

**ASSESSMENT OF GIS-INTERPOLATION TECHNIQUES
FOR GROUNDWATER EVALUATION:
A CASE STUDY OF THE SANDVELD, WESTERN CAPE, SOUTH AFRICA**

ZAHN MÜNCH



*Thesis presented in partial fulfilment of the requirements for the degree of
Master of Natural Sciences at the University of Stellenbosch*

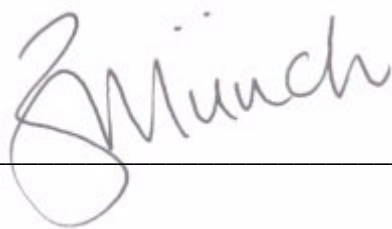
Supervisor: Prof H.L. Zietsman

December 2004

AUTHOR'S DECLARATION

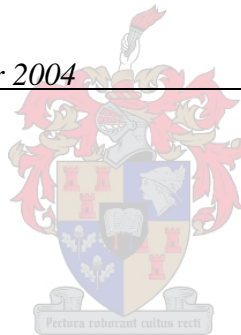
I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

Signature:

A handwritten signature in black ink, appearing to read 'Z. Münch', written over a horizontal line.

Date:

25 November 2004



ABSTRACT

The Sandveld, a potato growing area of the Western Cape is subject to significant groundwater abstraction for both municipal and agriculture purposes. The climate is arid and sensitive and important ecosystems in the area are showing varying degrees of impact. Management measures are needed to ensure ongoing sustainable development of the area.

In this study, different interpolation techniques were evaluated to calculate values for unsampled variables rainfall and groundwater elevation. Local deterministic techniques as well as geostatistical techniques were used. It was found that geostatistical techniques, especially with collateral information, such as topography, provided a more accurate result. For environmental studies of this nature, Kriging is recommended as interpolation technique. The underlying data will determine the selection of the particular type of Kriging.

Data was extracted from a customized relational database, *geoMon*, used for data capture, retrieval, processing and reporting. Ease of data extraction facilitated analysis.

The interpolated grids were applied in two scenarios: Recharge calculations and quantification as well as a new classification approach according to Resource Directed Measures (RDM). Management classes were defined based on GIS-derived data.

OPSOMMING

Die Sandveld, 'n aartappelverbouingsgebied in die Wes-Kaap, ondergaan aansienlike grondwateronttrekking vir beide munisipale sowel as landbou doeleindes. Die klimaat is dor en droog en sensitiewe en belangrike ekosisteme in die area ondervind wisselende impakvlakke. Bestuursmaatreëls word benodig om volhoubare ontwikkeling van die area te verseker.

In hierdie studie is verskillende interpolasie tegnieke om onbekende waardes vir veranderlikes gebruik in grondwater evaluasie te bereken, evalueer. Lokale deterministiese tegnieke sowel as geostatistiese tegnieke is gebruik. Geostatistiese tegnieke, veral gebruik saam met addisionele inligting soos topografie, bereken meer akkurate resultate. Vir omgewingsstudies van hierdie aard, word Kriging aanbeveel as interpolasie tegniek. Eienskappe van die onderliggende data word gebruik om die tipe Kriging aan te dui.

Data is onttrek uit 'n gebruikersaangepaste databasis, *geoMon*, wat gebruik is vir datavaslegging, onttrekking, prosessering en verslaggewing. Die gemak waarmee data onttrek kon word het die analise vergemaklik.

Geïnterpoleerde data is gebruik vir grondwateraanvullingsberekeninge en -kwantifisering sowel as 'n nuwe benadering tot klassifikasie volgens hulpbron gerigte maatreëls. Bestuursklasse gebaseer op GIS-afgeleide data, is gedefinieer.

ACKNOWLEDGEMENTS

I would like to thank the following people for their support in many ways during the process of writing this thesis:

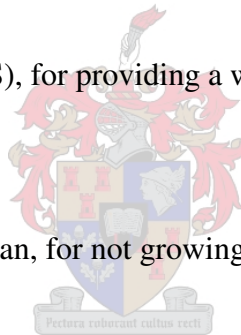
- Cecil, for encouragement and support

- Eric, Alex and Jo-Jo, for not complaining about all the hours in front of the computer

- Julian Conrad (GEOSS), for providing a workplace, data, time and input

- Professor Larry Zietsman, for not growing weary with the ever changing topics

- Edith Katzenellenbogen, for editorial input, crossing the T's and dotting the I's.



Above all, thank you to God my Creator without whom none of this would have been possible.

CONTENTS

Tables	iii
Figures	iv
Abbreviations	v
CHAPTER 1: INTRODUCTION	1
1.1 Setting the scene: The Sandveld	1
1.2 Foundation for research	1
1.3 Aims and objectives	3
1.4 Literature review	3
1.5 Focus on groundwater	5
1.6 Research design	6
1.7 Location of study area	8
1.8 Description of data used for analysis	9
1.8.1 Groundwater level and chemistry	10
1.8.2 Rainfall data	11
1.8.3 Elevation data	11
1.8.4 Geology data	12
1.8.5 Land cover data	12
1.8.6 Rivers and catchments	13
1.9 Document organization	13
CHAPTER 2: GEOMON – A RELATIONAL DATABASE	14
2.1 Information systems and relational databases	14
2.2 Database requirements	15
2.3 Database description	15
2.4 Database structure	16
2.4.1 BHBASE	16
2.4.2 WLMON	17
2.4.3 CHEMMON	17
2.4.4 BHImage	17
2.5 Functionality of <i>geoMon</i>	17
2.5.1 Data capture	18
2.5.2 Analysis	18
2.5.3 Reporting	20
CHAPTER 3: INTERPOLATION – WHICH GRID TO CHOOSE	22
3.1 Interpolation methods	22
3.1.1 Local interpolation methods	23
3.1.1.1 Thiessen polygon	23
3.1.1.2 Inverse distance weighted interpolation	23
3.1.1.3 Splines	24
3.1.1.4 Comments on local interpolations	24

3.1.2	Geostatistical methods	24
3.1.2.1	Kriging	25
3.1.2.2	Semi-variogram computation	26
3.2	Interpolating rainfall data	27
3.2.1	Thiessen polygons	27
3.2.2	Inverse distance weighting	28
3.2.3	Spline	28
3.2.4	Kriging	29
3.2.5	Spatial prediction using other parameters	30
3.2.6	Rainfall results – local methods	30
3.2.7	Rainfall results – deterministic interpolators	32
3.3	Water levels – how to achieve a good result	35
CHAPTER 4:	GROUNDWATER RECHARGE	39
4.1	Recharge methodology	42
4.2	Recharge per catchment	44
CHAPTER 5:	RDM – DEFINING MANAGEMENT CLASSES	47
5.1	Resource directed measures	47
5.1.1	Classification	48
5.1.2	Setting the reserve	49
5.1.3	Resource quality objectives	49
5.2	Determine the reserve using RDM	50
5.2.1	Classification	50
5.2.1.1	Delineating groundwater response units (GRUs)	50
5.2.1.2	Level of modification	50
5.2.1.3	Importance	54
5.2.1.4	Vulnerability (DRASTIC)	55
5.2.1.5	Defining management classes	57
5.3	Classification – the outputs	58
5.3.1	Geohydrological response units (GRUs)	58
5.3.2	Level of modification	61
5.3.3	Importance	62
5.3.4	Vulnerability	63
5.3.5	Management classes based on present ecological status	64
5.4	Rainfall and recharge calculations per GRU	66
CHAPTER 6:	DISCUSSION AND CONCLUSION	67
	References	70
	Personal Communications	77
	Additional Sources	78
Appendix A:	Recharge ratings	79
Appendix B:	Interpolation data	82
Appendix C:	DRASTIC ratings and weights	87
Appendix D:	<i>geoMon</i> Tables	89

TABLES

Table

1.1	Study area catchment names, main rivers and areas	9
3.1	Significance testing using different deterministic interpolation techniques	34
3.2	Comparison of analysis of variance of different Kriging techniques used to derive groundwater elevations	36
4.1	Recharge statistics per quaternary catchment	46
4.2	Comparison of variance statistics for recharge calculated from different rainfall input data sets	46
5.1	Summary of ratings per factor influencing level of modification	51
5.2	Final level of modification classification	54
5.3	Factors and weighting for calculation of importance output grid	55
5.4	Future management classes and descriptions	58
5.5	Present status and management units per GRU	64
5.6	Rainfall and recharge per GRU	66

Table

APPENDICES

A.1	Land Cover reclassification for recharge rating	79
A.2	Recharge rating classification according to slope	80
A.3	Recharge rating reclassification for depth to water level	80
A.4	Recharge percentage based on geology	81
B.1	Rainfall stations with rainfall values obtained through interpolation ...	82
B.2	Comparison of interpolated values for boreholes	83
C.1	Depth to groundwater ratings used in the DRASTIC method	87
C.2	Recharge ratings used in the DRASTIC method	87
C.3	Soils ratings used in the DRASTIC method	87
C.4	Topography (slope) ratings used in the DRASTIC method	87
C.5	Ratings used in the DRASTIC method based on underlying geology: aquifer media, impact of vadose zone and hydraulic conductivity	88
D.1	BHBASE	89
D.2	BHImage	91
D.3	WLMON	91
D.4	CHEMMON	92

FIGURES

Figure

1.1	Research design	7
1.2	Location of the study area	8
1.3	<i>geoMon</i> screenshot of data collected for borehole G31019	10
1.4	Rainfall data for rainfall stations in the Sandveld for the period 1988 to 2003	11
2.1	Data relationships in the <i>geoMon</i> database	16
2.2	<i>geoMon</i> screenshot of borehole selection screen	18
2.3	<i>geoMon</i> data capture screens	19
2.4	<i>geoMon</i> screenshot of a simple analysis of four boreholes	19
2.5	A sample of the report generated by <i>geoMon</i>	20
3.1	Components of a semi-variogram	26
3.2	Comparing local interpolators	28
3.3	Relationship between rainfall and topography for the study area	29
3.4	Variance for local interpolators using the map calculator	31
3.5	Kriging interpolation and associated standard deviation grids	33
3.6	The relationship between groundwater elevation and topography	35
3.7	Results from Bayesian interpolation: Groundwater elevations and depth to water table	38
4.1	Main factors controlling groundwater recharge	40
4.2	Natural groundwater processes	41
4.3	The GIS recharge model	43
4.4	Recharge calibration	44
4.5	Recharge comparison	45
5.1	Resource directed measures for groundwater protection	47
5.2	Derived data sets used as input to level of modification classification ..	53
5.3	Inputs to the groundwater importance rating showing intermediary results: Ecological, social and economic importance	56
5.4	Reclassified DRASTIC input layers	57
5.5	Geohydrological response units	59
5.6	Level of groundwater modification	61
5.7	Overall groundwater importance	62
5.8	DRASTIC result showing relative groundwater vulnerability	63
5.9	Proposed management units shown against present ecological status ...	65

Figure

APPENDICES

A.1	Map calculator equations for calculating recharge	80
-----	---	----

ABBREVIATIONS

°C	-	Degrees Celsius
DWAF	-	Department of Water Affairs and Forestry
EC	-	Electrical conductivity
ha	-	hectare
hr	-	hour
IWRM	-	Integrated Water Resources Management
km	-	kilometre
km ²	-	square kilometres
ℓ	-	litre
ℓ/s	-	litres per second
m	-	metre
m ³	-	cubic metre
m ³ /a	-	cubic metre per annum
m ³ /s	-	cubic metre per second
MAE	-	Mean Annual Evapotranspiration
mamsl	-	metres above mean sea level
MAP	-	Mean Annual Precipitation
MAR	-	Mean Annual Runoff
mbd	-	metres below datum
mbgl	-	metres below ground level
mg/ℓ	-	milligram per litre
mm	-	millimetre
mm/a	-	millimetre per annum
mS/m	-	milliSiemens per metre
NGDB	-	National Groundwater Database
NWA	-	National Water Act
RDM	-	Resources Directed Measures
TMG	-	Table Mountain Group
WGS84	-	World Geodetic System, 1984
WR90	-	Water Resources – South Africa, 1990
WRC	-	Water Research Commission

CHAPTER 1: INTRODUCTION

1.1 SETTING THE SCENE: THE SANDVELD

Sandwiched between the undulating wheat fields of the Swartland and the cold Atlantic Ocean, lies a sandy region called the Sandveld, the largest potato production area of the Western Cape, producing 38% of the total seed potato crop in South Africa. This agricultural crop uses large amounts of groundwater irrigated by pivot sprayers. The Sandveld has grown to one of the macro production areas in South Africa in the last 5 years, requiring increasing volumes of water (Potatoes 2004).

The West Coast of South Africa is characterized by infrequent winter rains, arid countryside, high offshore winds and high summer evapo-transpiration rates. The cold Benguela current flowing from the Antarctic contributes to the Mediterranean climate of the region, consequently the vegetation comprises mostly succulents and succulent-type plants, low bushes, sedges and some coastal fynbos. During spring, the area is transformed into a floral paradise, with wild flowers growing everywhere, forming the southwestern fringe of the famous flower carpets of Namaqualand. Various wetland systems can be found in this semi-arid paradise of which the Verlorenvlei wetland system, a declared RAMSAR site, is the best known.



1.2 FOUNDATION FOR RESEARCH

Since the hidden nature of groundwater makes it prone to misunderstanding and mismanagement, the Sandveld has been the focus of many groundwater studies. The already low rainfall in the area (< 400 mm/a) has been showing signs of decrease since 2001, yet agricultural expansion is on the increase. Significant groundwater abstraction occurs for both agricultural and municipal purposes. The sensitive and important ecosystems in the area are showing varying degrees of impact.

