GROUNDWATER MANAGEMENT USING A GIS

Case Study :

Uitenhage Subterranean Government Water Control Area

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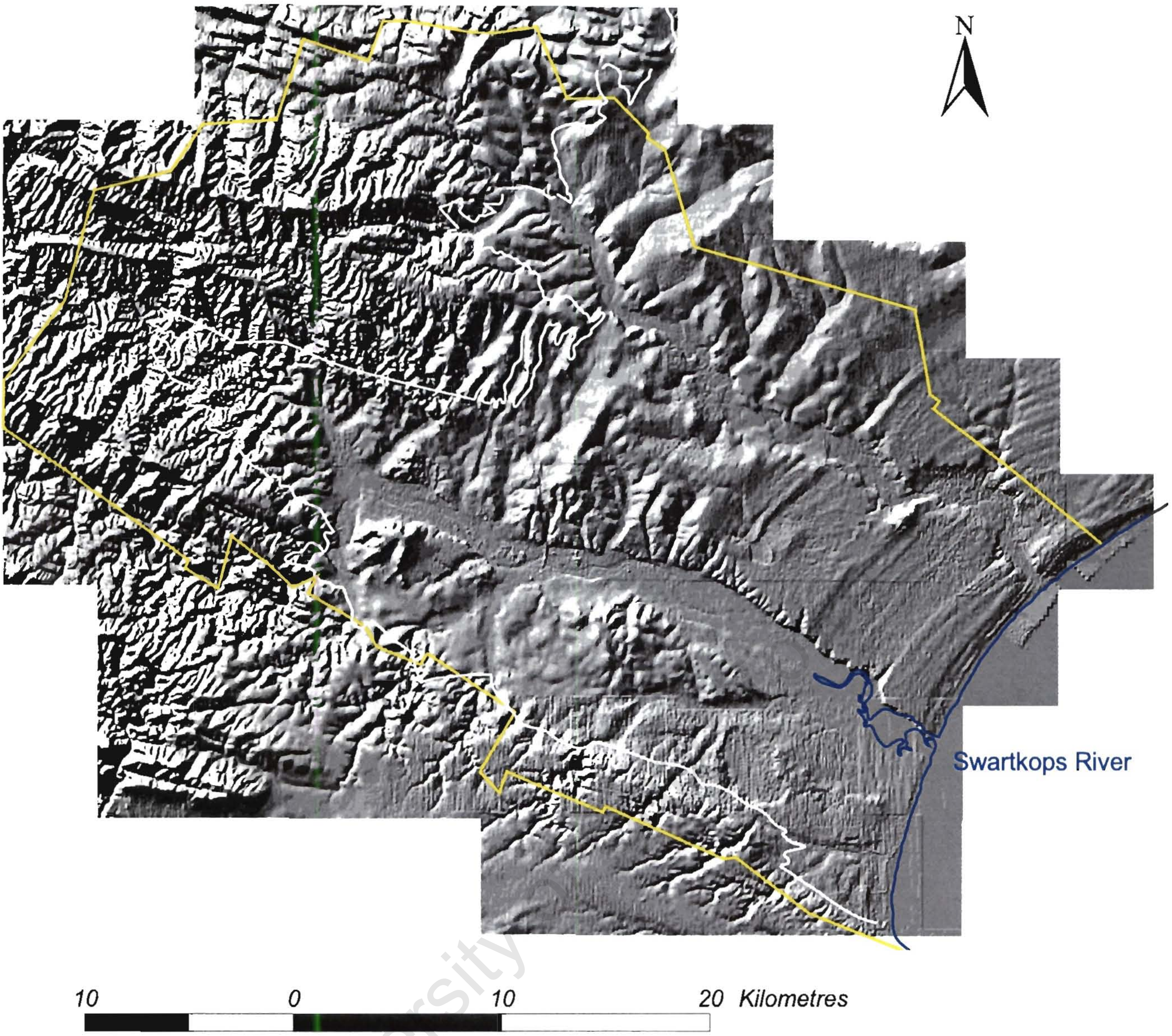

The white line shows the extent of the post-Palaeozoic sediments which display a smoother terrain. Step features referred to in section 1.2.1 can be seen in the coastal region north of the Swartkops River.
The yellow line shows the boundary of the Uitenhage Subterranean Government Water Control Area.

Frontispiece :
The 50m DEM of the study area hillshaded as if illuminated from the NW.

ABSTRACT

The area around Uitenhage in the Eastern Cape forms the centre of one of the biggest artesian groundwater basins in South Africa. The Table Mountain Group quartzitic sandstones are overlain by a thickness of post-Palaeozoic sediments giving rise to artesian groundwater. The most well-known of this manifestation are the springs at Uitenhage which have been used since pre-historic times and are currently a principal source of water for the municipal supply.

At the turn of the 20^{th} century, with the introduction of drilling machines into the area a number of boreholes were constructed. The resultant tapping into the artesian supply resulted in the spring-flow lessening and a decline in groundwater levels on introduction of further boreholes. At the request of the local community this special region was proclaimed a groundwater protection area.

Over the years the abstraction within the area has risen and is currently at 3.24 million m^3/a. However the licensed, legally abstractable, figure stands at 6.15 million m^3/a. Groundwater levels have declined although the flow from the boreholes has not.

Using GIS all the available and pertinent information required for the management of the control area and for the estimation of the groundwater resource has been brought together. Using raster modelling techniques the amount of groundwater available within the system and the viability of sustained abstraction were assessed. A site-specific raster model has been designed to visualise and quantify the expected effects of new boreholes in the area.

PREFACE

This entire thesis represents the original work of the author and has not been submitted in any form to another University. Where use was made of work or comment of others due acknowledgement has been made in the text.

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GLOSSARY OF TERMS AND ABBREVIATIONS

AML	Arc macro language. A language for designing programmes to run within the GIS, automating a set of procedures.
Aquiclude	Impermeable geological formation that does not transmit water e.g. unfractured crystalline rocks
Aquifer	Permeable geological formation that is capable of storing or yielding economic quantities of groundwater.
Aquitard	Geological formation capable of transmission of water regionally over long time periods but economically untenable.
Artesian borehole	A borehole within an artesian aquifer such that the water level rises above the aquifer.
Artesian conditions	Confined groundwater where the pressure is higher than that of atmospheric pressure.
CCWR	Computing Centre for Water Research
Competent	Rock beds which during folding are able to not only lift their own weight but that of the overlying beds without appreciable internal folding
Confined Aquifer	Aquifer bounded above and below by an aquiclude. (Artesian aquifer.)
DEM	Digital Elevation Model
DWAF	Department of Water Affairs and Forestry, South Africa.
DXF	Drawing files from a computer aided design package: Drawing Exchange File
GIS	Geographical Information System
GUI	Graphic User Interface
HIS	Hydrological Information System
Hydrocensus	Collation of all borehole data for an area which includes hydrogeological parameters and any abstraction information.
IDW	Inverse Distance Weighed. An interpolation method of determining remote values based on the distance from the known point.
Isopachyte	A line joining points of equal thickness of a geological unit.
l/s	Litres per second. A measure of borehole yield.

MAP	Mean Annual Precipitation.
Metadata	Documentation referring to the contents of the database.
NGDB	National Groundwater Data Base
NWQDB	National Water Quality Data Base
Optimal yield	Deployment of the groundwater resource for social and economic benefit, of a community or region, which may even involve mining of the resource.
Recharge	The portion of water which reaches an aquifer, irrespective of which path it follows, resulting in a change in aquifer storage.
Safe yield	The volume of groundwater equal to the amount of groundwater returned to the system by natural or artificial recharge.
Storage Coefficient / Storativity (S)	Volume of water yielded per aquifer area per unit decline or rise of water table.
Sustainable yield	Utilisation of the groundwater resource for a very long period of time with minimal negative effects.
TDS	Total Dissolved Solids (mg/*l*). Indicator of the salinity of water. The upper limit for drinking water is 350 – 550 mg/l according to the South African Bureau of Standards.
TMG	Table Mountain Group.
Transmissivity (T)	Rate at which groundwater can be transmitted through a unit area of aquifer under a hydraulic gradient, measured in square metres/day (m^2/d)
USGWCA	Uitenhage Subterranean Government Water Control Area.
Water level	Depth at which the groundwater level was measured at a particular time. Expressed in metres below ground surface or metres above sea level.
Water strike	Recorded depth at which the groundwater was struck during drilling. Expressed in metres below ground surface or metres above sea level.
WRC	Water Research Commission

1 INTRODUCTION

The Uitenhage Subterranean Government Water Control Area (USGWCA) is a unique groundwater area featuring a sizeable artesian basin. The area is located in the Eastern Cape of South Africa, centred on the town of Uitenhage. At the behest of the farmers of the area it was proclaimed a groundwater protection area in 1957. The request was made after noticeable reduction in borehole flow was observed, relating directly to the introduction of drilling machines into the area and the subsequent increase in the number of boreholes. Within this groundwater protection zone it is required that boreholes be drilled only after issue of a permit from the Department of Water Affairs and Forestry (DWAF). A further permit will detail the amount of permissible abstraction from the borehole. It is also necessary to have permits for the transportation of groundwater across cadastral boundaries. This is one of 12 such areas in the country and is the only one containing a sizeable artesian aquifer. (Maclear 1996:25).

The regional office of DWAF in the Eastern Cape is responsible for the recommendations regarding drilling permits. DWAF head office determines the amount of abstraction allowed. The permits, or Water Rights, database, the National Groundwater Database (NGDB), the hydrological database (HIS) and the National Water Quality Database (NWQDB) are the four databases, housed in Pretoria, containing the necessary information regarding the permits, boreholes, hydrology and water quality of the area. These databases are mainframe applications accessible by remote terminal to regional DWAF offices. The NWQDB, NGDB and HIS have a relateable item through the water chemistry analysis number, should an analysis have been carried out. If information other than farm, permit number and abstraction allocation are required a search on the other relevant databases must be done. There are plans to relate allocated borehole abstraction rate to the pertinent borehole in the NGDB.

There is no clear policy on how much groundwater any farm may be allocated and no summation of how much groundwater may be made available for abstraction from the whole of the groundwater protection area. The geology and the hydrogeology of the area are well documented. There has been no strict enforcement of the permit system. Observation of groundwater level fluctuations are monitored but no conclusion drawn on the implications for the USGWCA. This situation is being remedied with the approach of the National Water Act (1998) and the devolution of responsibility of geohydrological matters to regional management.

The proclamation area is made up of over 200 registered farms and the municipal areas of Port Elizabeth, Uitenhage and Despatch. The municipalities make up 428 km^2 of the area. The wilderness area of Elands River Forest Reserve covers 216km^2, with 569km^2 being farmland.

The geographic nature of the data and the large number of parameters to be interfaced indicate the problem is suited to the use of a Geographical Information System (GIS) as a management tool, which is the subject of this thesis.

1.1 Geography of the Area.

The USGWCA is on the east coast of south Africa between latitudes 33° 31' and 33° 55' S, longitudes 25° 15' and 25° 45' E. Proclaimed by Government Gazette (No.260 of 23rd August 1957 and No.266 16th October 1964) the groundwater protection area includes farms, municipalities and the Elands River Forest reserve.

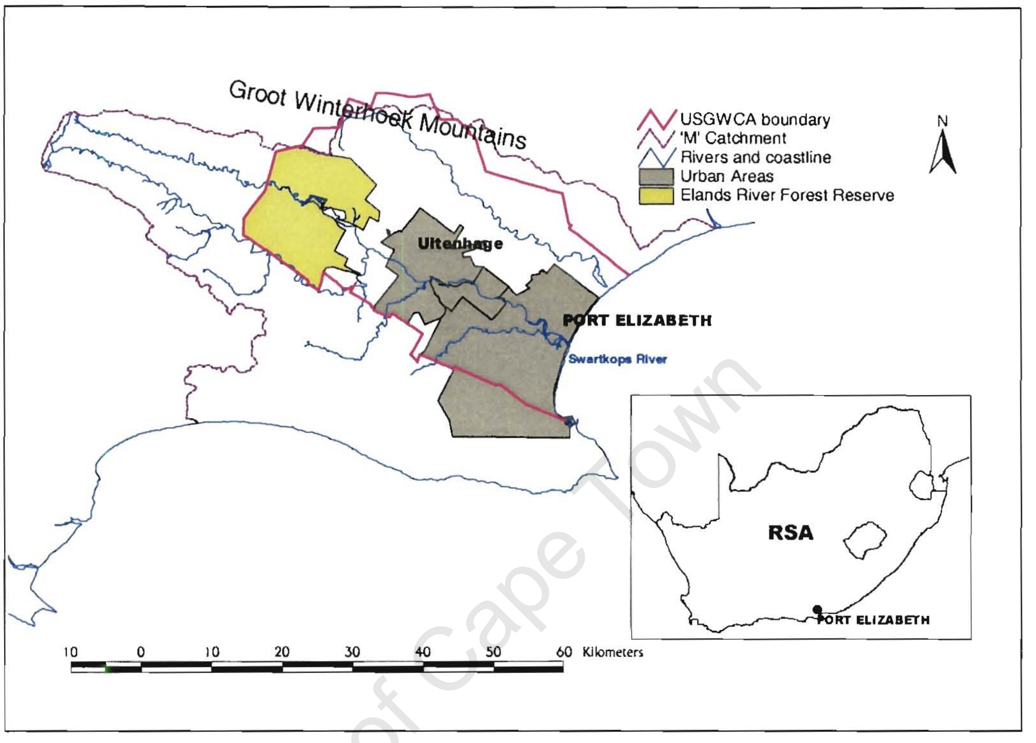

Figure 1: Geographical location of the USGWCA.

Topographically the area rises inland from the sea to the heights of the Groot Winterhoek Mountains, reaching 1840m, in the west. The rainfall of the area is in the region of 500mm/a, higher rainfall of 773mm/a being recorded in the western mountain areas and lower rainfall of 341mm/a in the less elevated regions of the coast and toward the north-east.

The protection area lies within the primary drainage region, "M" in the DWAF river basin naming scheme. This drainage region contains the Swartkops, Coega, Van Stadens and Maitlands Rivers. Within the protection area the Swartkops and the Coega drain eastward to the sea from the Groot Winterhoek Mountains (Figure 1).

1.2 Geology and Geohydrology of the Area.

1.2.1 GEOLOGY

Toerien and Hill (1989) give an excellent summary of the geology of this area. The Palaeozoic rocks of the Cape Supergroup, the Table Mountain and Bokkeveld groups, form the oldest rocks of the USGWCA (although older rocks of the Gamtoos supergroup outcrop south of the control area). They were laid in the east-west Cape Trough. The predominant member is the Table Mountain Group (TMG) with its highly resistant quartzitic sandstone

(Figure 2). During the Permian (280-230 million years before present) to Triassic (230-200 million years before present) periods the Cape Trough was subjected to compressive stresses which resulted in the Cape Fold belt. Further stress during the Jurassic resulted in the development of graben structures, such as the Algoa basin filled with deposits of the Uitenhage Group (Figure 2). Ocean encroachment followed by isostatic adjustment has left well developed coastal plains with distinct step features, running parallel to shore, which are clearly seen on the hillshaded DEM which forms the frontispiece.

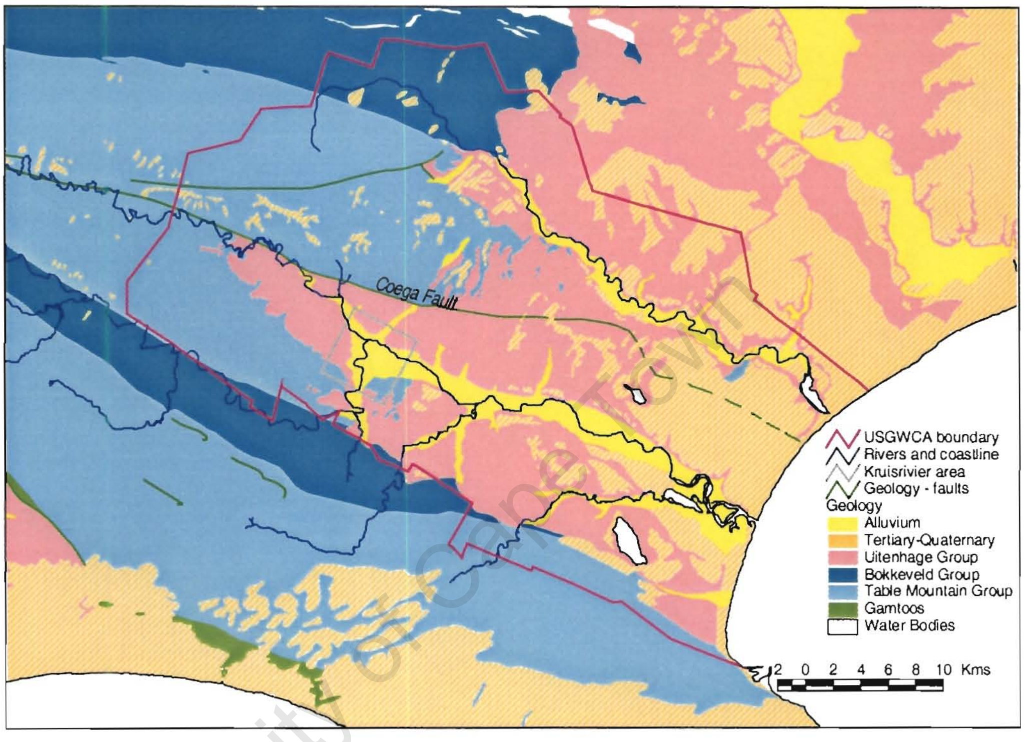

Figure 2: Geology of the control area, Council for Geoscience, 1:250 000 map.

