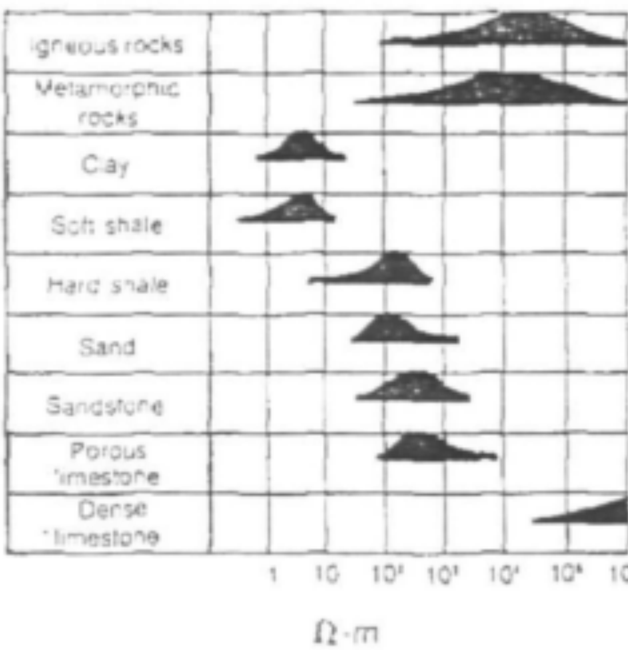

Figure 3-15 Typical ranges of resistivity of different rock types (Hallof, 1992)

The electrical resistivity method is used in groundwater exploration to map overburden depth, lithological changes and to locate faults, fractures and joints that are potentially water bearing. There are two facets to electrical prospecting, the electrical sounding and the horizontal profiling method. During the investigations for this project the Schlumberger electrical sounding method was applied to determine the depth to bedrock at selected points on the electromagnetic profiles.

Schlumberger electrical sounding

Schlumberger sounding is carried out with a four-electrode array. Artificially generated electrical currents are introduced into the ground between two current electrodes called A and B and the resulting potential differences are measured at the surface between two potential electrodes called M and N respectively (Figure 3-16). The distribution of electrical resistivity with depth is studied by progressively increasing the AB electrode spacing. The current electrode progression has been based on an average of √2 (Van Zijl, 1985). At each current electrode spacing an apparent resistivity can be calculated according to the formula

$$\rho a = K \bullet \Delta V/I,$$

Where
ρa= apparent resistivity [Ωm]
K= geometric factor, depending on the electrode spacing [m]
ΔV= the potential difference between the two potential electrodes [V]
I= the current flowing in the ground [A]

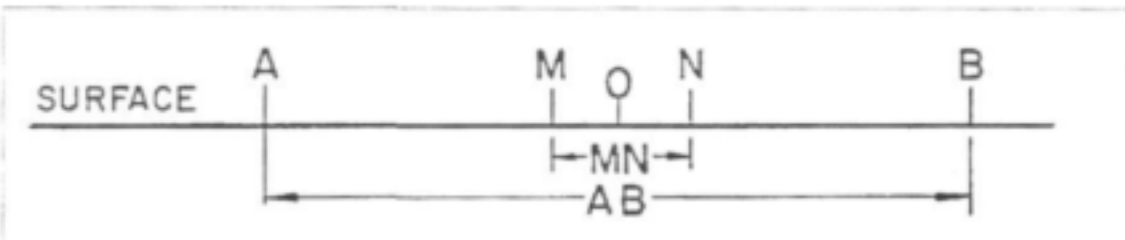

Figure 3-16 Schlumberger configuration (Van Zijl, 1985)

The values of ρa are plotted against half the current electrode spacing (AB/2) in log-log form to give the apparent resistivity as a function of apparent depth (Figure 3-17).

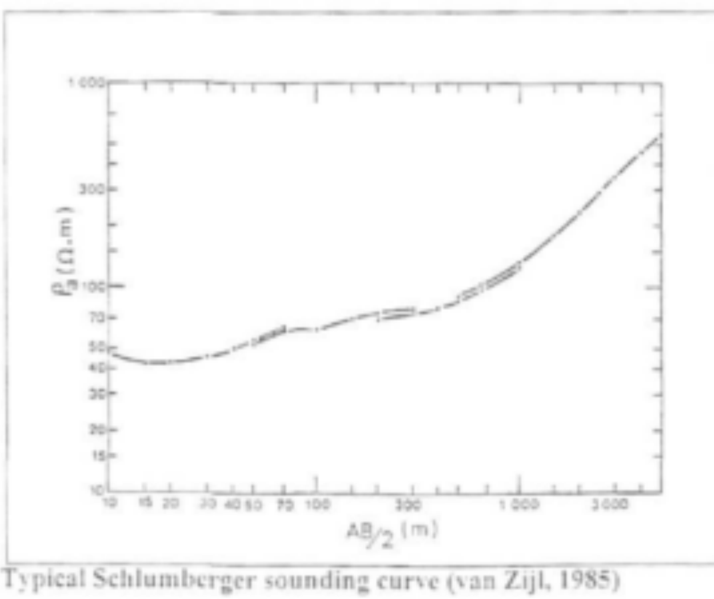

Figure 3-17 Typical Schlumberger sounding curve (van Zijl, 1985)

The electrical sounding curves were interpreted using master sounding curves calculated for horizontally stratified media (Joubert, 1977), a technique known as curve matching. For further details on the resistivity method the reader is referred to the detailed literature (Van Zijl, 1985; Warde 1990, Hallof, 1992; Kearey & Brooks, 1984).

3.3.3 Magnetics

Magnetics, one of the simplest and most abused geophysical methods to trace possible water bearing features was applied to locate contact zones between different rock types. If a geological body has a magnetic susceptibility contrast with the surrounding formations, its location and possible shape can be identified. Magnetic anomalies can be caused for instances by igneous intrusions such as dykes or sills, where preferential groundwater flow occurs, either along the contact zones or fractures in these igneous units. However, this method has its limitations for groundwater investigations, as not all magnetic anomalies are related to hydrogeological targets.

The Magnetometer used was a Geometrics Model G-816 portable Proton Magnetometer. Readings were taken in 10 m or 20 m intervals respectively. The traverses were conducted perpendicular to the expected anomalies.

3.4 Test-Pumping

A constant rate discharge test was carried out on all of the newly drilled boreholes that had a measurable blow yield in order to characterise hydraulic properties of the penetrated lithologies, to assist with developing a conceptual model of aquifers, and to determine sustainable borehole yields. The recovery of water levels was also measured.

The transmissivity (T) and the storativity (S) were calculated using the Cooper-Jacob method (Equation 2) from the portion of the test pump data where radial flow conditions were observed. Radial flow conditions are exhibited on log-log graphs of time versus the first derivative of drawdown versus when the derivative curve was a horizontal straight line (Van Tonder & Bardenhagen, 2001). The sustainable yield of a single borehole was calculated on the basis of following methods described in Sami & Murray (1998):

The recovery method

This method (Kirchner, 1991) involves calculating the maximum number of hours a borehole should be pumped each day at the tested rate based on the time it takes for the water level in a pumped borehole to return to the original rest water level (prior to pumping). Borehole water level measurements during the recovery period following a constant discharge pump test are plotted on semi-log graph paper against the total time since pumping began (t), divided by the time since pumping was stopped (t').

The following formula is then used to determine the maximum number of hours (h) a borehole should be pumped for each day, at the pumping rate of the preceding test:

$h = 24 - (24/x)$ **(Equation 1)**

where:

x = the x-axis intercept of zero residual drawdown versus recovery plot (t/t') on semi-log graph paper after a constant discharge pumping test (Figure 3-18). Residual drawdown is the water level in a borehole after pumping has ceased.

Theoretically zero residual drawdown should occur at t/t' = 2 if the abstraction rate equals lateral recharge. In this case the recovery time for the borehole is equal to the preceding pumping time and a 12 hour pumping day can be maintained at the rate of the constant rate test. A more rapid recovery may be observed if either vertical recharge has occurred or if the storativity is different during pumping and recovery due to air entrapment or elastic deformation of the aquifer. A longer recovery time or incomplete recovery would indicate a limited extent of the aquifer or lower permeability boundaries.

Sami and Murray (1998) indicate that a major problem in applying the recovery method is when incomplete or rapid recovery is experienced. Recovery readings are seldom taken for a longer period than the pumping period, that is beyond t/t' = 2, hence extrapolations are necessary. Extrapolations can produce non-unique t/t' intercepts, which may have serious implications for yield derivations. For example, if intercepts could fall between 1.01 and 1.1 from a pumping rate of 4 l/s, which is a very plausible range given the standard error of slope extrapolations, yields of 3.4 to 31.4 m^3/day would be calculated. Extrapolations may also produce a t/t' value which is less than one, which gives a negative yield recommendation.

In cases where rapid recovery occurs due to leakage from overlying material or variations in storativity, relatively high t/t' values may be obtained. This results in the calculation of large yield values. Since the extent of storage in these horizons is not taken into account, the sustainability of these yields would be uncertain.