The National Water Act 36 of 1998 (South Africa 1998) charges the Department of Water Affairs and Forestry (DWAF) as custodians of all water resources to manage this scarce resource equitably and sustainably. As part of the water management strategy, a “Reserve” has to be determined. This “Reserve” comprises of the basic human needs reserve as well as the ecological reserve. The basic human needs reserve refers to the water required for the

essential needs of humans served by the water resource. The ecological reserve addresses the water required to sustain the ecological status of aquatic systems in the particular area. DWAF as implementers of the National Water Act (Act 36 of 1998) are calling for such a “Reserve”.

The Sandveld is showing clear signs of ecological stress and irrevocable damage. Anecdotal information abounds on the deteriorating condition of the area and the specialist studies confirm this finding (DWAF 2003b). Urgent action is required to inform water users of the status in the area, to reduce groundwater abstraction and determine optimal location of groundwater abstraction boreholes and well-fields. Management measures are needed to ensure ongoing sustainable development of the area. To this end concise, processed, integrated information must be provided, to create a management plan.

A geographical information system (GIS) is one of the most important tools for integrating and analysing spatial information from different sources or disciplines. It helps to integrate, analyse and represent spatial information and databases. Spatial interpolation is an essential feature of GIS. It is a procedure for estimating values of a variable at unsampled locations, roughly based on Tobler's Law of Geography, which stipulates that observations close together in space are more likely to be similar than those farther apart. Different approaches can be taken to calculate values for unsampled locations which may lead to very different results. These results, the visual output of interpolation, can play a crucial role in decision-making. Therefore, an understanding of the initial assumptions and methods used in the spatial interpolation process is key (Dubois 1998). A spatial and temporal database of Sandveld data, linked with GIS, has been used extensively for processing data and deriving management information.

This research originated as a result of generating information required for determining a high confidence groundwater Reserve in the Sandveld, DWAF project 2003/03/08 (DWAF 2004b). The intention of this thesis is to describe the assumptions and methods used to derive this information. It is well known that different individuals use different approaches, yielding a large assortment of distinct solutions (Genton & Furrer 1998). This study provides insight and describes the various GIS techniques, tools and methodologies used in extracting solutions which are used to determine the Reserve. It is necessary to establish a solid scientific basis for selecting various estimation procedures.

1.3 AIMS AND OBJECTIVES

One of the critical components in the “Reserve” determination process (DWAF 2004b) was to calculate a water balance for the area in order to quantify the so-called groundwater “Reserve”, which will indicate if additional allowable allocation is possible in the Sandveld. GIS and a customized relational database were used extensively for data capture, retrieval, comparison, and processing. The datasets required for the water balance calculation are discussed along with the processes to calculate the data for unsampled locations.

The aim of this study is therefore to review the data collection steps and discuss associated methodologies used to extract information that determines the groundwater Reserve of the Sandveld.

In order to fulfil this aim, the following objectives were set:

1. To present the relevance of a relational database with links to GIS for data capture, retrieval, processing and reporting.
2. To compare spatial interpolation techniques and to select and apply the best methods to extract information on a regional level.
3. To devise a method of recharge calculation and quantify the recharge for the area.
4. To devise Management Classes for the Sandveld based on objective classification using calculated data as a component of Resource Directed Measures.

1.4 LITERATURE REVIEW

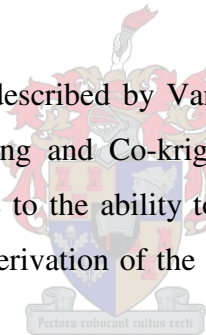
In reviewing literature for this study, the focus was three-fold: to gain an understanding of spatial statistics and geospatial techniques; to study groundwater concepts as well as specific groundwater studies in the Sandveld; and to become familiar with Resource Directed Measures (RDM) concepts. Like Gatrell (1983), the researcher found the diversity of approaches to Geography impressive, yet perplexing.

When venturing into the realm of spatial statistics methodology, the reader is overwhelmed by the complex mathematics that underpins this discipline (Isaaks & Srivastava 1989; Cressie 1991), yet the simple implementation thereof in the available software (Pannatier 1996; Van Tonder *et al.* 1996, Surfer 2002). Spatial statistics solve problems ranging from the Highland

Haggis' traversal around a mountain (McNoleg 1996) to estimating the hydraulic conductivity in the vadose zone (Li & Yeh 1999). Burrough & McDonnell (1998) gives a clear exposé of the different techniques available based on a case study without losing the non-mathematical reader.

A very useful tome of work for the uninitiated was found on the AI-GEOSTATS website (AI-GEOSTATS 2004). In 1997 the Spatial Interpolation Comparison 97 (SIC 97) was organized as a scientific exercise where participants were invited to estimate daily rainfall measurements at unsampled sites as well as their extreme values. Its objective was not only to present the variety of the possible approaches adopted by individuals when confronted with the same set of data, but also to introduce the latest developments in the science and art of spatial interpolation (Dubois 1998). Dubois (1998) observed in his introduction to the SIC97 that GIS and spatial statistics were not well integrated and usually additional statistical software would be required and that GIS often forced fixed parameters onto the user. Six years later (2004) this is still the case.

Bayesian interpolation was well described by Van Sandwyk *et al.* (1992) and compared to Ordinary kriging, Universal kriging and Co-kriging. Bayesian interpolation is especially useful in groundwater studies due to the ability to use correlated data to estimate unknown variables. Todini (2001) uses a derivation of the Bayesian interpolation model implemented by Van Sandwyk *et al.* (1992).



The progress made in spatial statistics is usually presented in journals dedicated to statistics, mining and engineering. Environmental scientists and GIS users with a different technical background are discouraged from the proper use of spatial interpolation techniques by the experience and statistical knowledge necessary for the proper use of these techniques (Dubois 1998).

Groundwater literature abounds with reports from the Water Research Commission (WRC) to the Department of Water Affairs and Forestry (DWAF). A quick overview of these documents are given in the next section "Focus on Groundwater".

Authoritative work on the RDM process as it applies to groundwater, was done by Xu *et al.* (2003). Based mainly on the work done by MacKay (1999) on classification, Xu *et al.* (2003) give a step-by-step method for moving towards Resource Directed Measures. The Institute for Water Quality Studies' website (IWQS 2003) is a useful source of information regarding

the history of RDM. Conrad & van der Voort (2000) use GIS to implement classification as part of RDM. Chapter 5 describes the RDM process in detail.

1.5 FOCUS ON GROUNDWATER

Groundwater plays a strategic role in meeting basic human needs, sustaining the environment and alleviating the impacts of drought. Groundwater is a reliable source of drinking water, locally as well as regionally. Previously groundwater was classified as private water and belonged mostly to farmers. In recognizing water as a finite resource, a new perspective has been placed on the importance of groundwater and the imperative of sustainable development of available water resources (Xu *et al.* 2003). According to Xu *et al.* (2003:5) “it is recognized that groundwater contributes between 45-60% to domestic water supply” in South Africa, so it is clear why groundwater management has been included as one of the focus areas for implementation of Integrated Water Resource Management (IWRM) in South Africa (Saayman *et al.* 2002).

To move away from traditional impact management and to successfully implement the principles set out in the National Water Act in terms of the comprehensive and pro-active protection of water resources, combined use must be made of four types of regulatory activities:

- Resource Directed Measures (RDM)

The desired protection level for a particular water resource is defined, and clear numerical or descriptive goals are set for the quality of the resource (Resource Quality Objectives).

- Source Directed Controls

Impacts on the water resource are controlled through the use of regulatory measures (registration, permits, directives and prosecution) and economic incentives (levies and fees).

- Demands on water resources are managed to keep utilisation within the limits required for protection.

- The status of water resources is monitored on a continual basis (MacKay 1999).

Various groundwater studies have focused on the Sandveld over the last thirty years. The most recent work completed in the Sandveld was a comprehensive Reserve determination

carried out in 2003 and 2004 (DWAF In press; DWAF 2004a). This followed on from the rapid Reserve determinations carried out in 2003 (DWAF 2003a; DWAF 2003b). Rapid Reserve specifications were established for a number of sites, within the six study catchments and a groundwater Reserve established for the entire area (DWAF 2003a). The specialist studies in support of the Reserve determinations included studies on the geology (including geophysical surveys), groundwater, surface water, botany, macrobenthos, fish and bird life (DWAF 2003b). In addition to this work a project funded by the Danish government (DANIDA) was conducted in the Sandveld area to test previously developed Integrated Water Resources Management (IWRM) guidelines for groundwater management in South Africa (DWAF 2003c). A number of area specific groundwater studies have been completed:

- Groundwater studies of Leipoldtville by Havenga (1989), Malan (1998) and Rasmussen (1999).
- The Wadrif well-field studies by van Doolaege (1981), Dyason (1991), Maclear (1994), van Kleef (1997) and SRK (1998).
- The Elands Bay area studies by the CSIR (1983), SRK (1985, 1986), DWAF (1992), Jolly (1992) and GEOSS (2001).
- Investigations of the Graafwater area by Jolly (1992), Visser (2002a, 2002b, 2003) and Visser & Esterhuyse (2002).
- The Sandveld area as part of the CAGE project area (Umvoto-SRK 2000).
- The Sandveld area and Citrusdal region as test areas for the Groundwater Management Guidelines developed for the Integrated Water Resources Management initiative of DWAF (DWAF 2003c).

DWAF continues groundwater monitoring and GEOSS is involved in specific monitoring to assess the impact on groundwater levels and quality as a direct result of agriculture activity. On-going work in the Sandveld is focusing on groundwater issues and includes detailed groundwater sampling, groundwater modelling and using remote sensing and field mapping for the assessment of groundwater dependent ecosystems.

1.6 RESEARCH DESIGN

According to Canter *et al.* (1994), the fundamental aspects of GIS are the five elements: data acquisition, preprocessing, data management, manipulation and analysis, and product generation. In this project, these components were used to produce the resultant output products which fed into the Reserve determination project.

As observed by Englund (1990), Burrough & McDonnell (1998), Genton & Furrer (1998), and others, creating environmental data from known points can be a daunting task in the light of the many available techniques, yielding many different results. Generating accurate data for areas that are unsampled has been the challenge of this part of the Reserve determination project (DWAF 2004b). The design for this research is summarised in Figure 1.1.

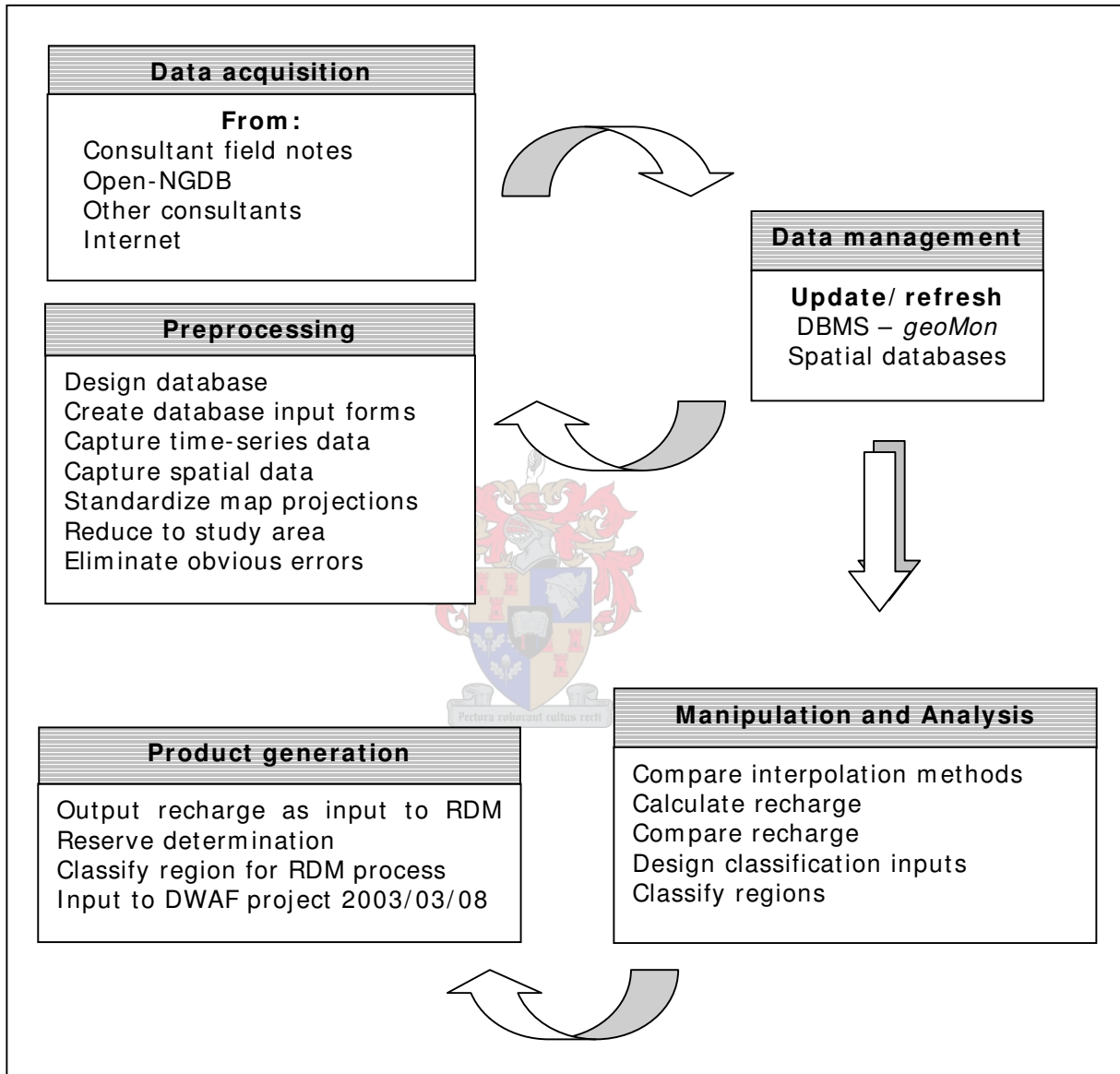


Figure 1.1 Research design

1.7 LOCATION OF STUDY AREA

The study area comprises three coastal quaternary catchments (G30E, G30F and G30G) covering three wetland systems in the Sandveld, and the three catchments feeding into the coastal catchments (G30B, G30C and G30D). The most well known of these wetland systems is the Verlorenvlei leading into Elands Bay in quaternary catchment G30E which is a declared RAMSAR area of international standing. A well-field used for municipal water supply to Elands Bay is found in close proximity to this wetland. The town of Redelinghuys is supplied from a spring at Matroozefontein (G30B), which feeds into the Verlorenvlei. This spring has a strong yield (16 L/s).