1.2.2 GEOHYDROLOGY

The area may be broadly divided into three hydrogeological areas as shown on Figure 3:

- Fractured secondary aquifer (Gamtoos, TMG and Bokkeveld)
- An aquiclude and aquifer (Uitenhage Group)
- Primary alluvial aquifer (Tertiary-Quaternary and Alluvium)

1.2.2.1 *Fractured secondary aquifer*

The western part of the control area contains quartzites of the Table Mountain Group (TMG). The permeable zones of this secondary aquifer are controlled by the regional stress patterns of the TMG. The dominant fracture direction is WNW-ESE, parallel to the Coega fault which lies north of the Swartkops River (see Figure 2). These rocks are highly competent and intensely fractured. Transmissivity values are estimated at 20 to 200m²/day, the large range being due to the variation in fracture density. The total discharge, estimated in 1989, for the Uitenhage springs and the boreholes in this formation was 150 *l/s* (Reynders 1987:8). The water quality is excellent and is suitable for drinking in raw form with a TDS of 190mg/l (Maclear 1996:40).

The Bokkeveld group shales generally provide weakly yielding boreholes with poor water quality in the region of 3300mg/*l* TDS.

1.2.2.2 *Aquiclude and aquifer*

Conglomerates, sandstones, mudstones and silts make up the formations of the Uitenhage group. Hydrogeologically the conglomerates in the west, the Kruisrivier area, and the southern Swartkops valley show individual borehole yields of 0.4 to 10 *l*/s with a TDS on average of 200 mg/*l*. The transmissivity values range between 2 and 118m²/day.

The mudstones are generally considered to be an aquiclude, confining the groundwater and giving rise to artesian conditions. These mudstone areas contain groundwater of very poor water quality.

In the Kruisrivier area (outlined on Figure 2) a local sandstone facies forms an important aquifer of transmissivity 22 – 97m²/day with TDS of 370mg/*l*.

A summary of the aquifer characteristics of the above two areas is given in Table 1.

Table 1: Summary of the aquifer characteristics.

	Fractured Secondary Aquifer		**Aquifer and Aquiclude (Uitenhage Group)**		
	TMG	Bokkeveld	Conglomerate	Mudstone	Sandstone
T (m^2/d)	20 - 200	Very low	2 – 118	Very low	22 - 97
BoreholeYield (l/s)	5.0	0.5	0.4 – 10	0	0.5
TDS (mg/l)	190	3300	200	450– 9350	370

1.2.2.3 *Primary alluvial aquifer*

Late Tertiary to recent deposits of sands, gravels, silts and clays are less than 15m thick. They are confined to the river valleys and coastal plain. There is an insignificant amount of groundwater abstraction from these deposits, mainly from areas along the Swartkops River. They are potentially subjected to pollution from the industries sited in the vicinity of the Swartkops River, (Maclear 1996: 69-75) an aspect which will not be dealt with here.

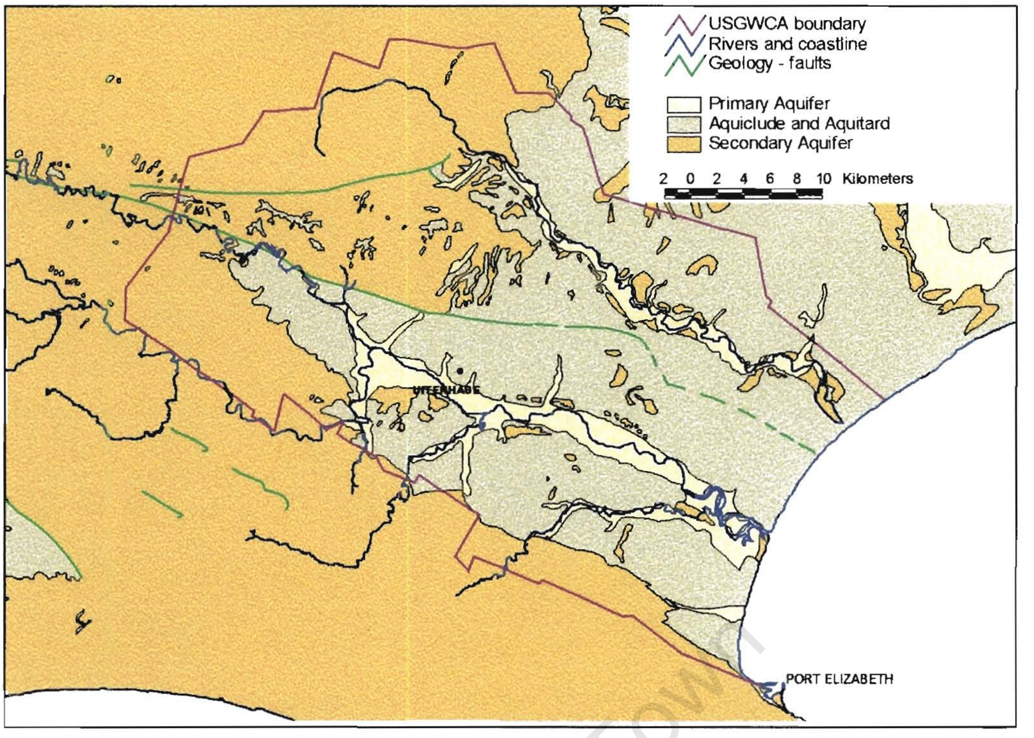

Figure 3: Hydrogeology of the control area.

1.2.3 CURRENT GEOHYDROLOGICAL SITUATION

The most important feature of the last three sub-sections is the combination of the fractured secondary aquifers capped by the aquicludes and aquitards which give the artesian feature unique to this area. The Uitenhage Springs, with a mean annual flow rate of 52 *l*/s, supply 15% of the water requirements for the town of Uitenhage. The water quality of the springs is excellent at 90mg/l TDS, less than the average of the TMG at 190mg/l (Maclear 1996:40).

There is currently an area of 51916ha under irrigation. It is calculated from a 1996 survey that 3.24 million m^3/a of groundwater is being abstracted. This is lower than the total licensed abstraction of 6.2 million m^3/a. In 1963 an abstraction of 0.99 million m^3/a was reported which increased to 2.05 million m^3/a by 1984 (Reynders 1987:13). The current estimate was made from field visits to the 319 boreholes (of which 168 are abstraction holes) on the 407 farms and farm portions within the area.

Although the municipal areas also contain boreholes, generally for domestic garden use, the licensing and abstraction of the groundwater (at the time of writing) is not controlled by the DWAF. Consequently, urban groundwater use will not be included here. It should be noted that groundwater usage of the greater Port Elizabeth municipal area has been the focus of a recently completed study by the WRC (Lomberg *et al*, 1997). The portion of Port Elizabeth contained within the USGWCA was excluded from this study.

2 PROBLEM TO BE INVESTIGATED

The *safe yield* of the aquifer systems needs to be determined. This is defined as the "long term balance between the annual amount of groundwater withdrawn and the annual amount of natural and artificial recharge". According to the geohydrological discussion document for National Water Act (1998) (Lazarus 1997: 64) this should be the guiding factor in the granting of licences. The concept of safe yield, for management practices, could well be replaced by *optimal yield*. Groundwater has value only through it's use (Freeze and Cherry 1979:364). Only by choosing a management scheme from a set of alternatives, involving scientific, social and economic parameters can the optimal yield be determined. An optimal yield may even involve mining of the resource. This could well be an option in the very arid parts of South Africa, such as the Kalahari areas of the north-west, but will not be discussed further in this study. Sharp (1998:1) defines the safe yield as the volume which may be abstracted from the aquifer which does not exceed average annual recharge. This is the conservative approach generally accepted and used in this country. Sharp (1998:2) defines the *sustainable yield* as using the water resource beneficially, but not necessarily optimally, for an exceptionally long period at the minimum. The sustainable yield also means that potential negative effects must be minimised in order to allow such long term use. If the amount of groundwater in storage is greater than demand the aquifer may be used on a sustainable basis for years. In semi-arid areas (such as South Africa) Boehmer (1998:18) recommends that the volume in storage should be 2 to 3 times the recharge to the system.

Should an aquifer system which has low storage capacity but a high mean annual recharge be allocated an abstraction based on the 'safe yield' the resource would fail simply due to its inability to met the demand in the drier seasons or in times of drought.

However if an allocation of abstraction is made on the basis of 'sustainable yield' which takes into account the storage capacity of the aquifer system the resource is being managed in a way that will allow for continuation of supply through short and long term fluctuations in recharge.

The groundwater volume allocations, the actual groundwater use and the aquifer parameters of the USGWCA need to be assessed. This will show whether the past management of the allocation of groundwater volumes is the correct one or whether it should be altered from the 'safe yield' to a 'sustainable yield'.

Quantification of the groundwater resource by determination of the amount in storage, the recharge, allocated and actual abstraction will determine how the yield is being addressed. Predictive GIS tools could be implemented to assist in the management of the resource through visualisation and quantification of the effects on the resource of further development.

2.1 Hypothesis to be investigated

To investigate the extent to which GIS will assist towards permit quantification of the groundwater resource and effects of future development on the groundwater levels in the USGWCA.

2.2 Study products

Resulting from this work

- a method will be evolved to predict the effect on the groundwater levels of additional groundwater abstraction allocation;
- a comprehensive database of the determining factors in groundwater assessment and allocation will for the first time be accessible from within one system;
- the groundwater resource potential may be roughly estimated;
- data pertaining to the permit system will be geographically linked to farms and boreholes;
- the GIS database can be incorporated into an integrated catchment management system for the Swartkops River;

2.3 Study Limitations

- Due to data restrictions and the DWAF mandate to manage proclaimed groundwater sensitive areas, this study is relevant only to the USGWCA
- Quantification of most of the aquifer values are inferred from known point data or from similar aquifers in Southern Africa.
- Groundwater quality has not been considered as an issue. Due to time and data constraints the possibility of using water chemistry to define the source of the groundwater cannot be addressed.
- The alluvial aquifers will not be incorporated, as the groundwater use from these is minimal. In addition the USGWCA was established to protect the artesian groundwater source of which this does not form a part.
- Effects on groundwater withdrawal on the eco-system will not be addressed. As this is a confined aquifer it will not affect river base flow or local water-tables supporting indigenous vegetation.
- Seasonal variations will not form part of this study. As the boreholes are predominantly drilled into a confined aquifer the water strike level is unlikely to be affected by seasonal factors. Also the date of the water strike, which would be the drilling date, is frequently unavailable.

3 LITERATURE REVIEW

3.1 Geology and Geohydrology of the Study Area

The study area has been the subject of many projects, most of them dealing with a particular hydrogeological aspect or sub-area. A geohydrological analysis of the groundwater system and geology of the area around Kruis River and encompassing most of the area to the south of the Coega Fault was carried out by Bush (Bush 1985). He completed a hydrocensus of the area which detailed the groundwater use. A pump testing and drilling programme was carried out which provided parameter values, such as transmissivity, for the aquifers. The major aquifer in Kruisrivier is contained in the Uitenhage Group sediments. This is a local phenomenon arising through facies variation at the time of sedimentation. In this area there has been a decline in water levels as abstraction for irrigation has increased. However, in his investigations he discovered that in the area to the east of Kruisrivier, water demand had actually decreased where urban sprawl had brought about an end to irrigation.

To the north of the Coega fault a thorough hydrogeological investigation evaluated the TMG artesian aquifer (Venables 1985). This area contains large farming ventures which are heavily dependent on irrigation. The resulting exploratory drilling programme and test pumping of the boreholes provided geological reference points and hydrogeological parameters. Geophysical investigations performed by the researcher Venables, in combination with privately available data, allowed the construction of cross sections and maps showing the depth to the TMG under the Tertiary-Quaternary sediments. Results showed that the exploitable section of the TMG aquifer is confined to a narrow strip running the length of the fault for about 26km inland. As a result of his work Venables (1985) recommended the redefinition of the control area boundary to allow better management of the more important areas, such as this one, the Coega Ridge compartment.

Drawing predominantly on these previous two studies Reynders (1987) summarised the historical and actual groundwater use in the area. He re-iterated the suggestion for the redefinition of the USGWCA boundaries. He also initiated the process of sealing the damaged artesian boreholes, which were leaking water into the upper sediments. These leaking boreholes highlight the necessity of professional advice on the construction of boreholes in this area.

A collation and re-interpretation of all the previous studies in the Uitenhage area with additional information from a new study into the alluvial aquifer of the Swartkops River was compiled by Maclear (1996). Although the alluvial aquifer is not important from the groundwater resource point of view, discharge of effluents may reach the river through this medium and lead to undesirable effects on the river. The result of his work is a catchment wide view of the geohydrological situation of the Swartkops River basin with important recommendations on the pollution aspects of the river.

The area is geologically interesting and hydrogeologically complex. There are mainly two aquifers to be considered from the aspect of resource conservation, the Kruisrivier and the Coega ridge. Suggestions that the boundaries of the control area be amended have not been acted on. However, as Maclear points out, it will be voluntary co-operation among groundwater users, rather than legislation, which will conserve the groundwater resource.

The necessity for professional advice in construction of boreholes in this area, due to the hydraulic head and the groundwater chemistry, is highlighted by the repair work that Reynders initiated to conserve the resource.

3.2 Groundwater Resource Management

Outlines of the modelling techniques and administration approaches to water resource management are discussed in the report by van Tonder *et al.* (1994). They describe various management models, their applicability to aquifer types, as well as the mathematical and management implications. Estimation of the abstraction potential of an aquifer is only one of the inputs required in the management of the aquifer by means of a groundwater model. Other parameters such as cost indicators must be included in the model for economic development and optimal use of the groundwater.

Modelling, Moore (1979) asserts, is the tool to bring groundwater into the realm of a quantifiable resource. Quantification is essential for groundwater to be considered in planning terms on the same basis as surface water. In particular the data requirements for modelling are stated and grouped into the physical framework, hydrological stress, and model verification prediction and optimisation analysis.

Groundwater yield is an issue, which must be precisely defined to understand the implication on the resource. The way the yield is defined influences how it will be quantified. Sharp (1998) describes the issues surrounding groundwater yield of an aquifer or groundwater basin. The yield must be defined as safe, optimal, mining or sustainable for the management plan. Environmental issues, the proposed use of the water and policy are factors to be considered for the yield definition. In an example he describes a situation of spring protection (environment) weighed against the wellfield abstraction required for community development (water use) as influencing factors on whether the management plan should be aimed at the safe or the sustainable yield.

Boehmer (1998) is of the opinion that assessment of sustainable yield should be done using long term historical data. The climatic conditions and the size of the groundwater unit have dramatic effects on the calculation of the resource. Cumulative rainfall departure methods, a summation of the monthly departures of rainfall from the long-term average monthly rainfall, are the best estimates of the recharge to the groundwater systems in the usual South African conditions. Recharge can be related to the excess rainfall over for a specific period relative to a long-term average. Recharge to the groundwater is one of the determining influences in quantifying the utilisable portion of the resource.

Cost is not a factor which needs to be considered in this study as the boreholes are already established. Cost would be a consideration in a choice between well-field development or surface water supply. Quantification of the resource is the most important for only then can it be brought into the planners thought processes where it can then be compared to surface water resources. The type of conservation practice that is to be followed depends on this quantification and determines the way the yield of the area will be treated.

Quantification of the groundwater resource is necessary for groundwater to be treated as a viable resource by planners. How much of this resource is actually available for use is another aspect of the quantification process.

3.3 GIS and Groundwater Modelling

In Germany hydrogeological maps are an important state-planning tool in matters relating to the environment such as groundwater supply. Hydrogeological data sets produced during a thematic mapping exercise are numerous and must be readily re-accessible for update and development. Sokol and Watzel (1997) outline their process toward hydrogeological map making. This brings in relational databases and the use of groundwater models using desktop GIS. Briefly the steps are:

1. borehole database checking and verification;
2. hydrogeological interpretation of time-series data;
3. cross section building (for vertical aquifer geometry definition); hydrogeological boundary definition (horizontal);
4. assigning hydraulic and hydrochemical boundaries;
5. metadata construction;
6. cartography and visualisation.

Again at the regional scale, in South Africa, Baron *et al.* (1995), used raster modelling to determine groundwater exploitation potential. Use was made of the datasets compiled for regional hydrogeological mapping. The additional hydrogeological parameter of transmissivity was determined using a formula which incorporates the yield of the boreholes. Computer modelling determined the permissible borehole density which would prevent water levels reaching the base of the aquifer during a drought. Methods for recharge estimation were investigated and combined in GIS with the other hydrogeological parameters to estimate the amount of groundwater available on a sustainable basis.