It is also necessary to examine the assumption that recovery time is related to the preceding pumping rate. Could a borehole pumped at a low rate relative to its potential require just as long to recover than if it were pumped at a higher rate? If a low rate was selected, a low pressure gradient would be induced in the fractures, which would limit their rate of replenishment from the surrounding matrix. Consequently, similar t/t' intercept values may be obtained irrespective of the preceding pumping rate. The implication is that a much lower yield value would be calculated relative to that which would have been calculated from a high pumping rate recovery test. The application of this method should possibly be restricted to tests where the pumping rate is close to the borehole's capacity and where the recovery is complete.

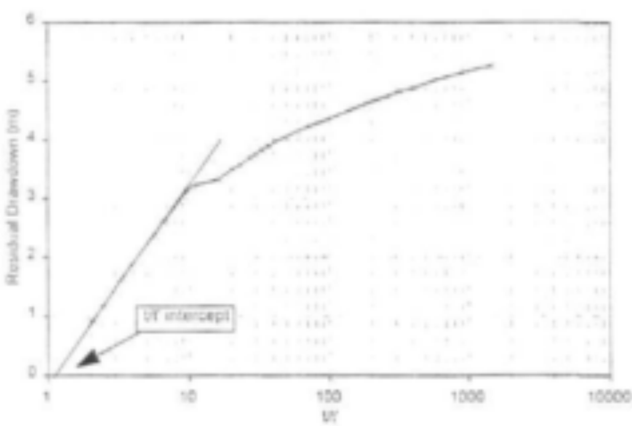

Figure 3-18 Graph of residual drawdown after a pumping test showing extrapolation of recovery and intercept of time of 0 drawdown.

<u>The late-T method</u>

The late-T method (Kirchner & Van Tonder, 1995) is based on the Cooper-Jacob equation as follows to calculate sustainable yield:

$Q = 4\pi Ts/(2.3 \log (2.25\ T\ t/r^2\ S))$ **(Equation 2)**

where:

Q	= sustainable yield (m^3/day)
T	= transmissivity (m^2/day)
s	= available drawdown (m)
t	= pumping time (days)
r	= radius of the borehole (m)
S	= storativity

For evaluating fractured rock aquifers, T values are calculated on the basis of the late time pumping data after boundary conditions are encountered (Figure 3-19). This segment of the curve reflects the rate of leakage from the matrix to the fractures, or reflects the transmissivity after zones of lower permeability are encountered. Where no observation boreholes are available, storativities are estimated and are assumed to be matrix storativities, usually greater than fracture storativities if a porous low permeability matrix exists. The available drawdown is taken as the distance from the rest water level to the main water strike in the borehole; hence sustainable yield is directly proportional to confining pressure. Sami & Murray (1998) note that this assumption is problematical when deep fractures are encountered below thin weathered aquifers as it assumes that the entire available drawdown can be pumped in a given year. They found that this method often significantly overestimated sustainable yield where available drawdown is large.

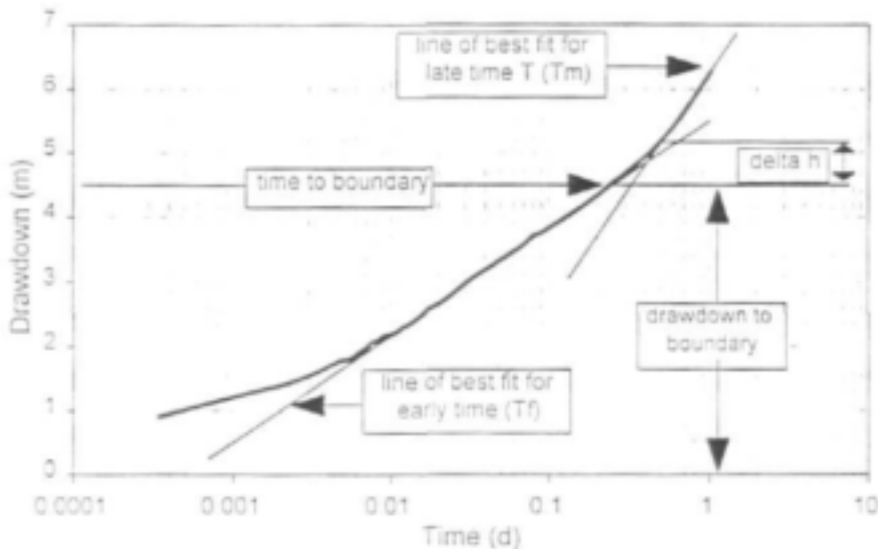

Figure 3-19 Drawdown graph showing period where early and late time transmissivity are calculated, and where boundary conditions are estimated.

The pumping time (t) is taken as one year. By using such a long time without any recharge, influences such as boundary conditions will be cancelled out. While this assumption may not hold in many cases, it is not possible to predict barrier boundaries which would be encountered beyond the duration of the pump test and therefore it makes sense to use a high t-value.

The drawdown-to-boundary method

In the drawdown-to-boundary method (Sami & Murray, 1998) emphasis is on determining the maximum drawdown permitted in order to prevent the dewatering effects that may result once a low permeability boundary is encountered. Equation 2 is used to recommend a daily discharge, Q, however, the definition of parameters is different.

The available drawdown, s, is limited to the difference between the rest water level and the drawdown at which a lower permeability boundary condition is encountered, as indicated by an increase in the rate of drawdown on the semi-log slope of the time-drawdown curve. This drawdown is marked 'drawdown to boundary' on figure 3-19. Transmissivity values are calculated using the Cooper-Jacob method on the basis of the early, pre-boundary pumping data where radial flow exists. The method attempts to limit drawdown after long time periods (e.g. 365 days) to a level at which dewatering of the more permeable zone occurs. This method does not consider the nature of the boundary; nevertheless Sami & Murray (1998) found that the method provided estimates that compared well to the maximum observed long-term yield of boreholes in nearly 95% of cases.

Alternatively, available drawdown is taken as the thickness of the weathered formation below the piezometric level or water table in aquifers which derive most of their storage from this zone. By limiting the long term drawdown to the base of the weathered zone, the risk of dewatering the storage component of the aquifer is reduced.

An advantage of the drawdown-to-boundary method is that it aims to limit the long-term drawdown in the borehole to a level at which a hydraulic boundary is encountered. As stated earlier in this section, such boundaries may be caused by different geological conditions. A boundary may consist of a geological barrier that delineates the lateral extent of the aquifer; it may consist of a geological formation with lower permeability, or zones within a formation of lower permeability; and it may consist of a matrix of lower permeability than the fracture zones of the aquifer.

Maximum drawdown method

The maximum drawdown method is similar to the drawdown to boundary method in terms of the calculation of available drawdown. However, it uses a graphical approach based on calibrating discharge so that, using calculated aquifer parameters, a Theis curve maintains drawdown below the identified boundary after long term pumping (Figure 3-20).

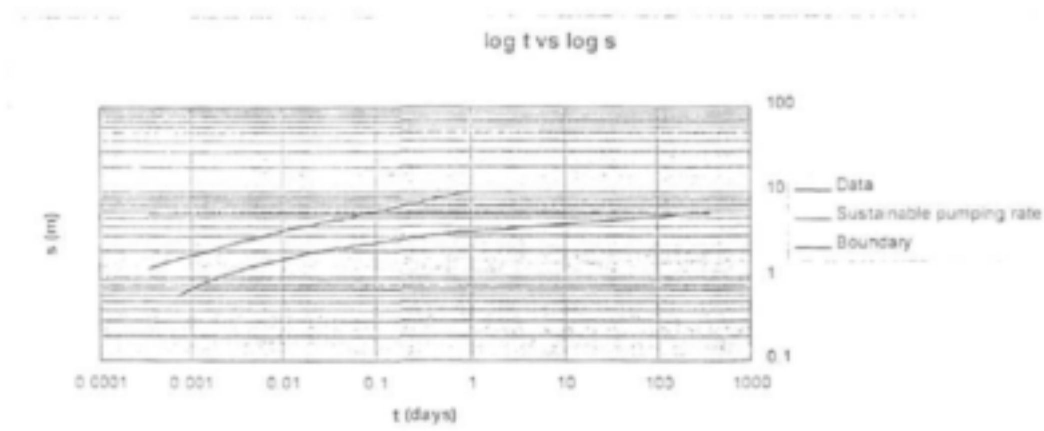

Figure 3-20 Drawdown graph showing the sustainable pumping rate that would maintain drawdown above the identified boundary.

The distance-to-boundary method

The distance to boundary method (Sami & Murray, 1998) utilises a modified version of the Cooper-Jacob equation. The radius of the borehole, r is replaced by the radius of influence in the aquifer when a boundary condition is encountered. This distance is determined from the point where an increase of the drawdown is observed in the semi-log drawdown curve, which is marked as 'time to boundary' on figure 3-20. For a fractured rock aquifer this represents the point in time at which the permeability of major fractures no longer controls the borehole's discharge-drawdown relationship. Thereafter the borehole's discharge is predominantly controlled by the rate of water leaking from surrounding matrix blocks or micro fractures into the fracture itself. At the time of this inflection point the radius of influence r at that time t is calculated using the following relationship:

$r^2 = 2.25\ T\ t / S,$ **(Equation 3)**

With T and S representing the early time transmissivity and storativity.

