A GIS-Based Experimental Methodology to Determine the Utilisable Potential of South African Aquifers

Report to the Water Research Commission
by the
Cape Water Programme
Division of Water, Environment and Forestry Technology
CSIR

WRC Report No 840/1/99

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Water Research Commission

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WRC Report No : 840/1/99
CSIR Report No : ENV/S-C 98094
ISBN No : 1 86845 505 X

EXECUTIVE SUMMARY

1. Background and motivation

This report presents the findings of research conducted by the CSIR for the WRC to develop a methodology to determine the Sustainable Utilisable Potential (SUP) of South African aquifers. The SUP is defined as the volume of groundwater that can be abstracted on a sustainable basis after the requirements of the **Reserve** have been met. The report provides a summary of the literature survey conducted in the initial phases of this project, it details the methodology developed and a theoretical case study is presented to assist the reader in understanding the methodology. The methodology is then applied to three study areas, (aquifers which have already been modelled and for which extensive data has been captured). Discussion, recommendations and conclusions are drawn. Finally, a glossary of relevant terms is included at the end of the report.

The limited occurrence of surface water resources in South Africa has led to more emphasis being placed on groundwater resources. In addition, the new South African National Water Act (1998) requires that water resources must be quantified per catchment as institutions managing water resources will be organised on a catchment basis. It is envisaged that the methodology proposed in this report will be employed by Catchment Management Agencies (CMAs) and carried out by geohydrological scientists to calculate the SUP of aquifers on a catchment basis. In this project a Geographic Information System (GIS) based methodology has been developed to calculate the SUP of groundwater at a catchment scale and builds on previous work conducted on quantifying South African aquifers.

2. Statement of objectives

The objectives of the research project are summarized as :

- To develop a scientifically sound GIS based methodology for the quantification of the SUP of aquifers.
- To work on data rich areas, with differing aquifer types (e.g. Atlantis, Zeerust and Beaufort West) to calibrate the methodology. A stochastic approach is to be

considered with confidence factors attached to the results. A crucial issue to this project is to establish and document the process.

- If a valid methodology can be developed to determine the SUP of aquifers and it is widely accepted, it will then possibly be extrapolated nationally. Approaches such as the national aquifer classification according to Parsons (1995), the 63 groundwater regions according to Vegter (1996), and a catchment based approach will be considered for this purpose.
- If a scientifically sound approach cannot be developed for quantification of the SUP, a more qualitative approach will be determined.
- The information will be documented in a booklet entitled "A methodology to determine the Sustainable Utilisable Potential of South African aquifers". If the national SUP is calculated, the data sets and results will be displayed as a map and made available in ArcView format.

3. Method and Summary of results

A GIS based methodology to determine the SUP of South African aquifers was developed by the project team. The methodology incorporates contributions from the Water Research Commission (WRC), the Department of Water Affairs and Forestry (DWAF), the CSIR and Groundwater Consulting Services. The methodology was applied to three areas for which there is extensive groundwater data. The three aquifers studied were a sandy porous aquifer (Atlantis), a dolomitic aquifer (Zeerust) and a fractured rock aquifer (Beaufort West). A granitic aquifer (Dendron) was also identified, however after numerous unsuccessful attempts to obtain the data, the area and aquifer type had to be left out of this project.

The key components of the methodology are:

- Physical parameters (e.g. recharge and storage potential of the catchment).
- Anthropogenic and ecological parameters (such as basic human needs, ecological requirements, exclusion and inaccessible zones).
- Cost parameters (such as the number of boreholes, depth to water and water quality considerations).

The resource potential (presented as $m^3/km^2/yr$ or mm/yr), which is only dependent on the physical parameters, is slightly lower than actual measured abstraction for the three case studies. The values, do however, correlate closely to the Groundwater Harvest Potential values (Seymour and Seward, 1997). The utilisable potential is slightly less than the *resource potential as it includes not only physical parameters but also anthropogenic and* ecological requirements. Although many assumptions and simplifications were made, this methodology will assist in assessing groundwater utilisable potential as required by the new National Water Act. It is viewed as a first attempt which will be refined as the quantification of the various parameters improves and as the methodology is tested further.

4. Meeting the objectives

All the objectives of this project were met with the exception of :

- A stochastic approach was not applied as it was decided to keep the suggested methodology as simple as possible. Many of the stochastic techniques use software based routines to determine their solutions. This may be developed at a later stage.
- The methodology was developed for a catchment scale, in line with the new legislative structure, and should not be applied at a national scale. It is envisaged that as the method is applied to catchments across the country, the results will be 'stitched' together to provide a national overview. Once this has been completed, the results will then be available in map and GIS ArcView format.

5. Discussion

The development of this method stems from the need to establish, as far as possible, a scientifically sound and documented process. The method introduces the concepts of anthropogenic, ecological and cost parameters. It is the first method designed to be used at a catchment level and is aligned with the principles of the new National Water Act.

Regarding the GIS methods used to determine the SUP of aquifers, two main fields of existing research were identified, namely: integration of GIS with groundwater models and secondly, work on sustainable potential and harvest potential of aquifers. However, research on the second topic is rather limited.

The project team feels that the use of GIS in calculating the SUP of aquifers is beneficial, as GIS methods allow data to be integrated from various sources, parameters to be varied spatially across the catchment and improved data sets can be incorporated into the GIS as they become available.

The methodology is a tool for integrated catchment management and it is intended that it be used by DWAF and in particular: the Directorate for Community Water Supply and Sanitation (CWSS), CMAs, Water User Agencies and water management consultants, to determine volumes of groundwater that can be used on a sustainable basis.

There are a number of terms used to describe the amount of water an aquifer can yield on a sustainable basis, such as 'safe yield', 'groundwater harvest potential' and 'exploitation potential' (see Appendix B for definitions). The original title of this project used the term 'exploitation potential', however during the course of the project the National Water Act was released and the terminology defined in this Act has been adopted, wherever possible, during this report. The preferred term used for the amount of water available for use in addition to the requirements of basic human needs and the ecology is *utilisable potential*. This methodology aims to derive utilisable potential, which is sustainable in the long term, and takes into account the financial implications of abstracting water, therefore the term Sustainable Utilisable Potential is used. This term is also favoured above exploitation potential which tends to have a negative connotation. It is proposed that this new methodology be termed the SUPAA methodology, i.e. Sustainable Utilisable Potential Application for Aquifers.

6. Limitations of the methodology

There are a number of issues that still have to be carefully addressed, such as the most appropriate scale for quantifying groundwater resources. The present methodology has been applied at a catchment scale. The catchment being defined by a surface water divide which in some instances is not the same as an aquifer boundary.

In many instances values for the physical parameters (e.g. recharge and storage coefficients) assume natural steady state conditions, prior to groundwater abstraction. It may therefore be necessary to re-calibrate the values once abstraction occurs and dynamic equilibrium is reached.

The Reserve, as defined in the National Water Act, is taken into account in the methodology. However, much work is still required for the quantification of The Reserve. A preliminary methodology is available. This will be superceded by the full determination methodology within 3 to 5 years (by 2003).

The cost rating was only calculated in terms of pumping groundwater to surface and ensuring it meets drinking water standards. Costs of piping water to users were not taken into account and these costs also need to be factored into the decision-making process.

Data interpolation has to be carried out with care as groundwater data is typically clustered and unevenly distributed across a catchment. The methodology should also be tested on data poor areas. Various geostatistical methods need to be considered and compared to obtain accurate interpolation results. A stochastic approach to further refine the methodology should also be considered.

7. Conclusions

The development of this methodology was driven by the need to establish a scientifically sound and documented approach to assess the SUP of South Africa's groundwater resources. This methodology was applied on a catchment basis as the new National Water Act stipulates that management of South Africa's total water resources will be carried out on a catchment basis. It is important to note that the methodology is seen as a first attempt to quantify SUP. The methodology has resulted from extensive consultation with groundwater experts throughout the country and this process has highlighted many challenges and uncertainties in trying to quantify a naturally occurring, very complex and highly variable environmental resource. However, the results obtained from the case studies correlate closely to the measured long term abstraction values and DWAF Harvest Potential values.

It is a challenge to quantify groundwater and some major assumptions have been made. It is intended that the methodology be improved in the near future by including the surface water/groundwater interaction and accurately determining the ecological portion of the groundwater Reserve. However the methodology can be used now and will provide results that can be used as a 'first pass' assessment of groundwater resources, including the relative costs of obtaining potable water at surface.

8. Recommendations for future research

Sustainable development of water resources refers to a holistic approach to development, conservation and management of water resources. This approach considers all components of the hydrologic system. The concept is a dynamic one and will be continually refined. Hydrologic systems are fraught with uncertainty, however decisions still have to be made. Good water yield estimates are the result of good monitoring and hydrologic balance calculations, based on the initial amount of water, and all inflows and outflows to the system. These quantities vary with time and location and can only be estimated, and thus may carry significant uncertainty. All sources of uncertainty need to be recognised, and their impact on the variables, such as water yield, need to be evaluated. Because uncertainty and risk are companions, evaluating uncertainty allows the assessment of risks and management of its consequences. Uncertainty needs to be incorporated into the analysis in a quantitative fashion, by means of probabilities. By doing this, decision makers can set policies that meet acceptable levels of risk. By recognising uncertainty we can make the most of the available information, thus leading to better decisions (Sophocleous, 1998).

An investigation should be carried out into what the most appropriate and representative "hydrogeological unit" or scale should be when performing calculations of sustainability. A number of different approaches have been taken for calculation of aquifer "yield" and The Reserve. These should be considered and evaluated through a "workshopping" approach, involving various relevant role players.

The components of The Reserve require improved quantification. Further work needs to be carried out to develop the methodology for determination of the ecological Reserve. The requirements of groundwater supply to aquatic ecosystems (base-flow) and critical terrestrial ecosystems dependant on groundwater (e.g. coastal dune sand vegetation) need to be determined.

An essential consideration in development of an aquifer is the chemical quality of water produced, because the quality of water can limit its use. Groundwater movement induced by pumping may change the groundwater chemistry. Consideration of water quality effects in sustainable yield assessments is an essential part of the evaluation.

The integrated use of GIS and three dimensional numerical models needs to be applied to modelling of the complete hydrogeologic system for a further understanding of groundwater abstraction and surface water or ecological depletion, to provide a predictive tool for assessing sustainable utilisable potential of groundwater.

Ultimately the methodology needs to be applied to the entire country. However as it is based on a catchment scale, the catchments need to be prioritised and a work plan established. Once the methodology has been accurately applied to the catchments for the entire country, the information can be 'stitched' together (pers. comm. Seward, 1997) to form a national map depicting the SUP of South African aquifers.

A decision support system for calculating SUPAA should be enhanced and made user-friendly and widely available. This should be carried out using the worldwide products from ESRI, such as ArcView and customisation can be carried out with the associated programming language Avenue. The dissemination of such information by use of the internet should be considered.

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission entitled:
"AN INVESTIGATION INTO A GIS-BASED METHODOLOGY TO DETERMINE THE SUSTAINABLE EXPLOITABILITY OF SOUTH AFRICAN AQUIFERS"

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

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The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is acknowledged gratefully.

This project was only possible with the co-operation of many individuals and institutions. The authors therefore wish to record their sincere thanks to :

Mike Smart, Jaco Nel, Ernst Bertram and Bill Orpen of Department of Water Affairs and Forestry, for their advice, ideas and data. Alan Woodford (ex-Department of Water Affairs and Forestry) is also thanked for his inputs. A special thank you is extended to Johanita Kotze (Steffen Robertson and Kirsten), Andrew Johnstone and Irene du Toit (Groundwater Consulting Services) and Prof Gerrit van Tonder (Institute for Groundwater Studies - University of the Orange Free State) for their contributions to the project. In addition our colleagues at the Cape Water Programme are thanked for their inputs and discussions during the project. In particular Christine Colvin is thanked for her assistance in compiling and reviewing the report.

Finally the project team would like to thank the Beaufort West Municipality and the Cape Metropolitan Council for their willingness to provide the CSIR with data.

LIST OF ABBREVIATIONS

ACRU	Agricultural Catchment Research Unit
Arc/Info	A GIS developed by Environmental Systems Research
CMA	Catchment Management Agencies
CWSS	Community Water Supply and Sanitation
DRASTIC	A methodology for calculating groundwater vulnerability
DWAF	Department of Water Affairs and Forestry
EC	Electrical Conductivity
EGIS	A Geohydrological Information System
GIS	Geographic Information Systems
GRASS	Geographic Resource Analysis Support System
GRID	A raster based module of Arc/Info
GSIS	Geoscientific Information Systems
HMS	Hydrological Modeling Systems
IDW	Inverse Distance Weighting
NGDB	National Groundwater Data Base
RDP	Reconstruction and Development Programme
SUP	Sustainable Utilisable Potential
SUPAA	Sustainable Utilisable Potential Application for Aquifers
TDS	Total Dissolved Solids
WRC	Water Research Commission

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1. INTRODUCTION

1.1 Motivation

In 1994, the South African government introduced the Reconstruction and Development Programme (RDP) to improve the quality of life for all South Africans. Water supply is an important component of the RDP since one of its objectives is to *ensure all households have a clean, safe water supply of at least 25 litres per capita per day within 200 metres walking distance, and an adequate, safe sanitation facility per site* (DWAF, 1994). Limited surface water resources in South Africa have led to more emphasis being placed on groundwater, necessitating quantification of this resource and improved groundwater management systems. In addition the government has revised the legislation governing water. The new National Water Act requires that resources must be quantified per catchment as institutions managing water resources will be organised on a catchment basis. The motivation for this project was to develop, as far as possible, a scientifically sound and well documented methodology for determining the Sustainable Utilisable Potential (SUP) of an aquifer. This project has incorporated the new philosophy of water management in South Africa, introducing concepts such as The Reserve and groundwater quality considerations. This methodology will hopefully be employed by Catchment Management Agencies (CMAs) and Water User agencies. It is envisaged that consultants will implement the methodology to determine sustainable groundwater abstraction rates.

There are a number of terms used to describe the amount of water an aquifer can yield on a sustainable basis, such as 'safe yield', 'harvest potential' and 'exploitation potential' (see Appendix B). The original title of this project used the term 'exploitation potential', however, during the course of the project the National Water Act was released and the terminology defined in this Act has been adopted during this report. The preferred term used for the amount of water available for use in addition to the requirements of basic human needs and the ecology is *utilisable potential*. This methodology aims to derive utilisable potential which is sustainable in the long term and takes into account the cost implications of abstracting water, therefore the term Sustainable Utilisable Potential is used. This term is also favoured above exploitation potential which tends to have a negative connotation. It is proposed that this new approach be termed the SUPAA methodology, i.e. Sustainable Utilisable Potential Application for Aquifers.

1.2 Approach

The aim of this project is to develop, test and document a scientifically sound, GIS based methodology to quantify groundwater resources.

The key components of the approach are:

- GIS based.
- Catchment scale (where possible quaternary).
- Physical parameters, for example groundwater recharge and storage potential of the catchment.
- Anthropogenic and ecological parameters, such as basic human needs, ecological requirements, exclusion and inaccessible zones.
- Cost parameters, such as the number of boreholes required to abstract a given volume of water, implications of groundwater quality and depth to groundwater.

A GIS based methodology allows data to be integrated from various sources, parameters to be varied spatially across the catchment and improved data sets can be incorporated into the model as they become available. Changes to the methodology can also be relatively easily carried out and evaluated.

This report provides a summary of the literature survey conducted in the initial phases of researching this project. It details the methodology developed. A theoretical case study is then presented to assist the reader in understanding the methodology. The methodology is applied to three aquifers, (which have already been modelled and for which extensive data has been captured) and these case studies include a comparison of the results to measured values. Discussion, recommendations and conclusions are then drawn. Consultations that occurred during the course of the project are listed in Appendix A. Finally, a glossary is included at the end of the report (Appendix B).

1.3 Limits of the Methodology

The limitations of the methodology are listed :

- The methodology is applied at a catchment scale, which is bounded by a surface water divide. In many instances the surface water divide may not be the same as the aquifer boundary.
- Values for physical parameters assume natural steady state conditions, prior to groundwater abstraction. It may therefore be necessary to re-calibrate once abstraction occurs and dynamic equilibrium is reached. New values for recharge and storage coefficients may have to be used.
- Cost implications are only considered in terms of pumping groundwater to surface and ensuring it meets drinking water standards. The costs of piping water to the *consumers is not taken into account.*

2. LITERATURE SURVEY

In order to develop a methodology, it was important in the first instance to conduct a literature survey to assess the current thinking and developments regarding the determination of SUP and to find out what GIS based work has been carried out. From this survey the most recent definition of sustainable yield came from Sharp (1998) who defined *sustainable yield (or utilisable water) of groundwater to be the minimization of potential* negative effects on an aquifer so that it can be utilised at an acceptable range of levels for a very long time period. Negative effects that are associated with over utilisation include: water quality deterioration, ecological requirements not being met, aquifer compaction, and insufficient water being available for basic human needs. Once the sustainable yield of an aquifer has been calculated the *utilisable potential* of an aquifer can be determined by considering the sustainable yield together with the cost implications of abstracting groundwater.

Regarding the GIS methodologies used to determine SUP, two main research fields were identified, namely: *integrating GIS with groundwater models* (Batelaan *et al*, 1993; Deckers, 1993; De Lange and Van Der Meij, 1993 and many others) and secondly, work on *sustainable potential* (Baron *et al*, 1995) and *harvest potential* of aquifers (Seymour and Seward, 1997). However, the research on the second topic appears limited. It is felt by the project team that the use of GIS in calculating SUP is very beneficial, as GIS methods allow data to be integrated from various sources, parameters to be varied spatially across the catchment and improved data sets can be incorporated into the model as they become available. Table 1 is a summary of useful references obtained as a result of the literature survey carried out on the project topic.

Table 1: Summary of the Literature Survey

Research Title	General Comments	Reference
Application of GIS for aquifer vulnerability evaluation	Pollution danger scenarios, identified by integrating georeferenced, geological, hydrogeological and soil use database.	Barrocu and Biallo (1993)
Groundwater exploitation potential using GIS	Main elements considered in such a map are: recharge, storage, transmissivity, quality and cost. Data on the actual groundwater abstraction is also included.	Baron, Seward and Smart (1995)
Development and application of a groundwater model integrated in the GIS GRASS	A regional groundwater flow model has been integrated at different levels in the GIS, GRASS. The model simulates quantitative recharge, discharge and groundwater elevation maps.	Batelaan, De Smedt, Otero Valle and Huybrechts (1993)
Use of volume modelling techniques to estimate agricultural chemical mass in groundwater, Minnesota, USA	Interactive volume modelling software was used to generate three dimensional models depicting the concentration distributions of nitrate and atrazine. Three dimensional grids are used to create display files for model visualization.	Battaglin (1993)
Re-Assessment of sustainable abstraction from groundwater basins of different size in semi-arid and arid areas	The sustainable abstraction from aquifers in semi-arid areas depends on recharge from rainfall and the size of the groundwater reservoir.	Boehmer (1997)
Sustainable groundwater management - A case study from New Zealand	Groundwater quality is identified as the key parameter that will indicate when the aquifer system is under stress and the sustainable management of the resource is threatened.	Brown, Dravid, Hudson and Taylor (1997)

Table 1 continued ....