This integrative aspect of a GIS, allowing information from various sources to be brought together for analysis of regional groundwater patterns, also permits use to be made of data from remote sensing programmes. Kamaraju *et al.* (1994) combined various thematic layers such as lithology, geological structures and landforms to derive a groundwater favourability index map. The favourable areas identified could then be assessed at the local scale, with resultant feed-back into the system for future management of the resource.

Qi and Sieverling (1997) used a GIS to generate data for the groundwater-modelling package MODFLOW and to subsequently display the results. Raster data manipulation allowed generation of surfaces such as water level and aquifer saturated thickness from items in the borehole logs using the Arc/Info GRID function SPLINE. Vector data such as geological boundaries and rivers were used to define boundary conditions for the raster interpolation. Data generated from MODFLOW were incorporated into the

GIS for meaningful graphical displays of the groundwater situation and of the change in situation on adjustment of selected parameters.

Using a mass balance approach, recharge calculations over a large area using raster GIS modelling was demonstrated by Rogowski (1996). Raster overlays were produced by interpolation from point observations for each of the parameters to be considered, precipitation, depth to water table, evapotranspiration etc. The point spread of 31 locations to 123km^2 proving to be an effective data density for realistic surface generation. Map algebra was then applied using the overlays for three seasons. The results tied in with observed and measurable field events.

Interactive GIS modelling has been successfully used to model groundwater vulnerability. Tim, Jain and Liao (1996) used established methodologies for determining the vulnerability of groundwater to pollution to develop an interactive system for the immediate assessment of contaminant movement through the soil to the groundwater. This incorporated the attenuation factor, leaching potential and ranking index models. This is an illustration, like Rogowski's, of the use of raster based modelling of environmental factors but in this instance with the use of a graphic user interface (GUI) to guide those unaccustomed to GIS command structure through the modelling process to view the created scenarios.

El-Kadi *et al.*, (1994) used a vector based GIS in combination with other computer mathematical modelling for groundwater parameter estimation. The use of external models was required due to the limited, vector only, capabilities of their GIS software. Geohydrological parameters from groundwater maps were captured into a vector grid pattern. This mesh was then used as input into a mathematical programme for groundwater modelling. Results of the site-specific modelling could be returned to the GIS for groundwater resource estimation.

For regional studies Rogowski (1996) gives some indication of the level of data density required for successful use of GIS for groundwater modelling who used 31 sites within an area of 123km^2. Currently, groundwater modelling within a GIS is useful at a regional scale, but more site specific modelling still requires links to specialist models. One of the great strengths of a GIS is the impact obtained from the visual display of the modelled results. GIS coverages can be easily adjusted, from within such a presentation, for scenario testing. It is the author's opinion that considering the mathematical capacities of raster GIS and the vendor specific groundwater models already developed, it surely cannot be long until full groundwater modelling is available as standard within GIS.

Under the National Water Act for South Africa, (National Water Act, 1998) a reserve will have to be determined. The 'reserve' is the quantity of water required to fulfil the needs of the people who rely on a particular resource and to sustain aquatic ecosystems. Access to water resources will be equitable but there will be registration of water use as well as monitoring of the use. Rate of abstraction will be regulated and checked through the establishment of national monitoring systems. Ultimately the quantity of the country's water resource will be calculated through the necessity to determine the reserve.

This study uses the knowledge from the previous hydrogeological researchers in the area, especially the that of Maclear (1996), in combination with the use of GIS in groundwater modelling, as outlined by Sokol and Watzel (1997), and Baron *et al.* (1995), to arrive at a current and a scenario picture of the status of the groundwater resource for management. Quantification and sustainability of the groundwater resource are the two main criteria required by resource managers and are two of the main factors to emerge from the new National Water Act (1998) as crucial to the national strategy.

4 GIS DATA PREPARATION

There were two main sources of data for this study. One was the DWAF corporate database and the other was the hydrocensus of 1996.

A number of coverages were built ranging from those necessary for the management of the area to those required for further GIS data interpolation and manipulation.

4.1 Borehole Data

The hydrocensus carried out by DWAF in 1996 was intended as an inventory of the current situation of groundwater use in the rural sections of the USGWCA. During that year every farm and portion of the USGWCA was visited and information was gathered regarding present ownership, contact information, borehole details (historical and current) and actual groundwater use. At the time no plans existed to incorporate this data into any existing system, it was simply a snapshot of known boreholes, abstraction of boreholes in use and an update on legal requirements such as ownership and permits. The resulting spreadsheet of the data that was created was cumbersome and structured in such a way that it was not easily convertible to database format. For instance the single spreadsheet field of 'Farm number' may often contain multiple numbers belonging to the same owner. The "water strike" column could contain more than one value for the borehole. A description of the datafields is given in Appendix A.

Urban use of groundwater had been considered insignificant and at the time of conducting this study was the subject of a WRC investigation in the Port Elizabeth municipal area for testing of this assumption. Data from this research was not incorporated into this study due to the incomplete nature of the information at the time of analysis (Lomberg *et al.* 1997).

Historical borehole data are available from the National Groundwater Database (NGDB). This is predominantly archived data from the government drilling services branch of DWAF and the Department of Agriculture or from internal reports. Data from the drilling services is usually far from complete and does not contain abstraction information. Borehole data from the internal reports are generally fuller with more pertinent information. The data are coded to give an indication of accuracy of the information.

4.1.1 Relational Database

The database was set up to contain the information collected in the 1996 USGWCA hydrocensus. Tables pertaining to a particular attributes of each borehole and related to each other through an identifier. The tables of the database and their field descriptions are given in Appendix B. Figure 4 shows the tables of the database. A relationship of 1:1 means referential integrity is enforced and only one record may be linked by that item to one record in the relating table. The 1:n relation allows a unique identifier in one table to find many other records from a related table. For instance the 'boreholes' table has a unique identifier of BoreholeNumber but the related table 'geology' will contain more than one record for a particular borehole if more than one geological layer was found.

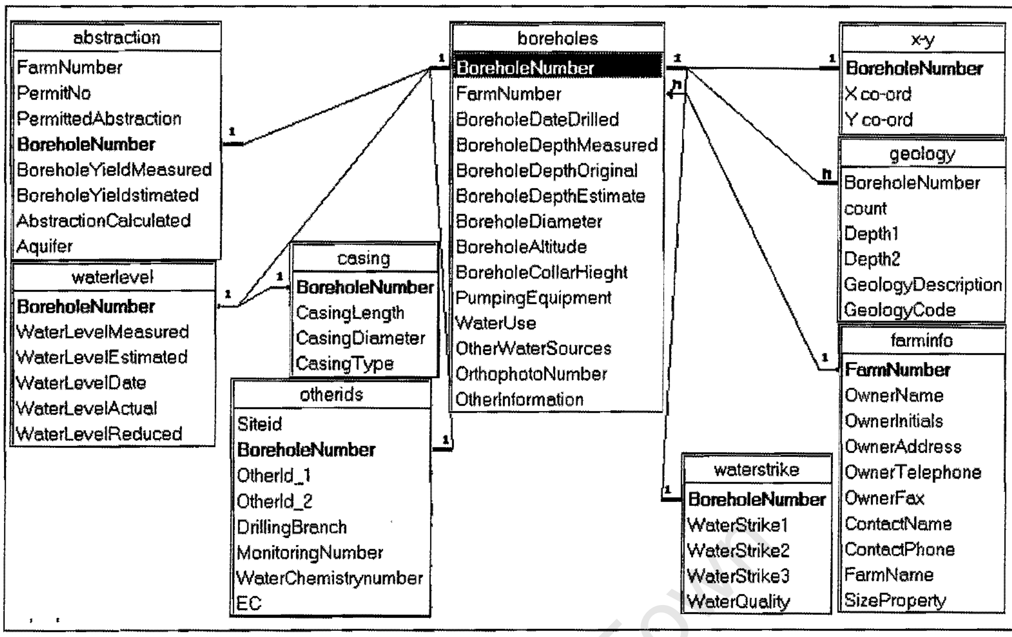

Figure 4: Relations and fields in the USGWCA hydrocensus database.

Additional tables contained within the database are made up from data from the NGDB. These data were used to supplement the hydrocensus data, which is limited to the control area, in order to allow a degree of parameter extrapolation over the USGWCA boundary. Some of the hydrocensus data could be linked through items in the 'Otherids' table to other identifiers contained in the NGDB files. The information from those 97 cross-referenced boreholes was used to update the data on the NGDB, the most important updating being to the accuracy code of the location of the borehole.

GIS point coverages of the NGDB and the hydrocensus were related and joined, with the reference number to the hydrocensus or the NGDB being maintained as an attribute. The duplicated boreholes, detected by the aliases the borehole is referred to within the NGDB record, were removed from the data set. Relate tables allow the point coverage of the boreholes to access relevant attribute information contained in database files. Boreholes on the NGDB are given an accuracy rating according to the method used to determine their position. For instance an accuracy rating of 0 means the position is correct to within 1m whereas an accuracy rating of 4 means the borehole location has been reported as simply being on a particular farm and accurate to 10000m. Boreholes from the NGDB with an accuracy code of 2 or less, translating to being within 100m of the given co-ordinate, were retained in the point coverage. Such an accuracy would mean the borehole location had been plotted on a 1:50 000 map. This reduced the NGDB data points from 667 available to 289 useable. A breakdown of the relevant information contained in the combined dataset is shown in Table 2.

Table 2: Summary of the borehole information

	Count	With wl	With ws	With geology	With ws and geology
Hydrocensus	318	128	142	51	49
NGDB*	289	188	102	1	0
Combined	607	316	244	52	49

*duplicates removed   wl = water level   ws = water strike

4.1.2 BOREHOLE DISTRIBUTION

Making use of the NGDB boreholes and the 1996 hydrocensus database the borehole point data coverage was built using the database co-ordinates with attributes of water level, water strike, depth and abstraction figures.

The geographical distribution of the borehole dataset is displayed in Figure 5. A concentration of data points occurs where there is farming activity. Toward the mountains and the wilderness area the information is sparse. At the time of the data collection for this thesis there were few known data points within the municipal areas. To a certain extent this has been rectified by the recently completed WRC study (Lomberg *et al.* 1997) but only to the extent of extra data points outwith the USGWCA.

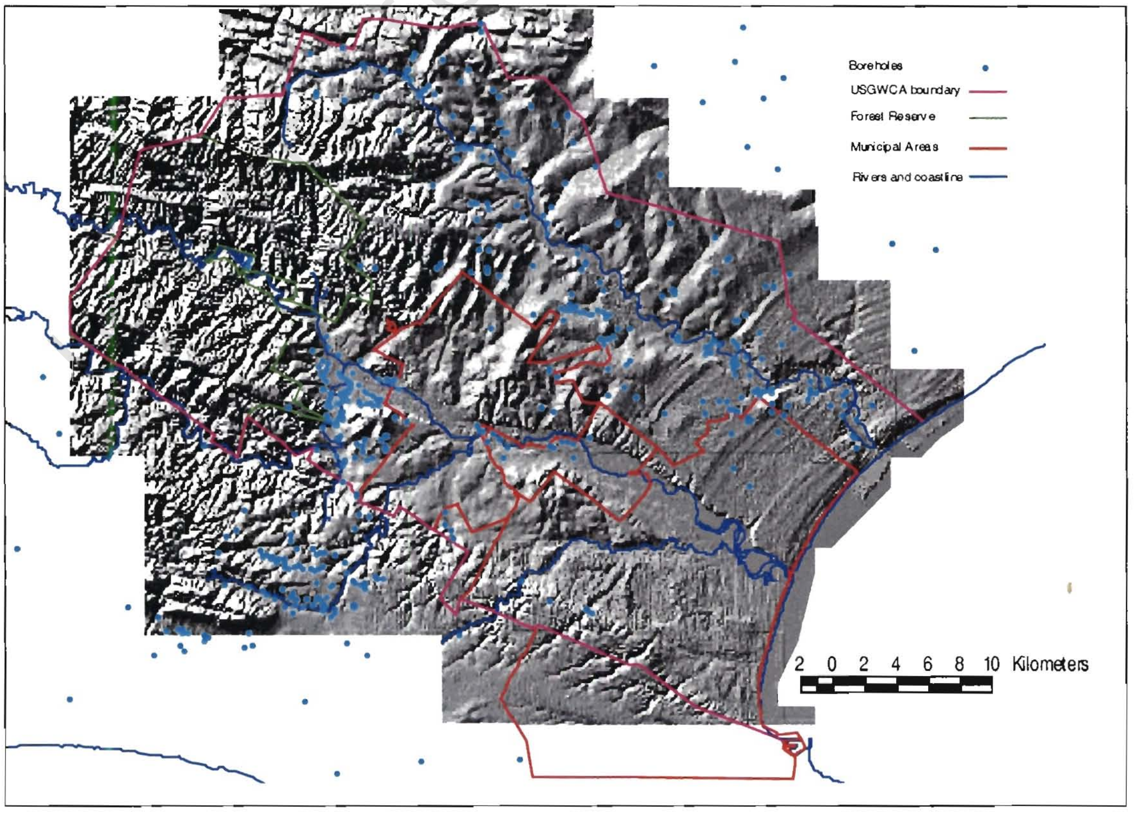

Figure 5: Geographical distribution of the combined dataset of boreholes on a shaded relief map of the area.

4.2 Farm boundaries

Farm boundaries were originally captured from orthophotos at 1:10 000 scale in DXF format, for the USGWCA and farms in its immediate vicinity. These had to be converted to GIS format followed by the lengthy process of cleaning and labelling the data for it to operate as polygon coverage to which information about individual farms could be related. The relation is through the "FarmNumber" in the "farminfo" table of the USGWCA database (Figure 4). Permits for groundwater abstraction are linked to the farm number.

4.3 USGWCA boundary

As prescribed under the Gazetted proclamation of the control area this is the boundary which determines whether a farm will require permission for borehole drilling and groundwater abstraction. The proclamation states the cadastral farms which fall within the USGWCA so the boundary is determined by using the outer polygon defined by joining the farm polygons.

4.4 Geographical situation

For illustrative and locational purposes, roads, municipal and forestry areas were acquired from the local DWAF office as DXF files, captured at 1:10 000 and the hydrological components, rivers and catchment boundaries sourced from DWAF head office as GIS coverages. The latter were scanned and vectorised by DWAF using map separates at 1:50 000 purchased from the Chief Directorate : Surveys and Mapping.

4.5 Yield

Groundwater occurrence of the area is available in GIS format from the DWAF hydrogeological mapping project. This is a published map at 1:500 000 and the yield polygon coverage, which is one of it's elements, is available from DWAF head office in ArcInfo format.

The groundwater occurrence boundaries for this project were determined by hydrogeologists from point data of borehole yield in association with the lithology. Original field work and interpretation were carried out at the 1:50 000 scale resulting in the definition of areas of distinctive groundwater occurrence. Subsequent statistical analysis to find the median of the yields within each area resulted in the specific yield class. Five yield classes were determined, specifically for this mapping project, according to the potential end use of the water. The defined classes are shown in Table 3 (W Orpen DWAF 1995 pers. com.).

Table 3: Groundwater occurrence yield classes.

Borehole Yield Range (l/s)	Abstraction equipment	End water user
< 0.1	Hand pump	Non-reticulated water supply for households. Population of < 250
0.1 – 0.5	Hand pump / wind pump	Non-reticulated water supply for households and stock. Approx population of 250
0.5 – 2.0	Small motorised pump	Small scale reticulated water supply for villages, clinics, etc. Approx population of 1 000
2.0 – 5.0	Medium motorised pump	Medium scale reticulated water supply for small town / small to medium irrigation. Approx population of 2 500
> 5.0	Larger motorised pump	Larger scale reticulated water supply for larger towns / medium to large scale irrigation. Approx population of > 2 500

A further consideration in devising of this classification was that it should be applicable to the whole country.

4.6 Geology

Specialist data for the geology, captured at 1:250 000 scale and provided in GIS (Arc/Info) format was purchased from the Council for Geoscience, Pretoria. In this data the polygons are related by a key to Info database files containing information on lithology and stratigraphy. A separate arc coverage contains information on the structural geology. Plotting this coverage at 1:50 000 allowed a check to be made against the original field maps held at the Port Elizabeth offices of the Council for Geoscience. The correlation of the two, in terms of spatial co-incidence of the geological boundaries, is excellent allowing application of the data at a smaller scale than which it was captured.

4.7 Depth to basement.

This was generated from isopachyte maps available from internal DWAF reports (Venables 1985:A13; Bush 1985:13). Hand-drawn contour maps were digitally captured and converted from a vector coverage to a raster surface.