Using this distance (r), the Cooper-Jacob is used to calculate the pumping rate (Q), which can be sustained over the long-term, such as t = 365 days. The aquifer parameters used are early time tranmissivity and an estimate of the storativity of the aquifer matrix, which is close to its specific yield. Available drawdown is assumed to be the drawdown during the transition from early to late time conditions, which is marked as delta h on figure 7; hence the method attempts to maintain minimal drawdown (h) at distance r after long term pumping. Sami & Murray found that this method provided accurate estimates in 80% of cases.

The concept of restricting the maximum abstraction so that significant drawdown is limited in extent to the theoretical distance of an observed boundary seems appropriate in aquifers that are characterised by boundary effects. A drawback in the application of the distance-to-boundary method is that an h value may not be easy to obtain where delayed yield or double porosity effects are experienced.

Flow characterisation

The Flow Characterisation method (Van Tonder et al., 1999) utilises derivatives of pressure head to evaluate flow regimes since they are more sensitive to small phenomena. The derivative of drawdown with respect to log t is the gradient of semi-log drawdown. Characteristics of the derivative curve are indicative of aquifer conditions. For example, dips indicate dewatering of fracture zones, steep upward trends of slope = 1 indicate closed boundaries and slopes of -1 indicate leakage.

Sustainable yields are calculated taking into account pumping and recovery characteristics, the type of boundary encountered and transmissivities after boundary conditions are encountered by :

$Qs = s\ Q/(F1(s_{100} + 4\ \Delta s\ F2))$ **(Equation 4)**

Where

- Qs = sustainable yield
- s = available drawdown as the distance between the rest water level and water strike
- Q = pumping rate during pumping test
- F1 = drawdown after 100 minutes/recovery after 100 minutes
- s_{100} = drawdown after 100 minutes
- Δs = drawdown per log cycle after boundary conditions are encountered
- F2 = parameter related to boundary conditions such that for homogenous aquifers it is 1, single boundary conditions 2, matrix flow at late time 3, recharge or leakage 0.5, and closed boundary conditions at < 100 m 6. Alternatively F2 can be calculated by dividing the derivative value of the point at which the curve is first horizontal by the derivative value at which the derivative curve is horizontal after boundary conditions are encountered.

An infinite aquifer would have an F2 of 1 and the derivative plot would have a horizontal straight line. A single boundary would be expressed as a doubling of the derivative, while a closed no-flow boundary would exhibit a straight line of unit slope at late time. Leakage would appear as a strong downward trend.

3.5 Down-the-hole Geophysics

The newly drilled boreholes were also logged using gamma, apparent resistivity and self-potential logging to determine the formation composition in terms of lithology, permeability and conductivity. The data were obtained with the CHEMTRON bore logger, R 300, which is with a portable bore hole logger that records the number of pulses detected per unit of time.

3.5.1 Gamma Logs

In gamma logging, measurements of naturally occurring radiation emitted by radioactive elements encountered in the rock formation are taken. Gamma radiation is emitted from elements, which are unstable and decay spontaneously into other more stable elements. Certain radioactive elements occur naturally in geologic materials such as potassium 40, uranium 238 and the thorium 232 decay series. Relatively high radiation is found in clay and shales (potassium 40), whereas mature sand and gravel contain mostly stable elements like silica. Therefore a natural gamma log shows increasing radiation opposite sedimentary beds that contain potassium-rich shale or clay and can be used for stratigraphic correlation and permeability determination.

3.5.2 Spontaneous Potential Logs (SP log)

The SP log is an electrical logging technique, which measures naturally occurring electrical potentials that result from chemical and physical changes at the contacts between different types of subsurface geologic materials. The borehole has to be uncased and filled with drilling fluid or groundwater.

3.5.3 Apparent Resistivity

The resistivity log is an electrical logging technique that gives a detailed picture of the character and thickness of the various strata as well as an indication of the water quality at the well site.

The resistivity log usually distinguishes between clay, silt and shale layers due to their relatively low resistivity, and sand, gravel, sandstone, limestone, and dense igneous and metamorphic rocks due to their very high resistivities. It is also possible to use the method to detect fracture zones. The log usually responds clearly to open saturated fractures, hence there is a limitation in that low resistivity anomalies which characteristically occur in the vicinity of fractures can also be caused by lithological changes or by washouts caused by drilling (Howard, 1990). Additionally, the water quality influences the log. In general, the resistivity of a formation will vary inversely with the total dissolved solids content in the water.

A drawback of the method is that logging can only be done in uncased boreholes filled with drilling fluid or water.

3.6 Financial Analysis

The objective of groundwater exploration is to ensure that water bearing targets offering the greatest probability of success in terms of borehole yield are identified. In this manner drilling costs are kept to a minimum by reducing the risk of drilling dry holes and the number of boreholes required. This requires that exploration follow a carefully considered plan of approach aimed at maximising the success rate in the most cost effective and productive manner. Borehole siting must not be limited to a fixed methodology or a limited exploration maintenance costs. It may also impinge on the financial viability of the project due to the high costs of drilling. With limited exploration the drilling period may also require more time than would have been incurred by additional exploration, hence time constraints on exploration may also adversely affect project scheduling.

The objective of the financial analyses were to evaluate the extent to which additional exploration is financially viable in terms of a reduction in overall borehole establishment costs (average cost for each successful borehole) and the cost of the yield obtained (average cost per litre per second borehole yield) based on experiences in the four research areas investigated. The costs associated with exploration work include a desk study, LANDSAT interpretation and aerial photo interpretation, geophysical surveys, structural mapping and community liaison. Test pumping costs were excluded.

Two, and if sufficient data was available, three scenarios were investigated to establish 10 successful boreholes in the study areas:

1 *No structured exploration, or drilling randomly or by visual observation*

This scenario is based on historic drilling records obtained form the NGDB, which are assumed to represent borehole siting without modern exploration methods. Success rates in the NGDB records were used to estimate the costs to achieve 10 yielding boreholes.

2 *Limited exploration based only on the frequently used method of EM-34 and magnetometer geophysical traverses and a desk study of existing maps.*

This scenario is based on the success rates achieved during the Critical Intervention Programme and/or data from consultants who worked in the area. It is based on current practice in the hydrogeological industry for borehole siting. EM-34 and magnetometer investigations following a brief desk top study can be considered the current industry standard for rural water supply schemes based on the budgets available for borehole siting from funders such as DWAF, Mvula Trust and other international NGO's. Success rates from these records were used to estimate the costs to achieve 10 yielding boreholes.

3 *Full exploration based on structural mapping, LANDSAT and aerial photo interpretation, geophysical exploration using the most appropriate method under the given hydrogeological conditions.*

This scenario is based on the methods used for this project, where a MAX-MIN system was used to investigate LANDSAT lineaments considered to be tectonically significant. The MAX-MIN has the advantage of depth of penetration over the EM-34, albeit at a higher cost. Electromagnetics was used in conjunction with the resistivity sounding method and a magnetometer. Boreholes were sited on structural features, such as lineaments, faults and brecciated zones and on deeply weathered rock profiles identified in the field. The costs to establish 10 yielding boreholes were calculated in order to compare the results to scenario 1 and 2.

The costs were based on the Council for Geoscience rates (based on the conventional 15% rule for consultant's tariffs). Quantities were based on the standard number of man-hours per activity expected during the investigation (Figure 3-6).

Table 3-3 Applied matrix to calculate the approximate costs to establish 10 yielding boreholes according to scenarios 1, 2 and 3

ITEM		Units	Rate	Scenario1		Scenario2		Scenario3	
				Qty	Cost	Qty	Cost	Qty	Cost
Desk Study[1]	E	Day	1600						
EM34 survey[3]	X	Day	1500	*9		*10		*11	
Max Min survey[4]	P	Day	2500	*9		*10		*11	
Resistivity survey[5]	L	Day	2500	*9		*10		*11	
Geophysical interp.	O R	Line	100	*9		*10		*11	
Accommodation	A	Day	150	*9		*10		*11	
LANDSAT image[6]	T	Each	2500						
LANDSAT interp.	I	Day	1200						
Structural mapping[7]	O N	Day	1350						
Sub total - Exploration									
Community liaison[2]		Hr	100	*9		*10		*11	
Drilling[8]		Hole	11000	*9		*10		*11	
Drill supervision		Day	1000	*9		*10		*11	
TOTAL									
Per successful site		R							
Median yield		L/s							
R/l/s									

1: Review of topographical and geological maps and geological reports
2: At 1h per drilling site
3: At 1 technician and one labourer and 3 boreholes sited per day, including magnetometer surveys
4: At 2 technicians and 2 boreholes sited per day including magnetometer surveys
5: At 2 technicians and 2 boreholes sited per day
6: At 22% recovery per usage of R10000 per 180 x 180 km image and R1200 in man-hours for co-ordinate registration
7: Field mapping of outcrops and aerial photo interpretation
8: Casing costs are not considered as it is assumed that only successful boreholes would be cased, which would result in similar casing costs for all scenarios
*9: According to the drilling success rate determined from the drilling records in the NGDB
*10: According to the drilling success rate as determined from the drilling records in the CIP
*11: According to the drilling success rate achieved during this investigation
Shaded areas: figures according to scenario in every research area

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4. SUMMARY OF RESULTS IN STUDY AREAS

This chapter briefly describes the outcomes of field investigations in the study areas. For a more detailed discussion, the reader is referred to Volume II of this report.