Research Title	General Comments	Reference
Application of a geographical information system in analysing the occurrence of atrazine in groundwater of the mid-continental United States	Atrazine use estimates were selected to make spatial comparisons with well-specific detections of atrazine in groundwater. These are analysed on two scales, regional and subregional, using polygon coverages derived from classifications of soils and hydrogeological factors.	Burkart and Kolpin (1993)
EGIS, a geohydrological information system	The system contains two subsets: The first is made up of a range of general purpose packages for data presentation and processing, integrated with a database, the second subset extends this environment with a set of advanced geohydrological applications which cover either processing and interpretation of a specific type of data (e.g. pumping test data) or focus on a specific type of analysis (e.g. numerical modelling).	Deckers (1993)
A national groundwater model combined with a GIS for water management in The Netherlands	A national analytic element technique groundwater model was coupled to the national geohydrological database which are both integrated with GIS.	De Lange and Van Der Meij (1993)
Development of a three-dimensional hydrogeological framework model for the Death Valley region, southern Nevada and California, USA	Geoscientific Information System (GSIS) techniques are used for the synthesis of geological, hydrogeological and climate information gathered together from many sources including satellite imagery, published maps and cross sections.	Faunt, D'Agnese and Turner (1993)
Models, GIS and expert systems: integrated water resource models	The integration of water resource management models, geographic information systems, expert systems and interactive graphics are combined as tools for the management of groundwater resources.	Fedra (1993)
Application of GIS in Decision Support Systems for groundwater management	Linked 2D groundwater model to GIS. Disadvantage: GIS is raster based so that a minimum resolution has to be decided on when created. Therefore, if for a given area analysis needs to be done on different scales, the raster images have to have huge dimensions or information might be lost.	Fürst, Girstmair and Nachtnebel (1993)

Table 1 continued ....

Research Title	General Comments	Reference
Development of a water supply protection model in a GIS	Water supply protection model was determined from weighting and rating the following layers: groundwater supply suitability, protection areas for surface water supply, protection areas for major public supply wells, susceptibility to groundwater contamination and recharge.	Griner (1993)
High resolution satellite imagery and GIS as a dynamic tool in groundwater exploration in a semi-arid area	Satellite data integrated with field data and geophysics in GIS are used to facilitate the identification of target areas in groundwater exploration.	Gustafsson (1993)
The importance of GIS in regional geohydrological studies	A methodology is presented for the execution of regional geohydrological studies, with GIS enhancing the processing of data and the visualization thereof.	Hoogendoorn, Van Der Linden and Te Stroet (1993)
Environmental modeling and GIS: dealing with spatial continuity	Linking a GIS to spatially distributed, physically-based environmental models.	Kemp (1993)
Application of a GIS for simulating hydrological responses in developing regions	Data capturing, processing and manipulation as well as the coupling of processes between ARC/INFO GIS, ACRU (agricultural catchment research unit) and HMS (hydrological modeling systems).	Kienzle (1993)
Groundwater system modeling and management using Geoscientific Information Systems (GSIS)	Six procedures are combined using GSIS namely: data preparation, field conceptualization, surface characterization, subsurface characterization, geohydrological system characterization and numerical model simulation.	Kolm and Downey (1993)
Sustainable management of a coastal urban aquifer	Sustainable aquifer management occurs when (1) the rate of aquifer exploitation maintains aquifer storage within pre-specified and adequate levels, (2) ground water quality meets acceptable criteria and (3) negative long term environmental impacts associated with groundwater pumping are avoided.	Loàiciga (1997)

Table 1 continued ....

Research Title	General Comments	Reference
Preparing input data for a national scale groundwater vulnerability map of Southern Africa	The DRASTIC methodology was applied: Depth to groundwater, recharge due to rainfall, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity. GRID was used to rate and weight the factors influencing groundwater.	Lynch, Reynders and Schultze (1994)
Raster based modelling of watersheds and flow accumulation	GIS is used to combine the computation of groundwater capture zones (by means of a numerical groundwater flow model) with a raster based computation of watersheds, flow accumulation and residence time in the unsaturated zone.	Merkel and Sperling (1993)
Comparative study of methods of preparing hydraulic-head surfaces and the introduction of automated hydrogeology - GIS techniques	GIS techniques take into account hydrogeomorphic classification and topographic controls. Advantage: ability to prepare maps with very little data. Incorporated relationships *between:* a reduced water levels and surface topography b groundwater and hydrogeometric units.	Salama, Ye and Broun (1996)
Integration of three-dimensional groundwater modelling techniques with multi-dimensional GIS	GIS was used for the multi-dimensional analysis of spatial and temporal quantification of variables. Merged data displays were then created.	Schenk, Kirk and Poeter (1993)
Sustainable groundwater supplies- an evolving issue: Examples from major carbonate aquifers of Texas, USA	Sustainable use issues include water-budget analyses and the effects of overexploitation-depletion, subsidence, salt-water intrusion, water quality issues, and protection of special environments.	Sharp (1997)
Mapping procedures for assessing groundwater vulnerability to nitrate and *pesticides*	*Mapping procedures are primarily based on an* assessment of the filter capacity of the soil layers covering the aquifer. Groundwater recharge is estimated by a simple storage model.	Sokol, Leibundgut, Schulz and Weinzierl (1993)

The above table is a summary of relevant publications obtained whilst carrying out the literature survey on the project subject. The references were used, some more extensively than others, to help develop the thinking on SUP of groundwater.

3. METHODOLOGY

3.1 Approach and data requirements

A GIS based methodology to determine the SUP of South African aquifers was developed by the project team. The methodology incorporates contributions from many geohydrologists and other scientists (refer to Appendix A). In addition, it not only builds on previous work conducted on quantifying South African aquifers (Baron *et al*, 1995; Vegter, 1995; Seymour and Seward, 1997) but also introduces the concept of anthropogenic, ecological and cost parameters. It is the first method designed to be used on a catchment basis and is aligned with the principles of the new National Water Act (1998) in that it incorporates the concept of The Reserve. Figure 1 shows a schematic representation of The Reserve as it is applied to all water resources. The Reserve concept has been established so that:

a. basic human needs for all people who are, or who may be, supplied from the relevant resource are satisfied;
b. the aquatic ecosystems are protected in order to secure ecological sustainability; and
c. once the above two needs are met, the use of the relevant water resource is allowed.

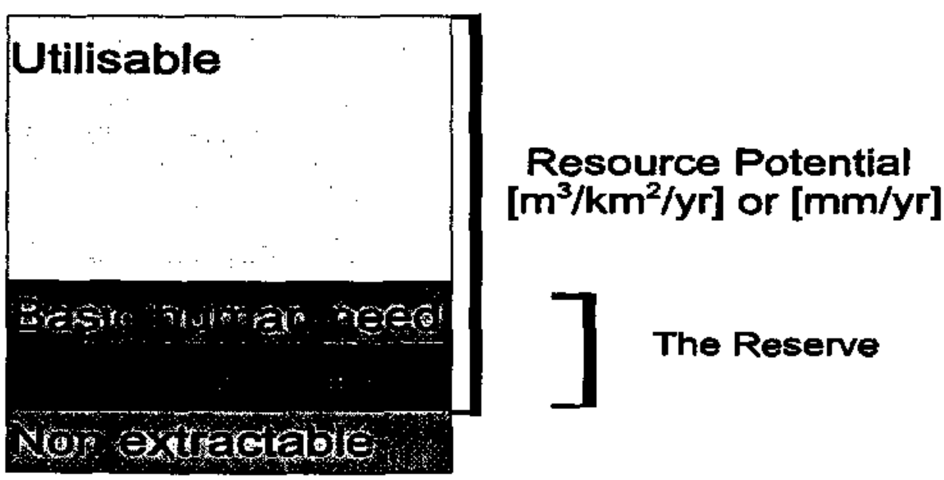


Figure 1: Allocation of water resources (modified from DWAF, 1996)

The main focus of this study was on the utilisable portion of the Reserve (Figure 1). In order to calculate this utilisable portion the volumes required for basic human and ecological needs were considered, however in a simple and lumped manner. A Rapid Reserve Assessment methodology is currently being developed (Parsons, 1998). The non extractable portion was not considered. The utilisable potential and components thereof are a volume of water that is expressed in $[L^3/L^2/T]$ or $m^3/km^2/yr$. These units can also easily be converted to [L/T] or mm/yr. A cost rating overlay is added to the utilisable water to give a qualitative indication of the relative costs involved in abstracting groundwater.

Institutions managing water resources will be organised on a *catchment* basis therefore it is appropriate that methodologies for groundwater management are developed at this scale. This methodology will hopefully be employed by CMAs. It is envisaged that hydrogeological consultants will implement the methodology therefore it is aimed at that level.

According to the methodology there are three parameter groups that influence SUP. They are physical parameters, anthropogenic and ecological parameters and lastly cost parameters. Figure 2 is a flow chart indicating how the various parameters fit together to determine the utilisable potential of the aquifer on a catchment basis.

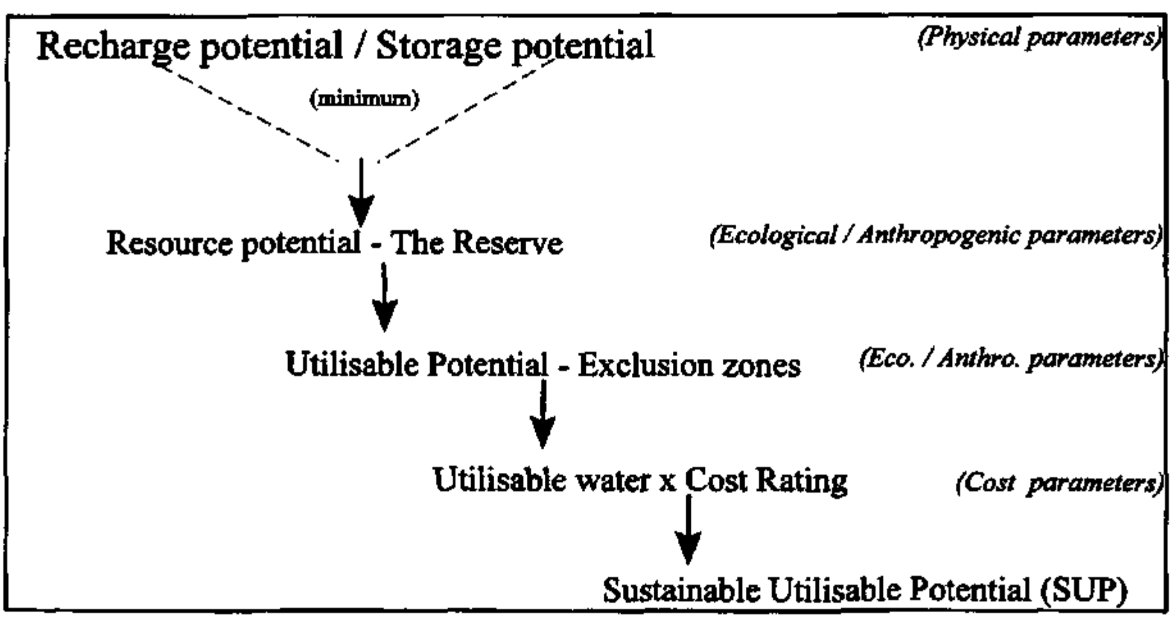


Figure 2: Flow chart of parameters influencing utilisable water

Physical Parameters

There are two key physical factors namely: recharge potential and storage potential. These two values are used to determine the *resource potential* (as shown in Figure 3) of the aquifer. This value is expressed in $m^3/km^2/yr$ (and can be easily converted to mm/yr).

Recharge Potential

Recharge potential refers to the amount of water that enters the aquifer per unit time. The recharge potential includes recharge from precipitation and surface water bodies (such as rivers and ponds). In addition artificial recharge is also taken into account. Factors that can be taken into account when calculating recharge potential are: slope, land cover, infiltration capacity, rainfall, surface water bodies, percentage recharge and injection rates.

Storage Potential

Storage potential is the product of the storage coefficient, the saturated thickness of the aquifer and the area of the aquifer. It is assumed that this volume can be abstracted over a year.

The lesser of the storage potential and recharge potential is then taken as the resource potential. Figure 3 is a schematic representation of the calculation for the resource potential. For drought scenarios, the resource potential is not going to be sufficient for ecological factors and basic human needs, it may therefore be necessary to supplement this volume with a percentage of the storage potential.

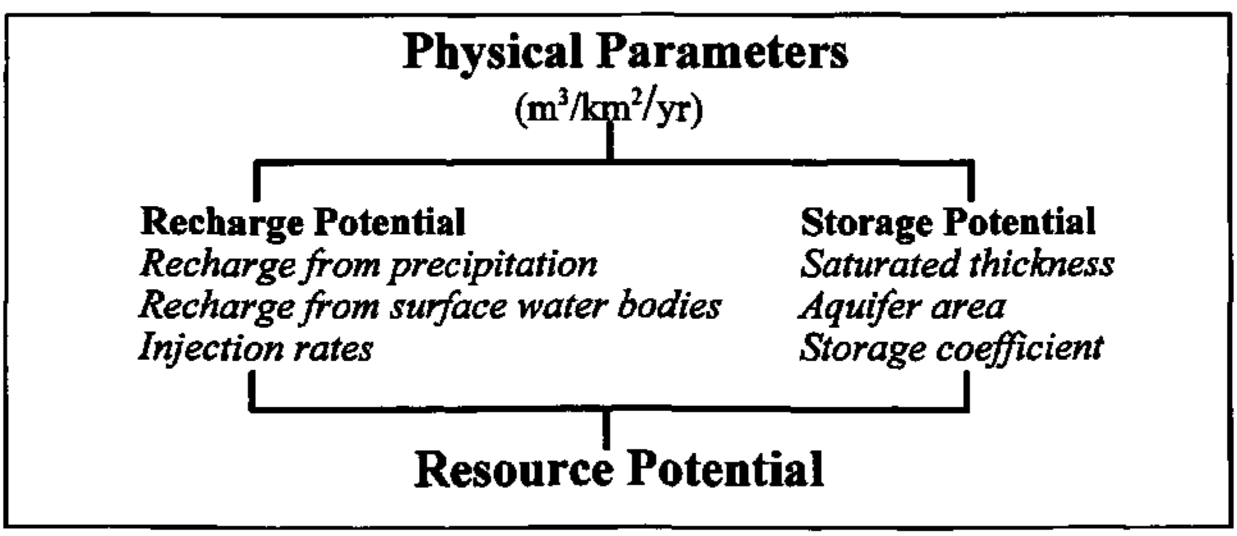


Figure 3: Flow chart of the main factors influencing resource potential

Confidence factors should be attached to all data sets to give the user an indication of how accurate the results are going to be. Table 2 is a suggested simplistic confidence rating.

Table 2: Confidence Ratings according to the source of the data

Data Source	Confidence Rating
Field data and numerical modelling data	High (3)
NGDB, Maps, Interpolated field and modelling data	Medium (2)
Theoretical values, Interpolated NGDB and map data	Low (1)

Each input data set should be rated according to Table 2. To determine the confidence of say for example storage potential, you rate each one of the initial data sets: saturated thickness = 3, aquifer area = 1, storage coefficient = 2. Add all these values and divided by the number of data sets: (3 + 1 + 2)/3 = 2. Therefore the confidence in storage potential will be 2 or medium. Similarly the confidence for recharge potential can be calculated.

Anthropogenic and Ecological Parameters

A certain volume of water is then deducted for ecological requirements from the resource potential. The volume of water will depend on the ecology of the catchment. There is currently work in progress aimed at the improved quantification of this volume. If the water resource is intended for basic human needs, then a further amount is deducted from the resource potential. If the volume of water is not intended for basic human needs as there are other sources such as surface water bodies for this purpose, then no groundwater should be set aside. If, however, the community is dependent on groundwater for basic human needs, then the volume of water for this purpose must be calculated. This can be done by multiplying the number of people in a catchment by 25 litres and by 365 days. Two approaches can now be followed: (1) the volume for basic human needs can be subtracted from the resource potential and a cost rating for both the utilisable water (Figure 4) and the basic human needs can be calculated separately or (2) the water for basic human needs can be lumped with utilisable water and the cost rating can be calculated for the total volume.

In addition, areas where it is potentially hazardous to abstract groundwater are also identified. It is assumed that no water can be abstracted from these areas and they are considered exclusion zones. Exclusion zones include waste sites, coastal zones (as sea water intrusion may occur due to abstraction of groundwater in this zone), mines and quarries. These features are considered exclusion zones as they all have the potential for negatively impacting groundwater quality. In addition, surface water bodies and wetlands are also considered exclusion zones. This is to ensure that groundwater is not considered for abstraction in close proximity to these features, as it is quite likely that groundwater contributes toward the existence of these features. All these exclusion zones are buffered by one kilometre as a conservative measure so as to ensure that they are taken into account. The volume of water that remains once all these factors have been taken into account is known as the *utilisable water* (refer to Figure 4) for that specific catchment. Inaccessible zones, where abstraction cannot take place are also flagged. Examples of these zones are shifting sand dunes and slopes steeper than 15°, which would usually prevent access to drilling sites. These inaccessible zones do not have any impact on the groundwater volumes.

Anthropogenic & Ecological Parameters
($m^3/km^2/yr$)

|

Resource potential - (ecological volume + exclusion volume + basic human needs)

|

Utilisable water + basic human needs

Depending on whether the abstracted water is needed for basic human needs

Figure 4: Calculations to determine utilisable water

The amount of water needed for basic human needs can be determined relatively accurately so no confidence rating is calculated. The ecological reserve is unknown at this point in time and it is therefore impossible to work out a confidence rating.

Cost Parameters
Three factors are considered important when determining the relative qualitative cost of abstracting groundwater:

1. The number of boreholes required, as the more boreholes needed to abstract groundwater the greater the cost. Depending on whether the water is going to be used for basic human needs, the number of boreholes is calculated as follows :

$$\text{No of boreholes} = \frac{\text{Utilisable water + (water for basic human needs)}}{\text{Average groundwater yield per square area of aquifer}}$$

2. Water quality is considered in terms of capital or establishment costs (for example construction of a water treatment plant) and running or operational costs (which include the day to day expenses in running a plant). All water quality data for the area should be considered and if necessary taken into account. However there are four key factors that effect water quality that must be taken into consideration: faecal coliforms, electrical conductivity, fluoride and nitrate concentrations. In addition water quality is also rated according to its use. In other words it can be rated according to whether it is to be used for domestic, industrial, or agricultural purposes.