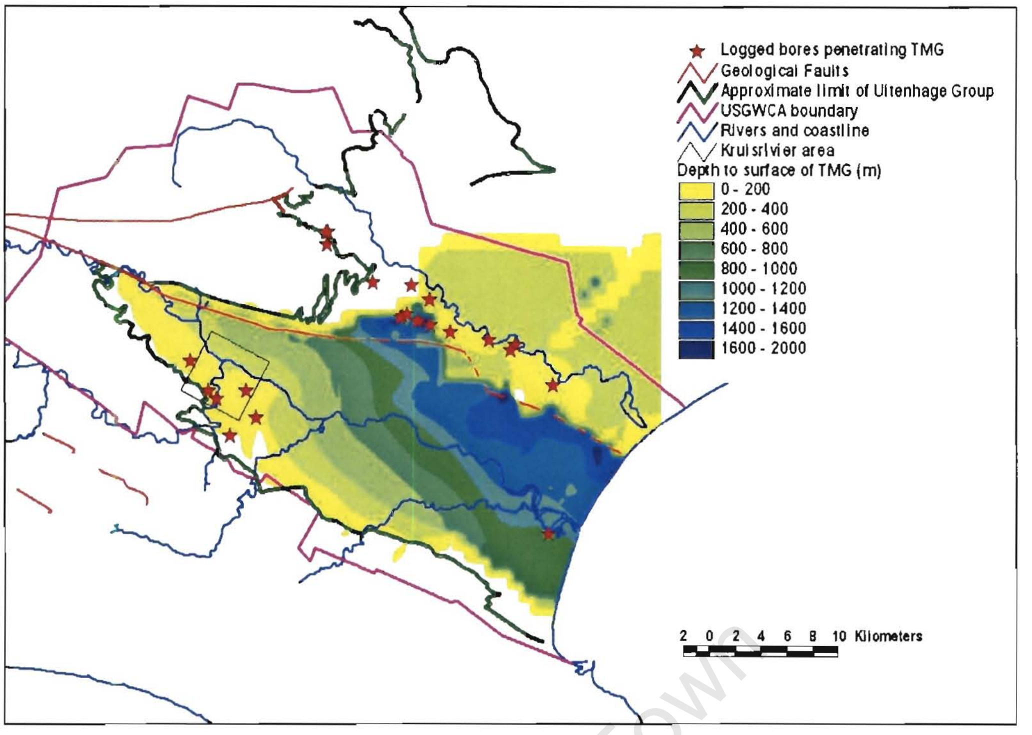

Figure 6: Depth to the surface of the TMG - thickness of the post-Palaeozoic.

Using borehole depth in conjunction with this raster data the relevant aquifer (TMG or overlying geological group) that each borehole is within can be judged. Management could use this surface as a guideline on borehole depth allowable at a particular location in order to prevent entry to the artesian TMG system.

4.8 Topographical Maps

The six 1:50 000 topographical maps which cover the area were scanned in greyscale, georeferenced and clipped to remove the borders. These form useful backdrops for information display on screen and for field map generation with addition of useful features such as borehole sites and geology as displayed in Figure 7.

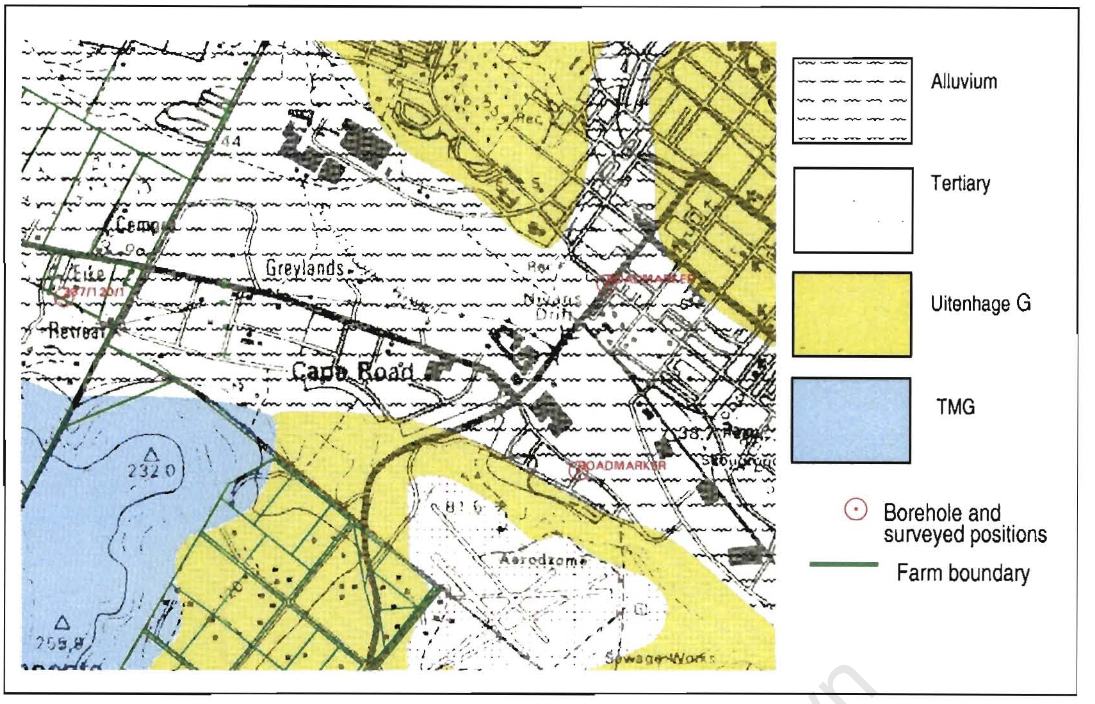

Figure 7: Map generation; section of 1:50 000 topographic map overlain with geological, farm and borehole information.

Copyright on the use of the information in this way is not infringed as the original data was purchased at the official source and the derived maps are not used for profit or distributed.

4.9 Elevation

A Digital Elevation Model (DEM) of the control area was produced from the 50m interval data obtained from the Chief Directorate:Surveys and Mapping, Department of Land Affairs. This data is in National Exchange Standard format and was converted into a point coverage using a 'C' script followed by the ArcInfo "generate" sub-routine. The point coverage was converted back to a raster surface with a 50m resolution. There are other means to achieve the generation of this surface but the process outlined was very quickly accomplished in ArcInfo on a UNIX platform. Predictive generation of a surface was unnecessary due to the even distribution and assumed accuracy (expected from a national mapping agency) of the point data.

This DEM will be used in conjunction with detailed geological logs to produce accurate geological surfaces. This is a project under-way with the aid of the Council for Geoscience. The resultant surfaces will allow recommendations to be made on permissible drilling depth and alternative groundwater sources to the TMG.

The resultant elevation surface is shown as the frontispiece of this study, hillshaded with ArcInfo default values. Changes in terrain pattern reflect differences in lithology. Smoother undulating hills of the east are younger softer rocks compared to the fractured and jointed rocks of the TMG mountains in the west.

5 DERIVATION OF HYDROGEOLOGICAL PARAMETERS

5.1 Water strike surface

The depth from the surface at which groundwater was first encountered in drilling is the water strike. This information is recorded in metres below ground level. The water strike is subtracted from the borehole altitude to give the figure in relation to sea level. For the majority of the dataset this was achieved through cross referencing to the digital elevation model which was formatted for the area. Due to financial constraints additional DEM data could not be purchased.

As only 24 data points (containing either a water strike or a water level) lie outside the range of the DEM, the altitude of the borehole was abstracted from the NGDB. As with the DEM these altitudes are in integers whereas the water strike and water level parameters are given to two decimal places. Additionally as the majority of boreholes are subject to the DEM level of accuracy, with error limits of 2.5m, there is some degradation of the accuracy of the data vertically. This would be significant if the location information was available to a similar level of accuracy. However, as only boreholes with a location accuracy rating showing the borehole position to be within 100m of the given co-ordinates were used in the surface creation, accuracy to two decimal places is unwarranted. The resultant surfaces are each subjected to the same error limits and consequently can be used within the same data model.

An examination of the point data using GIS methods for distance determination (in ArcInfo with the pointdistance command) revealed the following:

1. There are instances within the dataset of duplication of points. This is inevitably the result of multiple boreholes being drilled at one site due to drilling problems. There is no preference on which of the duplicate data points is the best one to use, the attributes being the same. Such duplicates are eliminated within the GRID module as coincident points fall within a single cell.
2. The shortest distance between 2 boreholes, excluding multiple drilling efforts, was 23.1m.

The cell size for surface creation was chosen as 20m. This gave a resolution which would handle the dense information without data loss. The distribution of the data points for the creation of the surface is shown in Figure 8.

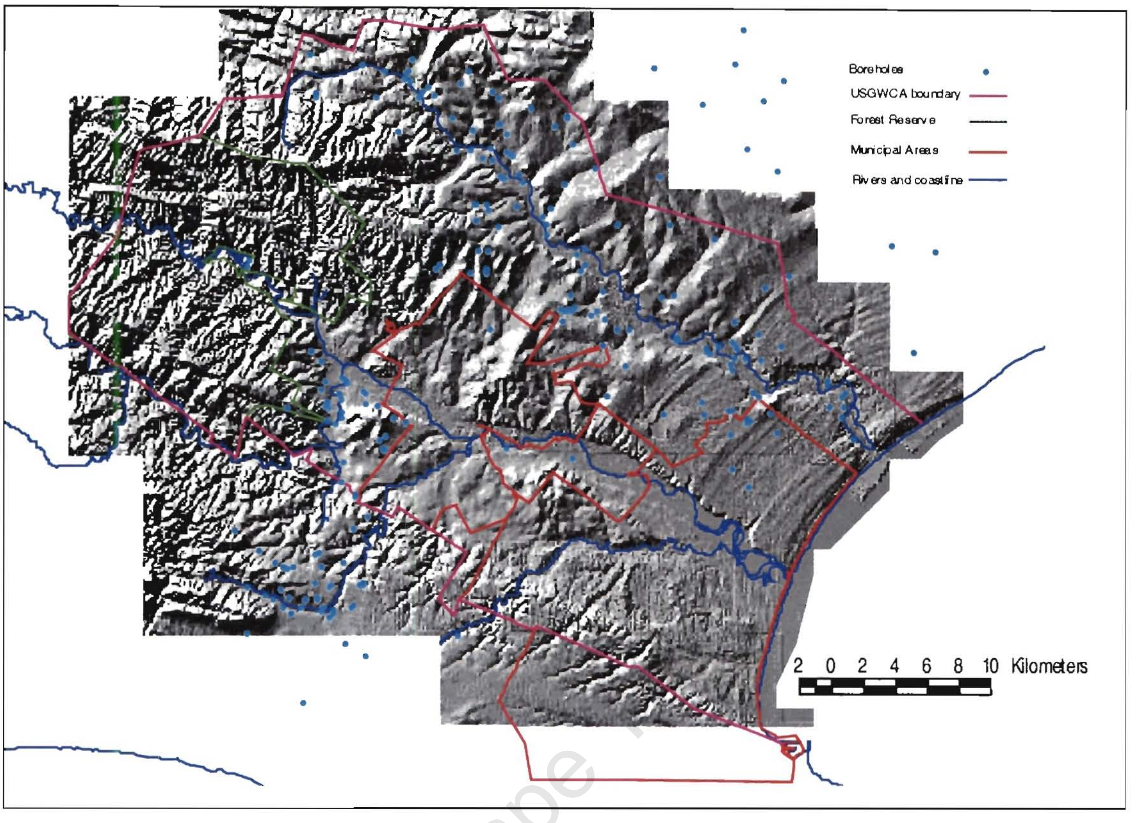

Figure 8: Distribution of boreholes with relevant water strike information, 244 points.

Water strike information recorded as 0m inevitably means the figure was not recorded and is not necessarily any reflection on artesian conditions. The date of the water strike, which would be the drilling date, is frequently absent. If the primary source of such information is the current landowner it is possible they simply do not know or cannot remember.

However it is interesting to see the number of boreholes drilled, with water strike, in relation to time as shown in Figure 9.

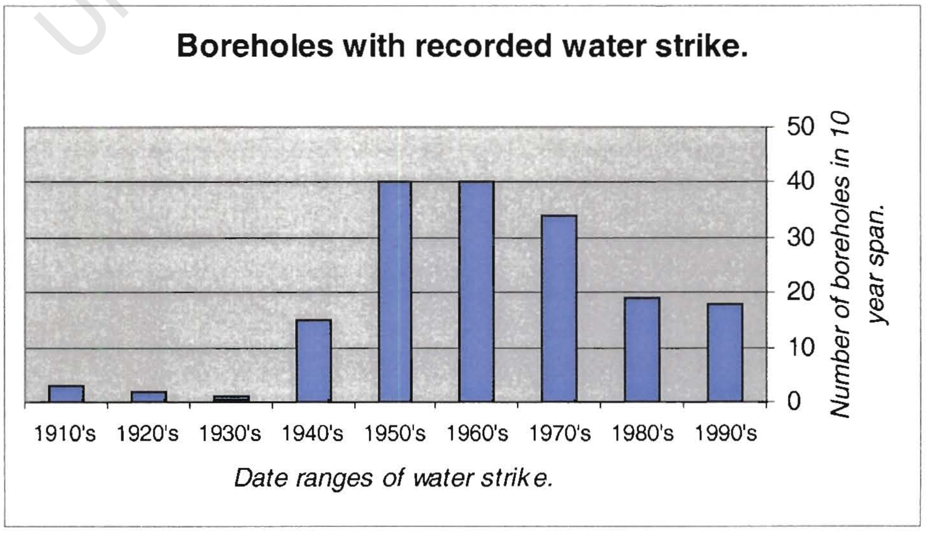

Figure 9: Frequency of boreholes drilled with recorded water strikes.

With the declaration of the USGWCA in 1957 there seems to have been little impact on the drilling of new boreholes with high numbers of boreholes drilled from 1960 to 1980. In the 1980's there were a number of hydrogeological studies undertaken (Bush 1985, Venables 1985 and Reynders 1987) highlighting the reduction of groundwater levels which may have caused managers to be more cautious with the issuing of drilling permits.

As the boreholes are predominantly drilled into a confined aquifer the water strike level is unlikely to be affected by seasonal factors or increase in water abstraction activities.

Using the IDW method of surface creation the groundwater strike surface was created and is shown in Figure 10. In this method the number of points to be sampled was taken as the default value with a search radius of 10000m. A lesser radius search value would have yielded gaps in the final surface. The extent of the surface is determined by the useable data in the input coverage i.e. boreholes with an altitude and water strike measurement.

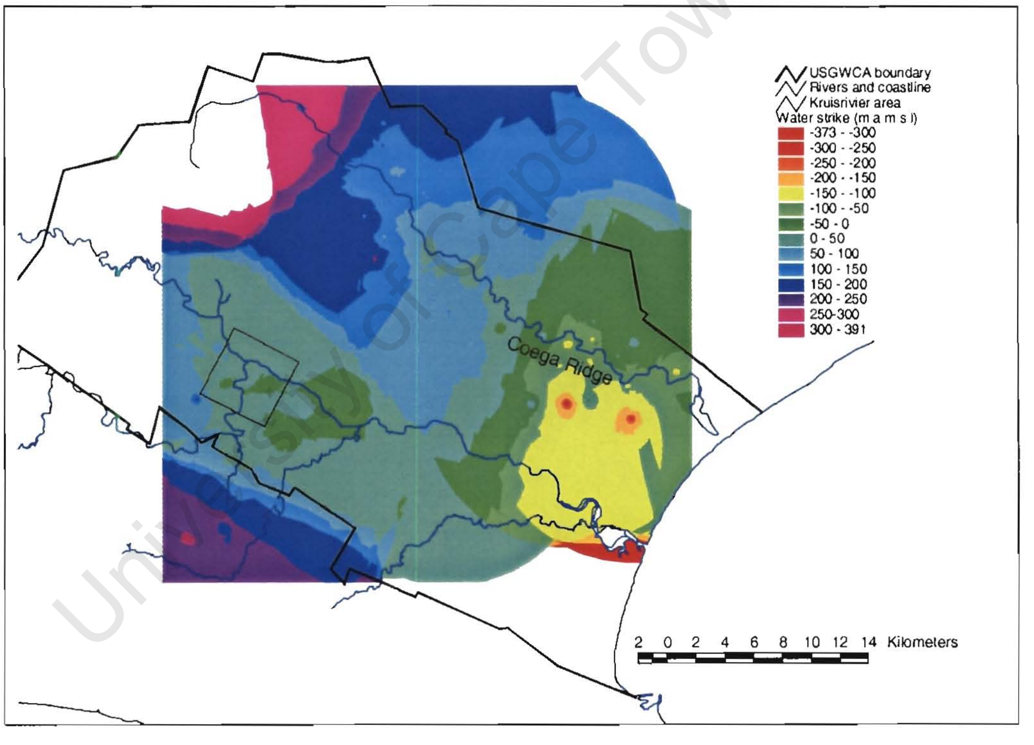

Figure 10: Groundwater strike surface.

Referring to this surface as (Figure 10), the negative values show that groundwater was encountered at depths below the mean sea level, i.e. a borehole drilled at an altitude of 50m and striking water at 51m below surface would give a water strike of minus 1m in relation to mean sea level. The extreme negative values to the south of the Swartkops River are due to influence of one extremely deep borehole with an exceptionally deep water strike.

5.2 Water level

The water level, as in water strike, is recorded as depth from the ground surface. This was converted into the water level with respect to mean sea level and is often referred to as the reduced water level. The method of obtaining these figures is the same as described for the water strike. As with water strike only boreholes with a location accuracy rating showing the borehole position to be within 100m of the given co-ordinates were used.