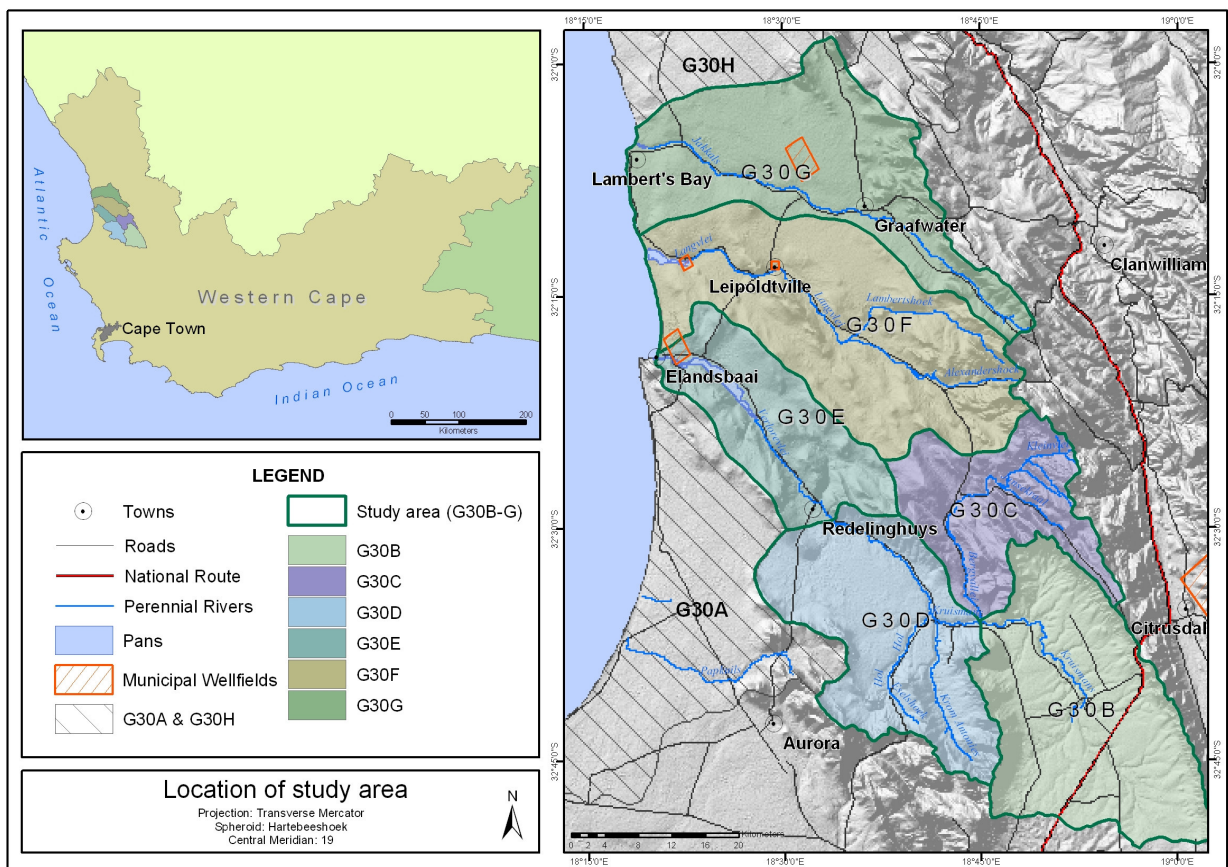


Figure 1.2 Location of the study area

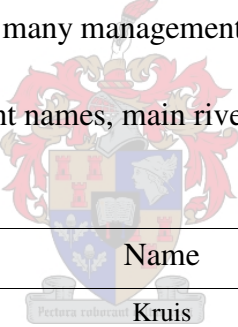
The town of Lamberts Bay (G30G) is supplied by a well-field that is found practically in the heart of the Wadrif wetland (G30F). This wetland has been seriously impacted. It has not yet recovered from an underground long-burning fire which destroyed much of the root mass of the vegetation in the wetland. The Wadrif salt pan is regarded by some to be of greater avifaunal importance than the Verlorenvlei (DWAF 2003b). Leipoldtville is upstream from

the Wadrif wetland and is supplied by a municipal borehole, which seems to be coping adequately with the demands (G30F).

The northernmost wetland in this study can be found at the town of Lamberts Bay and is called Jakkalsvlei Pan leading from the Jakkals River (G30G). A wall prevents the vlei from breaching into the sea. Investigations conducted during 2003 (DWAF 2003b) indicate that the water quality in the lower reaches become progressively more brack with progression downstream while the upper reaches are of good quality (low pH, low in salts and nutrients). Upstream on the Jakkals River is the town of Graafwater, which is supplied by a well-field just north of the town (G30G).

All of these systems were found to be largely groundwater driven or comprising groundwater dependant ecosystems (GDEs). The boundaries of quaternary catchments obtained from WR90 (Midgley *et al.* 1994) and their associated areas are listed in Table 1. Even though groundwater does not follow the natural boundaries delineated by quaternary surface water catchments as described in WR90, many management processes function at catchment level.

Table 1.1 Study area catchment names, main rivers and areas



Catchment	Name	Area (km ²)
G30B	Kruis	658
G30C	Bergvallei	351
G30D	Krom Antonie, Hol	534
G30E	Verlorenvlei	352
G30F	Langvlei	780
G30G	Jakkals	647
Total area:		3 322

1.8 DESCRIPTION OF DATA USED FOR ANALYSIS

Data selected for this study comprised spatial and non-spatial data. The various data sets are discussed in the sections that follow.

1.8.1 Groundwater levels and chemistry

Groundwater level and groundwater chemistry time-series data have been accumulated over a period of at least 8 years for most of the sampled locations. For one of the boreholes, G31019, data is available for over 20 years and the drop in groundwater level over this period can be clearly observed. This data as captured in the *geoMon* database, is depicted in Figure 1.3.

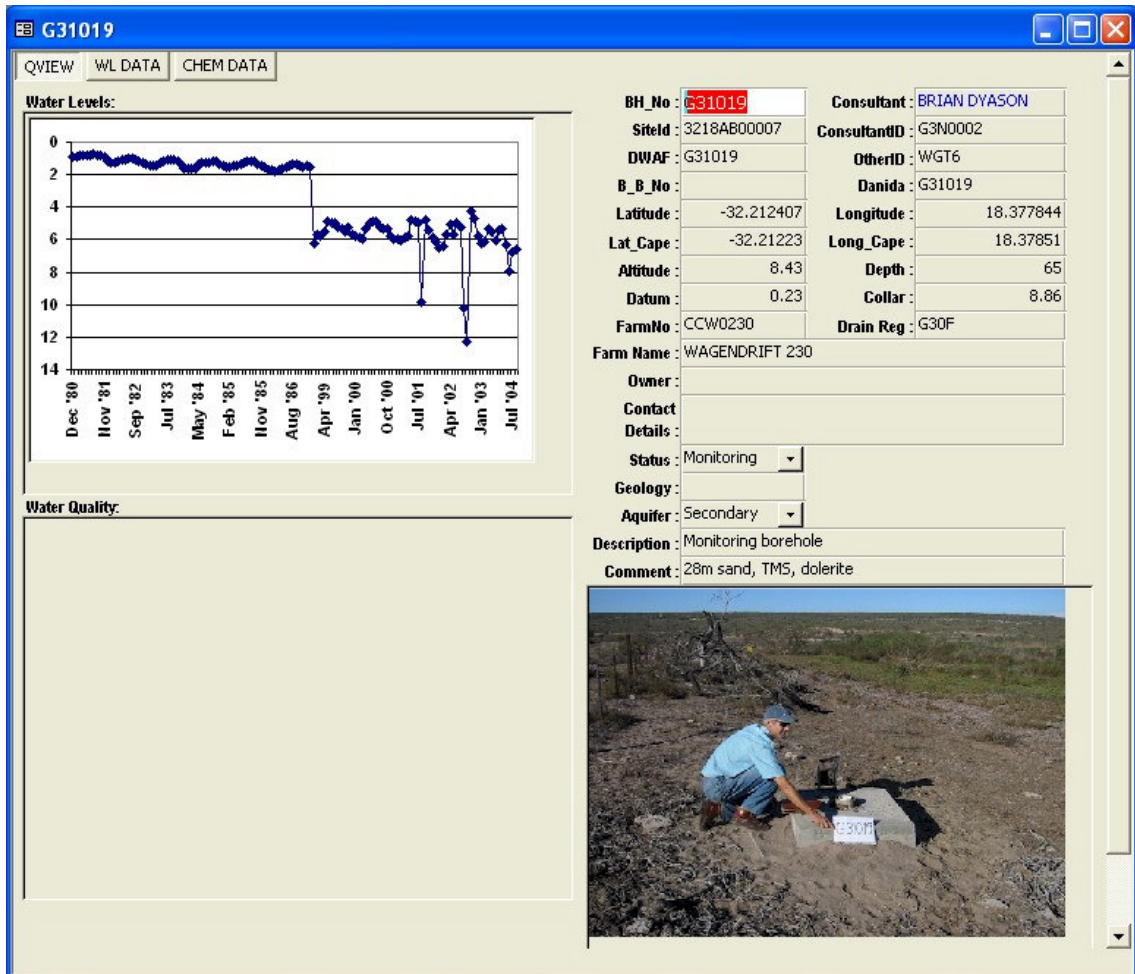


Figure 1.3 *geoMon* screenshot of data collected for borehole G31019

Groundwater data has been obtained from the DWAF Open-NGDB, GEOSS archives for various studies, DWAF regional consultant (Brian Dyason) and reports as described in section 1.5 on groundwater studies in the area.

1.8.2 Rainfall data

Rainfall data is collected by the South African Weather Bureau as well as Infruitec (Institute for Soil, Climate and Water) and can be obtained from them at a fee (COFUR or cost of furnishing the data). Rainfall stations were spatially selected and data collated and graphed. Data obtained and used for this report is shown in Figure 1.4 (the red line indicates the trend in the data). Rainfall data for 1998-2003 are compared in this study with data obtained from the South African Atlas of Agrohydrology and –climatology (Schulze 1997), which covers rainfall data for the period leading up to 1990.

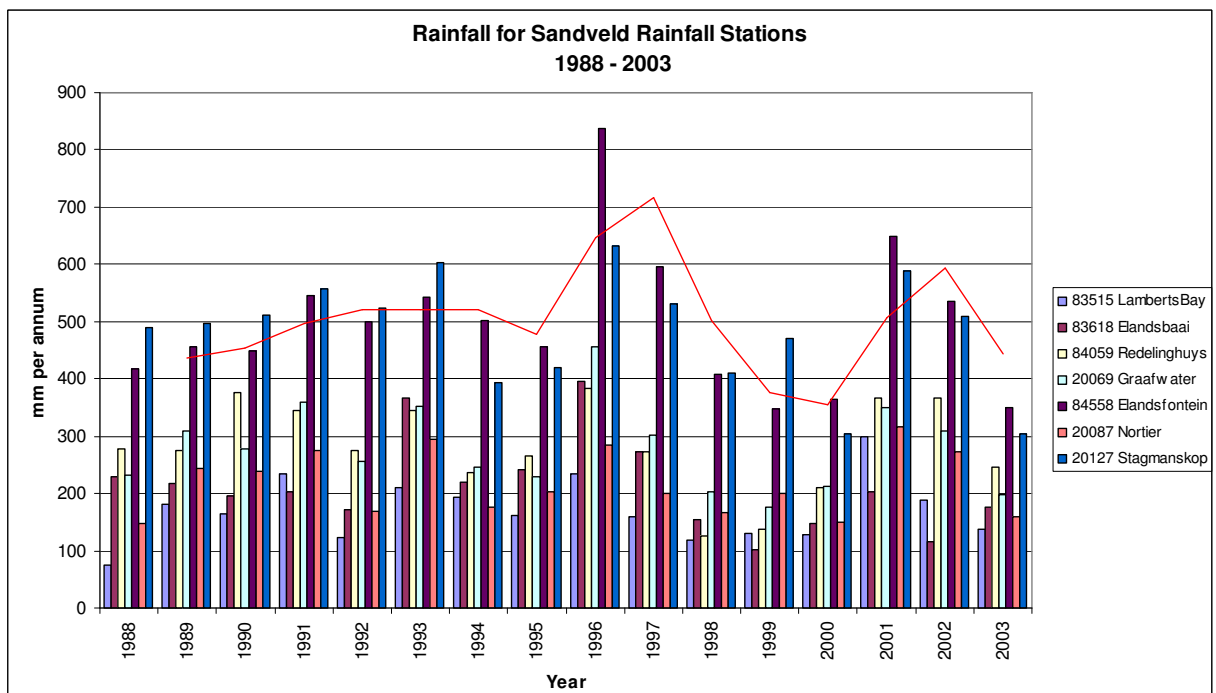


Figure 1.4 Rainfall data for rainfall stations in the Sandveld for the period 1988 to 2003

1.8.3 Elevation data

SRTM30 is a near-global digital elevation model (DEM) comprising a combination of data from the Shuttle Radar Topography Mission (SRTM), flown in February 2000 and the U.S. Geological Survey's GTOPO30 data set. The SRTM data resulted from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Imagery and Mapping Agency (NIMA), as well as the participation of the German and Italian space agencies, to generate a near-global digital elevation model (DEM) of the Earth using radar interferometry.