3. Depth to groundwater is also considered, as the deeper the water the more energy is required to bring it to surface.

A rating process is then used for each of the above mentioned factors. The number of boreholes, water quality and depth to groundwater is rated on a scale from one to ten. The higher the rating the more expensive it is to abstract groundwater. **Capital costs** are then determined by adding the rating for the number of boreholes and the rating for water quality and dividing by two to get a value between one and ten. Similarly the **running costs** are determined by adding the depth to water level ratings and the running cost rating for water quality together and dividing by two. The capital costs and running costs ratings are then added together and divided by two. The value obtained then is the **cost rating** of abstraction per unit area. The cost rating is a number from one to ten. The higher the number the greater the relative cost to abstract groundwater.

The rating values given to the various factors contributing to the calculation of the cost rating are documented in Table 3.

Table 3: Ratings for number of boreholes and depth to groundwater

Rating	1	5	10
Number of boreholes (per km^2)	0 - 1	1 - 2	> 2
Depth to water (m)	0 - 50	50 - 100	> 100

It is important to note that cost rating *gives a qualitative indication of the cost of having groundwater at surface that meets the drinking water standards.* The above rating process can also be applied to other water standards, such as for industrial use and agricultural use, (irrigation and livestock water). This would involve classifying the water classes into similar groupings, such as optimal, marginal and exceeding of limits and then applying similar ratings. In essence just minor adaptations would be required to Table 4 and the same methodology could be applied.

Table 4: Ratings for groundwater quality

Rating	1	5	10
Drinking water standards	Optimal	Marginal	Exceeding Limit
Faecal coliforms (per 100 mL)	0	1	> 1
Electrical conductivity (mS/m)	0 - 370	370 - 600	> 600
Flouride (mg/L)	0 - 1.5	1.5 - 4	> 4
Nitrates (mg/L)	0 - 10	10 - 50	> 50

Figure 5 is a schematic representation of the process followed to calculate the cost rating. The cost parameters are already rated qualitatively and therefore it is not necessary to work out an additional confidence rating.

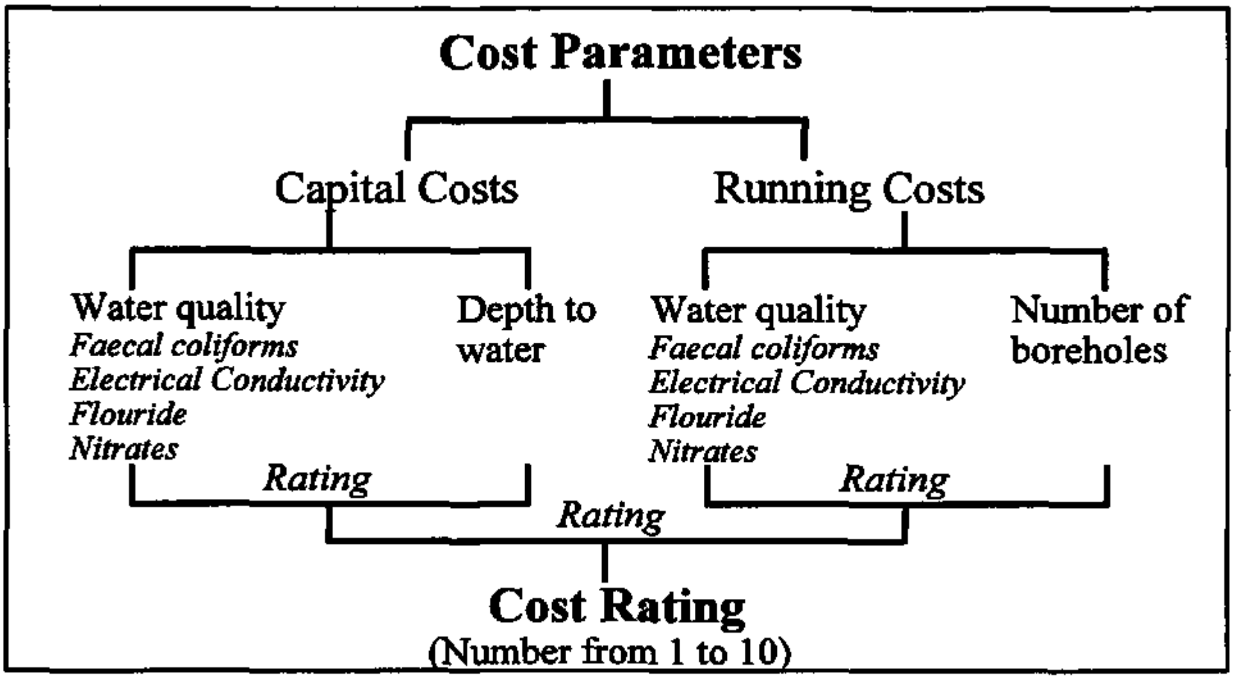


Figure 5: Flow chart depicting the calculation of the cost rating

3.2 Processing methods

The actual data processing for this project was carried using the GIS, Arc/Info and its GRID module. A cell size of 1 km by 1 km was used. This cell size can be varied and should be done so in accordance with the scale of input data sets. The total utilisable potential for the catchment can be calculated by summation of the individual cell values for the catchment.

The Inverse Distance Weighting (IDW) algorithim within the GRID module was the geostatistical technique used to interpolate point data sets. The reasons for choosing this method above kriging and bayesian approaches are as follows:

- Spatial variation is assumed to be the major source of uncertainty and
- Future modelling can be carried out in either ArcView (with Spatial Analyst) or Arc/Info.

4. METHODOLOGY : STEP-BY-STEP

Before commencing with actual case studies step by step instructions of how to implement the methodology are discussed together with a detailed hypothetical case study to provide the reader with a clear understanding of the methodology. Each step contains a set of instructions followed by notes on how they are applied in the hypothetical example. No confidence rating was calculated for this example because hypothetical data sets were used.

4.1 Step 1 - Collection and interpolation of data

- Select the quaternary catchment and collect all relevant data. Table 5 is a check list of all the data required and possible data sources.
- Decide why the water is needed. Is it needed for drinking water, agricultural or industry purposes?
- Generate a spatial data base within GIS and interpolate all data sets over the whole of the catchment. Divide the catchment into kilometre by kilometre cells (this may vary depending on the accuracy of the input data sets).

Table 5: Data check list

Essential data is indicated with a ✓

Data required		Possible source	Min
Quaternary catchment outline	Location of catchment boundaries	WR90	✓
Physical Parameters			
Recharge Potential	Rainfall	WR90	✓
	Slope	Surveyor-General	
	Geology	Council for Geoscience	✓
	Land cover	CSIR - ARC	
	Methods to calculate recharge from precipitation:	Bredenkamp *et al* (1995) Kirchner *et al* (1991) Murray (1996) Vegter (1995) Water Research Commission (1990)	
	Surface water bodies		
	infiltration rates	Field data - reports	
	Artificial recharge		
	infiltration rates from infiltration ponds	Field data - reports	
	injection rates	Field data - reports	

Data required		Possible source	Min
Storage Potential	Saturated thickness		
	Bedrock map	Council for Geoscience	✓
	Water levels	National Groundwater Data Base (NGDB)	✓
	Aquifer area	Field studies - reports	✓
	Storage coefficient		
	geology	Council for Geoscience	✓
Anthropogenic and Ecological Parameters	Land use / Land cover (vegetation types)	CSIR - ARC	
	Population distribution	Human Sciences Research Council (HSRC)	
	Number of people requiring 25 L per day	DWAF (CWSS)	
Exclusion (E) and inaccessible(I) zones	Position of coast (E)	Surveyor-General	✓
	Location of wetlands and water bodies (E)	CSIR - ARC	
	Location of mines, quarries and waste sites (E)	DWAF, CSIR - ARC DWAF,, Surveyor-General	
	Location of special aquifers, shifting dunes (I) and slopes > 15° (I)	Surveyor-General	
Cost Parameters			
Capital Costs	Number of boreholes		
	Water levels	Field data, NGDB	✓
	Water quality		
	Faecal coliforms	Field data, NGDB	
	Electrical Conductivity	Field data, NGDB	✓
	Fluoride	Field data, NGDB	
	Nitrates	Field data, NGDB	
Running Costs	Depth to water	DWAF - reports	✓
	Water quality		
	Faecal coliforms	Field data, NGDB	
	Electrical Conductivity	Field data, NGDB	✓
	Fluoride	Field data, NGDB	
	Nitrates	Field data, NGDB	

Catchment A

Figure 6.1 is a sketch of catchment A. Water is needed for basic human needs and farmers to irrigate their crops. The quaternary catchment is divided into 1 km by 1 km cells as shown in Figure 6.2. All data sets are then interpolated over the whole catchment area (Figure 6.3 (A - J)).

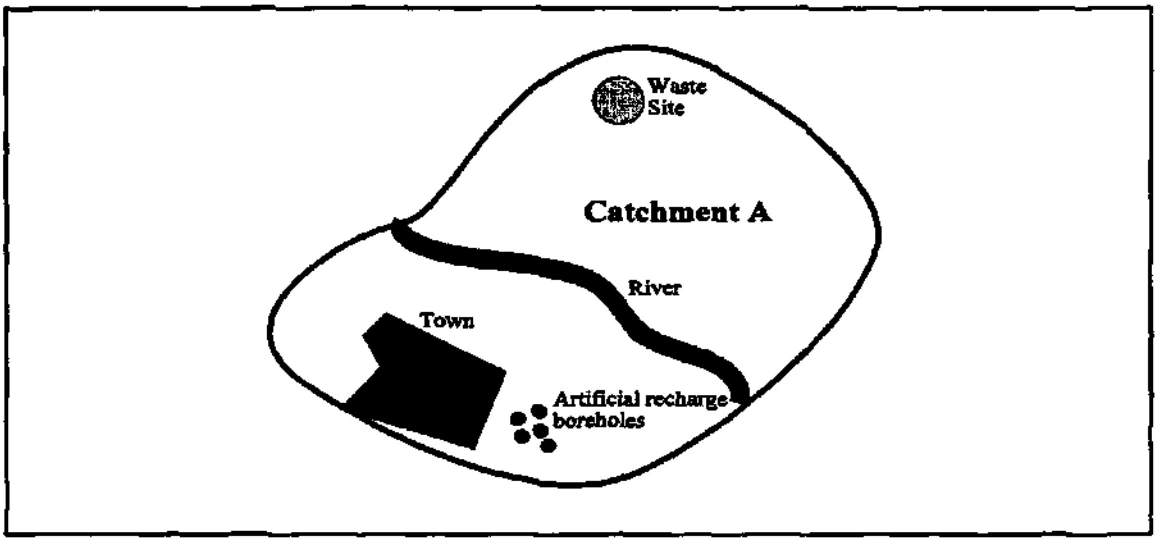


Figure 6.1: Hypothetical quaternary catchment A

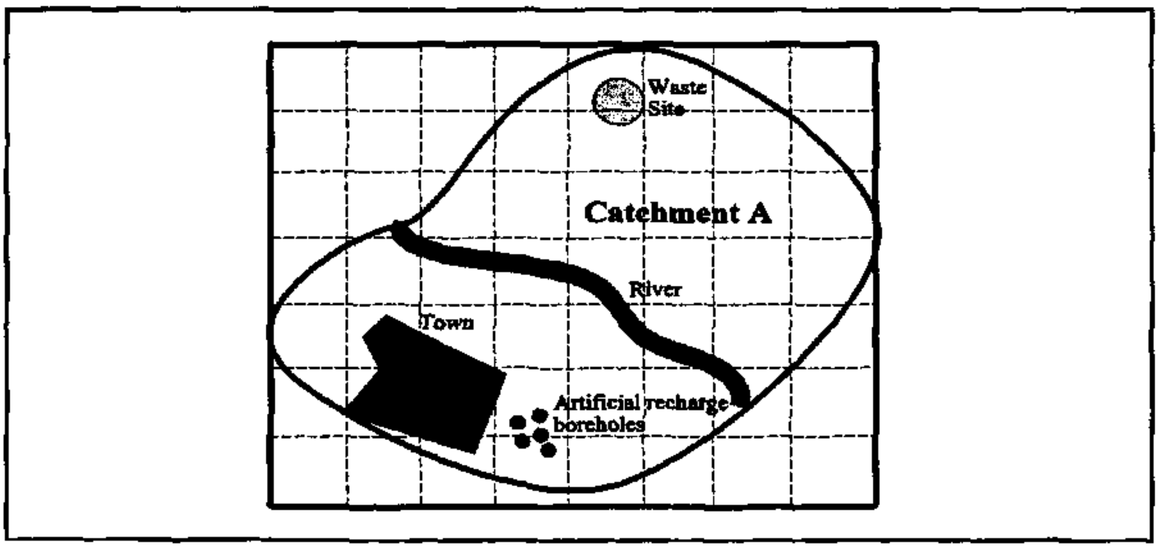
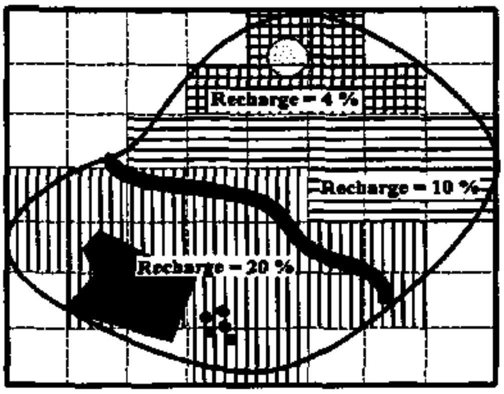
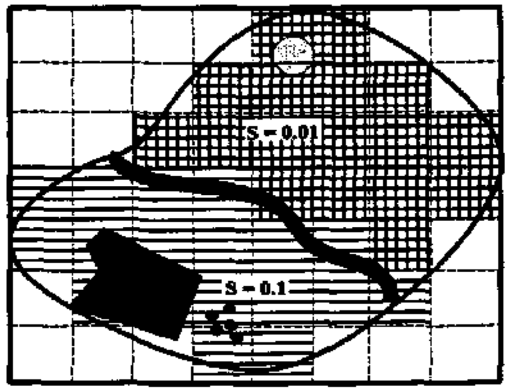


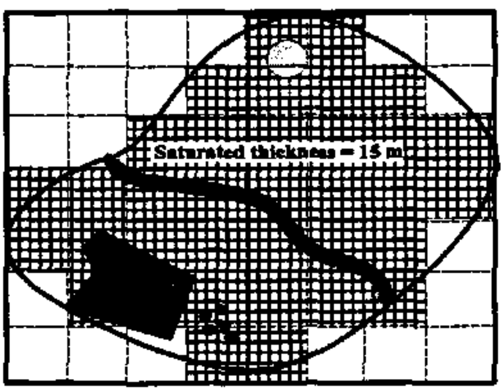
Figure 6.2: Square kilometre grid over catchment A



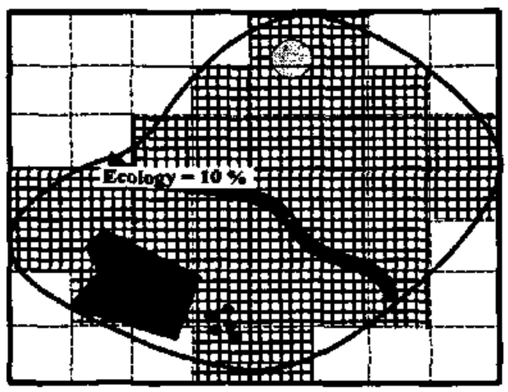
6.3A Percentage of precipitation recharging into the aquifer



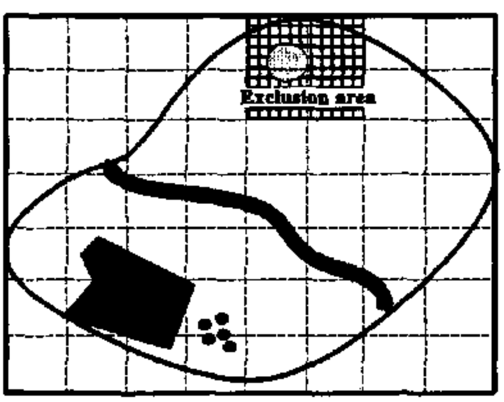
6.3B Storage coefficient



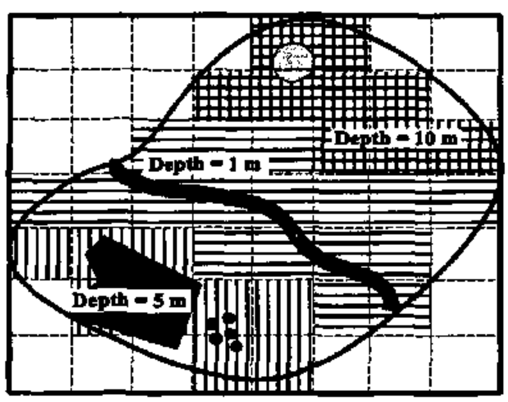
6.3C Saturated thickness



6.3D Ecological factors

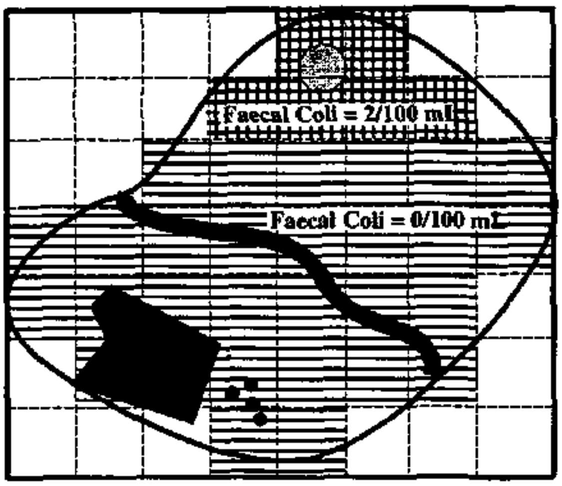


6.3E Exclusion areas

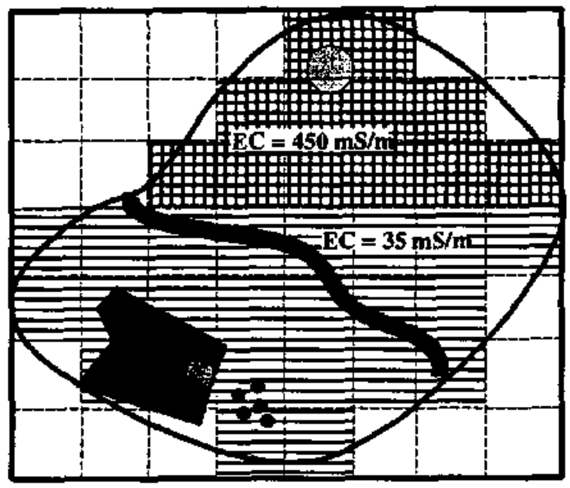


6.3F Depth to water

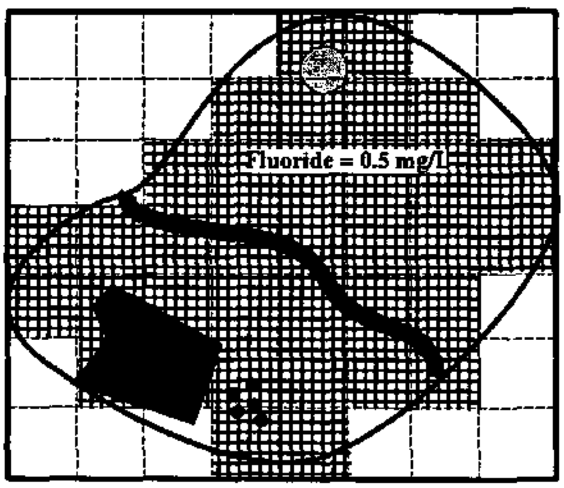
Figure 6.3: Interpolation of data sets



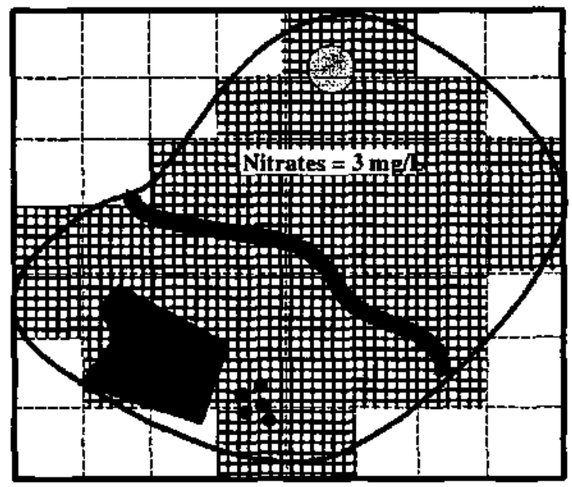
6.3G Faecal Coliforms



6.3H Electrical Conductivity



6.3I Flouride



6.3J Nitrates

Figure 6.3 (continued)

4.2 Step 2 - Physical Parameters

- Calculate the total amount of water entering the aquifer from surface water bodies, natural and artificial recharge (recharge potential).