The water level measurement is given as a positive number of meters from ground surface. In this area, with the artesian conditions, it is possible to have water levels recorded as 0m or as a negative number. For the purpose of creation of the surface, boreholes with a water level report of 0m were not included in the dataset. Artesian conditions in the area mean that a water level of 0m could be water at surface level. Unfortunately this measurement has also been used as a way to record no water level information available.

The surface is greater in area compared to that obtained for groundwater level due to the distribution of data points (shown in Figure 11) containing the relevant attribute especially in the western section of the area.

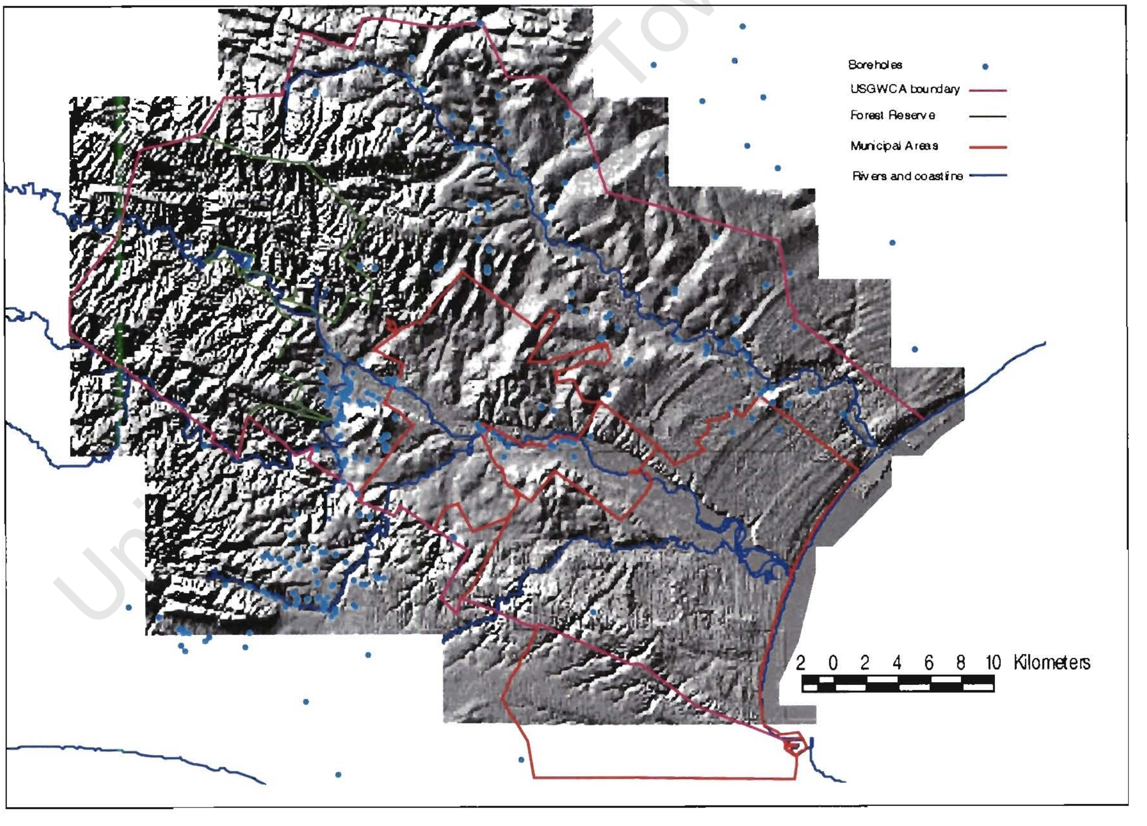

Figure 11: Distribution of the borehole data with water level information, 316 points.

Data points for input were chosen using the same criteria as in water level. Using the same method of surface interpolation as for the water strike surface, a water level surface was generated. The resultant surface, shown in Figure 12, displays the expected pattern of decreasing gradient toward the coast.

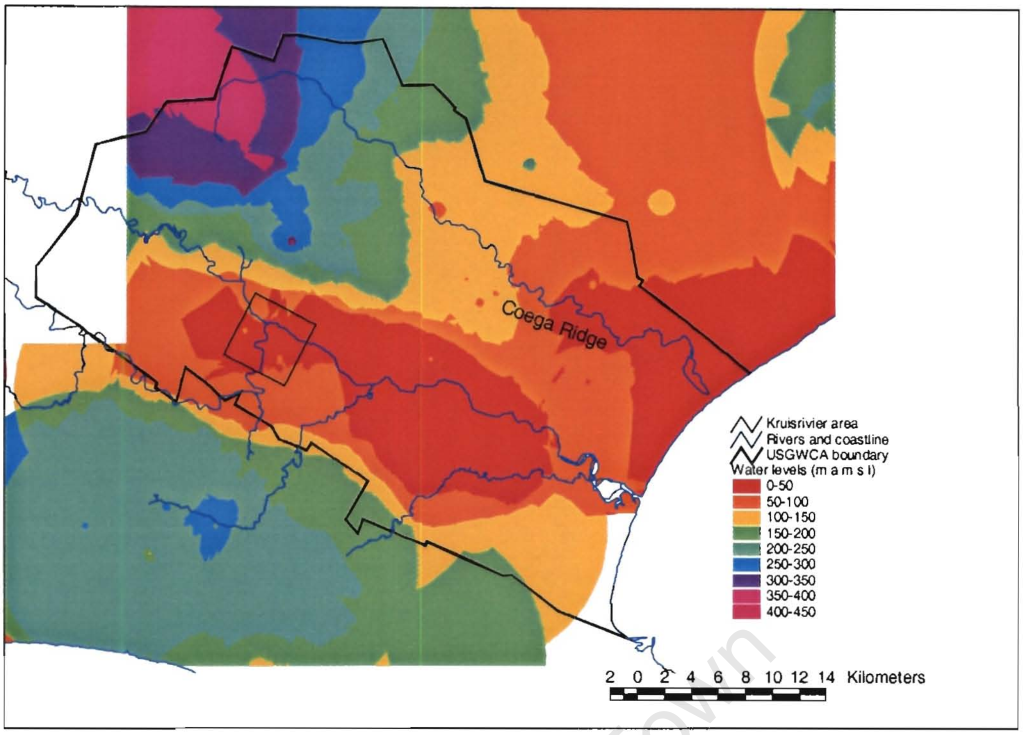

Figure 12: Groundwater surface with respect to mean sea level.

Archived hard copy data on the water levels of the control area dates back to 1967. This has recently been captured into a database. Using these earliest water levels (1967-1968) a surface was created using the same method and is shown in Figure 13.

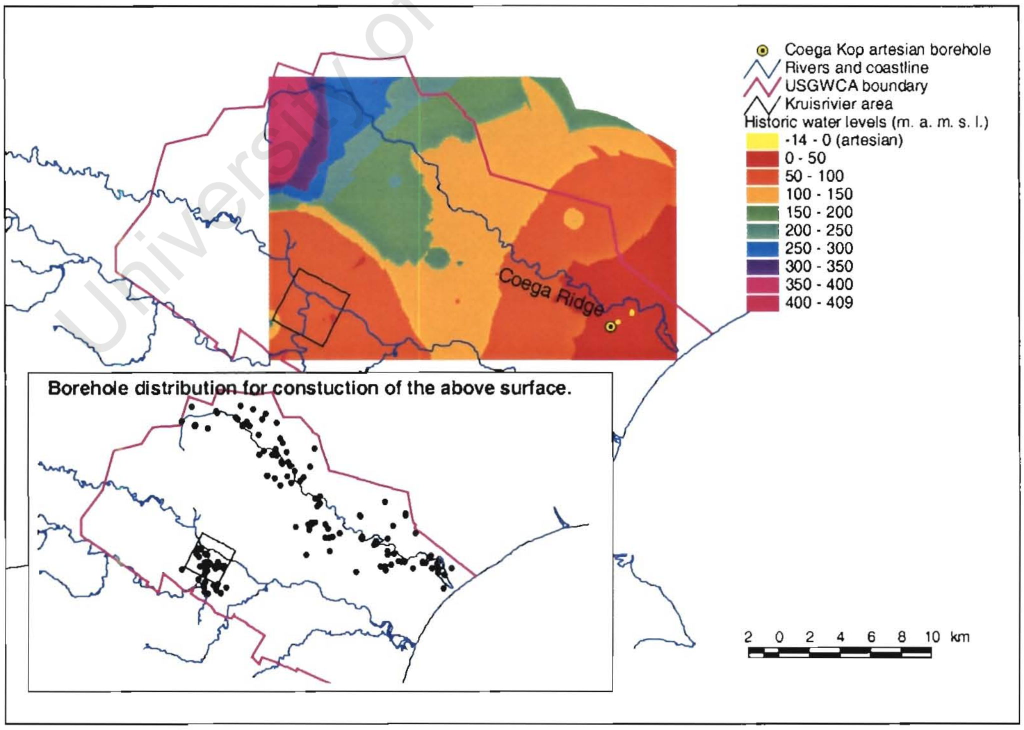

Figure 13: Pre 1970 water level surface.

The historical surface is rather restricted due to the fact that water levels were collected and monitored solely for the USGWCA. Comparison of the two surfaces shows a decline in the water levels in the vicinity of the Coega

Ridge and Kruisrivier areas, reflecting the years of continual abstraction.

5.3 Groundwater occurrence

In order to subdivide the USGWCA into hydrogeological compartments for further analysis use was made of the Port Elizabeth 1: 500 000 hydrogeological map (1998) in conjunction with geological boundaries.

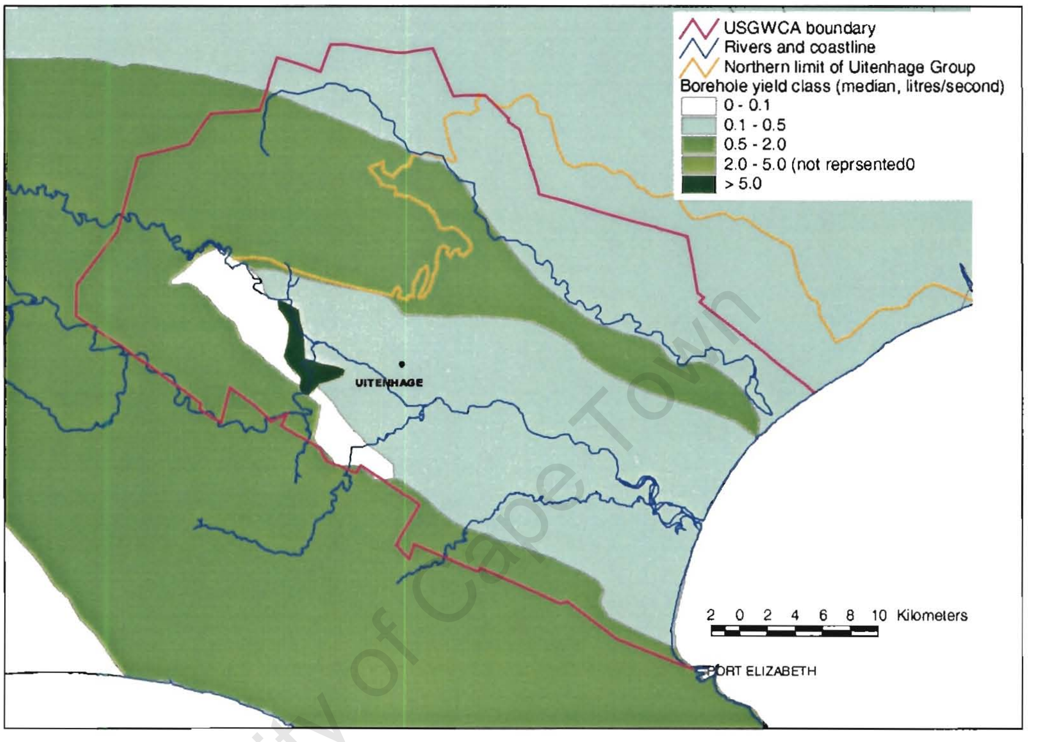

Figure 14: Groundwater occurrence divisions by median borehole yield. (from Port Elizabeth Hydrogeological Map 1:500 000, 1998)

In Figure 14 the occurrence of groundwater is depicted according to the aquifer type. Yield class spatial boundaries are determined by a hydrogeologist, followed by a statistical study of the known borehole yields within these boundaries. The median of the yields determines the yield class for a given unit. The hydrogeological trends in the southern study area follow the Uitenhage Group limit. Adding the Uitenhage Group boundary to the north of the area will allow a distinction to be made between the confined and unconfined groundwater sources.

5.4 Abstraction

Aquifer zones were delineated using a combination of the yield class boundaries from the hydrogeological map of the area, the limit of the Uitenhage Group and the 'M' primary catchment boundary. In Figure 15 the aquifer zones are coloured and numbered. The numbered zones can be related to the Table 4 which shows the volume of groundwater abstracted annually according to the 1996 hydrocensus (where actual usage was observed) compared to the authorised abstraction attached to the permit.

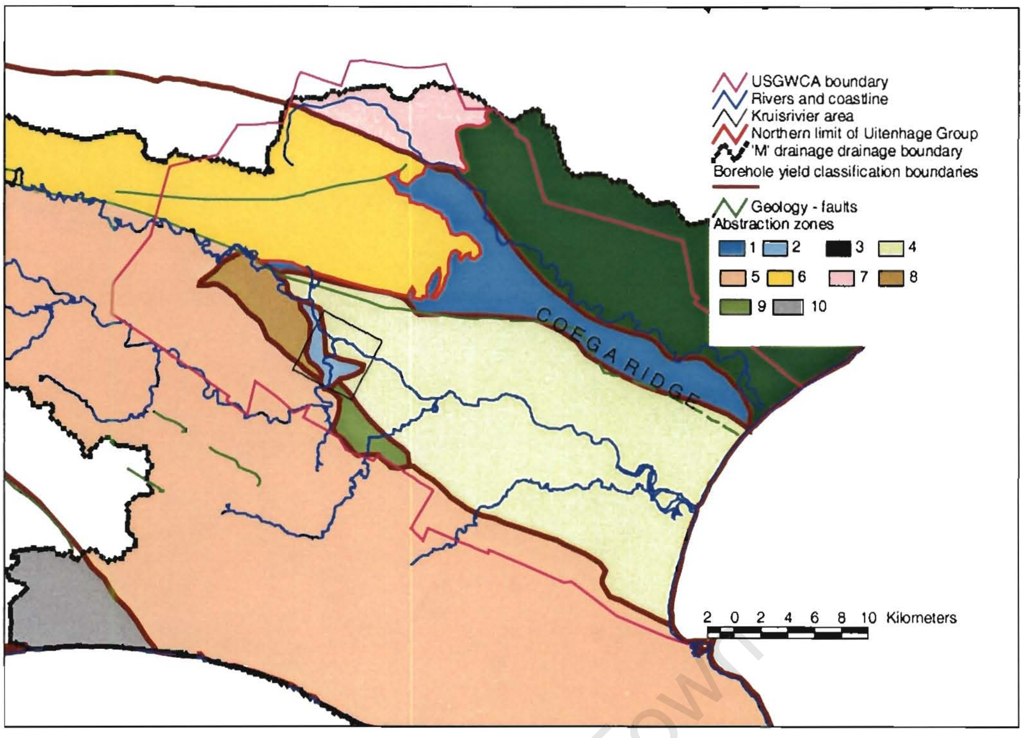

Figure 15: Abstraction zones in the 'M' catchment.

The majority of the abstraction takes place from two zones: the Coega Ridge (zone 1) and the Kruisrivier area (zone 2). Note the discrepancy in the Coega Ridge where the actual abstraction far exceeds the allocated amount by a factor of three.

Table 4: Comparision of actual and allocated groundwater abstraction.

Zone Number	Actual abstraction (m^3/a)	Allocated abstraction (m^3/a)
1	1565415	544057
2	1174921	2533025
3	172749	932723
4	161107	841191
5	29904	592469
6	27645	532837
7	17832	124755
8	0	27265
9	0	24346
10	0	0 (this zone not included in the USGWCA)

The contrast arises from the fact that the Coega Ridge area has a well developed citrus industry which has a higher water demand than the Kruisrivier area and abstraction allocation limit is not enforced.

5.5 Transmissivity

Transmissivity will be a determining factor in the calculation of the exploitation potential of the aquifer. Transmissivities can vary over a wide range within the same formation in the USGWCA this is due to the fractured nature of the aquifer. Higher yielding boreholes are generally sited on or near structural features. The increased fractures in these vicinities result in higher transmissivities. Transmissivity of an aquifer is determined from standardised hydrological tests on the boreholes and need to be located as accurately as possible in order to map local variation.

Transmissivity has a profound influence on the water level in the vicinity of a pumping borehole. In general, for boreholes being pumped at the same rate, high transmissivities will result in less change in water levels compared to those situated in low transmissivities.

In the USGWCA there are few data points available where geohydrological parameter testing has been carried out. These data points are too few for creation of a GIS regional surface but may be used in the estimation of local surfaces and the modelling of local wellfields.