4.1 Introduction

The results obtained in the 4 selected study area, the Dwyka tillites, the Natal Metamorphic Province (NMP), largely granites and gneisses, the Limpopo Mobile Belt (LMB), gneisses, amphibolites and quartzites, and the Barberton Greenstone Belt (BGB), mafic, ultramafic and felsic lava, and carbonaceous cherts metamorphosed at a zeolite to green schist facies, show that the methodology employed results in increased borehole success rates and median yields compared to previous drilling (Table 4-1) and a reduction in both the average cost of establishing successful boreholes and the cost of the water obtained (Table 4-2):

Table 4-1 Borehole Success Indicators

Geology	Success Rate			Median Yield		
	1	2	3	1	2	3
Dwyka Tillite	12%	27%	50%	0.16 l/s	0.1 l/s	0.1 l/s
NMP	50%	63%	89%	0.1 l/s	0.1 l/s	1.8 l/s
LMB	40%	38%	66%	0.39 l/s	0.1 l/s	3.9 l/s
BGB	50%		89%	0.4 l/s		1.0 l/s

Where:

1: National Groundwater Data Base, assumed to be a record of random drilling

2: Critical Intervention Programme where siting was based on geophysical methods only

3: Results obtained by the methodology described in this study

Table 4-2 Financial Indicators

Geology	R/successful borehole			R/l/s		
	1	2	3	1	2	3
Dwyka	99473	52100	28600	621706	521000	286000
NMP	22990	20710	18370	229900	207100	10206
LMB	30250	34855	24390	77564	348550	6254
BGB	22400		19875	60500		18370

4.2 Dwyka Group

The study showed that successful groundwater exploration for the area is possible, but should be limited to establish hand pump schemes. An evaluation of the structural geology and the hydrogeological conditions of the area, together with a suitable geophysical method for the environment pushed the drilling success rate up from a historical 12 % to 50 %. The unfavourable hydraulic properties of the tillite however, limit the yield of holes and median yields of successful holes could not be increased. Therefore, groundwater abstraction in the area will mostly be restricted to exploitation through hand pumps to support small communities. High yielding boreholes are seldom encountered and can only be found at major fault zones where interconnected fracture zones are present to distinctively enlarge the permeability of the subsurface. These are located at the margins of the Dwyka Group.

Median yields of successful boreholes of all three data sets are approximately 0.1 l/s, which suggests that exploration did not result in significantly improved yields as well as success rates.

Low historic success rates have resulted in an expenditure of nearly R100 000 for the establishment of each successful borehole. In comparison, a limited expenditure of about R33

000 for geophysical exploration during the CIP, or R735 per borehole drilled, would improve drilling success rates to 27% and would result in an expenditure of about R52000 per successful borehole. If exploration expenditure were increased to R50 000 using the methodology described in this project, success rates of 50% could be expected, hence the drilling budget could be greatly reduced. Expenditure would then be about R28600 per successful borehole.

In some cases, such as reticulated systems where production rates are more important than the number of water points established, it may be beneficial to evaluate program efficiency in terms of costs per unit yield of water. In the Dwyka Group costs per unit yield are less relevant as the low yield of boreholes and the rugged topography constrain borehole schemes which supply several communities, hence the number of individual developed water sources is a more important indicator of success. Nevertheless, it is possible to measure the cost of water production in terms of R/l/s. Drilling without prior scientific exploration results in a cost of R621706/l/s of water produced. Minimal geophysical exploration (scenario 2) results in costs of R521000/l/s of water produced. The data suggests that more detailed exploration results according to the proposed methodology results in reducing production costs of R286000/l/s.

Although of low potential, groundwater is an important resource in the study area, providing a clean and consistent water source. The geology in the area consists of low permeable tillite of the Dwyka Group, however it does not provide a productive aquifer. The low primary porosity of the tillite and extensive calcite veining restricts groundwater flow to poorly connected fracture zones. Successful groundwater exploration in the area has to delineate fracture zones by taking the following geological, hydrogeological and geophysical considerations into account:

- Fractures follow a distinct joint set, with three dominant strike directions: NNE-SSW, N-S and SE-NW. This joint pattern is imprinted in the morphology of the area. Depressions along ridges, valleys and river beds are often the expression of a buried fracture zone and can be promising drill sites. Aerial photographs and LANDSAT imagery should therefore be used to pinpoint target areas before beginning the field exploration and visual borehole siting on these structures has been shown to be the most successful approach.

- Structures like dykes or sills are very seldom found and do not play an important role in the area. For this reason magnetic surveys are of limited value in the area.

- To delineate water-bearing features, the electromagnetic technique has not been a promising geophysical method to use in the study area. Water strikes are generally very deep, with 75% of the boreholes showing a water strike below 60m, and structures dip steeply. Therefore, only electromagnetic exploration techniques with a sufficient depth of penetration are suitable to delineate fracture zones, however, these structures are invariably thin, hence geophysical detection is masked by the overlying rock mass. The EM34 has proved to be inadequate in these hydrogeological conditions, especially when used with a 20m coil separation giving a penetration depth of about 25m. The APEX Max-Min electromagnetic system proved to be effective in locating buried narrow conductors, but geophysical anomalies were not always water bearing. With a coil separation of 100m, a depth of penetration of up to 50m or more can be obtained, depending on the lithology.

- The most promising electromagnetic response is where a dipping conductor is observed, exhibited as a trough in both the in-phase and out of phase signal. The distance where the borehole must be located relative to the centre of the trough depends on the depth of the static water level. As 82 % of the fractures in the area dipping steeper than 65°, a site of only a few meters off centre to the dipping side of the conductor is sufficient to hit the feature below the water table. However, steep dips indicate that boreholes must be accurately sited and based on a short station interval.

- Ramp, ridge or valley discontinuities in the conductive overburden layer are a common response in the study area. These can be an indication of a buried fracture zone and but did not prove to be promising drilling sites. If the discontinuity has its origin merely in a change of overburden thickness, the chances of hitting water are very low. These types of geophysical anomalies proved to be shallow features unrelated to water bearing features.

- Results obtained from the Max-Min survey indicate that the low frequencies of 220 Hz and 110 Hz often fail to produce a significant anomaly, even where water bearing features were subsequently detected. This can be attributed to the thin nature of deeper structures. The highest operating frequency of the Max-Min instrument, 56320 Hz is susceptible to background noise and variations in the shallow overburden. Therefore frequencies from 880 Hz up to 28160 Hz should be used.

- Fractures in the study area are seldom interconnected and are of limited thickness. Additionally, the horizontal extent of fracture zones is limited due to the generally steep dipping angle of the features and the steepness of the topography. Therefore, drilling sites should be carefully selected on a geophysical or structural anomaly in order not to miss the feature.

- The topography is a decisive factor controlling the availability of groundwater. At low altitude groundwater rest levels are generally shallower and the chances of hitting a fracture zone below the static water level are higher, resulting in more confining pressure, hence potentially higher yields. However, population distribution and poor access to valley bottoms limits the feasibility for boreholes at a low elevation. In addition, the low yields and high pumping heads from the valley bottoms to the high lying areas limit the economic feasibility of this option.

4.3 NATAL METAMORPHIC PROVINCE

The study showed that an evaluation of the structural geology and the hydrogeological conditions of the area together with a suitable geophysical method for the environment pushed the drilling success rate up from a historical 54% (NGDB) and 63% (Critical Intervention Program) to 89%. Beside the improved success rates, the proposed methodology resulted in significantly improved yields. Whereas the median yield for the NGDB and CIP records is 0.1l/s, a median yield of 1.8l/s was achieved during this study, which accordingly lowers water production costs considerably. The average yield of all boreholes was pushed up from a historical 0.96l/s to 2.55l/s.

Historic success rates have resulted in an expenditure of approximately R23000 for the establishment of each successful borehole. In comparison, an exploration budget of R13500 for geophysical exploration would improve drilling success rates and result in expenditure of about R20700 per successful borehole. If exploration expenditure is increased further to about R50600 for the proposed methodology, then success rates of 89% can be expected and establishment costs would come down to about R18370 per successful borehole.

The costs of water production in terms of R/l/s suggest that drilling without prior scientific exploration results in a cost of R229900/l/s of water produced. Minimal geophysical exploration results in costs of R207100/l/s of water produced. Increased exploration results in reduced production costs of R10206/l/s, or 5% of those achieved during the CIP. This saving can be attributed to the high median yield achieved during this study.