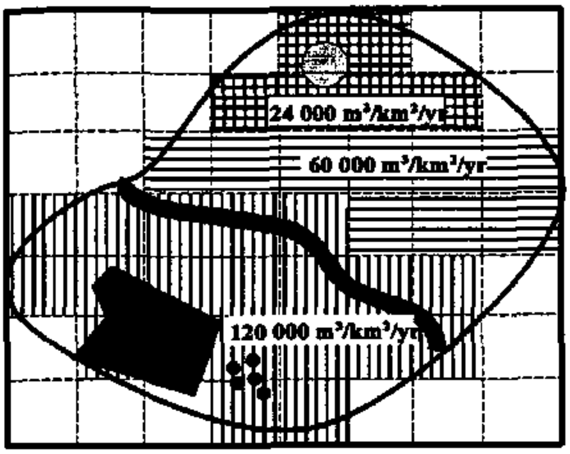
- Calculate the amount of water that the aquifer can store (storage potential) by multiplying the saturated thickness of the aquifer by cell area and by the storage coefficient.

- Compare the recharge potential and storage potential for each cell. The lesser of the two values will be the resource potential.

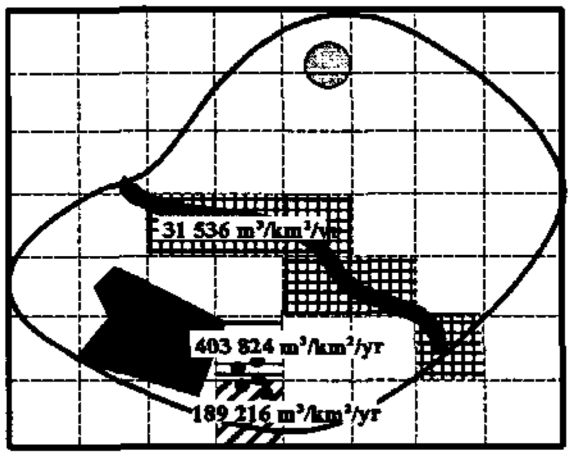
Catchment A

The mean annual rainfall for catchment A is 600 mm/yr. The aquifer is a porous aquifer. The percentage recharge varies across the catchment (Figure 6.3(A)). Figure 6.4(A) is the amount of water that is recharged into the aquifer as a result of precipitation. The amount of water infiltrating the aquifer along river is 1 L/s/km. There are five artificial recharge boreholes each injecting 3 L/s. Figure 6.4(B) is the sum of water recharging the aquifer from the river and artificial boreholes. The recharge potential (Figure 6.4(C)) is the sum of the recharge from precipitation, surface water bodies and the injection boreholes.

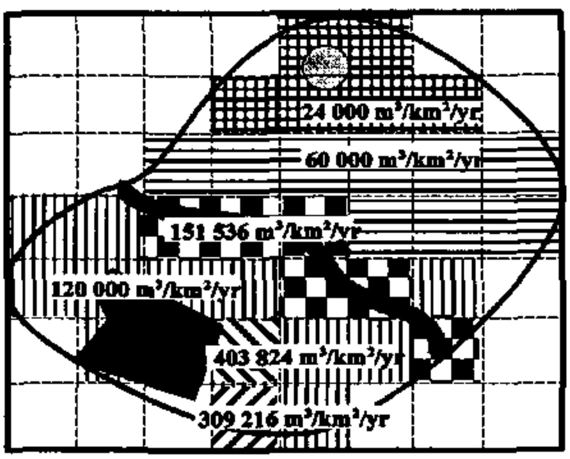
The storage potential (Figure 6.4(D)) of the aquifer is calculated by multiplying the storage coefficient (Figure 6.3(B)) with the saturated thickness (Figure 6.3(C))per square kilometre. The recharge potential is the limiting factor and is therefore taken as the *resource potential*.



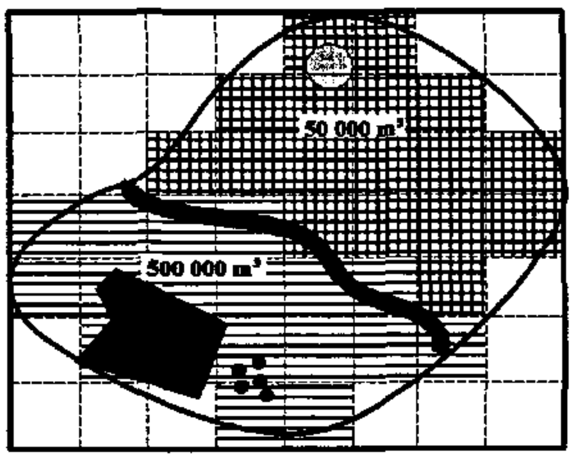
6.4A Recharge from precipitation



6.4B Recharge from surface water bodies and injection boreholes



6.4C Total Recharge Potential



6.4D Storage Potential

Figure 6.4: Recharge and storage potential

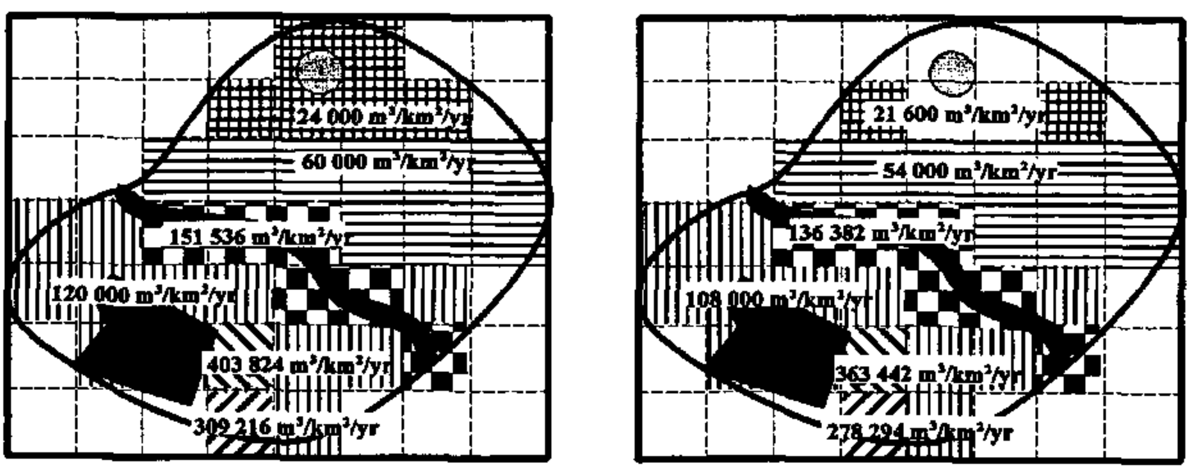
4.3 Step 3 - Anthropogenic and Ecological Parameters

- *Deduct the volume of water required to sustain ecological systems.*
- A certain volume of water should always be allocated for basic human needs even if there are surface water resources. In such a situation this allocated amount is seen as being a reserve during periods of drought or when there may be problems with the surface water supply. The amount of water kept for basic human needs can be estimated by multiplying the number of people per square kilometre by 25 L/day.
- Identify exclusion zones and buffer them by a kilometre. These exclusions zones are considered to have no abstractable water. The volume of water that remains once all these factors have been taken into account is known as the utilisable water for that specific catchment.
- Demarcate inaccessible zones.

Catchment A

Figure 6.5(A) is the resource potential for catchment A. There is very little groundwater dependent ecological activity in the catchment, therefore only 10% of the resource potential is deducted for these activities (Figure 6.5(B)). The groundwater resource is going to be used for basic human needs as well as agricultural activities, therefore the volume of water has to be subtracted for basic human needs. There is however a waste site (Figure 6.3(E)) that needs to be buffered and the volume of water from the area surrounding the waste site must be subtracted from the total volume. The amount of water remaining is the utilisable water together with the water for basic human needs.

There are no inaccessible zones.



6.5A Resource Potential

6.5B Resource Potential - volume of water for ecological requirements

Figure 6.5: Determination of utilisable water

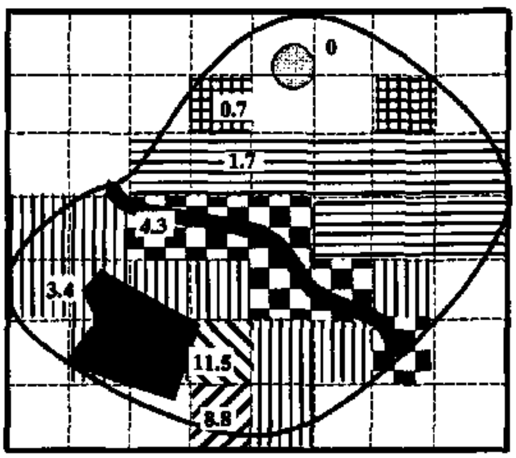
4.4 Step 4 - Cost Rating

- Calculate the number of boreholes needed to abstract groundwater by dividing the utilisable volume by an estimate of the aquifer's yield.
- Rate the number of boreholes according to Table 3.
- Rate faecal coliforms, electrical conductivity, fluoride and nitrates according to Table 4.
- Add the ratings of faecal coliforms, electrical conductivity, fluoride and nitrates together and divide by four to get the water quality rating.
- Rate the depth to water according to Table 3.
- Calculate the capital cost rating by adding the number of boreholes rating and water quality rating and dividing by two.
- Calculate the running costs rating by adding the water quality rating and depth to water rating and dividing by two.
- Calculate the cost rating by adding the capital cost rating and running rating and dividing by two.

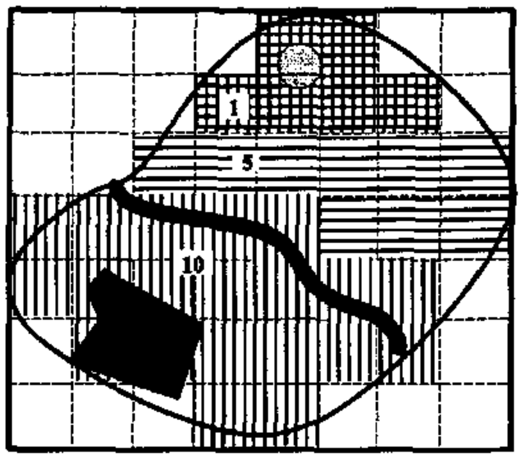
Catchment A

The number of boreholes needed to abstract the groundwater is shown in Figure 6.6(A). The rating for number of boreholes is according to Table 3 and is shown in Figure 6.6(B). Figure 6.6((C) - (F)) show the ratings for faecal coliforms, electrical conductivity, fluoride and nitrates. These ratings are added together for each cell and divided by four to determine the water quality rating Figure 6.6(G). The depth to water is then rated (Figure 6.6(H)).

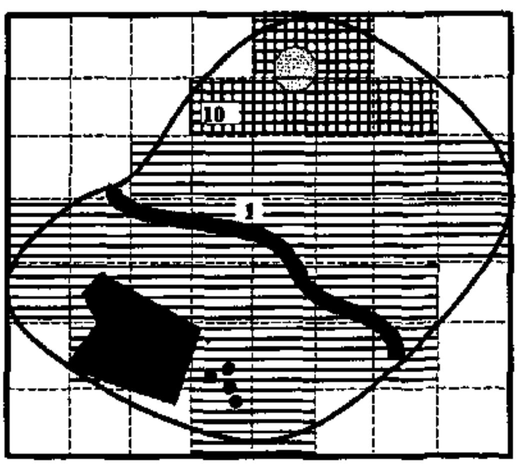
The capital costs rating (Figure 6.7(A)) is then calculated by adding the number of boreholes rating and the water quality rating and dividing by two. The high electrical conductivity and faecal coliforms values result in high capital costs in the vicinity of the waste site. The capital costs are strongly influenced by the rating for the number of boreholes in the vicinity of the town. Similarly ratings for the running costs, shown in Figures 6.7(B) are obtained by adding the water quality rating and depth to water rating and dividing by two. The running cost ratings are influenced only by water quality (faecal coliforms and electrical conductivity). The depth to water ratings are low. The final cost rating (Figure 6.7(C)) is a combination of the capital and running costs rating. The number of boreholes causes high values in the vicinity of the town.



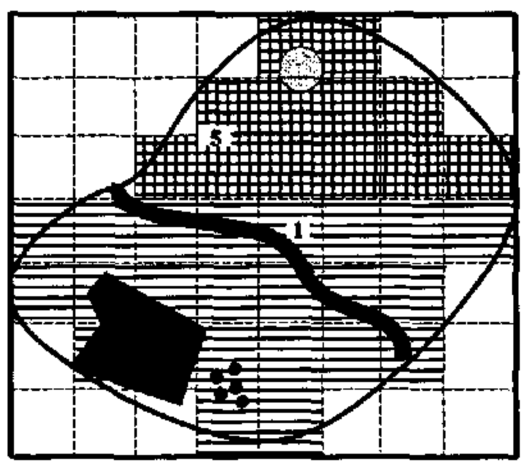
6.6A Number of boreholes



6.6B Rating for number of boreholes

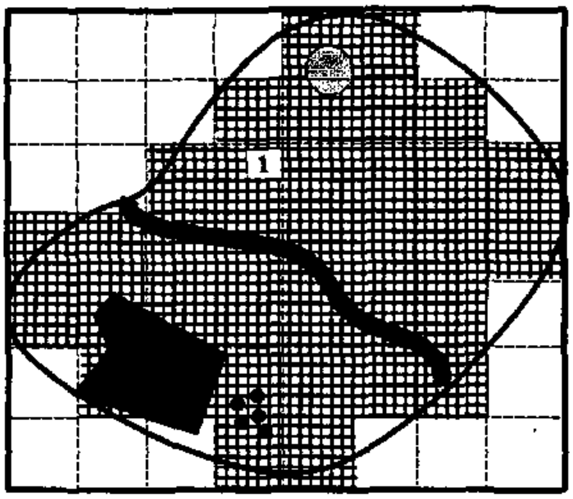


6.6C Rating for Faecal Coliform

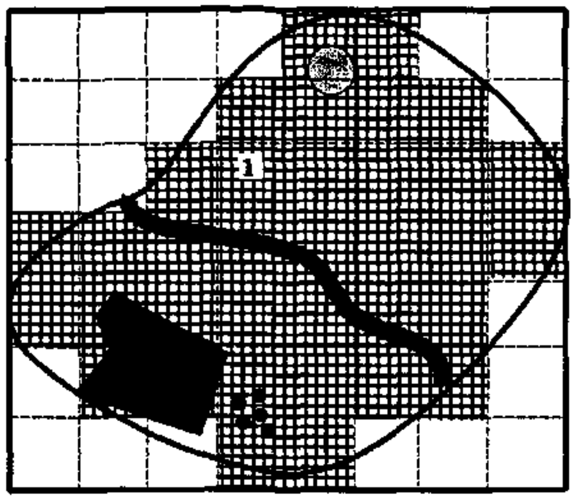


6.6D Rating for Electrical Conductivity

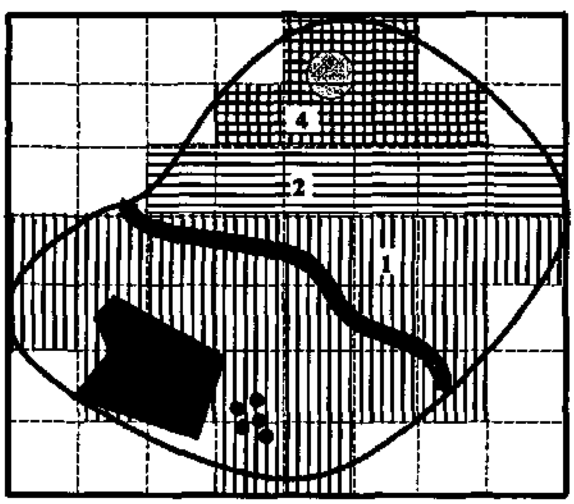
Figure 6.6: Determination of the number of boreholes, water quality and groundwater depth ratings