SRTM radar echo data were processed into elevation information in a systematic fashion using the SRTM Ground Data Processing System (GDPS) supercomputer system. Elevation data were mosaiced into more than 14,000 one degree by one degree cells producing a data set with approximately 30 meters resolution at the equator, subject to limited distribution (SRTM30 2004). A second product, with sample spacing of 3 arc-seconds (90m) was generated by a 3x3 averaging of the 1 arc-second data. This SRTM90 dataset was obtained from DWAF and used in this study.

The SRTM90 data set has certain advantages over a DEM generated from 20m contours, despite its coarser resolution, in that the raw data is regularly-spaced (originally at 30-metre intervals) and caters very well for flat areas, even showing dunes (Silberbauer 2004 (Pers com)).

1.8.4 Geology data

As part of DWAF project 2003/08/03, the Council for Geoscience resurveyed the Sandveld area, mapping the area in detail on a 1:50 000 scale (De Beer 2003). This data set was digitised by GEOSS and used as input to the recharge calculation found later in this document.

1.8.5 Land cover data

The National Land-Cover Project (NLC) is the first standardised land-cover database produced for the whole of South Africa, Swaziland and Lesotho that provides national baseline information on land-cover.

The land-cover database was mapped from a series of 1:250 000 scale precision-corrected satellite images referred to as SpaceMaps. The images were captured primarily during 1994 - 1995. The data are presented as a series of individual files with the same coverage as the standard 1:250 000 scale Surveyor General national map sheet files. The completed land-cover data set is public domain and available at a nominal cost. The standard Land-Cover Classification Scheme for Remote Sensing Applications in South Africa is based on known land-cover classes that can be identified on high-resolution satellite imagery. The 31 broad-level thematic land-cover classes in the database can be adapted to suit individual user requirements (NLC 1999).

1.8.6 Rivers and catchments

The river dataset used for this analysis was obtained from a 1:50 000 data set obtained from the Chief Directorate of Surveys and Mapping, Mowbray. The data set was clipped to catchments G30B – F using Arcview 3.2 Geoprocessing wizard. Surface water quaternary catchments were obtained from the WR90 dataset (Midgley *et al.* 1994). Only catchments G30B – F were selected using Arcview 3.2.

1.9 DOCUMENT ORGANIZATION

In this chapter, the situation in the Sandveld was explained in the light of the low rainfall and declining groundwater levels. Much data has been collected in this area, and the challenge is to be able to use the data effectively for decision-making.

Addressing data acquisition, pre-processing and data management, Chapter 2 discusses the database used to capture relevant time-series data and manage it throughout the process.

The bulk of this report is devoted to describing the interpolation techniques available to generate environmental data, a practical comparison of these techniques and selection of a preferred technique. Chapter 3 describes the methodology, data selection and results.

The focus of Chapter 4 is the practical application of interpolated data, for the calculation of recharge. The devised methodology is described. The proposed model is calibrated, results are summarised and conclusions reached.

In Chapter 5, interpolated data is used to implement a quantitative classification for the area according to RDM principles. The whole concept of Resource Directed Measures (RDM) is described in detail as well as the three essential components thereof, namely Classification, the Reserve and Resource Quality Objectives. Results from only Classification are covered by this document as the outcome of a high confidence comprehensive Reserve as well as the Resource Quality Objectives derived from Classification and Reserve determination are discussed in detail in a DWAF report entitled: *Completion of high confidence ecological reserve for the groundwater, wetland and salt pan components: Groundwater reserve determination required for the Sandveld* (DWAF 2004b). Chapter 6 concludes this document by summarising some of the pertinent findings.

CHAPTER 2: *geoMon* – A RELATIONAL DATABASE

In this chapter, the relational database used to capture time-series data for this study, is presented. The database was custom built to accommodate groundwater time-series data and integrate a manner of spatial analysis. The database requirements and structure are discussed. A short description is given of the functionality of the database and how it relates to groundwater studies.

2.1 INFORMATION SYSTEMS AND RELATIONAL DATABASES

Various databases and accompanying systems have been developed to help the groundwater consultant capture data.

DWAF, as custodians and managers of water resources, administer some of these systems, mostly on a centralised, distributable system. Groundwater records are stored in the National Groundwater database called Open-NGDB, which contains more than 225 000 borehole records. The National Groundwater Information System (NGIS) is a portfolio of projects designed to meet increasing demands for groundwater information in a rapidly changing water business environment. The system will be distributed among regional offices and will integrate both spatial and non-spatial data and information. It also accommodates increased visualisation and analytical functionality. The NGIS project includes several subprojects, amongst which the most important are REGIS Africa and the National Groundwater Archive (NGA). The NGA is a relational database management system that is to replace the Open-NGDB, mainframe based database of mainly boreholes and data related to them (DWAF 2004b). The National Water Quality Database (QUALDB), containing over 55 000 analyses of groundwater samples, mostly of macro elements, has been recently replaced with the Water Management System (WMS). Any of these elements can be queried by the groundwater consultant and information will be provided in one of many different outputs.

A need exists for a smaller tool applicable at a local level. *Aquimon* has been developed as a tool to assist managers of groundwater supply schemes at local government levels and is part of a larger CSIR project looking at the establishment of groundwater management systems on community water supplies (*Aquimon* In press). *geoMon* fits into this category of software – small and affordable, yet easy to use and customisable.

2.2 DATABASE REQUIREMENTS

Groundwater data has been monitored at selected boreholes for a number of years by different consultants. Water levels are measured, water samples are collected and sent for chemistry analysis and the results are returned to the consultants.

GEOSS (Geohydrological and Spatial Solutions) has been collecting groundwater data in the Sandveld over the last eight years and has built up a database of information previously kept in a Microsoft Excel spreadsheet. The data needs to be easily accessible and spatially enabled for analysis and reporting purposes. To this end, a relational database was built using Microsoft Access. Basic borehole details, time-series data for water levels and chemistry and a photograph are captured for each borehole via forms created in the database using Visual Basic for Applications (VBA). The database was spatially enabled using ESRI MapObjects LT™ Version 2.0, which can be freely distributed with the database. Boreholes can be selected from a menu or a spatial map. Data from other sources can be easily integrated into this database and data queries are simple to build. Using SQL connect in Arcview 3.2, data captured in the database can be accessed for analysis with the Spatial Analyst component of Arcview 3.2.

2.3 DATABASE DESCRIPTION

geoMon is a system used to capture spatial, descriptive and time-series data for use in groundwater monitoring and management. Groundwater levels as well as chemistry results from samples taken at boreholes can be captured. All information is kept per borehole. A photograph of the borehole can also be stored. Spatial information for the borehole is captured so it can be plotted on a map. A monitoring report per borehole can be printed from *geoMon*. This is useful to provide information on sampling runs and as a report to the borehole owner.

Three Microsoft Access database files (.mdb) function together as *geoMon*.

- *geoMon.mdb* contains the application: forms, code and logic to lead the user through from data entry to reporting;
- *GWmon.mdb* contains the descriptive and time-series data and is the heart of the database;

- gw_photos.mdb stores the photographs per borehole (This database is the largest component and the most static).

2.4 DATABASE STRUCTURE

The relational nature of the database ensures data integrity. Tables store the data. The relationships between the tables are shown in Fig 2.1. Usually a numeric field is used as foreign key, but it implies that the descriptive table is always needed when selecting the time-series data. The field BHNUM which contains a well-known name per borehole is used as foreign key to make the time-series data easy to share. Photos are linked in the traditional manner, using the record ID of the BHBASE table as foreign key to the BHImage table.

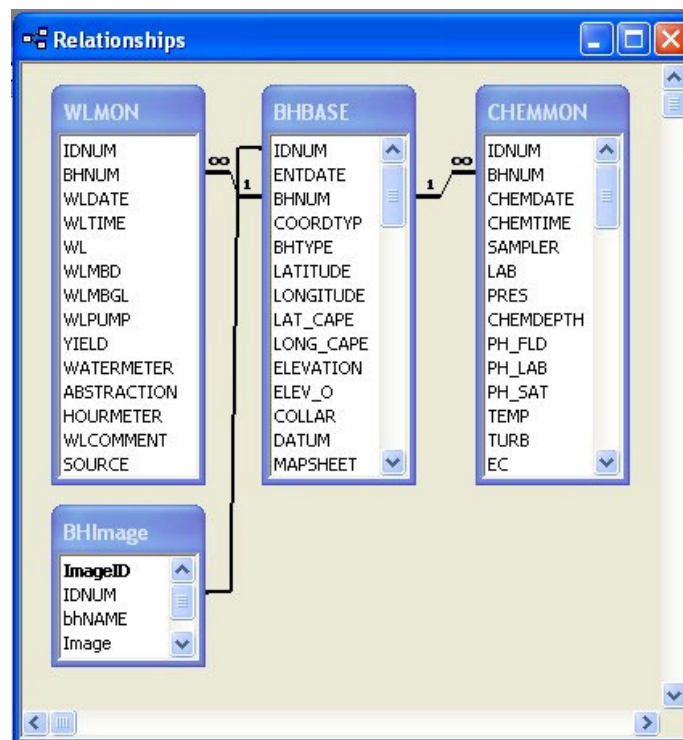


Figure 2.1 Data relationships in the *geoMon* database

2.4.1 BHBASE

This table contains all the descriptive data relating to a borehole. Borehole coordinates are captured in Geographical Units in both Cape and WGS84 projections. The field BHNUM is a unique name assigned to the borehole – there can be no duplicates. The full layout of the table can be found in Appendix D (Table D.1). The table resides physically in GWMon.mdb.

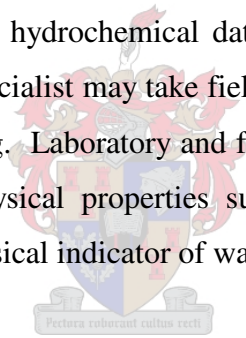
2.4.2 WLMON

The fields for this table, used to capture groundwater levels, can be found in Appendix D (Table D.3). In the table provision is made for storing water levels as sampled. Should the collar height be unknown to the groundwater specialist during sampling, the database assists by calculating the correct water levels from ground level using the collar height stored in the descriptive table BHBASE. Indexes prevent the adding of duplicate data: BHNUM, WLDATE and WLTIME make up the unique index. Water levels are captured as positive numbers. Monitoring data also known as piezometric data comprise three different types:

- Sporadic historical measurements;
- Complete hydrograph;
- Large scale measurements collected by consultants.

2.4.3 CHEMMON

This table is used to capture the hydrochemical data for the borehole water (Appendix D, Table D.4). The groundwater specialist may take field measurements and/or a sample may be sent to a laboratory for processing. Laboratory and field results can be captured in this table. Field results are mainly the physical properties such as Temperature, pH and Electrical Conductivity (EC) which is a physical indicator of water quality.



2.4.4 BHImage

This table stores the photographs per borehole and is linked to the descriptive data in BHBASE through the unique IDNUM of the BHBASE record (Appendix D, Table D.2). *geoMon* has been custom designed to capture essential data for groundwater management and analysis. The relational nature of the database ensures integrity and accuracy. The functionality, described in the next section, has been customised to suit the needs of someone capturing and querying groundwater data per borehole or per region.

2.5 FUNCTIONALITY OF *geoMON*

geoMon is used for data capture, simple analysis and reporting of borehole time-series data, comprising groundwater levels and groundwater quality data. All forms in the database are created in Microsoft Access with VBA interfaces, which make them easy to customise and update should user requirements change.

2.5.1 Data capture

Data capture can be done per borehole using the forms created using VBA, or imported from an external source such as a Microsoft Excel spreadsheet or a DBF file. The borehole can be selected from a list or spatially selected from the map. Figure 2.2 shows the borehole selection screen, with a borehole list as well as a selectable map.