The Botswana Government National Water Master Plan (by the consultants Snowy Mountains Engineering Corp 1991:3.4 – 3.6) evolved a formula for use in regional and national estimations of transmissivity from the limited data that is generally available. In common with Botswana, there are few boreholes in the USGWCA with full parameter estimation and those are usually from the higher yielding boreholes. The consultants' approach for the Botswana Master Plan was to develop a relationship from all the yield ranges of the boreholes to get a regional value for transmissivity.

Although the borehole data from the USGWCA may be too limited to provide a local mathematical relationship of transmissivity to yield, the incorporation of data from other TMG areas could give enough data to establish such a relationship for future use.

As the Botswana aquifers used for the formulation of T and the TMG in the USGWCA are both fractured aquifers the same formula was applied in this situation. From the DWAF hydrogeological mapping programme regional yields from within distinct lithostratigraphic units, have been statistically analysed, providing a yield figure per unit which takes into account the high and low yield values of the boreholes as described in section 4.5.

The mapped vector coverages were rasterised, for ease of mathematical application, and the formula (Snowy Mountains Engineering Corp 1991:3.4 – 3.6 derived from the non-linear regression of T vs Q) for obtaining a transmissivity value from a yield was applied across each cell. As the mapped yield values are given as ranges the median value of the range was used in the calculation.

$$T = 0.35(Q \times 3.6)^{1.34}$$

where T = transmissivity (m^2/d)

Q = yield (*l/s*)

The resultant transmissivities are shown in Figure 16. There is a great variation between the calculated T value and the geohydrologically measured value shown at the borehole site on Figure 16. This is a reflection on the type of aquifer.

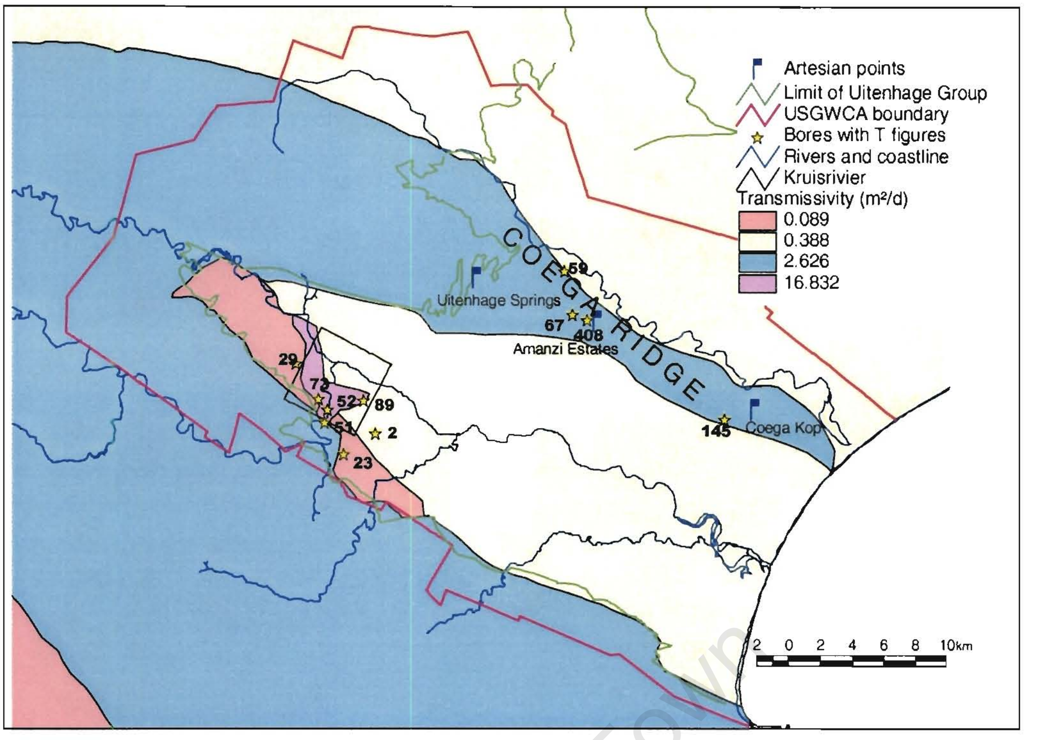

Figure 16: Transmissivities by formula with measured point values.

Transmissivity of a fractured rock aquifer is dependent on the amount, type and interlinking of fractures. In the vicinity of properly sited and developed boreholes the transmissivity will be higher reflecting the more open and possibly more intensive fracturing at that point. (Heederik 1984: 101–104; Krásný 1997:86-87,89). For regional values the lower and highly conservative estimations are appropriate for resource planning purposes considering the localised distribution of known transmissivities.

This method of transmissivity derivation used in the Botswana National Water Master Plan could be repeated using data from the USGWCA, supplemented with data from similar geology in other regions. Thus transmissivities specific to this regions aquifer type would be available providing better site-specific values.

5.6 Storage Coefficient

Derived from aquifer testing, by traditional pump-testing methods, the storage coefficient, S, is a dimensionless number. Applied to an aquifer volume the storage co-efficient will return the amount of groundwater contained within that mass. Storage co-efficient calculation by the usual methods is dependent on a pump-test design involving observations taken from a separate borehole close enough for water level drawdown effects to be observed. The study area can be divided into three zones on the basis of aquifer type, the Uitenhage Group aquifer, the confined TMG and the unconfined TMG. In two of these zones it was possible for storage co-efficient to be calculated.

The storage coefficient multiplied by the aquifer thickness and the aquifer area gives the volume of water held in the system. This volume would be variable as the aquifer thickness is determined as the saturated thickness of the aquifer at the time of calculation. In an unconfined aquifer this saturated thickness could show significant seasonal variation. Not all the water held in the system will be available for use and will not take into account water that is already being abstracted.

1. Kruisrivier Area. (Uitenhage Group)

Bush(1986: 32) calculated the S coefficient from seven boreholes in the Kruisrivier area resulting in figures ranging from 1.12×10^{-4} to 8.2×10^{-4}. The median of these figures is 5.6×10^{-4} and the average 5.37×10^{-4}. As we are dealing with a small sample with the mean and the median of nearly the same value, the average value was chosen and applied to the area of Uitenhage Group rocks in the Kruisrivier.

2. Coega Ridge. (Confined TMG aquifer)

Only two boreholes were suitable for determining the S coefficient in this area. The results were analysed by Venables (1985:16) using a range of standard pump test formulae. The seven figures he thus obtained gave close agreement averaging at 1.76×10^{-2} with a standard deviation of 0.51×10^{-2}. However from other pump test determined coefficients it is clear that these boreholes are leaking from the upper strata and therefore not a good indication of the storativity of the TMG as the S values would be too high. A third borehole whose construction does not allow such leakage, but whose zone of influence had to be estimated, resulted in a figure of 1.98×10^{-4}. Venables (1985:19) quotes Johnstone as giving artesian aquifers a value of $S = 1.0 \times 10^{-5}$ to 1.0×10^{-3}. The figure of 1.98×10^{-4} falls within this accepted range and is thus more acceptable to local hydrogeologists.

3. Unconfined Aquifer.

In the absence of any hydrogeologically controlled aquifer testing in this specific area, a general background figure of an unconfined TMG aquifer was used. The value of 4×10^{-3} is a figure that is frequently used in Karoo hydrogeology as the S value of an unconfined fractured aquifer. As the TMG is also a fractured hard rock aquifer this figure was used.

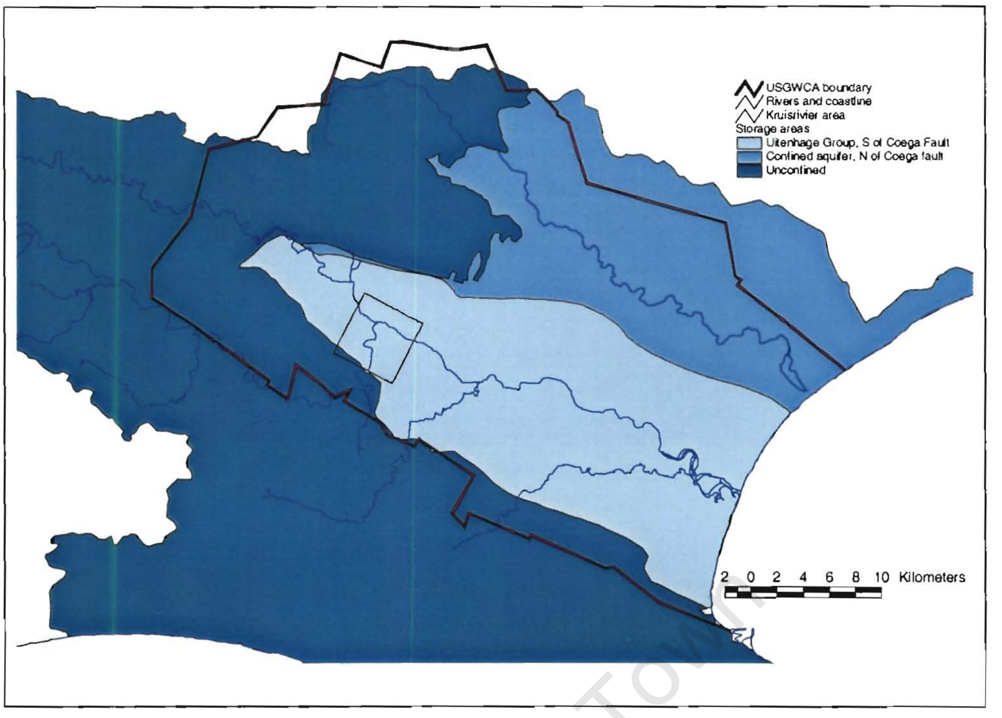

Figure 17: Areas of different storage values.

The above assignment of storage values over a large area is a rather simplistic picture given the internal variability that aquifers exhibit. Structural conditions in the TMG have already been mentioned as an influencing factor in the transmissivity of the aquifer. This would also apply to the storage value. In the Uitenhage Group aquifer is certainly likely by its nature to display lateral variation. The broad estimations are sufficient for a regional assessment of the groundwater resource. For the broad overview of resource management the actual amount in storage only becomes pertinent when abstraction is allowed to exceed the recharge, for instance during a drought period. It is at these times that some of the groundwater in storage may be used in the interim until the situation is normalised.

A summary of the transmissivity, storage and groundwater abstraction volumes is shown in Table 5, the zones being those defined in section 5.4 and illustrated in Figure 15.

Table 5: Zones, storage and transmissivity.

Zone	**S** (x 10^{-4})	**T (m^2/d)**
1	1.98	2.626
2	5.37	16.800
3	1.98	0.388
4	5.37	0.388
5	40.00	2.626
6	1.98	2.626
7	40.00	0.388
8	5.37	0.089
9	5.37	0.089
10	40.00	0.089

The transmissivities and the storage coefficient values vary over the USGWCA but not within the modelled zones.

6 GROUNDWATER MANAGEMENT

The previous chapters described the methodology whereby basic borehole data, GIS data and derived hydrological data were integrated using GIS to assemble a database for use in the management of the USGWCA.

One of the management principles is to ensure a sustainable yield, utilisation of the resource beneficially, but not necessarily indefinitely, minimising negative effects. One such negative effect would be the reduction of the water table and the consequent reduction of water in storage.

How much groundwater is in storage, how long it would last at current actual usage and how long it would last at the allocated rate, assuming no recharge, gives an idea of the sustainability of the resource.

In order to simplify discussions on the groundwater resource of the USGWCA reference is made to the zones as delineated in 5.4. Zones 4 and 10 have been omitted from resource evaluation as zone 10 does not fall within the USGWCA and zone 4 is not utilised as a groundwater resource.

6.1 Regional Resource Evaluation

6.1.1 VOLUME OF GROUNDWATER IN STORAGE

In order to estimate the volume of groundwater that is contained in the area the aquifer volume and storage co-efficient are multiplied together. Storage co-efficient and aquifer area are already available in the GIS. For the purposes of this study, aquifer thicknesses were estimated according to the geology of the aquifer, using studies by Bush(1985) and Vegter(1995).

<u>Uitenhage Group (Kruisrivier Area)</u>

Seven available accurate borehole logs show aquifer thickness in the Kruisrivier area (Uitenhage Group) (Bush 1985:32). The thickness ranges from 50 m to 172m, the spatial distribution of the boreholes and the thickness of the aquifer at each point is shown in Figure 18. The aquifer of this group shows considerable variation in thickness but a distinct split into two ranges on either side of the Elands River.

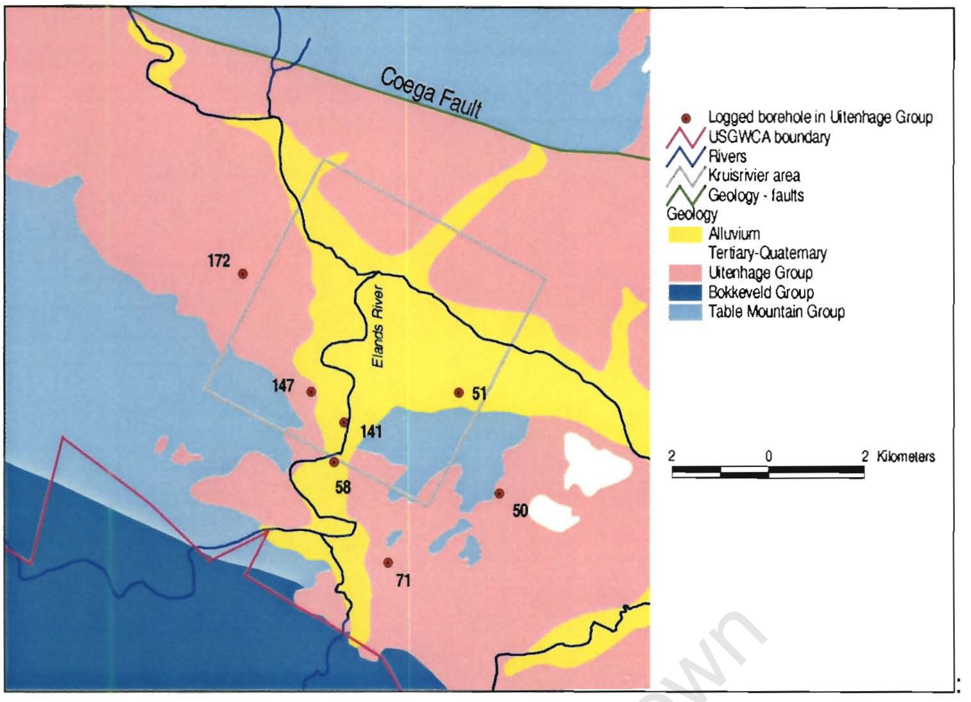

Figure 18:Boreholes in the Uitenhage group with thickness (m).

A simple statistical analysis of the seven values for aquifer thickness give a median of 71m, a mean of 98.5m, standard deviation of 52.5m with a skew value of 0.44. A median value is more resistant to very high and very low values. In this case, the median is also lower than the mean, therefore adopting the median would result in a more conservative estimation of groundwater in storage.

<u>Table Mountain Group (Coega Ridge and Unconfined Aquifer)</u>

As defined in 5.4 this group makes up abstraction zones 5, 6 and 7. In the statistical analysis of boreholes within this geological group for the South African national hydrogeological mapping project (Vegter,1995) the map author determined an aquifer thickness of 280m for this group in general. Vegter's estimate was adopted in this study. However it should be noted that this is likely to be a conservative figure. Current research indicates that the actual aquifer thickness of the TMG can be considered to be the combined thickness of the aquifer units of this group (current researchers in this field, J Kotze, C Hartnady, and S Meyer pers. comm.). In the USGWCA this would be in excess of 1000m.

Since it is estimated that only 70% of the volume in storage will be available for release (Sami 1994:131) due to hydraulic constraints, the storage volumes were estimated as follows:

$V = (S \times b \times A)\, 0.7$

Where:

V = volume of groundwater (m^3)

S = storage co-efficient (dimensionless)

b = aquifer thickness (m)

A = aquifer area (m^2)

Using this formula and the areas of the aquifers as defined by the primary catchment boundary and the sub-divisions of the three zones of storativity as described in section 5.6 the results shown in Table 6 were obtained.

Table 6: Aquifer values in the USGWCA (by abstraction zone)

Zone	Name	S ($\times 10^{-4}$)	Area (m^2)	Aquifer Thickness (m)	Storage Volume (Mm^3)
1	Coega compartment	1.98	118281286	280	4.59
3			308849025		11.99
2	Kruisrivier area	5.37	10840460	71	0.29
8			32193979		0.86
9			15605168		0.42
5	Unconfined	40.00	1253274219	280	982.57
6		1.98	308028309		11.95
7		40.00	52572129		41.22

6.1.2 RECHARGE

The recharge to the artesian groundwater comes from rainfall in the upper parts of the catchment and not by direct rainfall infiltration. (Maclear 1996: 53). For the Coega compartment the recharge is from 285km^2 of the Peninsula formation of the TMG which forms the mountainous area (Groot Winterhoek Mountains) to the west of the Coega compartment at the north of the 'M' catchment. For the Kruisrivier area the recharge comes from the TMG formation in the west of the USGWCA totalling 68km^2. These areas of TMG are in the M10A quaternary catchment. Rainfall data from the Surface Water Resources of South Africa 1990 project give the average for this catchment as 529mm/a.