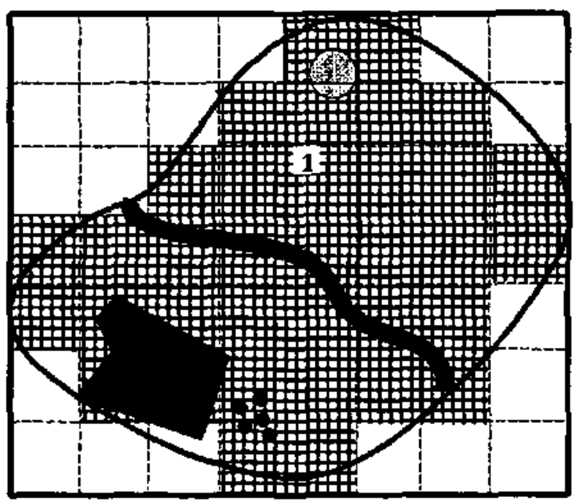
6.6E Rating for Flouride



6.6F Rating for Nitrates

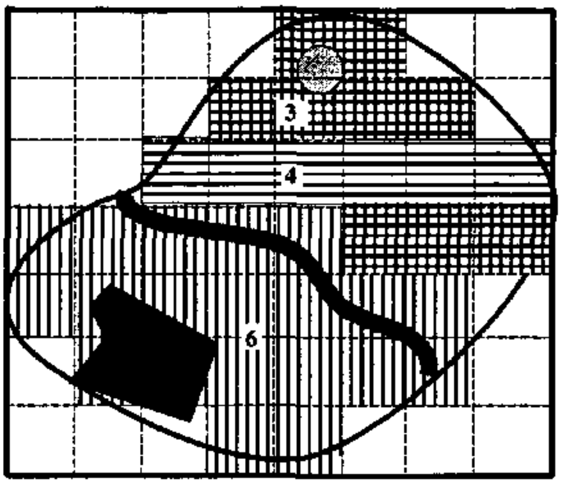


6.6G Rating for water quality

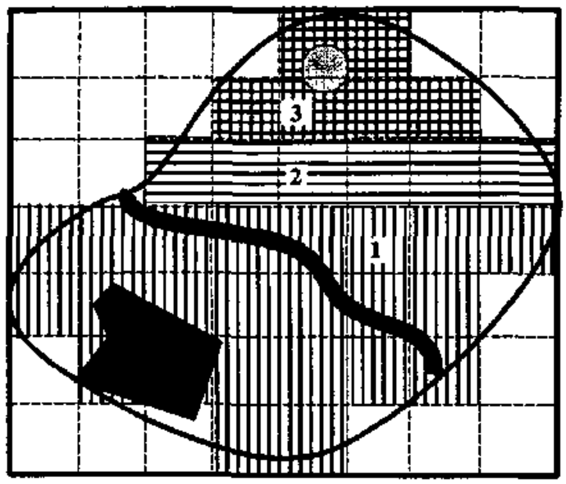


6.6H Rating for depth to water

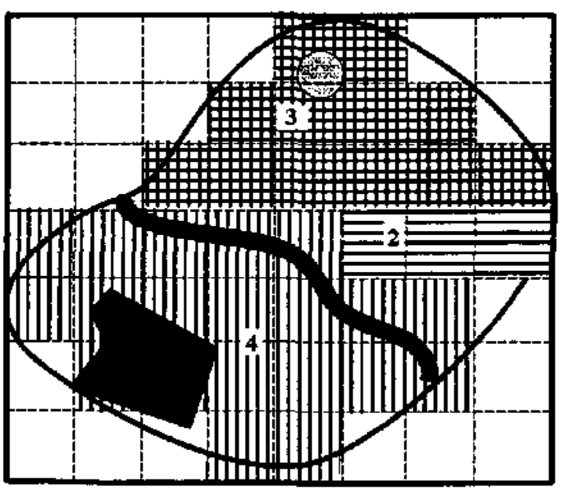
Figure 6.6 (continued)



6.7A Rating for Capital Costs



6.7B Rating for Running Costs



6.7C Cost Rating

Figure 6.7: Determination of the cost rating

5. CASE STUDIES

5.1 Atlantis

Atlantis is an industrial town 50 km north of Cape Town with a population of approximately 73 000 people. The industrial sector is made up of approximately 140 factories which require in excess of 5.5 x 10^6 m^3 of water each year. The town's population and industry is currently entirely dependent on groundwater. Unconsolidated Cenozoic sediments overlying the Malmesbury Group shales form the primary coastal aquifer. The water bearing units consist of two stratigraphic formations in a succession of permeable quartz sand. The lower Varswater formation is of shallow marine origin and the upper Bredasdorp Formation is of aeolian origin.

The data check list for Atlantis is summarised in Table 6. Figure 7.1 shows the quaternary catchment for the Atlantis area. The town and present wellfields are also shown. Atlantis has been using groundwater for many years and dynamic equilibrium has been reached. The aquifers supplying Atlantis are well understood and an extensive groundwater and monitoring data base exists. Recharge is the limiting factor for the catchment and is therefore taken as the resource potential. Figure 7.1 indicates the utilisable water volumes (resource potential minus basic human needs, ecological requirements and exclusion zones) for the catchment. Bedrock highs are responsible for the resource potential being zero at certain places. The volume of water for basic human needs and the ecology was estimated to be 25% of the resource potential. The exclusion zones are the coastline and the waste site which have both been buffered by one kilometre. The most utilisable water is in the area of the dunes where recharge values are approximately 40% of the annual rainfall and the artificial recharge basins.

Table 6: Data check list for Atlantis

Data needed		Source
Quaternary catchment outline		WR90
Physical Parameters Recharge Potential	Rainfall Recharge from precipitation Artificial recharge infiltration rates from seepage ponds	Field data Numerical groundwater flow model Land cover (CSIR) Numerical groundwater flow model
Storage Potential	Saturated thickness Bedrock map Water levels Aquifer area Storage coefficient	Field Data: Geological Survey of South Africa (RSA 1: 1 000 000 geological GIS data, 1984) Field data Cell size Numerical groundwater flow model
Anthropogenic and Ecological Parameters	Land use / Land cover Population distribution Number of people	CSIR Consulting engineers reports Consulting engineers reports
Cost Parameters Capital Costs Running Costs	Number of boreholes Water quality Faecal coliforms Electrical Conductivity Fluoride Nitrates Depth to water Water levels Water quality Faecal coliforms Electrical Conductivity Fluoride Nitrates	Field data - Field data Field data Field data Field data - Field data Field data Field data

The inaccessible zones are included in Figure 7.1. These zones depict areas where drilling is almost or totally impossible. The shifting sand dunes and Koeberg Power Station have been demarcated as inaccessible zones.

Figure 7.2 shows the ratings of the individual water quality parameters and then the final water quality rating. Figure 7.2 depicts the ratings of the factors influencing the capital costs and the capital cost rating. The number of boreholes needed to abstract water is large in the dune area and where artificial recharge takes place, therefore the capital costs in these areas are high. Similarly the running cost ratings are shown in Figure 7.3. The high electrical conductivity values in the south are responsible for the high cost of groundwater, as water treatment would be required. In the north and south west the water table is deep, therefore large quantities of energy are necessary to pump the groundwater to the surface. The combination of the capital and running costs determines the cost rating (Figure 7.4). The results from the application of this methodology were measured by comparing the GIS based results to actual measured groundwater abstraction volumes from the Atlantis aquifer. The results obtained are slightly lower than those measured but are generally in the same order of magnitude. When comparing the resource potential, which varies between 0 and 197 200 $m^3/km^2/yr$ (or between 0 and 197.2 mm/yr) and the harvest potential (Seymour and Seward, 1997) whose values range from 50 000 to 10 0000 $m^3/km^2/yr$ (or from 50 to 100 mm/yr), the upper limit of the SUP values exceeds the maximum harvest potential.

As already mentioned the recharge is the limiting factor and therefore it becomes the resource potential. Table 7 is a confidence rating for the resource potential and shows that the confidence rating is high.

Table 7: Confidence rating for Atlantis

Parameter	**Confidence Rating**
Rainfall	High (3)
Recharge from precipitation	High (3)
Artificial recharge	High (3)
TOTAL (sum of ratings/no. of parameters)	High (3)

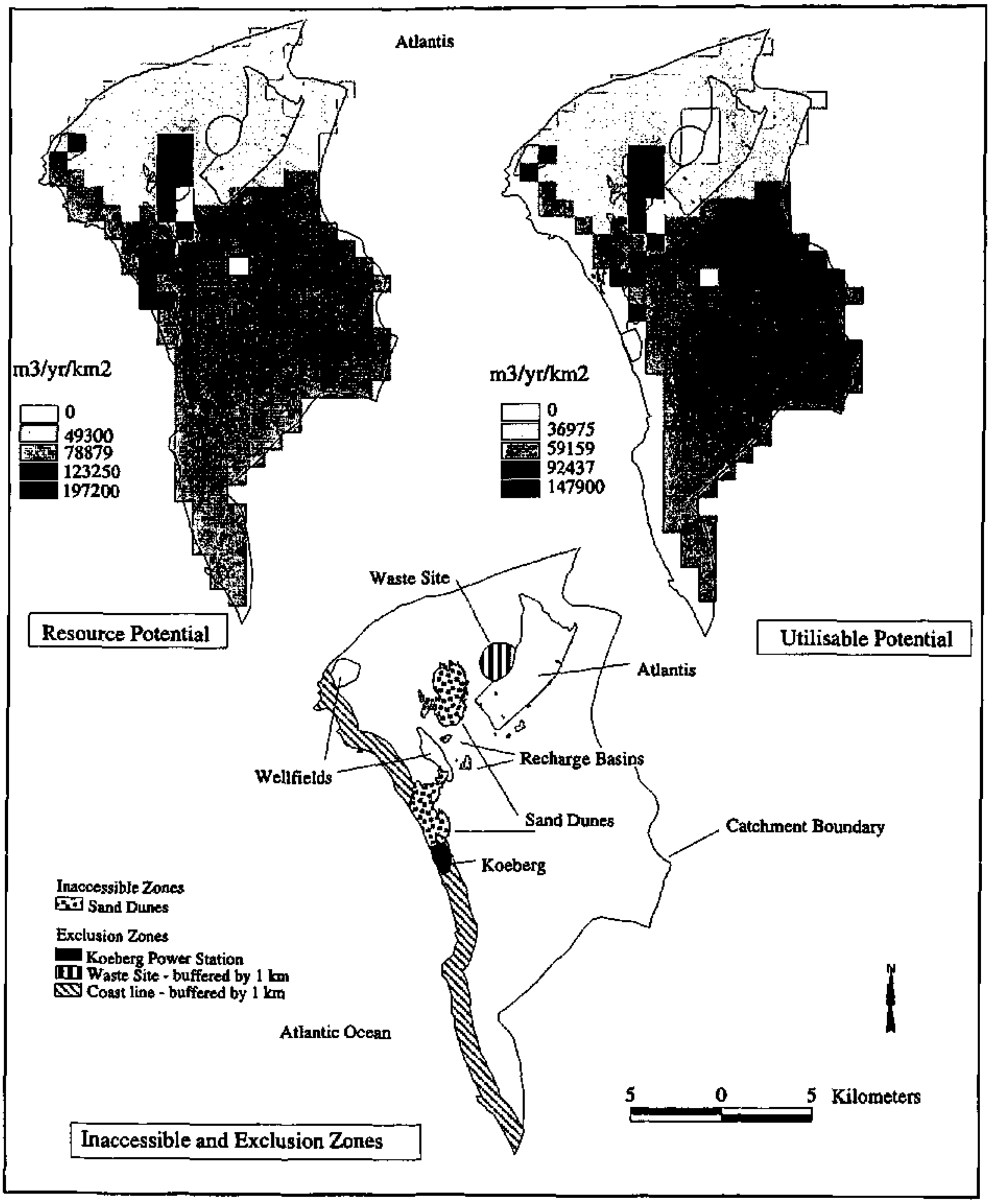


Figure 7.1: Atlantis - The resource potential and utilisable potential, with exclusion and inaccessible zones indicated

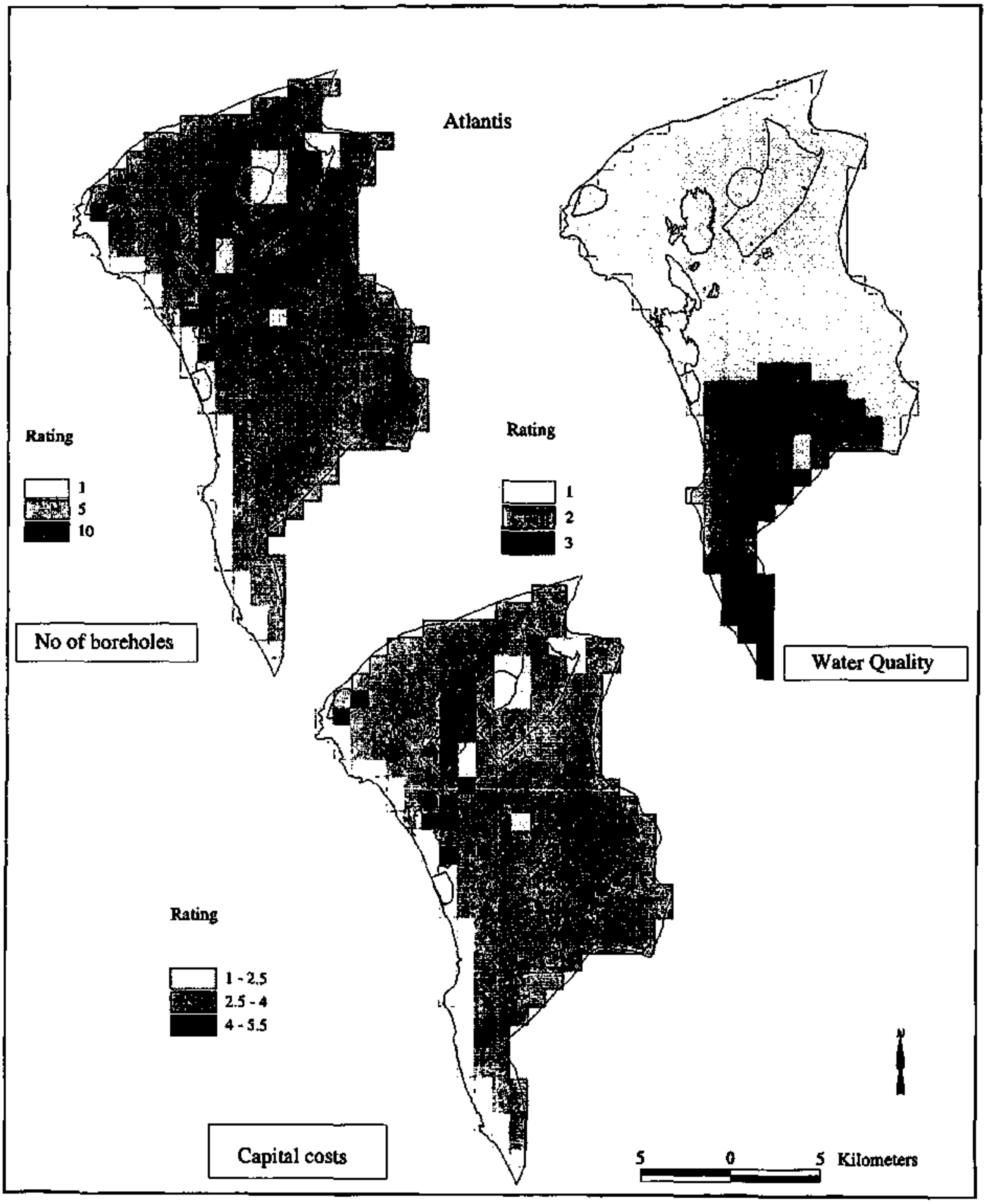


Figure 7.2: Atlantis - A rating of relative capital costs of abstracting groundwater

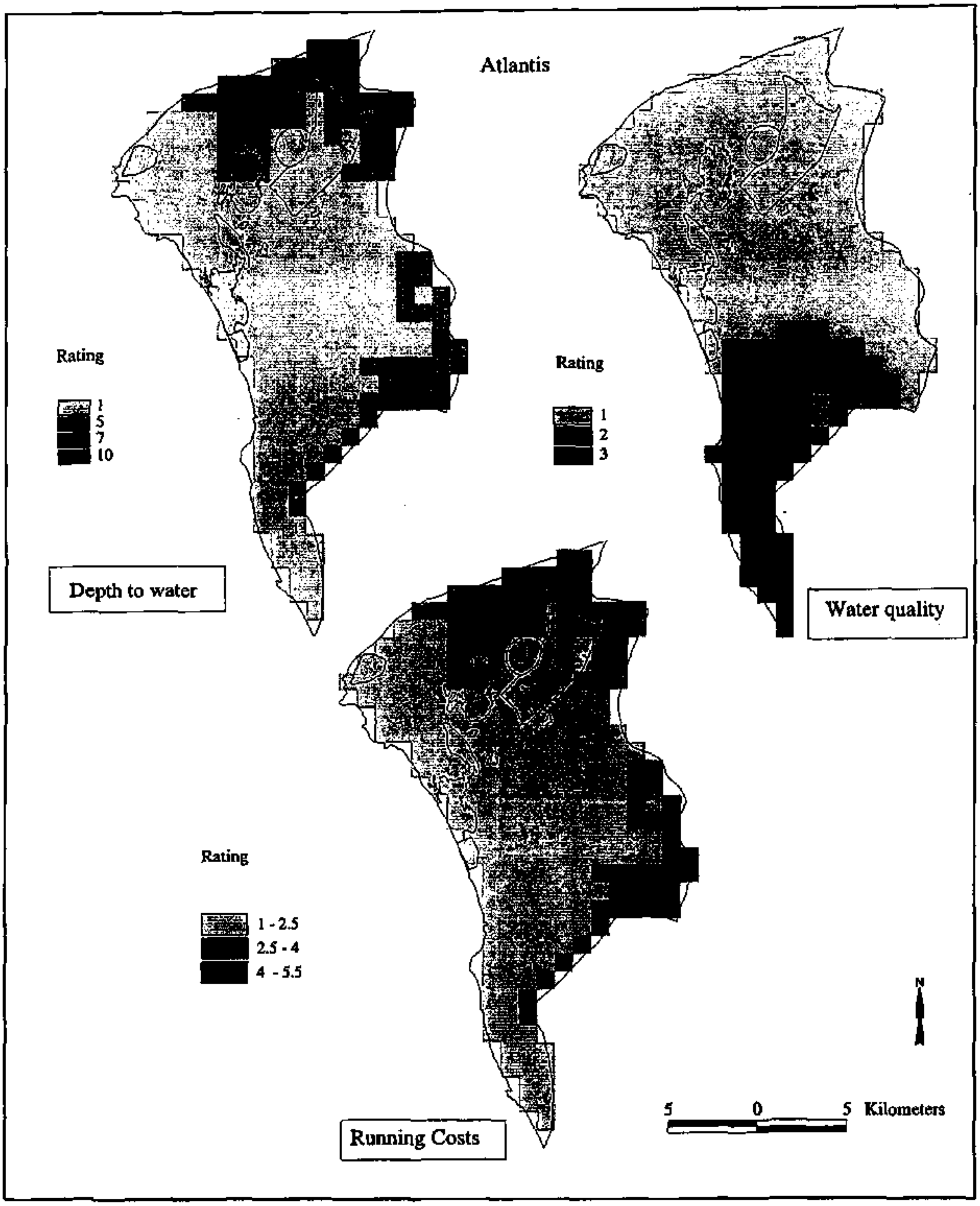


Figure 7.3: Atlantis - A rating of the relative running costs of abstracting groundwater