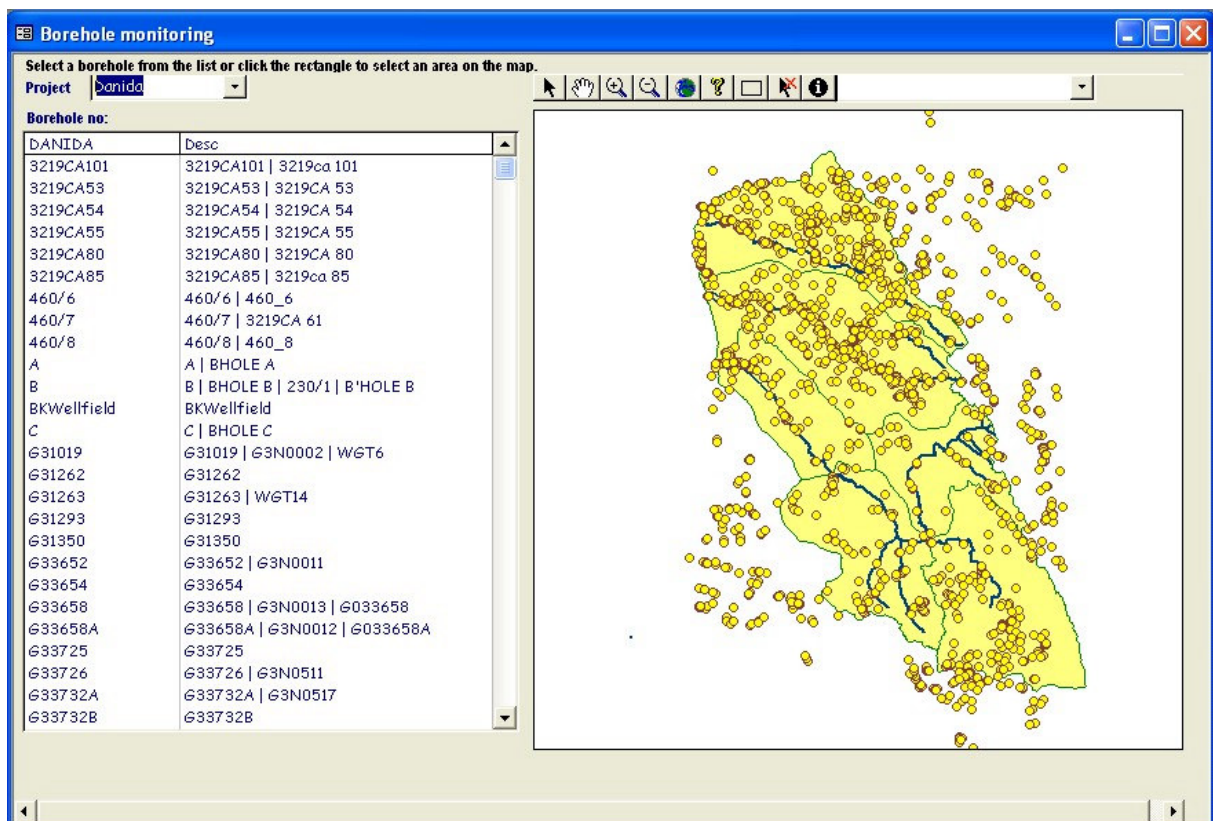


Figure 2.2 *geoMon* screenshot of borehole selection screen

Figure 2.3 (a) details the descriptive data captured per borehole, while Figure 2.3 (b) shows the groundwater level input form. Chemistry data can be captured on two levels: basic field measurements (pH, EC and temperature) with a further data capture screen for laboratory results.

2.5.2 Analysis

geoMon has limited spatial analysis capabilities, but is a powerful tool when used in conjunction with the Spatial Analyst component of Arcview 3.2. *geoMon*, however, has all the data analysis components available to Microsoft Access built in. The status of a borehole can be seen at a glance from the descriptive data capture screen (Figure 2.3 (a)) which shows the

groundwater level trend as well as the groundwater chemistry trend as portrayed by the electrical conductivity measured from the groundwater.

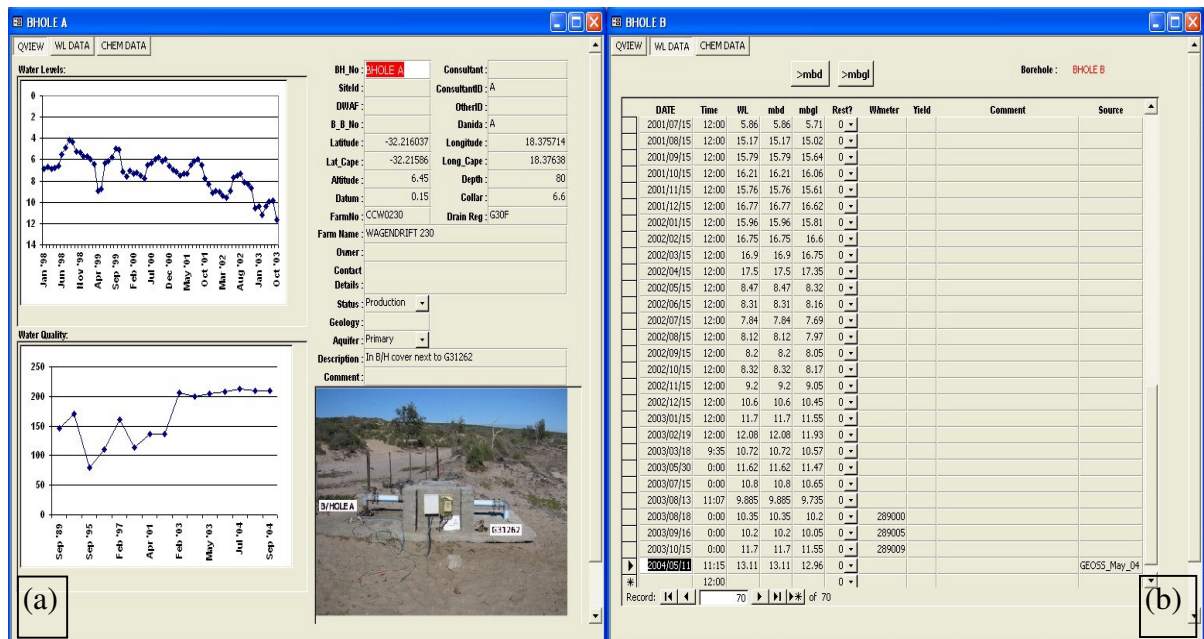


Figure 2.3 *geoMon* data capture screens [(a) descriptive data per borehole and (b) groundwater level data]

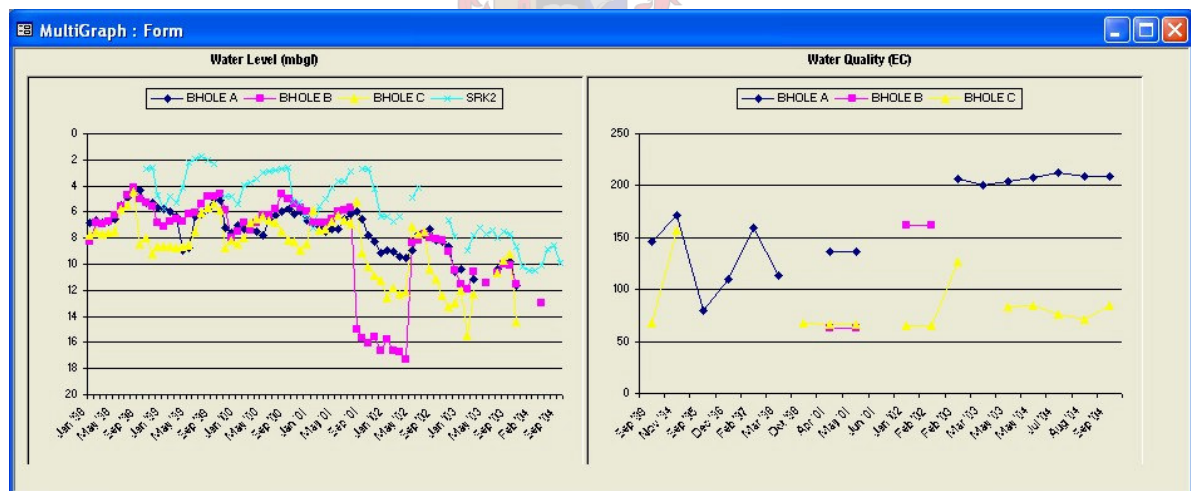


Figure 2.4 *geoMon* screenshot of a simple analysis of four boreholes

Two or more boreholes can be compared by selecting them from the list or the map on the data selection screen (Figure 2.2). The resultant comparison can be seen Figure 2.4. Data selection can also be done in the native Microsoft Access environment. Data from Microsoft Access can easily be exported and saved in many available data set formats.

2.5.3 Reporting

The standard report that can be generated from *geoMon* is useful for field work. It serves as a data capture sheet as well as a hydro census report, which can be given to the borehole owner. An example of this report can be seen in Figure 2.5. The report is created as a HTML document and stored to disk. This document can be opened using Microsoft Word for additional editing if required. Graphs and pictures are reusable and saved in a subdirectory under the borehole name.

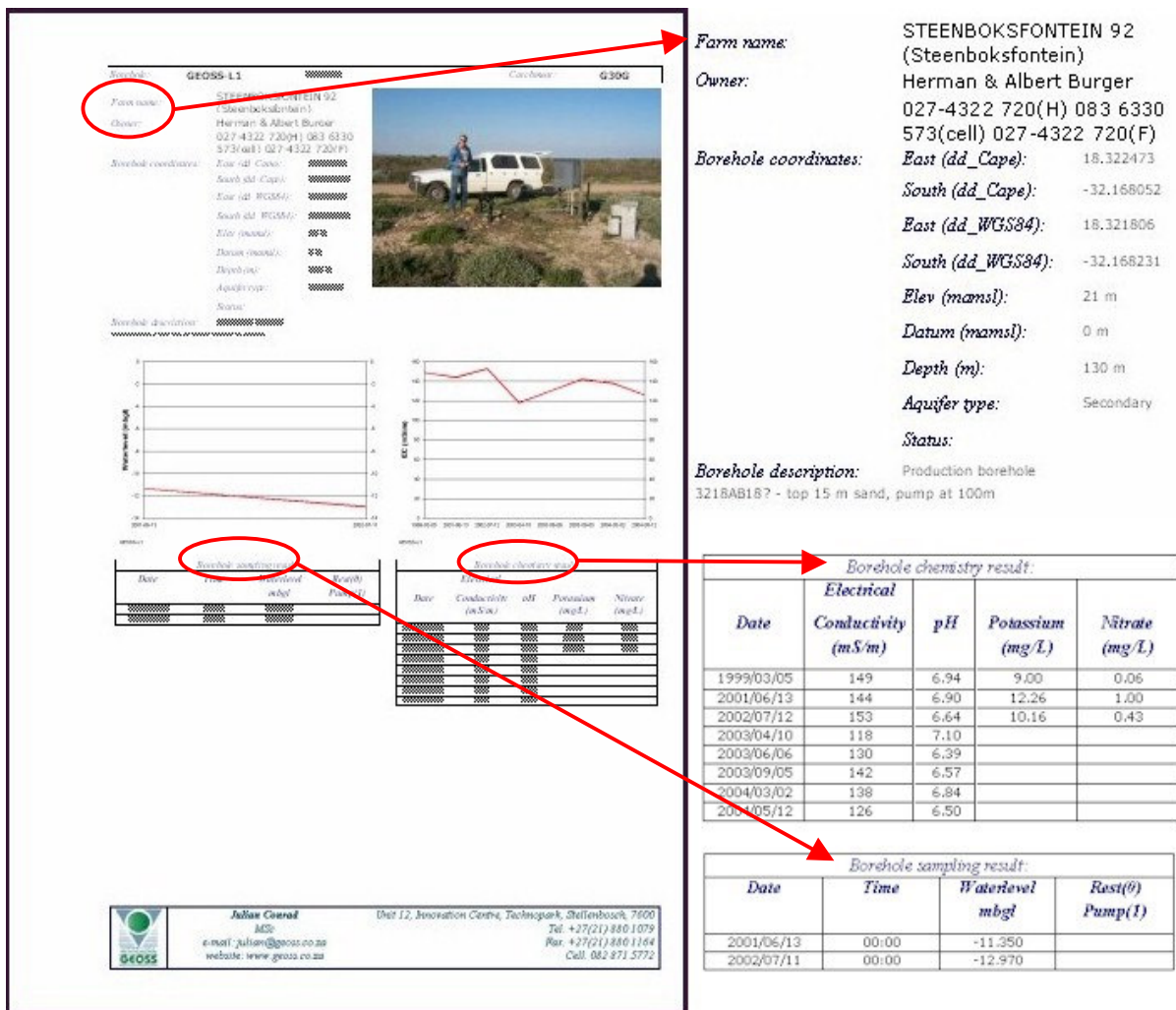
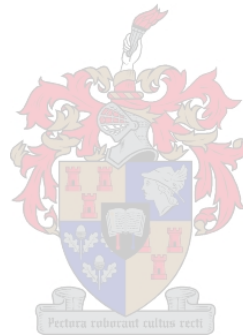


Figure 2.5 A sample of the report generated by *geoMon*

The *geoMon* database is constantly evolving as functions are added or data requirements change. It remains a useful source for extracting information for use. Due to the nature of the data store, it is easy to extract selected information merely by building a query using the built-in facilities supplied by Microsoft Access. Data can easily be exported to any of the many

supported formats. Data obtained from other groundwater consultants can be added by importing their data to the *geoMon* Access tables.

Groundwater level time-series data from the *geoMon* database was selected for use in the interpolation comparisons described in Chapter 3 and the recharge calculation in Chapter 4. Groundwater chemistry data and groundwater level data were extracted as inputs to the classification which is discussed in Chapter 5.



CHAPTER 3: INTERPOLATION – WHICH GRID TO CHOOSE

In this chapter, the reader will be introduced to various techniques and software packages that can be used to create a continuous surface from measured point values such as rainfall data per rainfall station or groundwater levels per borehole obtained from *geoMon*. From a continuous surface, spatial patterns in the data can be studied and compared to “other spatial patterns of other spatial entities” (Burrough & McDonnell 1998).

3.1 INTERPOLATION METHODS

When dealing with environmental data such as the occurrence of groundwater or rainfall which cover vast areas, it is not possible to measure these variables at all relevant points in space. Interpolation is a method to extract values for variables at unsampled points from measurements made at known locations within the same area. Data is converted from point observations to continuous surfaces so as to observe and compare spatial patterns. The theory of interpolation is based on the assumption that, on average, values at points close together in space are more likely to be similar than points further apart (Burrough & McDonnell 1998).

Most interpolation methods are only classes of procedures, containing many possible variations accessible to the researcher. Much can be said for the simple good sense method (Genton & Furrer 1998) where common sense, local knowledge and experience contribute to the interpolation process done without computer assistance.

Interpolation methods can be classified as exact (predicts a value identical to that measured) or inexact interpolators. The quality of an inexact interpolation method can be measured by looking at the statistics of the differences between measured and predicted values at data points (Burrough & McDonnell 1998).

Local deterministic interpolation methods need an understanding of deterministic or simple statistical methods. Local interpolation functions are: nearest neighbour, linear interpolators, splines and other non-linear functions. These local functions smooth the data to some degree in that they compute an average value within a window or search distance.