According to the map of the Groundwater Resources of the Republic of South Africa by Vegter (1995), this area has a recharge value of 15 – 37 mm/a, i.e. 3% to 7.4% of Mean Annual Precipitation (MAP). A recharge figure of 5% is frequently used in groundwater studies in South Africa (Baron *et al.* 1995) and was used by Bush (1985:57) in calculations for this area. As the average recharge figure for this area approximates to 5% of MAP, this value will be used in the recharge volume calculations.

The calculated recharge volumes (recharge area x rainfall x recharge value) are shown in Table 7. Recharge for zones 5, 6 and 7 have been calculated using the surface area of the zone as the groundwater there is unconfined.

Table 7: Calculated recharge volumes.

Zone	Name	Recharge (Mm^3/a)
1	Coega compartment	7.54
3		
2	Kruisrivier area	1.80
8		
9		
5	Unconfined	33.13
6		8.14
7		1.38

6.1.3 *RESOURCE SUSTAINABILITY*

For the resource to be used on a sustainable basis the amount of groundwater in storage should be 2 – 3 times the recharge estimates (Boehmer 1998:17). The summary of the groundwater volumes shown below indicate that, by using this method for determining sustainability, the resource is under stress in the Kruisrivier area.

Table 8: Comparison of groundwater volumes.

Zone	Name	Storage Volume (Mm^3)	Recharge Volume (Mm^3/a)	Actual Abstraction (Mm^3/a)	Allocated Abstraction (Mm^3/a)
1	Coega compartment	16.57	7.54	1.57	0.54
3				0.17	0.93
2	Kruisrivier	1.56	1.80	1.17	2.53
8				0	0.03
9				0	0.02
5	Unconfined	982.57	33.13	0.03	0.59
6		11.95	8.14	0.03	0.53
7		41.21	1.38	0.02	0.12

These figures are based on the conservative estimates of storage volume due to the lack of comprehensive data on aquifer thickness and the limited number of S values available.

If the recharge equals the amount being abstracted the amount of groundwater in storage would stay the same. Taking the quantity of current abstraction from the volume available will show the volume of the groundwater available for future allocation (assuming no recharge and no other losses in the system) and for maintenance of any groundwater dependent systems. This volume would be for sustaining any ecological systems supported by groundwater and the groundwater contribution to river baseflow. Due to the nature of the aquifer (confined) in the USGWCA the groundwater contribution to the river flow is negligible (Vegter,1995). The only contribution to the river flow from a groundwater source would be from the alluvial aquifer which is not included in this study.

It appears that for the area as a whole there is sufficient groundwater available to satisfy actual and allocated requirements. However this is a regional pattern and not applicable to areas in which the groundwater is intensively utilised as we can see in the Kruisrivier area and the Coega compartment.

Actual volume in storage depends on recharge to the system. The way the volume in storage is addressed depends on the recharge / storage relationship. For instance

1. it is possible that the recharge far outstrips the storage capacity of the aquifer or
2. the storage capacity could exceed recharge.

In the first instance it would be possible to set annual groundwater consumption greater than the storage capacity. As the groundwater is used so more space becomes available to store the recharge that could not normally be absorbed into the system. In the second scenario abstraction should not be allowed to exceed annual recharge, unless mining of the aquifer is to be permitted. In the case of the USGWCA the recharge to the system is less, (except for the Kruisriver were recharge approximately equals storage), than the storage capacity and the second scenario applies.

Storage time has been defined as "the time to deplete the aquifer if pumped at a rate equal to the mean annual recharge" (DWAF:1998). The time groundwater use would be sustainable is derived by dividing the current rate of abstraction is divided into the storage volume. This would assume no recharge to the system.

A similar exercise can be carried out for the allocated amount, which is frequently higher than the current use, to foresee the situation should users decide, or need, to use their legally allocated volume of water.

A table of results, Table 9, shows the years of use at current rate compared to years of use at actual rate.

Table 9: Groundwater zones and years of sustainable use.

Zone	Name	Years use at current rate	Years use at allocated rate
1	Coega compartment	3	8
3		69	13
2	Kruisrivier	0.25	0.11
8		No current use	32
9		No current use	17
5	Unconfined	32857	1658
6		432	22
7		2311	330

Continued abstraction in the Kruisriver area (zone 2) at the current rate during a time of no recharge would deplete the resource in a matter of months. This amount of time would be further reduced if abstraction were to increase to the actual allocated volume. For the Coega area (zone 1) reverting to the actual allocation would extend the life-span of the resource should it be under threat due to an extended drought.

6.2 Local Resource Management

6.2.1 Site Specific Drawdown Modelling, Kruisrivier Area

One of the main aims of the declaration of the USGWCA was to limit the decline in the water levels. It is undesirable that current or new boreholes be pumped at such a rate as to adversely affect other boreholes in the area. Management decisions have to be made on the licensing of the borehole and the abstraction that may be allocated.
The main factors to be considered in this process are the

- aquifer from which abstraction will take place
- transmissivity of the aquifer

- quantity that is expected to be abstracted
- effect on water levels of the area
- effect on storage

A model which could give an indication of the impact on the water levels of a specific zone, should there be an increase in abstraction from an existing or new borehole, would be a useful management tool. Such a model, to give a rough look at the scenario, can be constructed using one of the standard hydrogeological formulae. The necessary formula may be applied over a specific area containing the borehole site in question, making use of the raster surfaces (grids) constructed for the regional resource evaluation.

The drawdown at a particular point can be calculated using the following Cooper-Jacob approximation of the Theis equation (Sami and Murray 1997:7.49)

$$s = \frac{2.3Q}{4\pi T} \log \frac{2.25Tt}{r^2 S}$$

where
s = drawdown measured at distance r from borehole.
Q = discharge (yield) in m^3/d
S = storage coefficient
T = transmissivity (m^2/d)
t = pumping time (days)
r = distance from well (m)

This is done in the GIS using an AML (given in Appendix C) which
- retrieves the values of S and T for the given point
- calculates the drawdown for the expected abstraction
- determines the new water level by adding the drawdown to the current depth to groundwater

Time (t) is taken as 0.5 days. This is a reasonable estimate of the time that a farmer would run his borehole pump on a daily basis. An abstraction rate of $30m^3/d$ was used in the exercise. This is the figure that would be expected in this area for mixed farming, including irrigation, on a farm of 100ha.

Distance from the pumped well (r) is retrieved from a raster surface calculated from the proposed new borehole. Constructed for an area with a limit of r = 1km the distance grid is larger than the area of expected drawdown effect, given the values of S and T in the USGWCA and the proposed time and abstraction rate. Limiting the area in such a fashion also saved on processing time and computer disc storage space.

An area where groundwater is heavily utilised was chosen to illustrate the model, namely Kruisrivier. Results of running the model with the parameters used are shown in Table 10.

Table 10: Results from water level modelling.

Parameter	Value
Q (yield) m^3/d	30
S (storage)	0.00053
T (transmissivity) m^2/d	16.8
t (pumping time) days	0.5
Drawdown at 1m from borehole	1.4m
Drawdown at 133m from borehole	0.09m

The drawdown for the requested allocation barely makes any impact on the waterlevels. If Q were to be increased some 10-fold which would be approaching the sort of yield that an aquifer testing programme would use, a significant amount of drawdown would be generated.

The volume in storage may be re-estimated to take into account the increase in abstraction volume to determine the long-term effect on the resource.

This is a very limited look at the possible effects on the groundwater resource of increased abstraction. No account is taken of the recovery of the water levels when there is no pumping or the residual effects on the water levels. Possible influences from nieghbouring boreholes are also ignored. A more accurate picture would have to be obtained by linking a proper groundwater modelling package, such as MODFLOW, to the GIS.

6.3 Calculation of the 'Reserve'

With the implementation of the National Water Act (1998) it is necessary for the reserve to be determined for all or part of any significant water resource. The definition of the reserve is the "quantity and quality of water required to satisfy basic human needs by securing a basic water supply, as prescribed under the Water Services Act, 1997, for people who are now or will, in the reasonable near future, be relying upon, taking water from, or being supplied from, the relevant water resource; and to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource." (National Water Act 1998:16). Once the reserve has been determined the remainder may be allocated for use.

This will be done at quaternary catchment level (which is the third subdivision of a primary surface drainage basin) if the resource is deemed to be homogeneous within the catchment. Provision is made for this to be performed at a finer scale, such as a significant groundwater resource which may be within or straddle quaternary catchment boundaries. This is illustrated in Figure 19 where the hydrogeological zones may stretch across several quaternary catchments as in zone 1, or be wholly contained in a catchment as are zones 2 and 9.

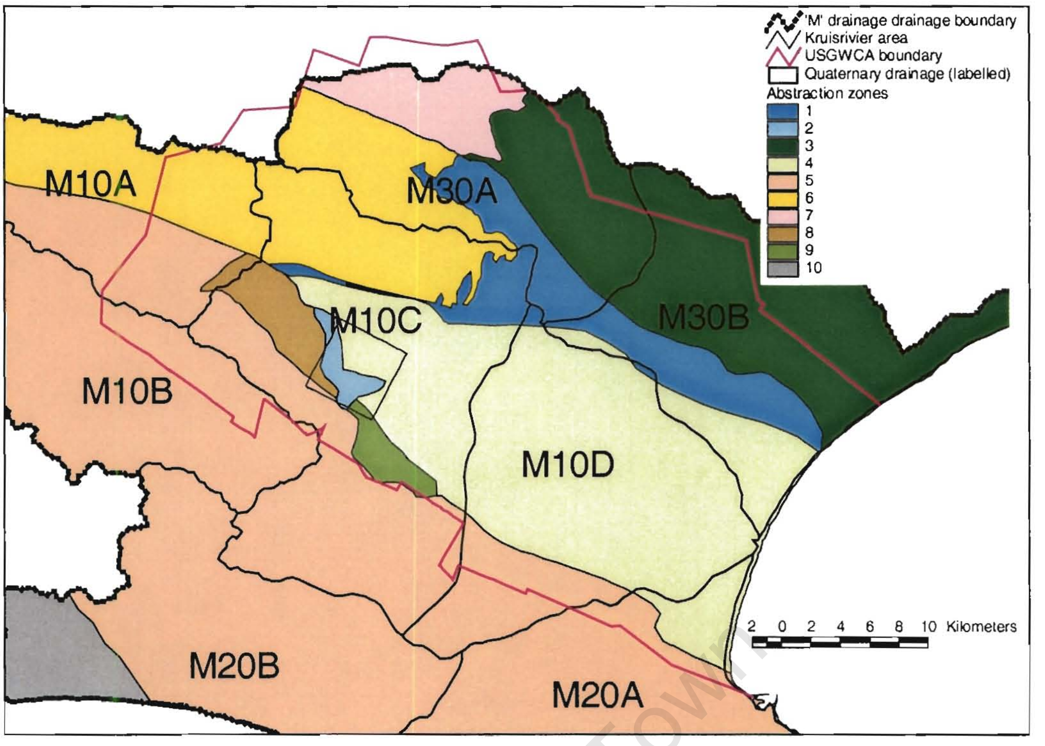

Figure 19: Quaternary drainage and geohydrological divisions.

A process for the intermediate determination of the groundwater component of the 'reserve' has been established by Parsons (1999: E5). The methodology as currently set out is ideally suited to application with a GIS. As the reserve determination will make use of a multidisciplinary team it is important that classifications made by members of the team can be represented on a map for their input.

A summation of the processes for the hydrogeological input and their relevance to this study is given in Table 11.

Table 11: Steps for the determination of the Reserve in relation to the data required.

Process step	Data required
1. Geographical boundaries of water resources	Catchment boundaries, drainage, topography
2. Geohydrological units	Geology, groundwater occurrence, recharge, groundwater volume
3. Groundwater reference (natural) conditions	Geology, historic water levels, historic abstraction, transmissivity, storage, groundwater occurrence
4. Current status of geohydrological unit	Water levels, volume of abstraction, licensed abstraction.
5. Desired management class for each geohydrological unit	Historic water levels, resource sustainability.
6. Determine recharge, baseflow, basic human requirements from groundwater, allocation from each geohydrological unit	Recharge, volume of groundwater in storage. (Volume of groundwater from Uitenhage springs for urban use available but no rural community use considered in this study.)
7. Review groundwater deemed available	Current abstraction and licensed abstraction, resource sustainability. Drawdown modelling.

The data required for each of the steps outlined are available within one system for the USGWCA thus expediting the calculation of the reserve for any of the groundwater zones or quaternary catchment. Input from other reserve team members can easily be incorporated into the system to allow for the integrated approach to the reserve determination.

As zones 1 and 2 are identified as being under pressure the reserve should be calculated for them before there is any renewal of licensing or consideration given to new abstracting boreholes.

Groundwater level data exists from a time when the resource had only just been impacted upon as illustrated previously (Figure 13) and required in step 5 of Table 11. The water levels drawn up from the 1968/1969 data show the situation when the actual abstraction for the whole USGWCA was estimated to be 0.99Mm^3/a. Water usage for the entire USGWCA has risen to 3.2Mm^3/a.

The difference between the historic water level situation and the 1996 levels is shown for the groundwater abstraction zone 2, the Kruisrivier area, in Figure 20.

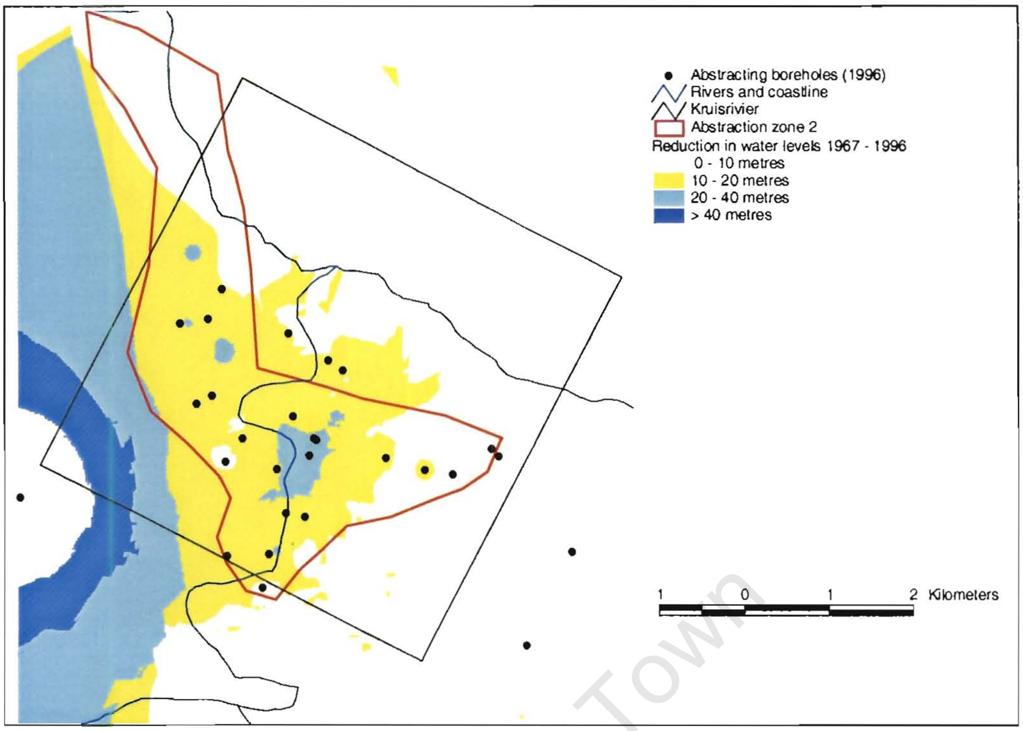

Figure 20: Groundwater level reduction in the Kruisrivier area.

Although the historic water levels do not give the pristine, pre-abstraction borehole, surface it is least a reference surface for the current situation. Figure 20 shows the actual reduction in water levels over the zone 2 where the resource is in under greatest pressure. This correlates with the reduction in water levels with the introduction of boreholes into the area and increased abstraction as described in Reynders (1987:13). Reynders then goes on to predict a decline to 110m below surface in approximately 126 years in the Kruisrivier area if abstraction was at a level of $2.05Mm^3/a$. Currently the abstraction is at $1.17Mm^3/a$.

Should boreholes be required for population development, such as water supply to a small settlement or irrigation scheme, the site-specific drawdown model could be utilised. This would allow a 'first-look' check for detrimental effects on any ecological system which would be effected by a lowering of the water table.

Usage figures are currently being captured which will allow a comparison of current to historic usage and water levels for each zone. This will assist in the calibration of water level change should pumping over a zone be increased or decreased.

7 SUMMARY AND CONCLUSIONS

The USGWCA is a hydrogeologically interesting and complex area containing an artesian aquifer of enormous water supply potential. Early exploitation of this aquifer led to the enforced protection of the groundwater within the geographical limits of certain cadastral boundaries. Legislation allows for abstraction to be limited and permission for possible future boreholes to be authorised. This requires accurate knowledge of the underground environment linked to the location of the borehole site or potential site.

The combination of all the data required for the resource monitoring and management is now available within a GIS. Predictive surfaces created using the GIS give additional information for assistance with resource management.

Preliminary site investigations by a hydrogeologist may now be aided with the printing on demand of site specific maps containing the necessary geological and cadastral information.