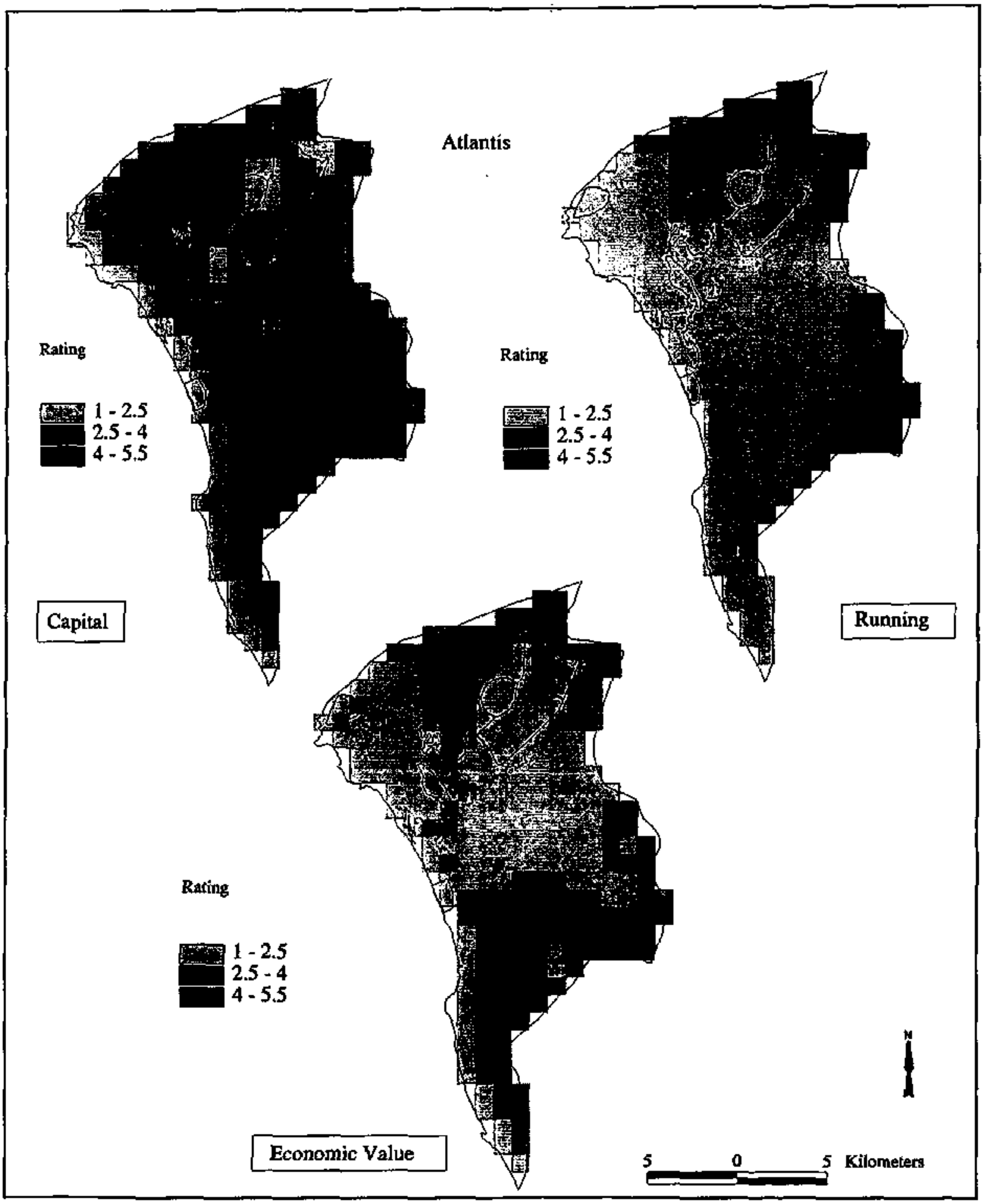


Figure 7.4: Atlantis - The overall cost rating of abstracting groundwater

5.2 Zeerust

Zeerust is approximately 200 kilometres west of Pretoria and is heavily dependent on groundwater, contained within the dolomites, for its water supply. Annual water consumption is estimated at 1.4 x 10^6 m^3. A two dimensional finite element model was constructed for estimating groundwater resources in the area (Bredenkamp and Nel, 1997). In addition to the modelled data, NGDB data was used as the model did not cover the entire catchment. Geology was a key factor in the determination of recharge values.

Springs are common in this highly dolomitic area. They are associated with structural contacts, dykes and a decrease in transmissivity adjacent to the dolomitic areas. The regional topography is essentially of low relief, sloping gently upward to the north. The dolomite formation dips to the north east below the Transvaal quartzite and shale formation. The chert-rich Eccles formation is the major aquifer. The mean annual precipitation is 480 millimetres. Table 8 lists the data used for this study area.

Table 8: Data check list for Zeerust

Data needed		Source
Quaternary outline		WR90
Physical Parameters Recharge Potential	Rainfall Recharge from precipitation	Field data Numerical groundwater flow model Geological formations Council for Geoscience (RSA 1: 1 000 000 geological GIS data, 1984)
Storage Potential	Saturated thickness Bedrock map Water levels Aquifer area Storage coefficient	Council for Geoscience (RSA 1: 1 000 000 geological GIS data, 1984) Field data Cell size Numerical groundwater flow model
Anthropogenic and Ecological Parameters	Land use / Land cover	CSIR (National Land cover data base, 1:250 000 scale)

Data needed		Source
Cost Parameters		
Capital Costs	Number of boreholes	Field data
	Water quality	
	Faecal coliforms	-
	Electrical Conductivity	NGDB
	Fluoride	NGDB
	Nitrates	NGDB
	Depth to water	
Running Costs	Water levels	NGDB
	Water quality	
	Faecal coliforms	-
	Electrical Conductivity	NGDB
	Fluoride	NGDB
	Nitrates	NGDB

The resource potential for the catchment is once again limited by the recharge values. The volume of water for the ecology and basic human needs was assumed to be 25%. Figure 8.1 shows the exclusion zones, which in this case are mines, and quarries, wetlands and surface water bodies. Wetlands and water bodies are considered highly important necessitating stringent protection measures and are considered exclusion zones even though a certain percentage of the resource potential had already been deducted for the ecology. Each of these exclusion zones were buffered by a kilometre. There are no inaccessible zones according to the data sets used for this catchment study.

The water quality in the area is good, however due to the high abstraction volumes of the dolomites to the west and south of the area, the capital costs in this area are slightly high (Figure 8.2). The running costs are generally low in the area due to the ratings for the depth to water being low (Figure 8.3). The cost rating (Figure 8.4) is largely dominated by the capital costs or more specifically the number of boreholes required to abstract groundwater from the high yielding dolomites.

The resource potential values for the area vary between 40 000 and 100 000 $m^3/km^2/yr$ (or between 40 and 100 mm/yr). The values for harvest potential (Seymour and Seward, 1997) range from 15 000 to 100 000 $m^3/km^2/yr$ (or 15 to 100 mm/yr). Table 9 is a summary of the confidence ratings of the Zeerust data.

Table 9: Confidence rating for Zeerust

Parameter	Confidence Rating
Rainfall	High (3)
Recharge from precipitation	High (3)
TOTAL (sum of ratings/no. of parameters)	High (3)

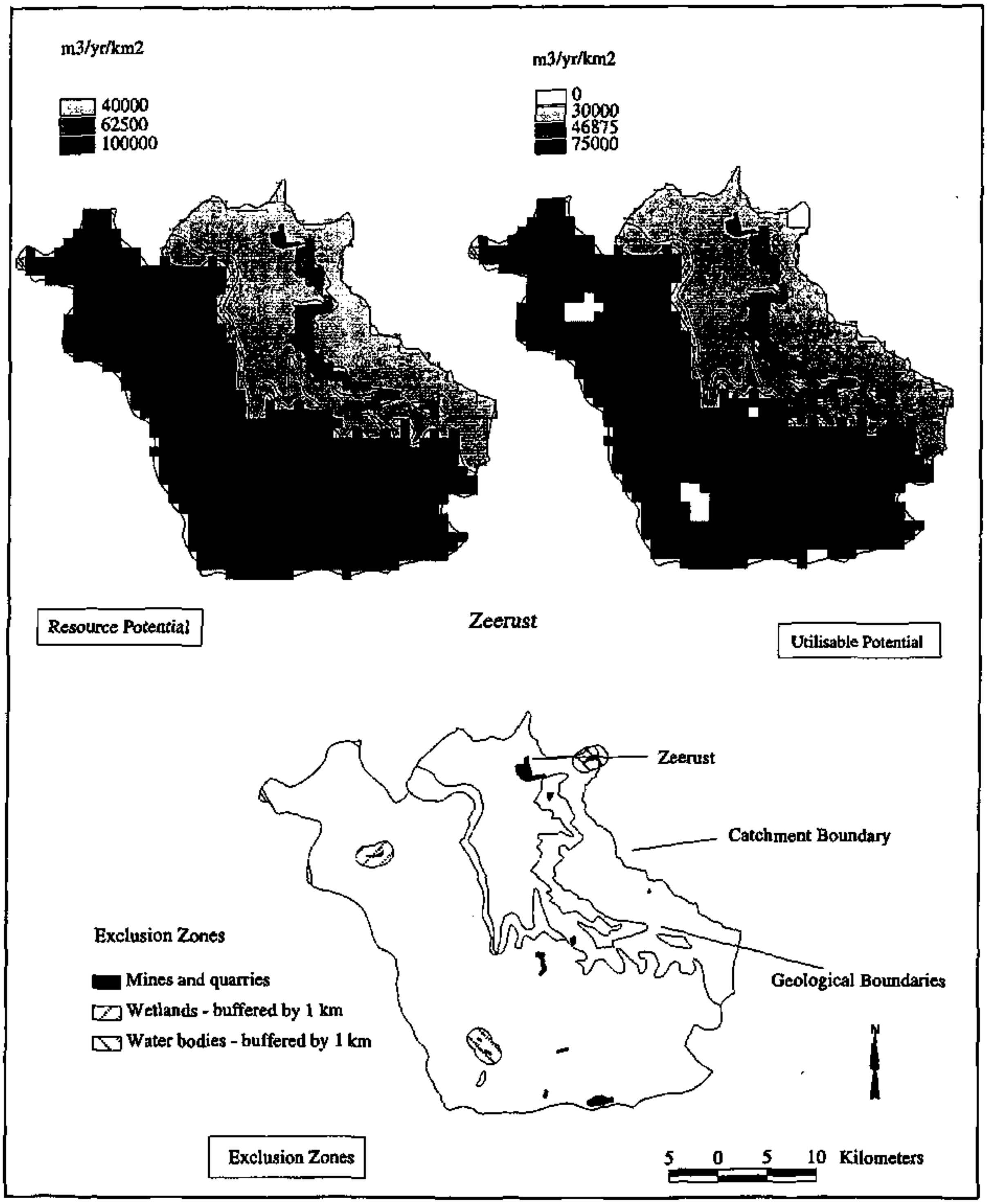


Figure 8.1: Zeerust - Resource potential and utilisable potential, with exclusion zones indicated

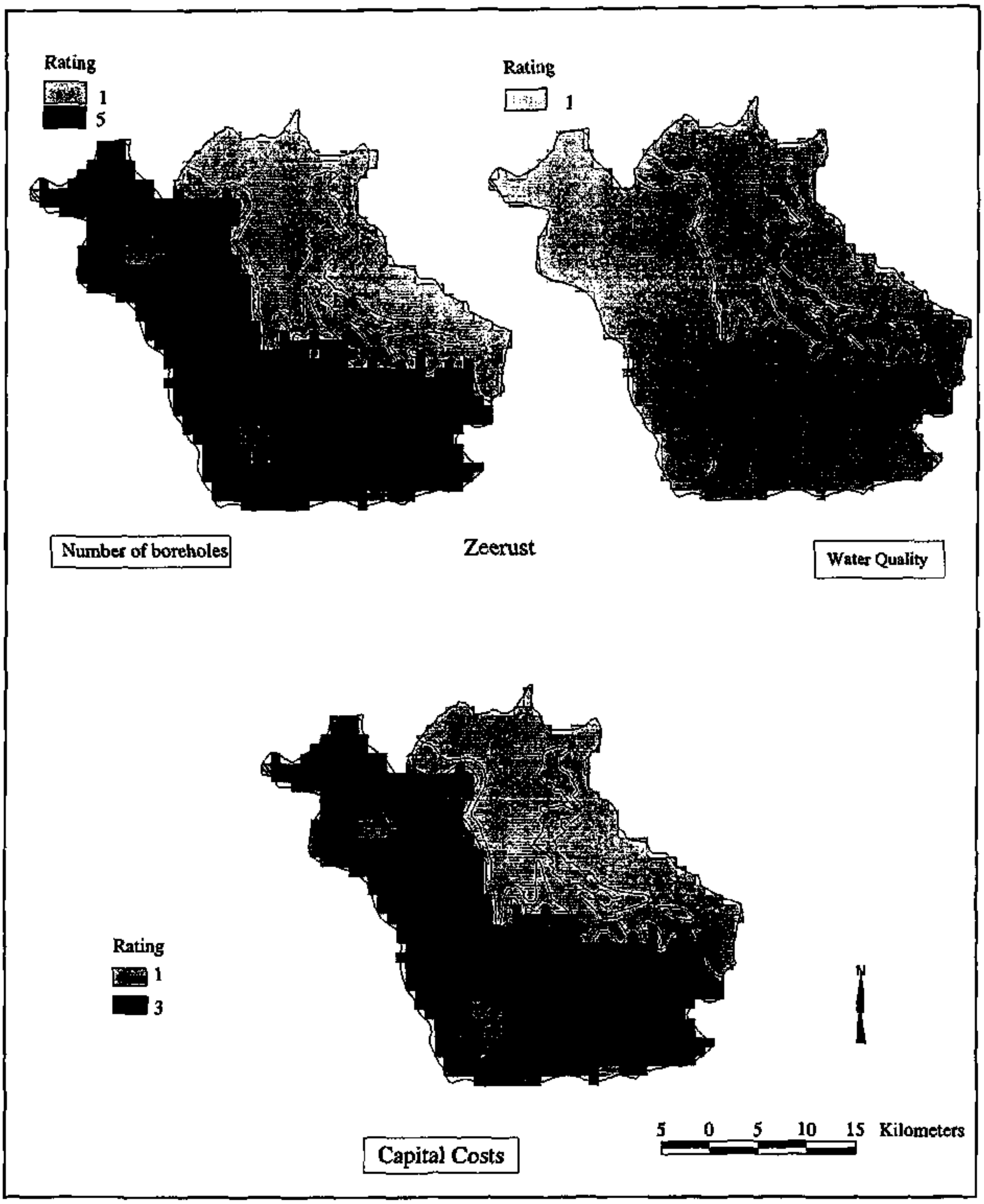


Figure 8.2: Zeerust - A relative rating of the capital costs of abstracting groundwater

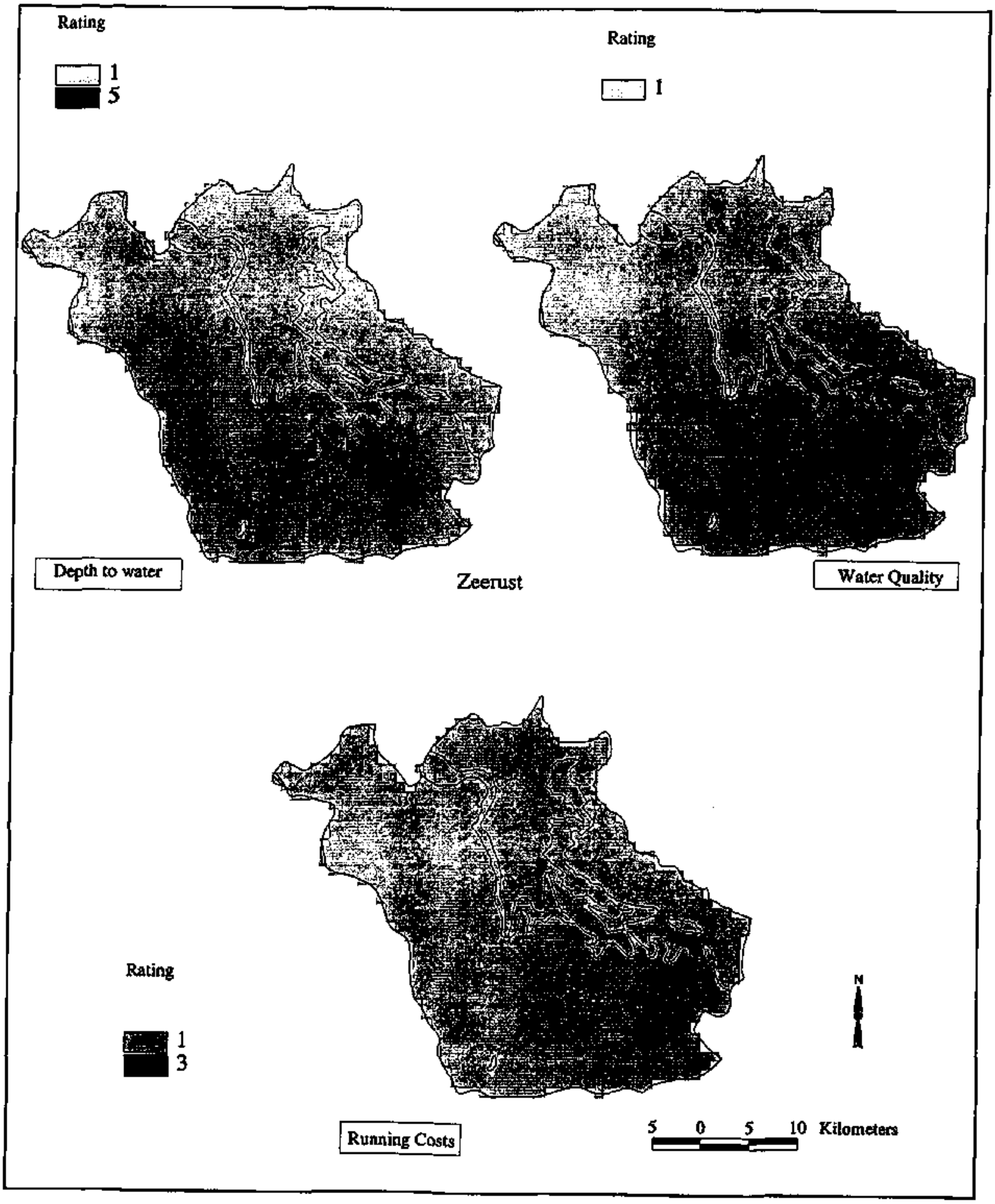


Figure 8.3: Zeerust - A relative rating of the running costs of abstracting groundwater