Geostatistical interpolation methods (e.g. Kriging) use the principles of spatial autocorrelation. These methods are used when simple methods of interpolation may give unreliable predictions and provide estimates of the quality of the interpolation. Predictions

can be made for areas greater than the sampling area. Geostatistical methods also permit the interpolation of indicator functions and can incorporate soft data to guide interpolation, thereby increasing the precision of the results.

In this section, local interpolation methods will be discussed, before venturing into geostatistical methods. First the theory behind the methods used will be described, then the methodology for each technique used, followed by the results and synthesis.

3.1.1 Local interpolation methods

Methods of interpolation can be divided into global and local interpolators (Burrough & McDonnell 1998). Global interpolators provide predictions for the whole area of interest, such as the regional trend, while local interpolators operate within a small zone around the point being interpolated to ensure that data from the immediate neighbourhood is considered. The local interpolation methods discussed in this chapter include: Thiessen polygons, inverse distance weighting and splines.

3.1.1.1 Thiessen polygons

The single nearest data point predicts the value of an attribute at an unsampled location. Thiessen polygons divide the region up in a way that is determined by the location of the data points, with one observation per cell. The form of the final map is determined by the distribution of the observations, creating a homogenous polygon which changes abruptly at the boundary. Tobler (1979) devised a solution known as pycnophylactic interpolation which creates a smooth surface removing the abrupt changes at boundaries.

3.1.1.2 Inverse distance weighted interpolation

With this method, the assumption is that the value of an attribute at an unsampled point is a distance-weighted average of data points that occur in a window around the unsampled point. The form of the inverse distance weighting predictor is given by the equation:

$$\hat{z}(x_0) = \frac{\sum_{i=1}^n z(x_i) d_{ij}^{-r}}{\sum_{i=1}^n d_{ij}^{-r}}$$

where x_j are the points where the surface is to be interpolated, x_i are the data points, d is the distance, r is the power parameter.

The inverse distance weighted (IDW) interpolator weights points closer to the processing cell greater than those farther away. The form of the resulting map is dependent on the value of the radius of the search window or a specified number of points required within the search radius. The power parameter in the IDW interpolation determines the influence of the surrounding points upon the interpolated value. A higher power results in less influence from distant points. A barrier input line theme can be used that will limit the search for input sample points. This usually increases the interpolation time. Inverse distance interpolation commonly has a “duck-egg” pattern around outlier data points.

Inverse distance interpolation is an exact interpolator: interpolated values match input values exactly. The method has no inbuilt method of testing for the quality of predictions and data quality has to be assessed by taking extra observations.

3.1.1.3 Splines

Splines are the modern mathematical equivalent of the flexible ruler used by draughtsmen to obtain a smooth curve (Burrough & McDonnell 1998). They are fitted to a small number of data points exactly while ensuring that the joins between one part of the curve and another are continuous. A problem of using splines for interpolation is the choice of break points to coincide with data points or to be interleaved with them. With splines the maxima and minima do not necessarily occur at the data points.

3.1.1.4 Comments on local interpolators

Burrough & McDonnell (1998) found that the IDW method with a power parameter of 2 gave results closest to the original data. None of these methods so far can provide direct estimates of the quality of the predictions made other than through validation points (not yet sampled). These would incur additional cost to the project. There is no method of knowing whether the best values have been chosen for the weighting parameters or if the size of the search neighbourhood is appropriate. Control parameters can be varied to produce different estimates of the distribution of the variable being mapped.

3.1.2 Geostatistical methods

When the spatial variation of a continuous attribute is too irregular to be modelled by a simple, smooth mathematical function, geostatistical methods of interpolation, better known as Kriging (after South African mining engineer, D.G. Krige) are used. Kriging not only

yields an estimate of the random variable, but also the error in the estimate (Burrough & McDonnell 1998).

3.1.2.1 Kriging

The best-known estimation method, based on this approach, is Ordinary Kriging. The spatial variability of an attribute is described in statistical terms, through the Theory of Regional Variables. Regionalized variable theory divides spatial variation into: (a) average behaviour such as mean levels or a trend; (b) spatially correlated, but irregular (random) variation; and (c) random, uncorrelated local variation or noise. A mathematical equation describes the relationship between these components.

$$Z(x) = m(x) + \varepsilon'(x) + \varepsilon''$$

where $m(x)$ is a deterministic function describing the average behaviour or trend, $\varepsilon'(x)$ denotes the spatially correlated variation and ε'' is spatially independent noise, also known as the nugget in the semi-variogram. To determine the terms of the mathematical equation, a semi-variogram is computed (Section 3.1.2.2). Since Kriging is a linear procedure, difficulties are experienced if the variable to be estimated contains a non-linear trend or drift.

Often data may be available for more than one attribute per sampled location. If the attributes are spatially correlated, it may be possible to use the information about one variable to help derive the other. Co-kriging, a multi-variate extension of Kriging, can be used. Co-kriging can produce predictions for both points and blocks (Isaaks & Srivastava 1989 in Burrough & McDonnell 1998), but needs information on the joint spatial covariation of both variables. Co-kriging is a difficult technique to carry out and some feel that the effort of doing this is too much for the results obtained (Burrough & McDonnell 1998).

An alternative that appeals to many environmental scientists is to use the knowledge from empirical (regression) transfer models as part of the Kriging procedure. This is sometimes known as Universal Kriging or KT Kriging (Burrough & McDonnell 1998) or Kriging in the presence of external trends. Bayesian Kriging is an implementation of this type of Kriging. When using Bayesian Kriging, the classical statistical analysis of Ordinary Kriging is replaced by a Bayesian statistical analysis. Using the Bayesian approach, expert knowledge of the variable can be expressed with a qualified guess that can be included in the estimation (Van Sandwyk *et al.* 1992).

3.1.2.2 Semi-variogram computation

The semi-variogram is a measure of how quickly things change on the average (often referred to as the drift or trend). The underlying principle is that, on the average, two observations closer together are more similar than two observations farther apart (stationarity). Because the underlying processes of the data often have preferred orientations, values may change more quickly in one direction than another (anisotropy). During the construction of a variogram, all observations in a data set are compared to all other observations, and for each distance h between observations, a semi-variance function $\gamma(h)$ is computed which is half of the variance for those observations (Figure 3.1). Non-spatial, stochastic variation shows up as a baseline or "nugget" variance which is the value of γ at $h=0$. Spatial variation shows up in the values of γ as h increases. A common pattern for variograms is for γ to increase up to certain values of h , and then remain nearly constant or only increase slightly for higher values of h . The value of h where γ no longer increases is called the range (a), and the value of γ at this h is called the sill (Shine & Krause 2000).

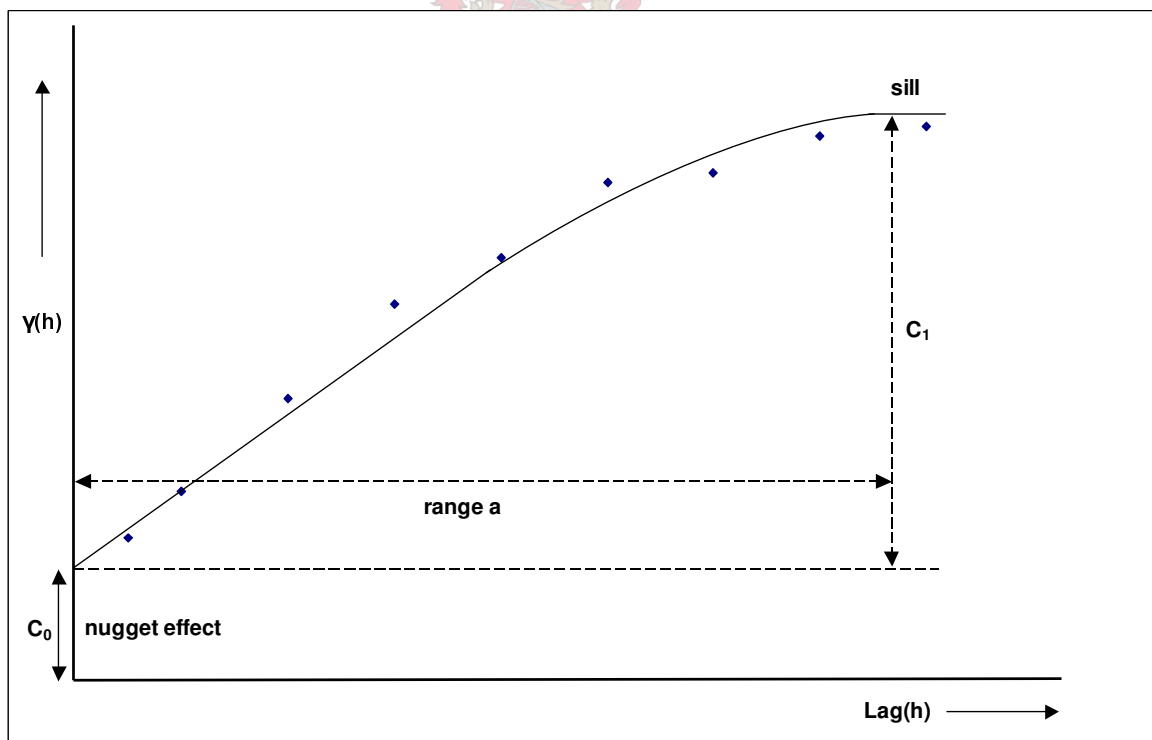


Figure 3.1 Components of a semi-variogram

A mathematical function is fitted to the semi-variogram values. The semi-variogram curve, the statistic of the data observations, is compared with theoretical variogram models. Various

theoretical models exist, such as the nugget effect model, the power model, the spherical model and the exponential model. The model with the best fit is chosen and the mathematical function associated with the particular model is used for estimating the required surface via Kriging (Shine & Krause 2000).

3.2 INTERPOLATING RAINFALL DATA

Rainfall data is collected at rainfall stations situated at various locations distributed over the study area. The location of the rainfall stations can be seen in Figure 3.2 against the backdrop of a rainfall grid obtained from Schulze (1997) covering the average rainfall for the ten years leading up to 1994. Selecting an interpolation technique best suited for the particular data, is a challenge. Rain-gauge measurements tend to be more accurate at the collection point while their spatial significance decays with distance and area (Todini 2001).

Four different local interpolation methods were applied to the average rainfall data obtained from Weather SA and Infruitec for the five-year period 1998-2002 and compared with the existing dataset. The data to be interpolated can be found in Table B.1 in Appendix B. Arcview 3.2 functionality and scripts were used to execute IDW and Spline methods. Surfer 8.0 was used for the different Kriging techniques due to the ease with which the semi-variogram could be computed (Surfer 2002). In the absence of estimates of the quality of the predictions, the Arcview Map Calculator was used to subtract the interpolated grids from the control data set, to compare the accuracy of the predictions.

3.2.1 Thiessen polygons

Using an Arcview 3.2 script, Thiessen polygons were derived for the study area. Selecting different boundaries for the study area gave varying results. Three cases were analysed:

- T1: An area greater than the six quaternary catchments bounded by the 1:50 000 mapsheet on which the particular catchment is situated. Twelve values were excluded.
- T2: The study area of six catchments. Twenty-five rainfall readings were excluded.
- T3: All readings were included buffered by a ten percent area around the points.

3.2.2 Inverse Distance Weighting

Using Arcview 3.2 Spatial Analyst, a grid was interpolated. IDW was selected as interpolation method to estimate the rainfall surface. Twelve points were selected as “nearest neighbours” and the power value (n) was set to 1, 2 and 4. The power parameter in the IDW interpolation controls the significance of the surrounding points upon the interpolated value. A higher power results in less influence from distant points.

3.2.3 Spline

After selecting Spline as interpolation method in Arcview 3.2 (with Spatial Analyst extension switched on), a spline type of “regularised” was selected, then “tension” as the spline type. Weight and number of points remained on the default values of 0.1 and 12.