Groundwater is an important resource in the study area, providing a clean and consistent water source. The geology in the area consists mainly of gneisses, granites and amphibolites of the Natal Metamorphic Province. The low primary porosity of this hard rock aquifer restricts groundwater flow to fracture zones or deeply weathered profiles, where successful boreholes can be established. Successful groundwater exploration in the area has to delineate these features by taking the following geological, hydrogeological and geophysical considerations into account:

- A tectonic analysis of faulting in terms of the potential of faults and their related joint systems to be water bearing requires that the orientation of tensional, compressional and shear couples be understood. On the Natal coast, this requires an understanding of tectonic processes at work on the Agulhas Transform Fault and the resulting onshore fault and fracture system. It is most probable that the faulting in Natal is related to divergent wrenching on the Agulhas Transform Fault, in which case the maximum extensional force would be directed perpendicular to normal faults. In this case, ENE transtensile normal faults are expected to have the maximum tensional strain, while NE trending faults are likely to be synthetic strike-slip faults and in shear. E-W faults are likely to be antithetic and in shear, while north trending faults can be interpreted as high-angle faults connecting synthetic fault trends.

- Field structural measurements and consequent strain analysis suggest that the most prominent features are the NNE and ENE trending fault sets, with subordinate NE and NW trending faults. The structures to favour for groundwater exploration are the major N to NNE and ENE fractures as they seem to be the open structures. The subordinate NW and NE fractures that dip steeper than +/- 60° may also be good water carriers, but the fractures dipping less than 45° are closed due to the presence of a thrusting component.

- Lineaments in the study area follow a distinct joint set, which is dominated by three major strike directions: N-S to NNW-SSE, ENE-WSW and NW-SE. The ENE-WSW and NW-SE features appear to be of greater regional significance, whereas the lineaments striking N-S proved to be of only local importance.

- Discharge tests carried out indicate that at least 4 types of aquifers occur in the research area: networks of uniform fractures, sub-vertical fractures with or without leaky weathered overburdens, bedrock contacts with a leaky overburden, and leaky deep seated horizontal fractures. High yields are generally derived from aquifers overlain by a thick weathered overburden, or from large fault zones.

- To delineate water-bearing fracture-zones, the electromagnetic technique can be a promising geophysical method to use in the study area where shallow weathered aquifers exist. However, water strikes are generally deep, with 50% of water strikes occurring below 70m. These targets were only detected using the 220 and 880 Hz frequencies (figs. 5-58 and 5-71). Therefore, only electromagnetic techniques with a sufficient penetration depth are suitable to delineate fracture zones. The EM34 has proved to be inadequate under the given hydrogeological conditions, especially when used with a 20m coil separation giving a penetration depth of about 25m in this lithology. The APEX Max-Min electromagnetic system proved to be effective in locating buried narrow conductors. With a coil separation of 100m reliable information from the subsurface of up to 50m and more, depending on the lithology, can be obtained.

- Resistivity sounding proved to be helpful in locating deep weathered profiles, which could be an indication of buried fracture zones. Consequently, resistivity profiling would be the most effective means of geophysical exploration. Furthermore, changes in lithology can be detected. Whereas thick weathered overburden is a promising groundwater target in the area, no evidence of any additional aquifer at contacts between different lithologies could be found.

- The magnetometer helps in delineating faults or fracture zones if the features are either broad so that weathering is significant and hence alters the magnetic properties of the fault or fracture zone compared to the unweathered bedrock, or if the fault or fracture zone separates different lithologies.

- Besides fracture zones, the most important water-bearing features in the study area are deep weathered profiles. The occurrence of deeply weathered zones is strongly linked to the geomorphology of the area. Where steep slopes encourage surface runoff, weathering has been entirely removed and groundwater is exclusively controlled by faults and fracture zones. Lower lying area or areas of a more gentle relief experience a significantly reduced surface runoff and aquifers can develop in both the weathered profile and the fracture zones of the basement rock. Additionally, the weathered overburden can increase significantly in depth over fault or fracture zones providing an additional shallow aquifer. The weathered material provides significant storage, replenishes the underlying aquifer.

- To delineate deeply weathered profiles all three geophysical methods, the Max-Min profiling and sounding, resistivity sounding and magnetometer profiles were beneficial. The electromagnetic technique indicates changes in the thickness or conductivity of the weathered overburden with ramp, ridge or valley discontinuities. To determine the thickness of the weathered overburden, resistivity soundings are necessary.

- Structures like dykes or sills are relatively rare and do not play an important role as groundwater targets in the area. Furthermore, they are difficult to detect by magnetics as the intrusions exhibits similar magnetic properties as the host rock.

- A correlation between lineament or fault azimuth and yield shows that successful boreholes are associated with N-S, E-W and NE-SW trending structural features, orientations of extensional nature. The only unsuccessful borehole was drilled into a NW-SE fault, the orientation regarded as compressional in nature. However, results have to be taken with caution, as they are based on nine boreholes only. In general, the wide range of azimuth trends related to successful boreholes suggests that a pervasive influence such as erosional unloading is operating on all existing fracture systems.

- The yield data set shows a strong correlation with lineament or fault length. The four highest yielding boreholes are associated entirely with regional scale structural features, whereas local features have a poorer groundwater potential.

- The topography is a decisive factor controlling the availability of groundwater in the study area. Besides the fact that geomorphology has a strong effect on the development of weathered profiles, it also influences the depth of the static water level. At low altitude static water levels are generally shallower and occur in the weathered profile, which serve as a storage horizon.

- The financial analysis suggests that a more comprehensive exploration programme and a larger exploration budget could in the long-term result in significant cost savings, especially in large regional programs where costs of regional geological and structural exploration are spread over many boreholes. In such cases dedicating a larger proportion of the budget to exploration than is currently the case may result in more efficient drilling and a net reduction in establishment costs per site. For such an exploration program to be successful it must incorporate field geological mapping, remote sensing and appropriate geophysical exploration based on the identified hydrogeological regime.

4.4 LIMPOPO MOBILE BELT

The results suggested that the Limpopo Mobile Belt has a poor water quality (class II-III) due to excessive nitrate levels. Low recharge and the extreme heterogeneity in targets severely hamper exploitation. Low success rates exist concurrently with very high yielding features, however, the latter are restricted to mainly regional scale fault zones. Widespread quaternary cover also hinders the identification of structures. Smaller fault zones and alluvial cover along the streams provide a more limited aquifer. Consequently, water abstraction will have to be reliant on regional abstraction systems from identified structures and reticulation to the point of need. Fortunately, the flat topography does not hinder reticulation.

The results obtained suggest that the use of the proposed methodology will reduce the costs per successful site from R30250 to about R24400, if success rates can be increased from 40% to the achieved 66%.

A substantial cut in costs in terms of water production expressed as R/l/s was achieved during this exploration programme. Median yields were increased from 0.4 l/s to up to 3.9 l/s, which brings down the costs for the water production from 52743 R/l/s in case of random drilling to 6254 R/l/s. The relatively high median yield achieved under this project suggests that water supply systems in the area could involve reticulated systems, however, the low recharge rate suggests that reticulated schemes require careful monitoring.

- Field structural analysis shows that the joint orientations in the Limpopo Mobile Belt lithologies are distinctly different from these in the Karoo-age cover and intrusive lithologies due to Pre-Karoo geodynamics. The joints in the Limpopo Mobile Belt mostly dip steeply and are oriented NW to N, suggesting E-W to NE/SW extension, or E-W shearing. The regional geodynamics (6.2.3) suggest that extensive ENE shearing occurred prior to Waterberg times (2.0 Ga.), hence pre-Waterberg shearing associated with the emplacement of the Central Zone of the Mobile Belt is the responsible mechanism.
- Subsequent or more recent tectonic events are superimposed in the Limpopo Mobile Belt structural geology, but are difficult to define due to the various ages of joint structures. The joints in the Karoo-age sedimentary rocks and basalts only record tectonic events that occurred in post-Karoo times, hence they provide information on structures in the Limpopo Mobile Belt that are of interest as hydrogeological targets. These all dip steeply and are oriented E to ENE in area II and ESE and NE in area I, suggesting N-S extension, and are associated with uplift and block faulting. Consequently it is fractures with orientations similar to those preserved in the Karoo-age lithologies that are likely to be more open and which therefore represent the best structures for ground water exploration.
- Lineaments in both study areas are primarily orientated in an ENE-WSW direction and are associated with normal faults related to block faulting. These targets are the most favourable hydrogeological feature in the region and yields of up to 50 l/s can be obtained from regional structures. A second complementary antithetic WNW-ESE trend is apparent, however, these are strike-slip structures and have a lower potential.
- A comparison between the geological map of the study area and the lineament orientation reveals that the majority of lineaments were picked along boundaries of different geological formations. As lithological boundaries within the Limpopo rocks itself are not particularly be considered a groundwater target, lineaments have to be taken with caution and examined in the field for their hydrogeological significance.
- Discharge tests carried out in the research area I indicates that a significant weathered zone aquifer exists, with yields of up to 4 l/s. Test pumping recovery suggests that this aquifer is extensive in nature. Deep seated fractures are only an aquifer when part of a regional fault structure.
- Regional scale fault lines can be picked up effectively with the magnetic and the Max-Min systems. However, smaller scale faults cannot be easily located by magnetic or electromagnetic methods where significant quaternary cover exists.