DWAF is frequently consulted for advice regarding drilling depth and borehole construction. This is to ensure abstraction from specific hydrogeological zones. This information maybe obtained with reference to the presence and the thickness of the Cenozoic sediments.

In conjunction with the derived geology surfaces the water strike surface will show the actual source rock of the groundwater. This will prove especially useful in areas where there is doubt over the origin of the groundwater as being from the TMG or local sandstone facies of the Uitenhage Group.

Long term effects on the resource may be calculated for current and proposed abstraction rates. These scenarios assist with the long-term management strategies.

Impact on the groundwater resource of abstraction rates and possible increased rates can now be assessed speedily. A programme, utilising known mathematical formula for water flow analysis, within the GIS may be used to view and analyse potential effects of increased or new point abstraction on the groundwater resource.

Comparing the amount of groundwater being abstracted compared to the actual allocation; it is evident that there has been little correlation between the two in the past. The Kruisrivier area aquifer will be under pressure if groundwater abstraction was to assume at the allocated rate. By contrast there is uncontrolled abstraction in the Coega Ridge area where the life span is approximately a predicted three times shorter than if it was utilised at the recommended rate.

Reviewing the figures for the amount of groundwater in storage compared to the actual and allocated abstractions (Table 8) it appears the resource is in fact under utilised. The amount in storage is dependent on the thickness of the aquifer, which in the case of the TMG is emerging from current research as much thicker than previously concluded. However the amount in storage is also not necessarily the amount that may abstracted on a sustainable basis. Long term drought records and recharge events have to be taken into consideration before a sustainable abstraction allocation is made. Transmissivity is also one of the factors which will determine the exploitation potential of the aquifer.

8 RECOMMENDATIONS

Continual maintenance of the database must be done in order to ensure currency, particularly of farm subdivisions, owners, water levels and abstractions.

Accurate geological surfaces need to be created. These would be utilised for the creation of customised geological cross-sections from anywhere within the USGWCA. This would allow for accurate drilling depths and borehole construction recommendations. In particular cases a maximum may be set in order to avoid entry to the artesian TMG aquifer.

Calculation of the groundwater in storage should be improved once better data is available on the aquifer thickness. A less simplistic model will need to be developed, as the upper and lower boundaries of an aquifer cannot be assumed to be planar as indicated by Figure 18.

Historical water level data allow a comparison with current water level trends. Discovery of historical abstraction to relate to this surface for use in comparison to the current water levels and abstraction would provide a basis for water level prediction on increased or reduced abstraction.

The current groundwater-monitoring network should be reorganised to give information reflecting the regional water level fluctuations for the unconfined TMG, Uitenhage Group and the confined TMG on either side of the Coega fault.

Modelling of the transmissivity parameter should be refined to derive a suitable model specific to this area.

A more sophisticated groundwater modelling package should be linked to the system to allow more detailed modelling of site-specific groundwater surfaces.

9 REFERENCES

ArcDoc	*ArcInfo* on line progamme documentation ver 7.1.1
Baron JH, Seward P and Smart M (1995)	"Groundwater Exploitation Potential Using a GIS" *Groundwater '95 Conference*
Boehmer WK (1998)	"Re-assessment of Sustainable Abstraction from Groundwater Basins of Different Size in Semi-Arid Areas" *Groundwater:Sustainable Solutions* IAH International Groundwater Conference, Melbourne 1998
Bush RA (1985)	"A Geohydrological Assessment of the Kruis River/Bethelsdorp Systems-Uitenhage." DWAF Geohydrology Technical Report Gh3458
DWAF : Geohydrology (1997)	"The Groundwater Harvest Potential Map of South Africa" 1:3 000 000 DWAF, 1996
DWAF : Geohydrology (1998)	"Hydrogeological Map Series of the Republic of South Africa. Sheet 3324 Port Elizabeth." 1 : 500 000 DWAF 1998
El-Kadi AI, Oloufa AA, Eltahan AA, Malik HU (1994)	"Use of a GIS in Site-Specific Groundwater Modelling" *Ground Water* Vol. 32 No 4, July-August 1994
Freeze RA and Cherry JA (1979)	*Groundwater.* PrenticeHall pp604
Heederik JP (1984)	"Water Resources Assessment study in Kiambu District, Kenya" *IAHS Publ. No 144* July 1984
Kamaraju MVV, Bhattacharya A, Sreenivasa Reddy G, Chandrasekhar Rao G, Murthy GS, Ch. Malleswara RaoT (1994)	"Ground-Water Potential Evaluation of West Godavari District, Andhra Pradesh Statem India-A GIS Approach" *Ground Water* Vol .34 No 2, March-April 1994
Krásný J (1997)	"Transmissivity And Permeability Distribution In Hard Rock Environment: A Regional Approach" *Hard Rock Hydrosystems*: IAHS Publ. No 241
Lazarus P (1997)	"Towards a Regulatory Framework for the Management of Groundwater in South Africa." Draft:for submission to the SA Water Law Review drafting team.
Lomberg CR, Rosewarne PN, Raymer DA and Devey DG (1997)	"Research into Groundwater Abstraction in the port Elizabeth Municipal Area" WRC Report No 515/1/97
Maclear LGA (1996)	*The Geohydrology of the Swartkops River Basin-Uitenhage Region, Eastern Cape.* MSc thesis, Cape Town University.

Maclear, LGA and Woodford AC (1995)	"Factors Affecting Spring-Flow Variations at Uitenhage Springs, Eastern Cape" *Groundwater Conference Proceedings.*
Moore JE (1979)	"Contribution of Groundwater Modelling to Planning" *Journal of Hydrology* Vol 43 pp121-128
National Water Act (1998)	Republic of South Africa, Act no 36 of 1998.
Parsons, R (1999)	DWAF Water Resources Protection Policy Implementaion. Resource Directed Measures For Protection Of Water Resources. Volume 6 Groundwater Component (Ver 1). September 1999.
Qi S, Sieverling J (1997)	Using Arc/Info to Facilitate Numerical modelling of Groundwater Flow" *ESRI User Conference Proceedings* 1997
Reynders AG (1987)	"Historical Overview and Potential of the Uitenhage Subterranean Water Control Area" DWAF:Geohydrology Technical Report Gh3560
Rogowski AS (1996)	"GIS Modeling of Recharge on a Watershed" *Environ.Qual.*25:463-474 (1996)
Sami K (1994)	"Groundwater Recharge and Exploitation potential of the Mid Kat River Basin" Report to the Kat River Citrus Co-operative
Sami K and E C Murray (1997)	*Guidelines for the Evaluation of Water resources with an Emphasis on Groundwater* WRC June 1997
Sharp JM (1998)	"Sustainable Groundwater Supplies – an Evolving Issue: Examples From Major Carbonate Aquifers of Texas, USA" *Groundwater:Sustainable Solutions* IAH International Groundwater Conference, Melbourne 1998
Snowy Mountains Engineering Corp., (1991)	"Botswana National Water Master Plan Study" Government of Botswana, Ministry of Mineral Resources and Water Affairs. Final Report Vo5-Hydrogeology. March 1991
Sokol G and R Watzel (1997)	"Organising GIS Data for Hydrogeological Applications" *ESRI User Conference Proceedings* 1997
Tim SU, Jain D, Liao H-H (1996)	"Interactive Modeling of Ground-Water Vulnerability Within a Geographic Information System Environment" *Ground Water* Vol.34, No.4 August 1996
Toerien DK and RS Hill (1989)	*The Geology of the Port Elizabeth Area* Geological Survey. Explanation of sheet 3324, 1 : 250 000. Government Printer, Pretoria. Pp35.

Van Tonder GJ, Janse van Rensburg H, Staats S, Cogho VE (1994)	"The Development of Groundwater Management Models" WRC report (unpub)
Vegter JR (1995)	"The Groundwater Resources of the Republic of South Africa" 2 sheets. WRC, 1995
Venables AJ (1985)	"The Geology, Geohydrology and Hydrochemistry of the Uitenhage-Coega Artesian System" DWAF Geohydrology Technical Report Gh3437

Appendix A: Access data tables for the USGWCA

EXCEL spreadsheet fields of the 1996 DWAF hydrocensus data

Owner, address, phone	General owner information
FarmName	Common name of farm
Farm Number	Farm number by registration district
Farm Size (Ha)	Farm size in hectares
Permit no.	Abstraction permit no as issued from DWAF
Permitted abstract (m3/a)	Abstraction allocated by DWAF
BoreholeNumber(alternative no.)	Borehole no by farm number, subdivision and borehole
Date Drilled	Date drilled
Borehole depth,measured(m)	Borehole depth measured (actual)
Borehole Depth,estimated(m)	Original depth of borehole (reported by driller/farmer)
Borehole depth estimated(m)	Borehole depth estimated
Borehole diameter(mm)	Diameter of borehole in millimetres
Water Strike(m)	Depth from top of water strike
Height (masl)	Elevation of the site in metres above mean sea level
Casing height(m)	Amount of casing above ground surface
Waterlevel Depth from casing(m)	Water level depth from the casing top, measured
W.l. est.from casing(m)	Water level estimated from casing arrangement
Date w.l. Measured(m)	Date water level measured
w.l. depth (m)	Actual water level depth (measured w.l. - casing above ground)
reduced w.l.	Water level in relation to sea level
Coordinate:Y	Y coordinate of borehole in Gauss LO 25
Coordinate:X	X coordinate of borehole in Gauss LO 25
Casing:length (m)	Length of casing in borehole
Casing:diameter(mm)	Diameter of casing in millimetres
Casing:type	Material casing made of
Yield Measured (l/s)	Measured yield of borehole
Yield estimate(l/s)	Estimated yield of borehole
Abstraction calculated (m^3/a)	Annual calculated abstraction
Water use	Use of the water
Borehole equipment	Equipment on borehole
Other water sources	Any other water source
Geology	Geology encountered
Aquifer (TMG) (Uitenhage)	Aquifer water is abstracted from
Groundwater EC(mS/m)	Water quality by electrical conductivity
Other information	Any other pertinent information
Date visited	Date of the site visit for these details

Appendix B: Spreadsheet fields of the 1996 DWAF hydrocensus data.

Access data tables for the USGWCA database

Section 1 : hydrocensus data

Boreholes	
BoreholeNumber	Borehole number from JCowley hydrocensus, 1996
Farmnumber	Cadastral and portion number of farm
BoreholeDateDrilled	Year borehole drilled
BoreholeDepthDrilled	Depth of borehole in m; actual measurement
BoreholeDepthOriginal	Depth of borehole in m; original depth
BoreholeDepthEstimate	Depth of borehole in m; estimated
BoreholeDiameter	Smallest diameter of borehole in mm
BoreholeAltitude	Height of borehole above sea level in m
BoreholeCollarHeight	Collar length above ground in m
PumpingEquipment	Pumping equipment on borehole
WaterUse	Use water is for
OtherWaterSources	Other sources water is obtained from
OtrthophotoNumber	Reference number of 1:10000 orthophoto
OtherInformation	Other useful information
Abstraction	
Farmnumber	cadastral and portion number of farm
PermitNo	Abstraction allocation permit
PermittedAbstraction	Abstraction allowed according to permit in cubic metres/a
BoreholeNumber	Borehole number from JCowley hydrocensus, 1996
BoreholeYieldMeasured	Yield of borehole measured in l/s
BoreholeYieldEstimated	Yield of borehole measured in l/s
AbstractionCalculated	Abstraction calculated in cubic m/a
Aquifer	Source of the groundwater [Uitenhage Gp/TMG]
Waterlevel	
BoreholeNumber	Borehole number from the hydrocensus
WaterLevelMeasured	Water level from collar, measured in m
WaterLevelEstimated	Water level estimated in m
WaterLevelDate	Date water level measured
WaterLevelActual	Water level below ground surface (minus collar height) in m
WaterLevelReduced	Water level w.r.t. sea level in m
Otherids	
Siteid	Siteid from the NGDB
BoreholeNumber	Borehole number from the 1996 hydrocensus
Otherid-1	Borehole number from previous hydrocensus
Otherid-2	Any other ID allocated
DrillingBranch	Borehole number allocated from drilling branch
MonitoringNumber	Monitoring point number

WaterChemistryNumber	H-no allocated by HRI for chemical analysis
Casing	
BoreholeNumber	Borehole number from JCowley hydrocensus, 1996
CasingLength	Length of casing
CasingDiameter	Diameter of casing in mm
Casing Type	Type of borehole casing
Waterstrike	
BoreholeNumber	Borehole number from JCowley hydrocensus, 1996
WaterStrike1	First water strike (measured from surface)
WaterStrike2	Second water strike(measured from surface)
WaterStrike3	Third water strike (measured from surface)
WaterQuality	MilliSiemens per metre
x-y	
BoreholeNumber	Borehole number from the hydrocensus
X co-ord	X co-ord in Gauss LO 25; by GPS or orthophoto
Y co-ord	Y co-ord in Gauss LO 25; by GPS or orthophoto
Geology	
BoreholeNumber	Borehole number from JCowley hydrocensus, 1996
count	Acts as repeating group flag
Depth1	Depth top of layer
Depth2	Depth bottom of layer
GeologyDescription	Personal description
GeologyCode	Geology code as per NGDB
Farminfo	
Farmnumber	Cadastral and portion number of farm
OwnerName	Name of registered farm owner
OwnerInitials	Registered owners initials
OwnerAddress	Registered owners address
OwnerTelephone	Registered owners telephone number
OwnerFax	Registered owners fax number
ContactName	Contact persons phone
ContactPhone	Contact persons phone
FarmName	Common name of farm
SizeProperty	Size of property in Ha

Section 2 : Additional information from the NGDB

ngdb-aquifer	
Siteid	Siteid from the NGDB
Rpgp	repeating group
Start-depth	Water interception
Code	Aquifer code
Text description	Description of code
ngdb-wls	
Siteid	Siteid from the NGDB
WaterLevelMeasured	Water level from collar, measured in m

BoreholeNumber	Borehole number from JCowley hydrocensus, 1996
WaterLevelMeasured	Water level from collar, measured in m
WaterLevelEstimated	Water level estimated in
WaterLevelDate	Date water level measured
WaterLevelActual	Water level below groundsurface(minus collar height)
WaterLevelReduced	Water level w.r.t. sea level in m
ngdb-oid	
Siteid	Siteid from the NGDB
Otherid	Any other ID allocated
ngdb-geol	
siteid	Unique no allocated by NGDB
rpgp	Repeating group. Geological 'layer' number
start-depth	Start depth of geology
end-depth	End depth of geology
code	Geological computer code
x-y updates	
Siteid	Siteid from the NGDB
X co-ord(ngdb)	from ngdb
Y co-ord(ngdb	from ngdb

Appendix C: AML to Determine Expected Drawdown At Proposed New Borehole Site.

```
/**A MODEL TO DETERMINE THE DRAWDOWN TO BE EXPECTED AT A NEW BOREHOLE
LOCATION IN THE UITENHAGE CONTROL AREA.
/**!!!! SITE SPECIFIC.!!!!
/**JANE BARON revised 23Nov2000

&terminal 9999
&messages &off &all
&echo &on
/**&severity &error &ignore
display 0
&messages &popup

&type "You will need the proposed borehole location in XY lo co-ordinates \
and the expected pumping rate in cubic metres per day"

      &sv .locationX = [response 'Enter the proposed X value in lo system
co-ordinates']
      &sv .locationY = [response 'Enter the proposed Y value in lo system
co-ordinates']


      &sv .Q = [response 'What is the proposed yield in cubic metres per
day?']


      /**&messages &off &all


/** generate a circle for the drawdown to be calculated in

generate ddcircle

/** ddcircle name of coverage to be generated with ID,X,Y,r

circle
1,%.locationX%,%.locationY%,1000

/**gives 2km diameter circle.

end
quit
build ddcircle poly   /** build a poly coverage from the generated circle
polygrid ddcircle ddcircle_grd   /** grid of the ddcircle
.5  /**for cell size
y     /**for convert all


generate ddpoint  /** point of new borehole
point
1,%.locationX%,%.locationY%
end
quit
build ddpoint point /**  build pint coverage from borehole location
pointgrid ddpoint ddpoint_grd  /** grid coverage of the borehole point
0.5
y
zero
```

```
grid   /** go into the GRID module

setcell 0.5

distance = costdistance(ddpoint_grd,ddcircle_grd)     /**this uses a 2km
zone

/**distance = name of grid that will be used for radius values


mape transmiss
setwindow ddcircle_grd

      &sv .T = [show cellvalue transmiss %.locationX% %.locationY%]

      &sv .S = [show cellvalue s_grid %.locationX% %.locationY%]

docell
begin
wl1 := 2.3 * %.Q%
wl2 := 4 * 3.142 * %.T%
wl3 := wl1 div wl2
wl4 := 2.25 * %.T% * 0.5
wl5 := distance * distance * %.S%
wl6 := wl4 div wl5
wl7 := log10(wl6)
ddgrid := wl3 * wl7
ddgrid_2 := con(isnull(ddgrid),0,ddgrid)
if (ddgrid_2 > 0) newwlgrid = wl + ddgrid_2
endif
end
end


q
```