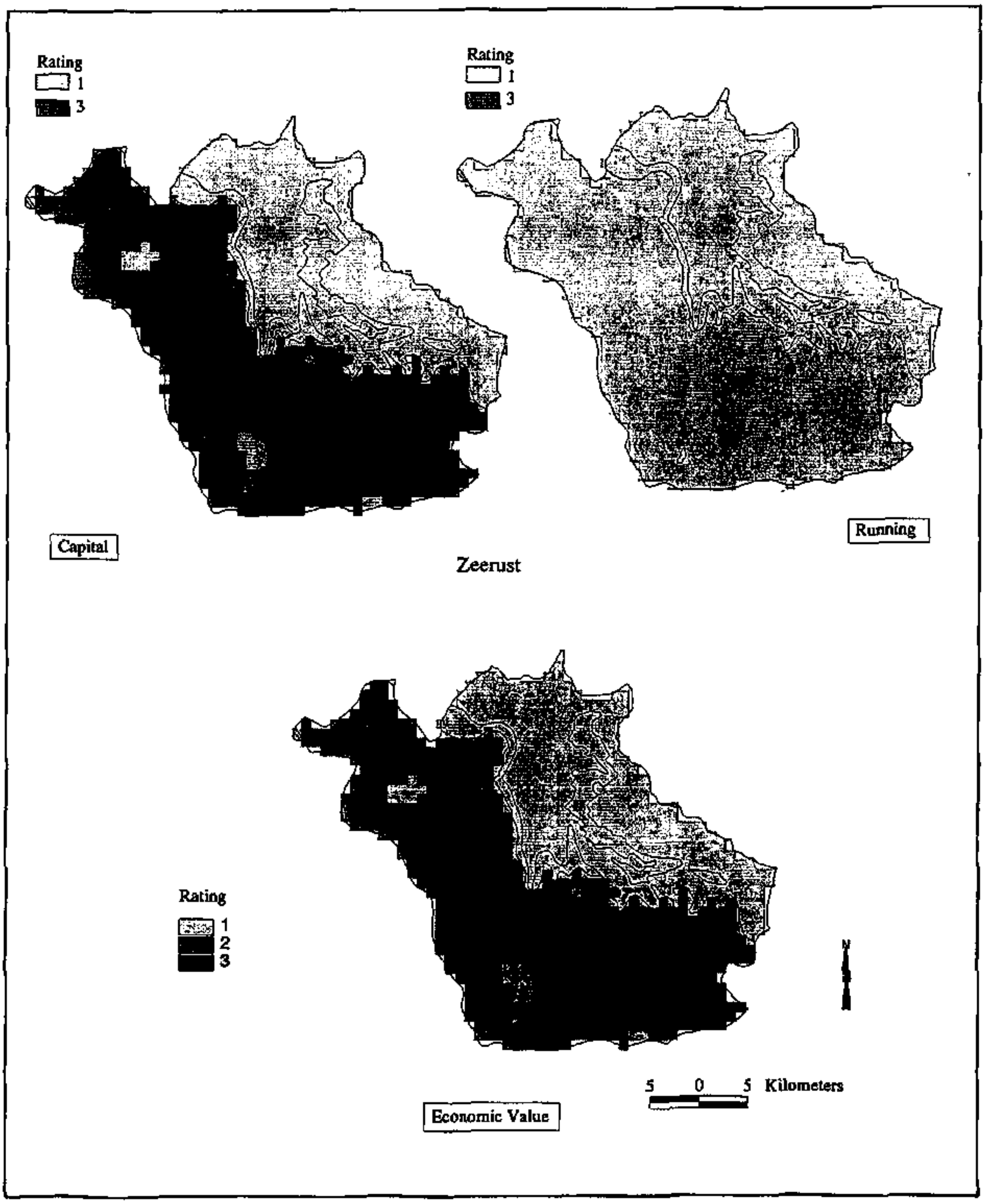


Figure 8.4: Zeerust - The overall cost ratings of abstracting groundwater

5.3 Beaufort West

Beaufort West is a Karoo town approximately 500 kilometres north east of Cape Town. Its water supply comes from the Gamka Dam and nearby well fields. The town is situated on the fractured Karoo Formation. Extensive groundwater investigations have been carried out by DWAF and SRK (Kotze and Rosewarne, 1997). Data was also used from the NGDB. Table 10 is the data check list for Beaufort West.

Table 10: Data check list for Beaufort West

Data needed		Source
Quaternary outline		WR90
Physical Parameters		
Recharge Potential	Rainfall	Field data
	Slope	Department of Surveys and Mapping, Mowbray (400 x 400 DEM for RSA)
	Recharge from precipitation	Numerical groundwater flow model
Storage Potential	Geology	Council for Geoscience (RSA 1: 1 000 000 geological GIS data, 1984)
	Saturated thickness	Numerical groundwater flow model
	Water levels	Field data
	Aquifer area	Cell size
	Storage coefficient	Numerical groundwater flow model
Anthropogenic and Ecological Parameters	-	-
Cost Parameters		
Capital Costs	Number of boreholes	Field data
	Water quality	
	Faecal coliforms	-
	Electrical Conductivity	NGDB
	Fluoride	NGDB
	Nitrates	NGDB
Running Costs	Depth to water	
	Water levels	NGDB
	Water quality	
	Faecal coliforms	-
	Electrical Conductivity	NGDB
	Fluoride	NGDB
	Nitrates	NGDB

The lower part of the Beaufort Group consists of fractured mudstones, siltstones and sandstones. Dolerite dykes and sills intrude into the Beaufort Group. Alluvial deposits occur along valleys, stream channels and around flood zones. Chemical and physical weathering takes place 30 m from the surface. The fractured Formations are the main conduits of groundwater. Groundwater flows from north to south.

The mean annual precipitation in 235 millimetres. The region is characterised by summer rainfall.

According to the numerical model (Kotze and Rosewarne, 1997) the recharge in the area is essentially dependent on slope. The recharge on the plain is only 2% of the mean annual rainfall, while it is 4 % of the mean annual rainfall on the escarpment. Areas with slopes greater than 5° are considered part of the escarpment. The recharge potential was the limiting factor and therefore taken as the resource potential. Ecological and basic human needs were taken as 25% of the resource potential. No land cover or land use data were available therefore no exclusion zones were included in Figure 9.1. Slopes greater than 15° were flagged as inaccessible zones. The ability of the aquifer to yield water is not large therefore the number of boreholes rating is not high. The water quality varies over the area and is responsible for slightly high capital costs (Figure 9.2). Similarly the water table in the area is fairly shallow and the water quality is once again responsible for the slightly higher running costs (Figure 9.3) and consequently the slightly high cost rating (Figure 9.4).

The maximum volumes of groundwater that may be abstracted to preserve a sustained abstraction according to the Harvest Potential map (Seymour and Seward, 1997) vary between 2 500 and 10 000 $m^3/km^2/yr$ (or 2.5 and 10 mm/yr), with the lowest values occurring south of the town. These values compare favourably with the resource potential values obtained which vary between 4 700 and 9 400 $m^3/km^2/yr$ (or between 4.7 and 9.4 mm/yr).

The confidence rating for the resource potential is summarised to Table 11.

Table 11: Confidence rating for Beaufort West

Parameter	Confidence Rating
Rainfall	High (3)
Recharge from precipitation	High (3)
Slope	Medium (2)
TOTAL (sum of ratings/no. of parameters)	Medium to high (2.7)

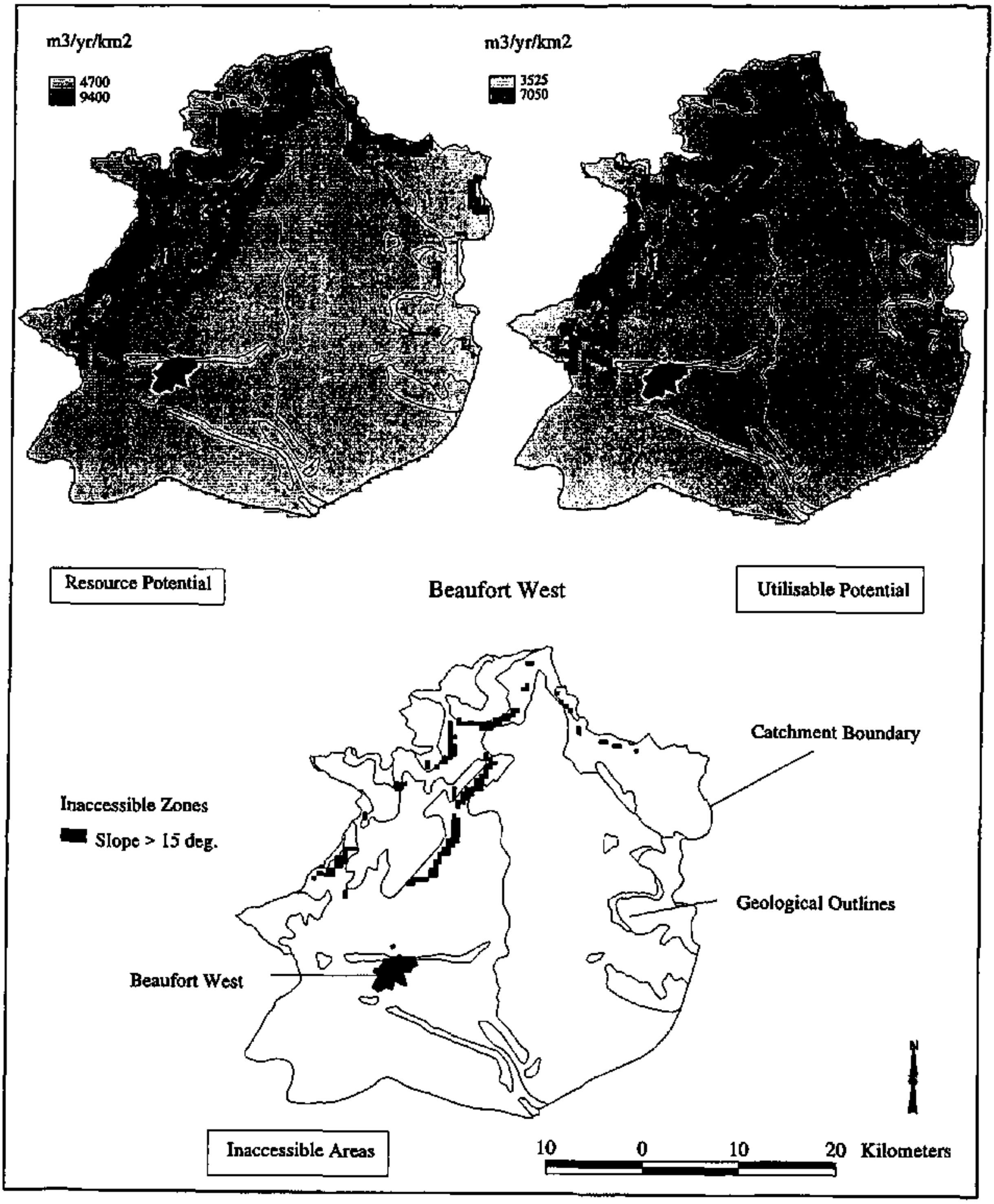


Figure 9.1: Beaufort West - Resource potential and utilisable potential, with inaccessible zones

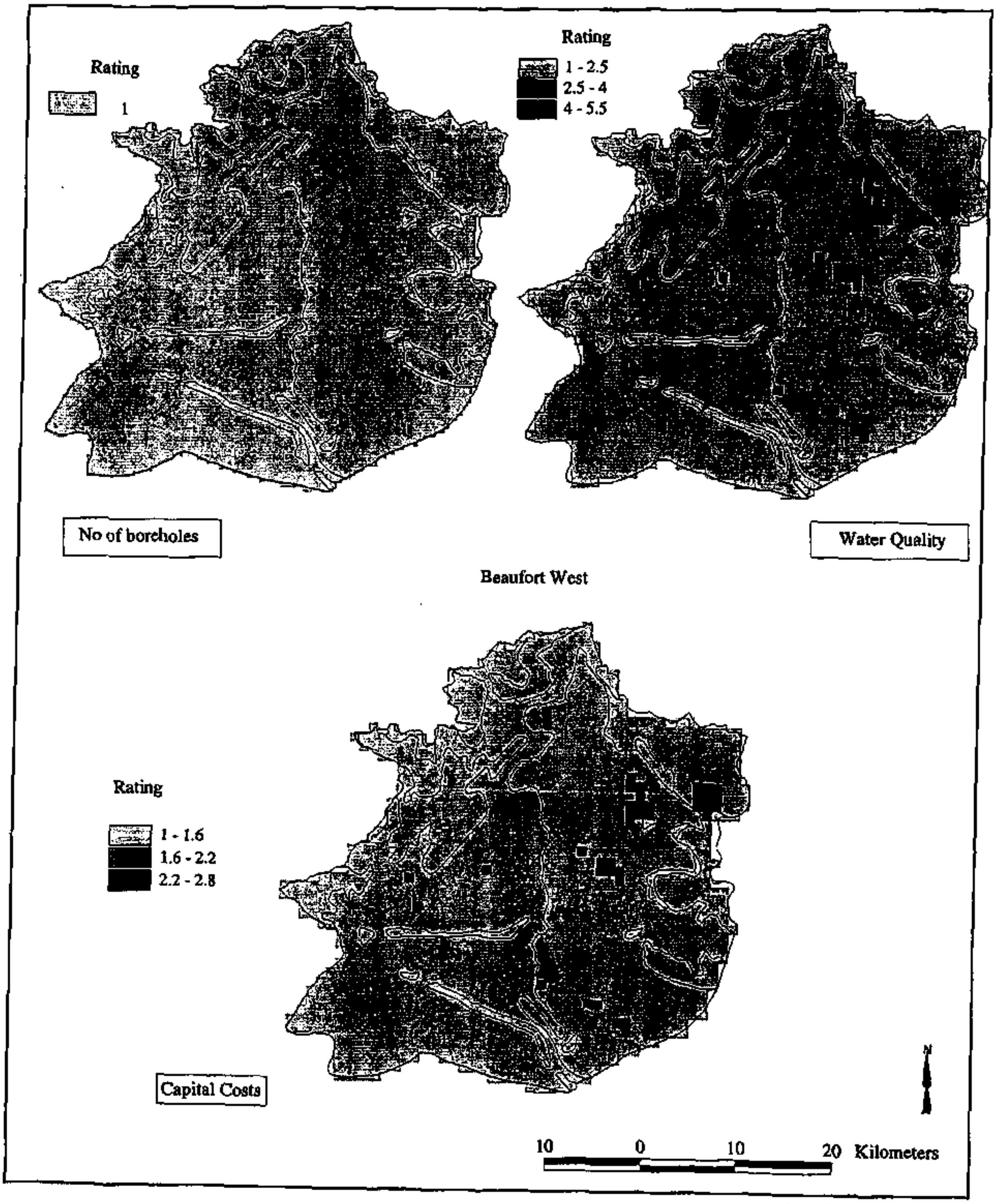


Figure 9.2: Beaufort West - The relative rating of capital costs for abstracting groundwater

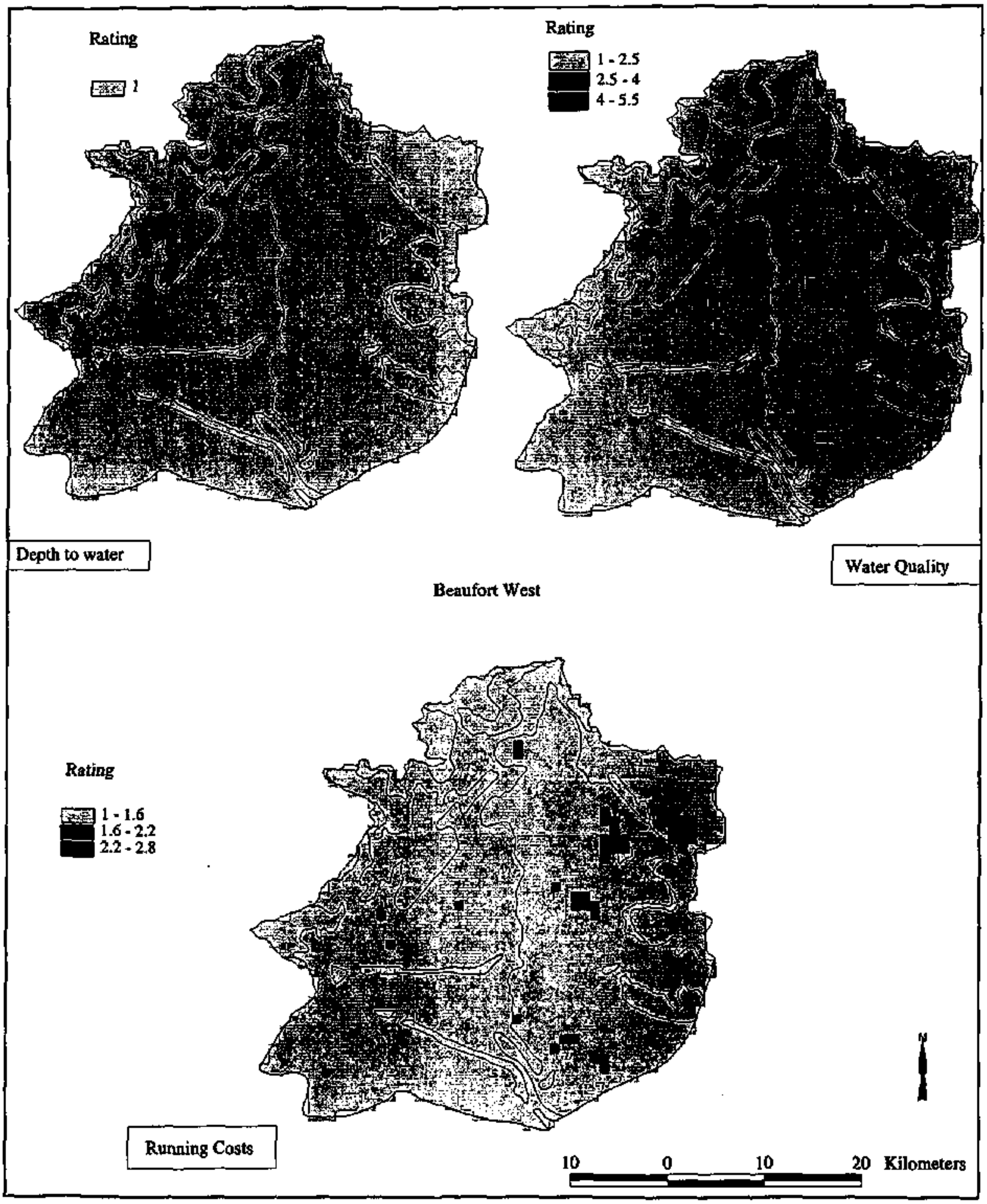


Figure 9.3: Beaufort West - The relative rating of running costs for abstracting groundwater