- Lineaments, which do not simply reflect geological contacts of different lithologies are scarce scares in both areas. Target identification requires differentiating between lithological and tectonic contacts. Lithological contacts investigated left no impact on none of the geophysical methods applied, unless associated with faulting.
- Magnetic structures are commonly found in both study areas and are easily detectable with the magnetic method. Caution has to be taken in terms of the geological origin of magnetic anomalies, as anomalies can result from dolerite and diorite sills and dykes, amphibolites, and variations in mafic content in LMB lithologies. The magnetic structures seldom had an associated anomaly on the EM profiles, implying that there might be no weathered zone accompanying these structures, which would impact on their hydrogeological importance.
- Electromagnetic borehole siting has been shown to be ineffective in the region, since success rates are similar to those obtained by random drilling (Vegter, 2001). Anomalies can be attributed to variations in weathering in the deeply weathered profiles. This proved to be the case in spite of supporting resistivity, VLF, magnetic, and seismic refraction profiling.
- From the exploration drilling it is evident, that regional scale dip-slip normal faults are the most important water-bearing features in the study area, with the most important of these being rejuvenated shear systems. Small-scale faults can be successful, but have a poorer groundwater potential. An additional aquifer is found within the alluvial deposits accompanying streams, which can be tapped through the underlying fault system. Consequently, regions where streams dog-leg in an easterly orientation are the most promising points. Lithological contacts as well as dyke or sill structures were found to be either not water-bearing or yielded only small amounts of water. The contact between overlying Karoo Sandstone and LMB rocks, which is a significant unconformity, appears to be dry, unless encountered at an ENE tectonic contact. Deeply weathered overburden acts as an additional aquifer where deep weathering has resulted or NE or NW faults.
- The financial analysis suggests that improved exploration results in significantly improved yields and considerably lower water production costs. The relatively high median yield achieved under this project suggests that water supply systems in the area could involve hand pump and low density reticulated systems.

4.5 BARBERTON GREENSTONE BELT

The study showed that an evaluation of the structural geology and the hydrogeological conditions of the area together with a suitable geophysical method for the environment pushed the drilling success rate up from a historical 50% (NGDB) to 89%. Beside the improved success rates, the proposed methodology resulted in significantly improved yields..

A substantial cut in costs in terms of water production expressed as R/l/s was achieved during this exploration programme. Historic success rates have resulted in an expenditure of approximately R22200 for the establishment of each successful borehole. In comparison, with an exploration budget of about R55000 for the proposed methodology, success rates of 89% can be expected and establishment costs would come down to about R19875 per successful borehole.

Median yields were increased from 0.4 l/s to up to 1.0 l/s, which brings down the costs of water production from 60500 R/l/s in case of random drilling to 18370 R/l/s in this project. The high median yield achieved during this project suggests that water supply systems in the area could involve reticulated systems.

Groundwater is an important resource in the study area, providing clean, reliable, low cost water source. The geology of the area consists of impermeable granites and met-basalts (i.e. low grade metamorphosed basalt to an amphibolite schist or green schist facies). The impermeable granites and extensive quartz veins, which often fill the fractures, are not recommended geological terrains for groundwater exploration. The meta-basalts are the best targets for groundwater exploration, especially when fractured by faults and dykes. Successful groundwater exploration in the area has to delineate fracture zones by taking the following geological, hydrogeological and geophysical considerations into account:

Fractures follow a distinct joint set, with three dominant strike orientations: NW – SE, N – S and NE – SW. This joint pattern is exhibited by various morphological features in the Barberton greenstone belt, which include gorges, straight valleys and other depressions that are the surface expression of buried structural features that can be identified on aerial photographs and LANDSAT imagery.

- The intrusive dolerite dykes and sills do not seem to be important groundwater exploration targets in the study area. This is proven by low yielding holes that were sunk through the dyke contacts, which were thought to be fractured. Therefore, the magnetic method is of limited use in the study area.

- Shear zones were found to be of low permeability due to presence of clay gouge which reduces the transmissivity of the sheared greenstones.

- The electromagnetic method is an appropriate geophysical method to delineate the water bearing structural features. The water strikes are generally less than 70m depth, with 70% of the boreholes having water strikes that are less than 70m deep. Both the E-M34 and Apex Max-Min were appropriate geophysical methods for the study area.

- Direct current resistivity soundings proved to be an effective means of locating deeply weathered zones, which indicates deep fractures and faults in the sub-surface. Furthermore changes in lithology can be detected.

- The best geological features for groundwater exploration in the Barberton Greenstone Belt are the major faults and the association of thin dykes in the vicinity of fault zone. The dip-slip and strike-slip faults have proven to be water bearing and are associated with formation of deep open cavities that enhance the permeability of the greenstones. The geodynamic and strain analyses suggest that structures having a NNE– SSW strike direction are more likely to be tensional and therefore open. They are the primary targets for groundwater exploration in the study area. The E-W striking lineaments are more likely to be strike-slip faults and are also the hydrogeological targets if the target is not a shear zone. The N-S lineaments were postulated as being high yielding as well, only if the targeted lineament is a fault, however, this was not substantiated by drilling results.

- Fractures in the granite plutons tend to be filled with quartz veins. There is least chance of drilling a high yielding hole in the granite terrains..

In conclusion, the research study showed that successful groundwater exploration for the study area is possible. An evaluation of the structural geological and hydrogeological conditions to identify targets, and subsequent geophysical delineation increased the success rate from 50% to 80%. Given the relatively high median yield achieved, it may be generalised that motorised reticulated schemes are possible. However, high yielding boreholes are limited to major faults with deep open cavities that are located in the greenstones.

4.6 CONCLUSIONS

The results from this project suggest that a more comprehensive exploration program and a larger exploration budget oriented to the identification of targets on a regional scale could in the long-term result in significant cost savings, especially where the costs of regional geological exploration are spread over many boreholes. In such cases dedicating a larger proportion of the budget to exploration than is currently the case may result in more efficient drilling and a net reduction in establishment costs per site. For such an exploration program to be successful it must incorporate field geological mapping, remote sensing and appropriate geophysical exploration based on the identified hydrogeological regime.

Groundwater exploration is significantly more cost effective when structural controls on groundwater occurrence are considered so that only potentially significant targets are considered for field investigation. However, groundwater exploration exhibits a significant economy of scale and unit costs per borehole decrease with the number of boreholes drilled. In the Dwyka Tillite exploration costs as a proportion of total borehole establishment costs were shown to drop from 27% for 3 boreholes to 14% for 20 boreholes to 12% for 50 boreholes. Consequently, such an approach is warranted only when the exploration costs can be distributed over several boreholes. Based on financial analyses for establishing 10 boreholes, the proposed methodology proved to be cost-effective in all the geological provinces investigated. Cost-effectiveness would subsequently increase with the number of boreholes required in each study area.

5. GUIDELINES FOR GROUNDWATER EXPLORATION IN COMPLEX TERRAIN

5.1 Introduction

This chapter is a brief critical review of the methodologies employed in this investigation and attempts to derive a cost-effective approach to exploration. The methodologies include:

- Hydrocensus
- Tectonics and geodynamics
- Strain analysis for field structural mapping
- Remote sensing
- Ground based geophysics

These methodologies are considered in terms of common constraints such as topography, land use or cover, water demand distribution, access and social constraints.

A summary of the recommended exploration approach is given in Figure 5-1.

Potential hydrogeological targets are often selected based on a hydrocensus and/or geological review from existing geological maps. Boreholes are subsequently sited using ground-based geophysics, with the EM-34 and magnetometer being the most widely used methods. This approach has been widely used in the study areas investigated, and has been shown to be relatively unsuccessful and uneconomical when compared to the results that could be achieved. However, using the data from the Critical Intervention Programme in KwaZulu-Natal, this approach has been shown to be more economical than historical success rates. The major disadvantage of this approach to geohydrological exploration is that the nature of the hydrogeological targets are rarely understood, neither are the structural and geological stress conditions that control the orientation of structures, which in turn control the distribution of groundwater yield. Consequently, the method is commonly no more than 'anomaly hunting', with geophysical anomalies being identified as hydrogeological targets. Often little is known about the effect of rock mineralogy, clay filled gouge or shears, and complex folding of the rock fabric that give observed anomalies. This results in geophysical anomalies over features that are not hydrogeologically significant or even water bearing. In addition, little is known about the regional extensiveness of potential targets or current structural stresses that determine whether the feature is hydrogeologically significant.