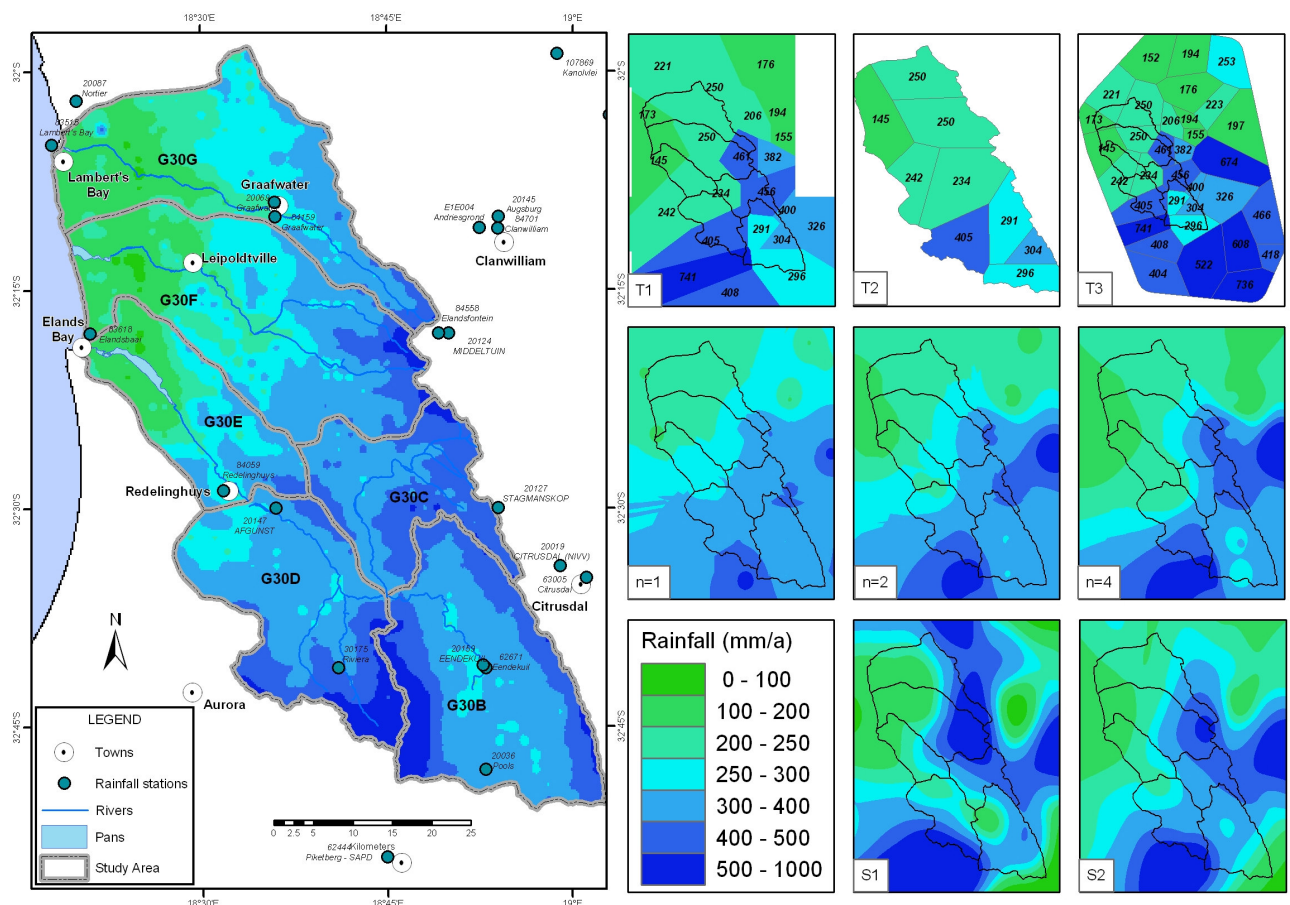


Figure 3.2 Comparing local interpolators [Thiessen polygons (T1, T2, T3); IDW (n=1, n=2, n=4); Spline methods (S1, S2) compared to data from Schulze (1997)]

3.2.4 Kriging

Kriging using Surfer 8.0 produced visually appealing maps from irregularly spaced data. Three semi-variograms were estimated: one with no drift, a second with linear drift and a third with quadratic drift. Point Kriging estimated the values of the points at the grid nodes. Block Kriging estimated the average value of the rectangular blocks centered on the grid nodes, thereby generating smoother contours (block averaging smooths). The following methods were compared:

- Point Kriging with
 - no drift
 - linear drift
 - quadratic drift
- Block Kriging with
 - no drift
 - linear drift
 - quadratic drift

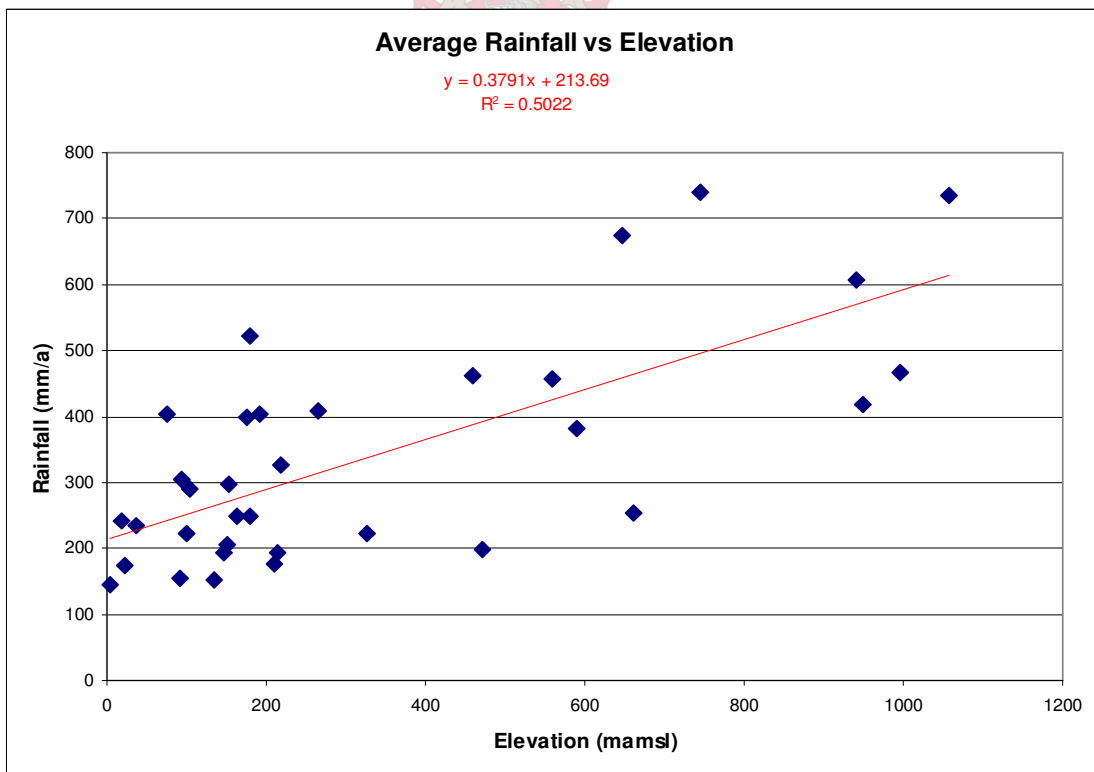


Figure 3.3 Relationship between rainfall and topography for the study area

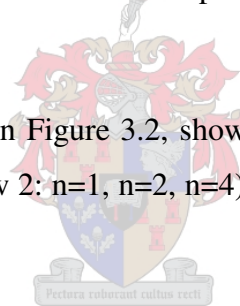
3.2.5 Spatial prediction using other parameters

Since a digital elevation model (DEM) of the area is available in SRTM90, it was considered using a regression type statistical technique such as simple regression (Atkinson & Lloyd 1998; Hutchinson 1998). For this study area and data set it was found that rainfall and elevation were weakly correlated ($r=0.709$; $p<0.0001$; $R^2=0.5022$) as illustrated in Figure 3.3, probably since all available rain gauges were used in the correlation equation and rain shadow effects were not taken into account. A rainfall grid was calculated using the linear regression equation.

3.2.6 Rainfall results – local methods

Figure 3.2 shows the result of applying Thiessen polygons, IDW and Spline as interpolators. The newly created rainfall surface for each method was classified in the same manner as the control dataset obtained from Schulze (1997). The larger map in Figure 3.2 shows the rainfall stations from which data was extracted for this experiment against the backdrop of the data set obtained from Schulze (1997).

The three rows of smaller maps in Figure 3.2, show the results from: (a) Thiessen polygons (row 1: T1, T2, T3); (b) IDW (row 2: $n=1$, $n=2$, $n=4$); (c) Spline (row 3: S1 “regularised”, S2 “tension”) methods.



None of these interpolators provided statistics on the goodness of fit of the data. Being exact interpolators, these methods estimate a value for rainfall at the existing observation points which is the same as the measured value. A visual examination of the results is required if no additional observations can be made. The grid calculation (using Arcview 3.2 Spatial Analyst’s Map Calculator) done between the control data set and the various resultant grids, to quantify the variation obtained using the interpolation methods, can be seen in Figure 3.4.

Figure 3.4 shows the variation between the control data set and the interpolated data sets for: (a) Thiessen polygons (row 1: T1, T2, T3); (b) IDW (row 2: $n=1$, $n=2$, $n=4$); (c) Spline (row 3: S1 “regularised”, S2 “tension”) methods.

When examining the graph in Figure 1.4 showing the rainfall for the area, it can be observed that rainfall for the period leading up to 1994 as used in the control data set (Schulze 1997), is higher than for the period (1998 – 2002) which was used for this analysis. Thiessen polygons in T1 and T3 provide values in similar ranges to the control data set (Schulze 1997). T2

misses out on the higher rainfall values obtained from the mountainous areas east of the study area. T2 also shows significant over-estimation in the three coastal catchments.

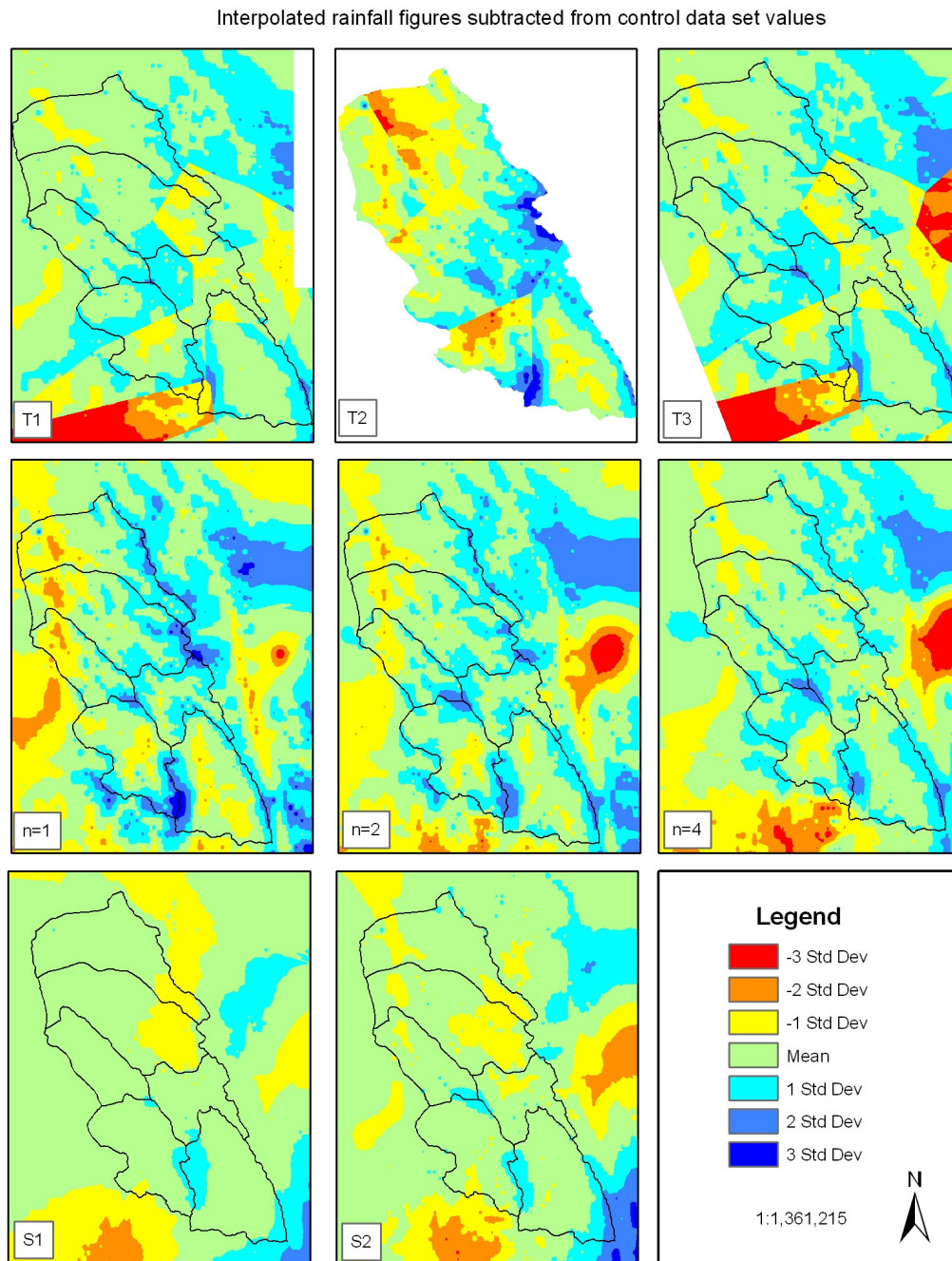


Figure 3.4 Variance for local interpolators calculated using the map calculator

With the IDW method, it appears as if the data set obtained by specifying $n=2$, provides a better fit, highlighting the very low rainfall at the coast and the much higher rainfall figures for the eastern areas at higher elevations, despite the overestimation in the coastal catchments. This is analogous to what Burrough & McDonnell (1998) documented in their analysis of zinc

data on the floodplain of the River Meuse in the Netherlands. IDW with $n=4$ seems to accentuate the lower rainfall in catchment G30B.

The Spline method with type “tension” (S2) provides a very good comparison, but extends the lower rainfall into catchment G30D. The pattern produced by the regularised spline method does not seem suitable at all. The spline interpolation method unfortunately produces very high and very low values, with differences between the control data set and interpolated values ranging from -905 to 1744 . If the interpolated surface is to be used for quantitative analysis, incorrect calculations may result.

3.2.7 Rainfall results – deterministic interpolators

Figure 3.5 shows the grids created by using the different Kriging techniques as well as the regression technique using elevation data. An output grid of Kriging Standard Deviations is shown for each of the grids created using the Kriging method. The estimated rainfall versus control data set rainfall for each of the methods is shown in the scatter plot in Figure 3.5. Table B.1 (Appendix B) shows the rainfall at the selected rainfall stations for each of the methods used.

The analysis of variance in Table 3.1 describes the statistical relationship between the control data set (Schulze 1997) and the input data set, and then between the control data set and each of the interpolated grids (“between groups” source of variation column in Table 3.1). The “within groups” source of variation indicates the variance within the particular interpolated grid. From the analysis of variance (ANOVA) between the interpolation input data set and the various Kriging results seen in Table 3.1, the F-test indicates that Kriging with a quadratic drift gives the best result, whether it be Point Kriging or Block Kriging.

The standard deviation map in Figure 3.5 shows that Point Kriging with quadratic drift has the smallest amount of over- and under-prediction of rainfall values. Stations without interpolated rainfall values were not included in the statistical analysis. Table 3.1 shows that none of the methods can predict the high rainfall values accurately which leads one to believe that there be an underestimation of rainfall using any of these methods.