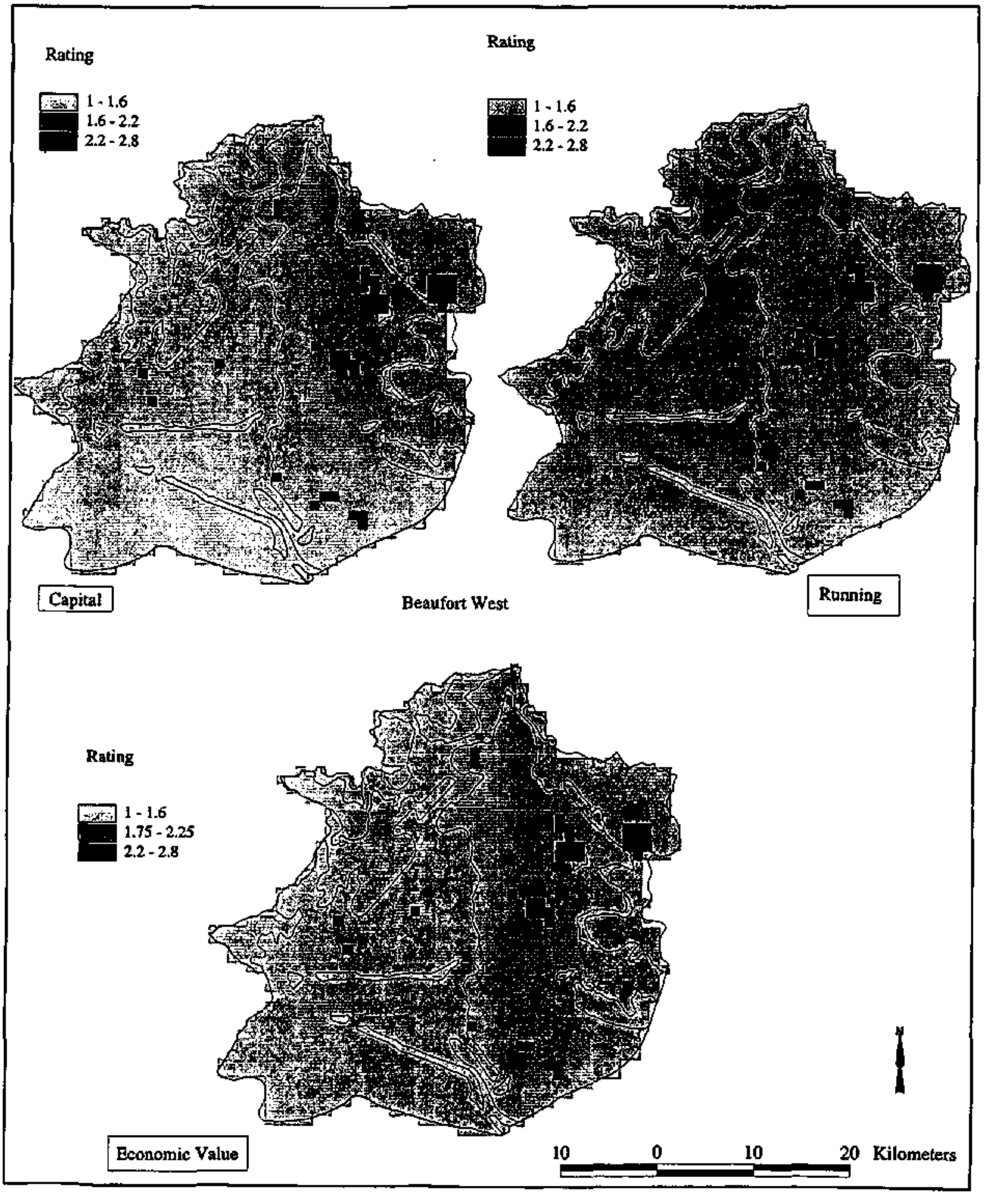


Figure 9.4: Beaufort West - The overall cost ratings of abstracting groundwater

6. DISCUSSION

The methodology was applied to three data rich areas with different geologies. The resource potential for all three areas was the recharge potential. However, if storage potential is the limiting factor then the methodology will vary slightly depending on whether the aquifer is confined or not. If the aquifer is confined then the amount of water stored in the aquifer is controlled by the storativity, which is the volume of water that the aquifer can release from storage per unit surface area per unit decline in hydraulic head normal to the surface. In unconfined conditions the storage potential is dependent on the specific yield, which refers to the amount of water that the aquifer can release from storage per unit surface area per unit decline of the watertable (Kruseman and De Ridder, 1991). In addition, the determination of storage for fractured rock aquifers is extremely difficult and therefore the accuracy of a resource potential dependent on such storage values will have a low confidence value.

For most catchments, it seems as though recharge is going to be the limiting factor and therefore the resource potential and the final utilisable potential is going to depend on the percentage recharge. The methodology is very sensitive to changes in the recharge potential.

7. RECOMMENDATIONS

The present methodology has been applied at a catchment scale, which is bounded by a surface water divide, which in many instances is not the same as an aquifer boundary. Further work needs to be carried out to develop the methodology for determination of the groundwater ecological Reserve. The requirements of groundwater supply to aquatic ecosystems (base-flow) and critical terrestrial ecosystems dependent on groundwater (e.g. coastal dune sand vegetation) need to be determined. Cost implications were only considered in relative terms of pumping groundwater to surface and ensuring it meets drinking water standards. Costs for piping water to users were not taken into account and this cost also needs to be factored into the decision making process.

Data interpolation is also a problem as the data is typically non-uniformly and sparsely spread across a catchment. The methodology should also be tested on data poor areas. Various geostatistical methods need to be considered and compared to obtain accurate interpolation results.

Geohydrologic systems are fraught with uncertainty, however decisions still have to be made. Yields vary with time and location and can only be estimated, and thus may carry significant uncertainty. Because uncertainty and risk are companions, evaluating uncertainty allows the assessment of risks and management of its consequences.

8. CONCLUSIONS

A basic methodology has been proposed for the quantification of sustainable yield and utilisable potential of South Africa's groundwater resources. An investigation should be carried out into what the most appropriate and representative "hydrogeological unit" or scale should be when performing calculations of sustainability. A number of different approaches have been taken for calculation of aquifer "yield" and The Reserve. These should be considered and evaluated through a "workshopping" approach, involving various relevant role players. A detailed hypothetical case study together with 3 case studies are included in the report to provide the reader with a clear understanding of the methodology.

It has been a challenge to quantify a variable and complex resource such as groundwater and some major assumptions have been made. It is intended that the methodology is improved in the coming years by including the surface water/groundwater interaction and accurately determining the ecological portion of the groundwater Reserve. However, the methodology can be used as it is now and will provide results that can be used as a 'first pass' assessment of groundwater resources, including the relative costs of obtaining potable water at surface.

Once the method has been refined to the extent that it can be accurately applied to the quaternary catchments for the entire country, the information can be 'stitched' together to form a national map depicting the sustainable yields and utilisable potential of South African aquifers.

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Appendix A

CONSULTATIONS

Throughout the duration of this project many groundwater scientists and professionals were consulted concerning a methodology to determine the sustainable utilisable potential of South African aquifers. Table A is a summary of the discussions held with these authorities.

Table A : Summary of the discussions held with various groundwater scientists

Date	People present	Summary
28 Aug 1996	Mr Reynders Mr Conrad Ms Mullins Mr Orpen Ms van der Voort Mr Vegter Mr Weaver	This project must add value to the Community Water Supply and Sanitation project. Duration of the project should be one year. Identification of the client and clear understanding of what must be done. Recharge is an important factor that is going to have to be sorted out. *Must look at Bayesian statistics, spatial and time variability.* Mr Vegter concerned with the quantification of exploitation potential. A quantitative map might be beyond our capabilities at the moment. Environmental issues also need to be considered. Emphasis must be placed on the methodology, must be a level of confidence in the final product. The methodology must be scientifically repeatable. Project must be client driven. Include feasibility/impact assessment studies.
15 Jan 1997	Mr Reynders Mr Conrad Ms van der Voort	Further the Harvest Potential map. Have a look at the Queenstown exploitation potential map. Regionalise data - safe yield, position of boreholes, geological logs, water levels and fractures The information available is as follows : recharge, surface hydrology and storage ? Must determine specific yield distribution and well field development potential. Literature review is very important. Costs must be taken into consideration. Must be a technical appendix to the booklet. Methodology should cover the statistical differences. Workshop must be held at the end of the project for a transfer of knowledge to take place.

Date	People present	Summary
14 Apr 1997	Mr Seward Mr Woodford Mr Conrad Mr Murray Ms van der Voort	Groundwater harvest potential (GWHP) is the maximum abstraction without depleting the resources and without taking the cost factors into account. GWHP takes storage and recharge into account - the deciding factor being the one limiting the amount of abstraction. Storage and recharge defines the source. Transmissivity can not be regionalised. Storage and recharge data used for GWHP map same or based on data from Vegter's maps. Groundwater quality came from Vegter's maps. The scale at which you are working determines the methodology that you should use. Identify areas where more research must be done. Definitions are very important. Focus should be on ways of determining transmissivity and on cost factors Must look at statistical methods and fractals. Look at relations between structure and density - central point being transmissivty as it forms the link between borehole yield and structure. Work on many different areas and then stitch them together to get a map on a national scale.
17 Apr 1997	Mr Smart Mr Conrad Ms van der Voort	For the Queenstown exploitation potential map the ACRU model was used. Thickness of the aquifer was taken as 20 m. Storage was divided by the drought length. Drought recharge was taken as 5% of the mean annual precipitation. Transmissivity is the critical factor. Must use geostatisctics and modelling. Hazard areas (e.g. high transmissivity and small resource) must also be considered.

Date	People present	Summary
27 May 1997 (Steering committee meeting)	Mr Reynders Mr Conrad Ms van der Voort Mr Seward Mr Maaren Mr Conley Mr Haupt Mrs Smit (secretary)	This research product must meet the requirements of the New Water Act. Need to provide basic science to understand the workings of the water cycle for licencing. Cost parameters must not be used. Sensitivity analyses must be done. Definitions are important - they must be correct. Must include demand management (i.e. what will happen during a drought). Risk assessment must be looked at. Assumptions on which the methodology is based must be very clear. Costs must be included. Add dynamics aspects by means of GIS. Look at catchment/sub-catchment scale. Look at frequency distributions.
4 Sep 1997	Mr Conrad Ms van der Voort Mr Chapman	Danger in producing a national exploitation potential map. Look at Pareto analysis. Use a catchment basis.
4 Sep 1997	Ms Genthe Ms van der Voort	Risk based approach and sensitivity analysis must be included.
19 Sep 1997	Mr du Plessis Ms van der Voort	Variety of treatments available for each water quality problem - to cost each treatment is just about impossible.
7 Oct 1997	Mr Johnstone Ms du Toit Mr Conrad Ms van der Voort	Ratio between recharge and storage is critical. Look at the permeability of soils and recharge mechanisms in soils. Look at the physical characteristics influencing the aquifer (soils types, catchment gradients, threats to aquifers, unsaturated zone, rainfall characteristics, veld types and geology). Consider using satellite images. Remember there are 2 phases of recharge : early and late. Look at drastic approach.

Appendix B

GLOSSARY

Aquifer (Vegter, 1995): A stratum which contains intergranular interstices, or a fissure/fracture (as such) of a system of interconnected fissures/fractures (as such) capable of transmitting groundwater rapidly enough to directly supply a borehole or spring. The fissures/fractures are generally bound by either aquiclude / aquitard or aquifuge.

Aquifuge (Vegter, 1995): A rock which contains no interconnected openings and therefore neither absorbs nor transmits water.

Aquitard (Vegter, 1995): A body of poorly permeable rock that is capable of slowly absorbing water from and releasing water to an aquifer. It does not transmit groundwater rapidly enough by itself to directly supply a borehole or spring. Synonym aquiclude.

Artesian boreholes (Driscoll, 1986): A borehole deriving its water from a confined aquifer in which the water level stands above the ground surface.

Artificial recharge (Driscoll, 1986): Recharge at a rate greater than natural, resulting from deliberate actions from man.

Base flow (Vegter, 1995): That part of stream flow which is contributed by effluent groundwater.

Basic human need (Parsons, 1998): This has been set at 25 liters per person per day within 200 m of their dwelling.

Borehole: Generic term used for any drilled or hand-dug hole used to abstract or monitor groundwater, irrespective of diameter or construction.

Catchment: The area of land which drains all runoff from rainfall to the sea (or a lake) via one or more watercourses. A catchment has a definable physical boundary which acts as a barrier to many of the physical and biological processes within it.

Confined groundwater (Vegter, 1995): Groundwater under pressure significantly greater than that of the atmosphere and whose upper surface is the bottom of a layer of distinctly lower permeability than the material in which the water occurs.

Contamination (Driscoll, 1986): The degradation of natural water quality as a result of man's activities. There is no implication of any specific limits, since the degree of permissible contamination depends upon the intended end use, or uses, of the water.

Cost rating: A qualitative indication of the cost of abstracting groundwater (i.e. bringing it to surface) and having it meet drinking water standards if needed.

Exclusion zone: An area where groundwater will not be part of the Sustainable Utilisable Potential due to it being contaminated or of very poor quality.

Evapotranspiration (Vegter, 1995): Loss of water from a land area though transpiration of plants and evaporation from the soils.

Exploitation potential (Parsons, 1998): The rate at which groundwater can be withdrawn from a catchment without causing any detrimental impacts.

Fault (Driscoll, 1986): A fracture or zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture.

Fissure (Vegter, 1995): A surface of fracture or crack in rock along which there is a distinct separation.

Fitness for use (Parsons, 1988): Water quality is such that it meets the requirements for a particular use, five major groups of water users recognised as domestic, agricultural, industrial, recreational or environmental users.

Fracture (Vegter, 1995): Any break in a rock whether or not it causes displacement, owing to the mechanical failure by stress. Fracture includes cracks, joints, faults.

Free groundwater (Vegter, 1995): See unconfined groundwater.

Geohydrology (Vegter, 1995): The branch of hydrology dealing with subsurface water ie water in both the saturated and unsaturated zones. Also used interchangeably with hydrogeology.

Groundwater (Vegter, 1995): Water in the zone of saturation. It flows into boreholes/wells or debouches as springs. Synonym underground or subterranean water.

Groundwater harvest potential (Seymour and Seward, 1997): The maximum amount of groundwater that may be abstracted per square kilometre per year without depleting the aquifers. In other words it is the maximum rate at which groundwater can be abstracted sustainably if socio-economic factors are not an issue. Socio-economic factors include, inter alia, the cost of bringing water to the point of demand, the value of the water, and the legal and environmental issues.

Groundwater level (Vegter, 1995): The water level in a borehole / well penetrating the zone of saturation and from which no water is being withdrawn. Synonym static (water) level.

Hard rock (Vegter, 1995): A compact rock that lacks primary porosity.

Hydraulic conductivity (Vegter, 1995): The rate of flow of water through a unit cross section of soil or rock, under unit hydraulic gradient.

Hydrogeology (Vegter, 1995): The geology of groundwater.

Hydrologic cycle (Vegter, 1995): All movement of water in its liquid, gaseous and solid phases, in the atmosphere, on the Earth's surface and below the ground surface.

Hydrology (Vegter, 1995): The science that deals with continental water on and under the Earth's surface.

Interception (Vegter, 1995): The process by which water from precipitation is caught and stored on plant surfaces and eventually returned to the atmosphere without having reached the ground.

Karoo: A stratigraphic term used for a series of sediments and lava flows of considerable extent in Southern and Central Africa.

Karst (Vegter, 1995): A type of topography that is formed over limestone and dolomite by solution and that is characterised by closed depressions or sinkholes, caves and underground drainage.

Lithology (Vegter, 1995): The description of rocks on the basis of colour, structures, mineralogic composition and grain size.

Percolate (Driscoll, 1986): The act of water seeping of filtering through the soil without a definite channel.

Permeability (Vegter, 1995): The capacity of rock and soil to transmit water.

Primary opening (Vegter, 1995): Interstices that were made contemporaneously with the formation of the sedimentary deposit or rock that contains them. Hence the property of primary porosity.

Porosity (Vegter, 1995): The property of a rock and soil of containing interstices.

Pumping test (Driscoll, 1986): A test that is conducted to determine aquifer or borehole characteristics.

Quaternary Catchment: The basic areal unit used and demarcated in Surface Water Resource in South Africa (WR90). All primary drainage regions are divided into secondary, tertiary and quaternary sub-catchments. Size varies with runoff- the greater the runoff volume, the smaller the area and visa-versa.

Recharge (Vegter, 1995): The processes involved in the adsorption and addition of water to the zone of saturation. Synonym replenishment.

Recharge potential: The amount of water that enters the aquifer per unit time. It includes recharge from precipitation, surface water bodies and artificial recharge.

Reserve, The (National Water Act, 1998): The quantity and quality of water required:

(i) to satisfy basic human needs by securing a basic water supply , as prescribed under the Water Services Act, 1997 (Act No. 108 of 1997), for people who are now or who will, in the reasonably near future, be relying upon, taking water from, or being supplied from the relevant water resource, and

(ii) to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource.

For groundwater, The Reserve includes water required to ensure there are no detrimental impacts on the aquifer (e.g. compaction).

Resource potential: The Reserve plus utilisable water. In terms of groundwater it is determined by the recharge potential and storage potential ($m^3/km^2/yr$), whichever is the limiting factor.

Safe Yield (Domenico and Swart, 1990): The abstraction of water that does not (1) exceed the average annual rainfall, (2) lower the water table so that the permissible cost of pumping is exceeded and (3) lower the water table so as to permit intrusion of water of undesirable quality.

Saturation, Zone of (Vegter, 1995): The zone below the water table in which all interstices are filled with groundwater.

Secondary openings (Vegter, 1995): Interstices that were made by processes that affected the rocks after they were formed. Hence the property of secondary porosity.

Specific yield (Driscoll, 1986): The ratio of the volume of water that a given mass of saturated rock or soil will yield by gravity to the volume of that mass.

Static water level (Driscoll, 1986): The static water level in a borehole that is not being affected by withdrawal of groundwater.

Stratigraphy (Vegter, 1995): The description of strata - sedimentary, igneous and metamorphic - in terms of lithologic composition, fossil content, age, origin, history.

Stochastic : Having an element of probability.

Storage coefficient (Driscoll, 1986): The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Storage potential: The product of the storage coefficient, the saturated thickness of the aquifer and the area the aquifer per unit area of the aquifer. It is assumed that this volume can be abstracted over a year.

Storm runoff (Vegter, 1995): Runoff reaching stream channels immediately after rainfall.

SUP (Sustainable Utilisable Potential): The volume of groundwater that can be abstracted on a sustainable basis after the requirements of the **Reserve** (that is the ecological and basic human needs) have been met.

SUPAA (Sustainable Utilisable Potential Application for Aquifers): The methodology to determine the volume of groundwater that can be abstracted on a sustainable basis after the *requirements of the Reserve have been met.*

Sustainable (Sharp, 1998): This refers to a very long period of time with minimal potential of negative effects on the aquifer

Sustainable development : The use, development and protection of natural resources in a way and at a rate which allows for social, economic and cultural needs of people and communities to be met without compromising the ability to meet the needs of future generations.

Transmissivity *(Driscoll, 1986): The rate at which water is transmitted through a unit width* of aquifer under a unit hydraulic head.

Unconfined groundwater (Vegter, 1995): Groundwater of which the upper surface is at atmospheric pressure, or in other words, its upper surface is the water table.

Unsaturated zone (Vegter, 1995): The zone between the land surface and the water table in which interstices contain air or gases generally under atmospheric pressure, as well as water under pressure less than that of the atmosphere. Synonym zone of aeration or vadose zone.

Utilisable potential: The volume of water remaining as the resource potential once The Reserve requirements have been met.

Vulnerability: A relative measure of the susceptibility of a groundwater body to be contaminated by anthropogenic activities; governed by the physical, chemical and biological properties of the soil and rock.

Water table (Vegter, 1995): The upper surface of the zone of saturation, in other words, the *imaginary surface below which all openings are filled with water.* On this surface the pressure is equal to atmospheric pressure.

Yield (Driscoll, 1986): Volume of water discharged from a borehole.