The addition of remote sensing to exploration has the advantage of adding regional attributes to the process. LANDSAT TM images or aerial photos assist with identifying potential geological lineaments that are regionally significant so that ground based geophysics can be more intelligently directed towards the location of specific targets. However, such lineaments are not always structurally significant, and the geological stresses responsible for the features are not understood, hence its ultimate water bearing potential is unknown.

Having an understanding of the tectonic history and the geodynamics of a region offers the advantage of providing a framework to identify targets that are hydrogeologically significant based on current stress conditions. Consequently, structurally significant lineaments can be identified and geophysical exploration restricted to precisely locating the targets considered to be of greatest potential.

5.2 Hydrocensus

5.2.1 Objective

The objective of a hydrocensus is to hydrogeologically characterise a region in terms of the physical and economic feasibility of meeting water demands through groundwater by quantifying:

- Expected borehole yields and their variability by geological domain
- Historic drilling success rates and probabilities of exceeding specific yields
- Proximity of boreholes to geological structures and their yield
- Depth to water strikes
- Static water levels
- Groundwater chemistry
- Potential hydrogeological targets

These investigations should attempt to determine the number of boreholes that will be required to meet water demands, the role of geological structures on yield, the depth to which boreholes should be drilled, and the suitability of water quality for the desired usage.

The location of high yielding boreholes may also assist in identifying targets that are potentially high yielding.

A hydrocensus should ideally also consider geological processes or mineralogies that may negatively impact on groundwater quality in the long term. Critical factors, such as the presence of volcanic massive sulphide deposits, hydrothermal alteration, carbonaceous shales, carbonatites etc., may be indicators of the presence of heavy metals, light metals and non-metals, heavy non-metals, halogens, alkaline earths, rare earths, noble metals, etc. and may pose a significant long term health hazard. These elements may be present in the rock but not observed in water samples from recently drilled boreholes; their mobility may be controlled by oxidation-reduction conditions that alter with time. A typical example is arsenic, which is prevalent in South Africa as arsenopyrites, but whose mobility is controlled by oxidation state. Consequently, its presence would only begin to appear in water samples after variations in drawdown due to pumping have introduced oxygen into the formation, resulting in oxidation and weathering.

5.2.2 Methodology

The hydrocensus is conducted by collecting data from the National Groundwater Data Base, previous hydrogeological investigations and overlaying the data onto existing geological maps using a GIS. The specific processes are:

- Inputting hydrocensus data into a GIS database, such as ARCVIEW, and creating layers for lithology, structures, yield, static water level, water strike depth and water quality
- Characterising domains by using domain boundary polygons to separate borehole data
- Determining the percentage of dry boreholes, and the yield of successful boreholes at various percentiles for each domain
- Determining the optimum drilling depth for each domain based on the depth below which few boreholes encounter water
- Identifying domains where poor water quality precludes water use by categorising median water quality
- Identification of geological indicators of potential geochemical hazards
- Proximity analysis of yield versus distance from known structures to identify important structures

5.3 Tectonics and Geodynamics

5.3.1 Objective

Geodynamic investigations require that the tectonic history of the target be unravelled so that mapped, identified or presumed structures and lineaments can be explained in terms of historic and present day geological strain. Depending on the age of the rocks and the structural complexity, this process may involve extensive literature review on the crustal evolution of the region. Since these processes are of a large scale, investigations often are much broader than the study area. For example, an understanding of the geodynamics of the Natal Metamorphic Province requires a comprehension of Archean craton movement and offshore transform faulting along the Aghulas Transform Fault during the break-up of Gondwanaland. The Limpopo Mobile Belt requires investigation into plate tectonics and craton collision during Archean times, and subsequent shearing during mobile belt emplacement.

Emphasis is given to tectonic events that resulted in brittle deformation, however, in many cases brittle deformation occurs along zones of existing weakness resulting from earlier ductile deformation, such as ENE faulting in the Natal Metamorphic Province along earlier ductile ENE shears.

The objective of geodynamic investigations is to obtain a conceptual model of pre- post- and syntectonic geological evolution that describes historical extension, compression and shear orientations in geological time in order to define a chronologically expected pattern of faulting by strain analysis using a strain ellipse. The potential rejuvenation of such structures by subsequent tectonic events can then be identified and the present strain on existing structures can be identified. Existing structures considered to be under extension present hydrogeological targets.

Strain analysis conducted during geodynamic investigations also permits an understanding or classification of observed lineaments and joint patterns in terms of their origin and present strain conditions, hence allowing the identification of preferred structures.

5.3.2 Methodology

The process involves investigations into:

- Identification of geological domains based on lithology, geochronology and structural setting
- Pre-depositional environment to identify aquifer boundaries and their nature (depositional-lithological versus post depositional or tectonic)
- Plate tectonics and its impact on geological strain in the region
- Metamorphism and ductile deformation episodes and their expression in the lithologies
- Intrusive and volcanic history
- Recent tectonic history and processes
- Mapping of faults and shears
- Application of stress analysis based on historic strain and stress to derive a pattern of faulting, folding, thrusting and shearing
- Verification of predicted faulting against observed fault pattern

5.4 Structural Analysis

5.4.1 Objective

A structural analysis attempts to identify strain conditions in rocks by identifying compressional and tensional orientations by mapping the strike and dip of joints and plotting the data on stereonets. The objective is to identify the orientation of tensional and compressional forces so that geological structures aligned perpendicular to extensional forces can be identified. These targets are then assumed to be open and are targeted as preferential targets.

The risk of using this methodology is that in many cases rocks have been exposed to several tectonic events, perhaps with different stress orientations, hence jointing from several generations may be superimposed in joint patterns. Consequently, joints may be aligned in many orientations and the resulting structural analysis would be meaningless unless conducted on subsets related to a specific event. Identifying joint patterns from specific events requires a geodynamic analysis to identify stresses originating at various periods in time. A specific example can be observed in the Limpopo Mobile Belt, where joints are the result of late Archean shear, with post Karoo extension superimposed. For this reason, it is often necessary to conduct joint mapping in the most recent lithological formation present, even if outside the study area, to identify stresses originating from the most recent tectonic event. This process allows coarse dating of joint sets.

5.4.2 Methodology

The investigations conducted include:

- Identifying the age relationship of various formations present in the region
- Mapping of the strike and dip of joint sets in the various lithologies post-dating the study area, as identified at road cuttings and stream beds
- Plotting joint lineation and bedding data on stereonets
- Classification of joints by age relationship or by dip to categorise features by tectonic origin
- Derivation of compressional and extensional relationships by structural analysis

5.5 Remote Sensing

5.5.1 Objectives

The objective of using remote sensing methods is to identify structures that may be of hydrogeological significance and that are not noticeable in the field, or that have not already been mapped. These can be identified by satellite images using variations in surface reflectance, by aerial photos using variations in tone and contrast, or by airborne geophysics, which is based on variations in rock physical properties. Often digital filters are used to enhance features considered to be of interest, such as vegetation, structure, soil moisture, clay content, magnetic field etc.

Identified lineaments are presumed to have a hydrogeological significance, and are presumed to be related to lithological variations, faults, variations in saturation, topographical depressions are linear vegetation trends. However, field proofing is necessary to verify the nature of the identified lineament.

Unless a geodynamic analysis has been undertaken, it is usually not possible to identify the stress regime of a lineament or its structural significance. To some extent this is overcome by an analysis of lineament orientation and length so that the predominant regional scale features can be identified.

The usefulness of remote sensing is hindered where:

- disturbance of the land surface hinders lineament identification
- surface cover such as sands prevents identification of subsurface structures
- lineaments are related to non-structural features such as lithological variations of non-hydrogeological significance
- rock physical properties are not sufficiently distinct to permit geophysical delineation
- features are too narrow to be delineated at the scale of the image

5.5.2 Methodology

Remote sensing investigations ideally require the following steps:

- Selection of applicable digital features to highlight features of interest
- Identification of lineaments and overlaying onto topographic and geological maps using a GIS
- Preparation of strike-frequency rose diagrams to identify dominant orientations
- Preparation of strike-total length plots to identify regional orientations and trends
- Preparation of strike-maximum length plots to identify regional structures
- Identification of target lineament orientations based on geodynamics, structural analysis, and lineament strike analysis

5.6 Field Verification Investigations

5.6.1 Objective

Field proofing investigations are required to identify the nature of target lineaments to determine their nature and origin, and to pinpoint the lineaments in the field using observation or geophysics, with due consideration being given to constraints on siting. The objective is to identify drilling sites on structural features identified as being of hydrogeological significance at locations where drilling and water abstraction are physically, economically, socially and legally acceptable.

A field survey is also required to evaluate the effect of constraints on target site selection. These constraints may include:

- topographic and access constraints affecting drilling rig mobilisation
- water demand location and topographical constraints on reticulation or distribution
- quantitative water demand and its impact on target location in terms of large regional structures versus smaller local structures
- access to properties and water rights
- contamination potential and vulnerability
- Acceptance of drilling site by stakeholders

These constraints impact on the point at which specific linear targets may be targeted and ultimately determine where the boreholes can be sited.

5.6.2 Methodology

Field investigations include:

- Observation of land use and geology to identify the nature of identified lineaments and ensure that they are potentially structurally significant
- Observation and evaluation of constraints in terms of land ownership, drilling rig accessibility, topographic constraints between source and demand location, distance from demand points, contamination
- Geophysical profiling using appropriate methods and techniques perpendicular to structures or lineaments identified from satellite imagery or aerial photos but not directly observable on the ground in order to pinpoint the target feature's location in the field

5.7 Conclusions and Recommendations

Cost effective groundwater exploration should:

- Have a regional focus and be based on identifying structurally significant target features for a region rather than be locally demand driven, where boreholes are sited only for a few specific communities. However, subsequent drilling of targets can be locally demand driven according to priorities.
- Consider the expertise required rather than the expertise locally available. Borehole siting is commonly undertaken by a local consultant using the tools and skills they have available. This often results in the repetition of poor practice and the use of instrumentation that cannot achieve the required results. This was seen to be the case in KwaZulu-Natal, where the EM-34 was consistently applied in spite of poor results resulting from its limited depth of penetration and a lack of understanding of the nature of structurally significant targets.
- In complex structural environments, exploration should be guided by a hydrogeologist with an understanding of the tectonic setting and geodynamics, together with the water bearing properties of identified targets, rather than be restricted to 'divining' using a variety for instrumentation. Only in this way a conceptual model of groundwater occurrence be developed and refined so that an improved understanding of groundwater is achieved.
- Consider the geological nature of targets prior to geophysical investigation. Some of the high yielding targets identified and drilled during this study did not exhibit any geophysical anomalies using magnetics or electromagnetics, yet were considered to be of structural significance and proved to be high yielding. Conversely, some promising geophysical anomalies yielded dry boreholes on targets that were drilled in spite of not being structurally relevant (compressional lineaments, compressional dykes, lithlological variations etc.).
- Consider the nature of the geological environment, hence no fixed methodology is applicable. Not all the methodologies adopted proved to be successful in all areas. For example, a quaternary cover may limit the usefulness of remote sensing, or several generations of tectonic events superimposed on a lithology may limit structural analysis, unless a younger formation is present.
- Groundwater exploration should be tendered on a per successful site or R/l/s basis. *Define Outputs Rather than Inputs.* The current practice of sub-contracting borehole siting to geohydrological consultants purely on cost or a per borehole sited basis does not promote incentive to increase success rates. In fact, the opposite may be the case, with consultants' income increasing with the number of boreholes sited and the number of boreholes where drilling supervision is provided, regardless of success. The sub-contracting of borehole siting independent of successfully establishing a borehole also reduces the responsibility of the Implementing Agent, who carries the drilling budget. An incentive to increase success rates could be achieved by tendering groundwater exploration on a per successful site or a per R/l/s basis (independent of drilling costs), creating a motivating factor for increasing success rates. This approach would also encourage consultants to use the most appropriate methodology for exploration, as opposed to the current approach, where the methodology is prescribed and standard rates are defined, as occurred during the Critical Intervention Programme, as well as in more recent programmes.

The above mentioned conclusions suggest that there is a significant need for a fundamental paradigm shift in groundwater exploration in South Africa. All of the above lessons can be considered as being opposed or contradictory to the current practice of groundwater exploration for rural water supply.

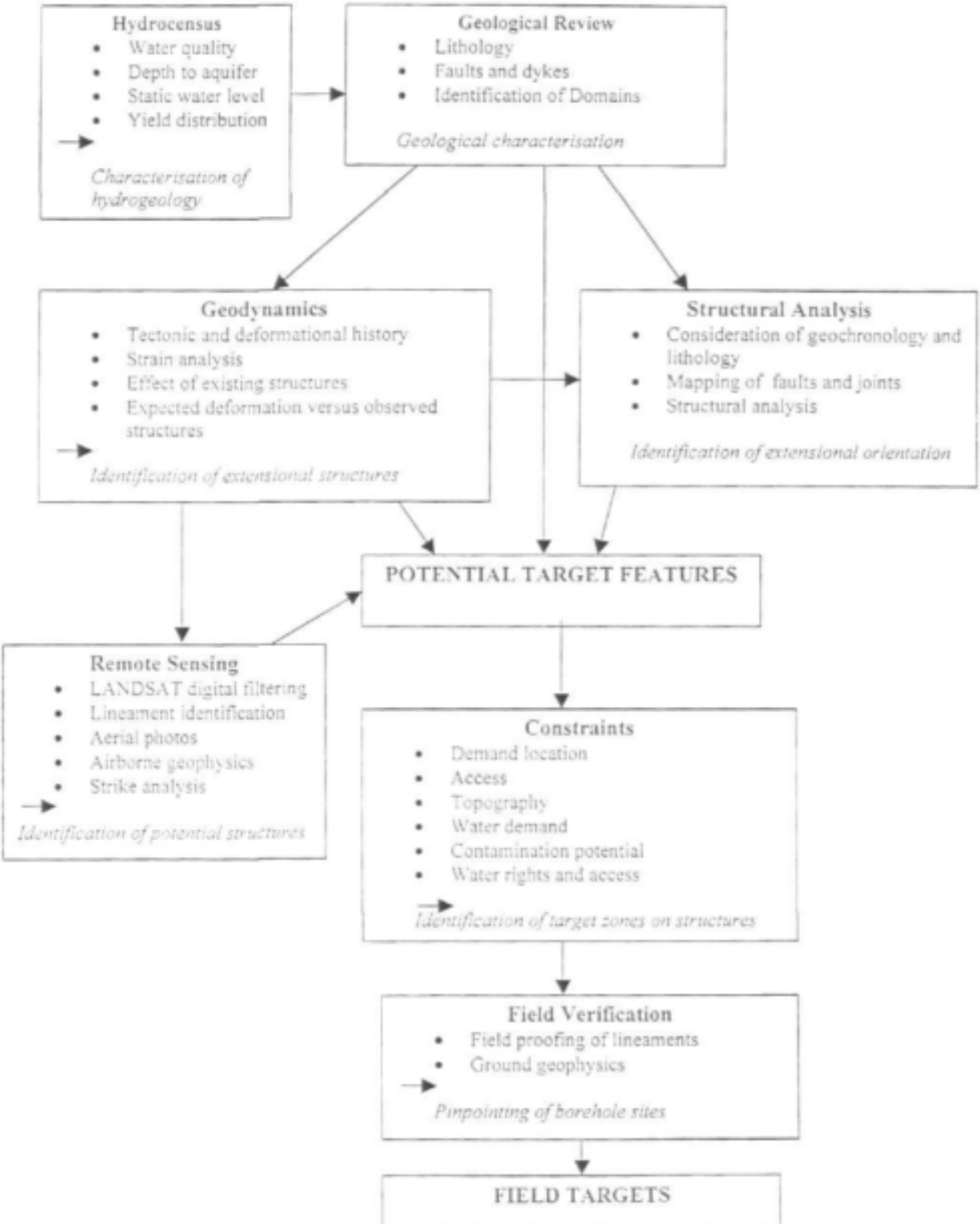
5.8 Recommendations for Future Research

The major shortcoming encountered during the project was that the current situation in South Africa has resulted in a fundamental split between geological mapping and groundwater exploration. Geological mapping has been lithologically and petrologically oriented, with little attention being paid to structures other than mapping the location of major faults. Little or no attention has been paid to joint mapping to permit a structural analysis. In addition, tectonic evolution, where it has been considered, has often ignored more recent post-deposition deformation. For example, resulting strain and stresses on Archean rocks resulting from the break-up of Gondwanaland is rarely described and the geological community has concentrated on Archean tectonics and unravelling the complexities related to the ages of metamorphic episodes. As a result, a hydrogeologist considering a structural analysis of target features must undergo a mapping exercise. This project has shown that structural analysis usually requires 2 days to complete 4 1:50 000 sheets, however, a tectonic interpretation may require extensive literature review and the application of strain analyses to an observed fault set since the required information on recent tectonics is rarely available. This shortcoming requires that the scope of geological mapping be broadened if the results are to be of greater value to the hydrogeological community. A programme of structural mapping is urgently required if groundwater targets are to be regionally identified.

In contrast, the hydrogeological community has paid scant if any attention to the importance of geodynamics and structural analysis in groundwater exploration. Consequently, exploration has not been focussed and has been relegated to an exercise in anomaly hunting that adds little to the identification of future targets. A structural understanding of the aquifer is rarely built up and mistakes are commonly repeated. This shortcoming may reflect a lack of training in structural geology in South Africa, which is fundamental to groundwater exploration in fractured aquifers. This lack of awareness has resulted in minimal attention being given to structural models in hydrogeological investigations.

Urgent attention also needs to be given to cost-benefit analyses of past and current groundwater exploration strategies, as it is only by using the language of economics that the voice of hydrogeologists calling for a revision in exploration strategy will be heard.

Figure 5-1 Flow chart of the recommended groundwater exploration process



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