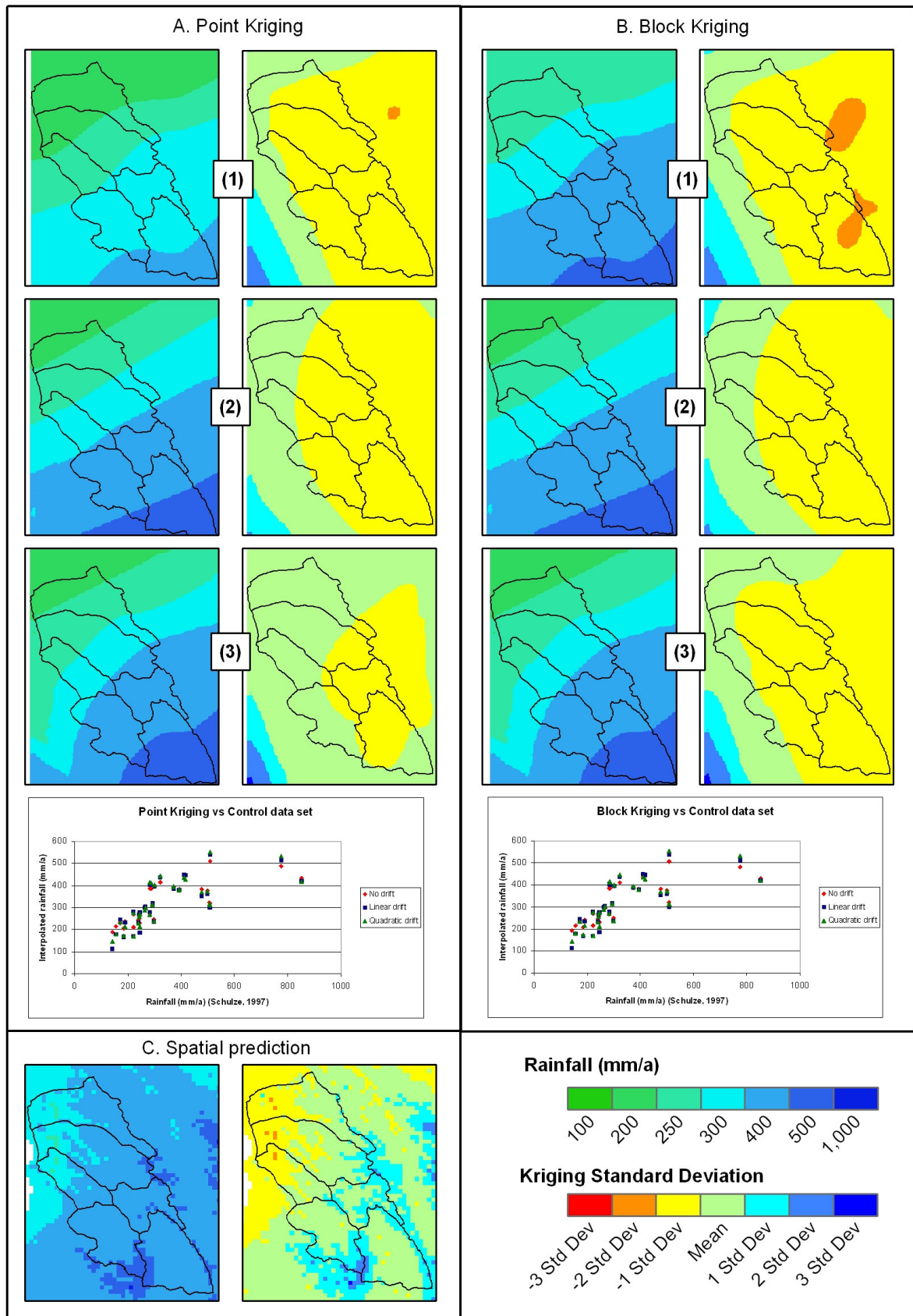


Figure 3.5 Kriging interpolation and associated standard deviation grids. [(A) Point Kriging; (B) Block Kriging with (1) no drift, (2) linear drift, (3) quadratic drift; (C) Spatial prediction]

Table 3.1 Significance testing using different deterministic interpolation techniques

Data sets	ANOVA						
	Source of variation	SS	df	MS	F	p-Value	F crit
Control data set Vs. Interpolation input	Between groups	3026.893	1	3026.893	0.102715	0.749609	3.986273
	Within groups	1944953	66	29469			
	Total	1947980	67				
Interpolation input Vs. Point Kriging No drift	Between groups	116.6376	1	116.6376	0.007121	0.933032	4.001194
	Within groups	982795.8	60	16379.93			
	Total	982912.4	61				
Interpolation input Vs. Point Kriging Linear drift	Between groups	87.96583	1	87.96583	0.004934	0.944236	4.001194
	Within groups	1069769	60	17829.49			
	Total	1069857	61				
Interpolation input Vs. Point Kriging Quadratic drift	Between groups	2.911026	1	2.911026	0.000163	0.989868	4.001194
	Within groups	1074173	60	17902.88			
	Total	1074176	61				
Interpolation input Vs. Block Kriging No drift	Between groups	145.973	1	145.973	0.00905	0.924528	4.001194
	Within groups	967800.1	60	16130			
	Total	967946.1	61				
Interpolation input Vs. Block Kriging Linear drift	Between groups	87.96583	1	87.96583	0.004934	0.944236	4.001194
	Within groups	1069769	60	17829.49			
	Total	1069857	61				
Interpolation input Vs. Block Kriging Quadratic drift	Between groups	6.661663	1	6.661663	0.000372	0.984671	4.001194
	Within groups	1073765	60	17896.09			
	Total	1073772	61				
Interpolation input Vs. Spatial prediction	Between groups	986.1763	1	986.1763	0.060803	0.805996	3.986273
	Within groups	1070465	66	16219.17			
	Total	1071451	67				

3.3 WATER LEVELS – HOW TO ACHIEVE A GOOD RESULT

Groundwater levels vary in time and space in ways too complex to represent with simple deterministic functions. It is also extremely difficult to measure at all locations of interest. Groundwater levels are an indicator of the stress the area is under and used to define the groundwater-surface water interaction and show the flow of groundwater. For the area, 187 points have sampled data that is recent and accurate.

Groundwater elevation was calculated by subtracting the measured groundwater level (mbgl) from the observed elevation. The latest available groundwater level data for each point selected from *geoMon*, was used in the interpolation. Upon examination, it was found that in this study area, groundwater elevation and topography are highly correlated ($r=0.989$; $p<0.0001$; $R^2=0.9776$), indicating that the aquifer is mainly unconfined. The relationship between groundwater elevation and topography is shown in Figure 3.6. It was therefore decided to use Ordinary Kriging, Bayesian Kriging and Kriging with added information to extract a groundwater elevation grid.

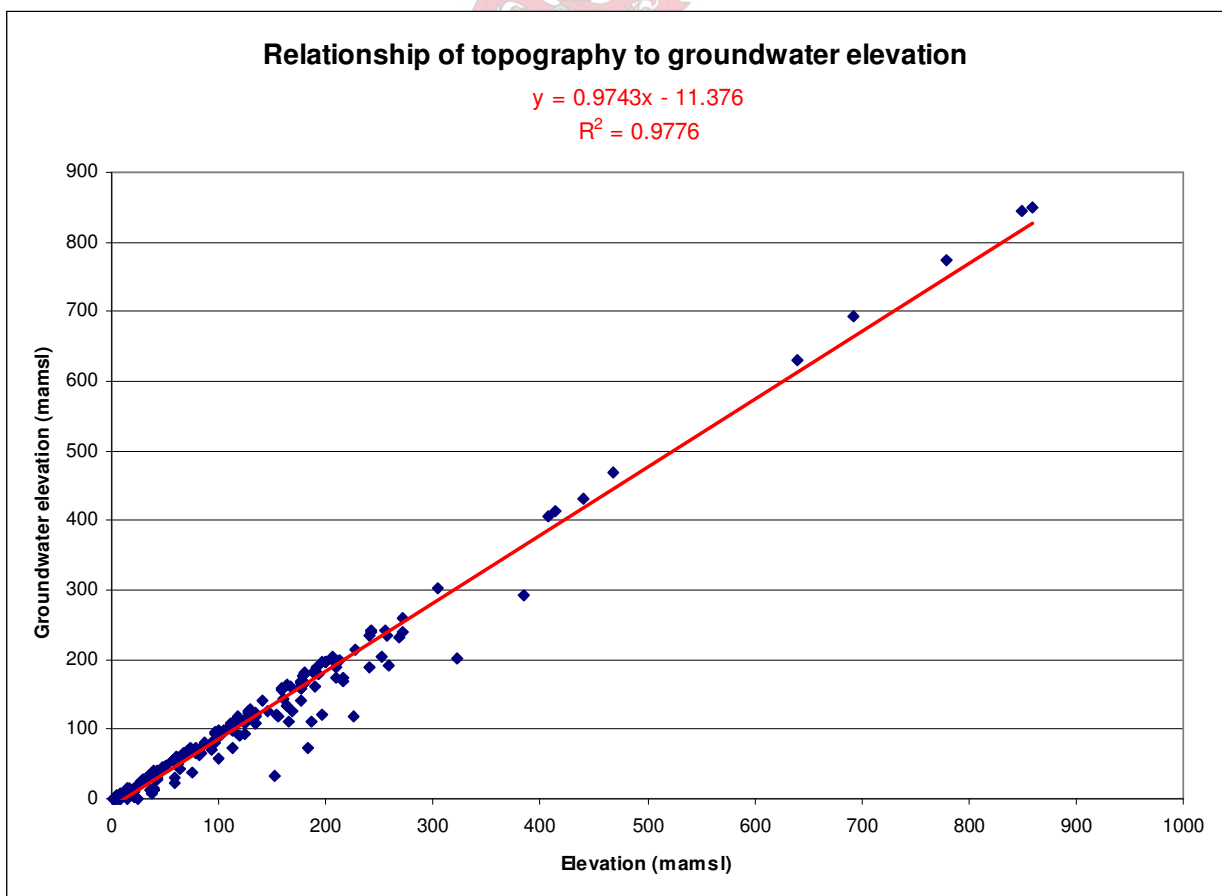


Figure 3.6 The relationship between groundwater elevation and topography.

Elevation is a frequently sampled observation that can be obtained from the DEM (SRTM90). TRIPOL, a program created by the Institute for Groundwater Studies (Van Tonder *et al.* 1996), can use this expert knowledge about a given regionalized variable (elevation) as a qualified guess to derive groundwater elevation. Surfer 8.0 was used to apply Ordinary Kriging since the speed of interpolation was quick and the resulting standard deviation grid was easy to produce. Using analysis of variance, the differences in estimated groundwater levels were calculated.

The TRIPOL input data set consisted of the measured groundwater levels and the elevation values extracted from the DEM. A semi-variogram was generated and used as input to the interpolation process. The resultant outputs consisted of a groundwater elevation estimate and a standard deviation grid. The groundwater elevation estimate is valid if the aquifer is unconfined. A groundwater level output grid, showing the groundwater levels as mbgl, was created using the map calculator in Arcview 3.2 by subtracting the interpolated output (mamsl) from the DEM. Small corrections had to be made to the output grid in places where artesian springs were generated by the interpolation program. The goodness of fit can be seen in the analysis of variance in Table 3.2.

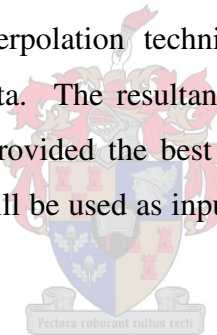
Table 3.2. Comparison of analysis of variance of different Kriging techniques used to derive groundwater elevations

Input data sets	ANOVA					
	Source of variation	SS	df	MS	F	p-Value
Groundwater elevation Vs. Ordinary Block Kriging	Between groups	1133.081503	1	1133.081503	0.133033098	0.715516094
	Within groups	3151397.378	370	8517.29021		
	Total	3152530.459	371			
Groundwater elevation Vs. Block Kriging River breakline	Between groups	870.7855772	1	870.7855772	0.101832518	0.749821606
	Within groups	3163927.114	370	8551.154361		
	Total	3164797.899	371			
Groundwater elevation vs. Block Kriging with River elevation	Between Groups	2814.462991	1	2814.462991	0.309840618	0.578114511
	Within Groups	3360925.731	370	9083.583058		
	Total	3363740.194	371			
Groundwater elevation vs. Bayesian interpolation	Between Groups	453.9754929	1	453.9754929	0.03827715	0.844995066
	Within Groups	4388282.058	370	11860.22178		
	Total	4388736.034	371			

Groundwater elevations were also interpolated using Ordinary Kriging. This result was compared to two additional cases of interpolation executed on the same data: (a) the perennial rivers in the area were used as a breakline; and (b) at regular distances along the river, the surface elevation was extracted from the DEM. These points were added to the 187 borehole water levels used in the other interpolations.

The results of the Bayesian interpolation process can be seen in Figure 3.7. The data set created as depth below ground level (mbgl) is also shown. The small area needing correction is obvious in the figure (marked in red). The analysis of variance (ANOVA) in Table 3.2, comparing the input groundwater elevation data with each of the interpolation techniques used, shows that Bayesian interpolation provides superior results to the other interpolation techniques, as found by Van Sandwyk *et al.* in 1992, despite the fact that estimating the variogram was more time consuming. The complete table of groundwater elevations for the 187 sample points can be found in Appendix B, Table B-2.

In this chapter, the Kriging interpolation technique was used to estimate groundwater elevations from existing point data. The resultant elevation grids created using the Bayes Kriging interpolation technique provided the best correlation. The groundwater level grid derived from this elevation grid will be used as input in the chapters on groundwater recharge and classification.



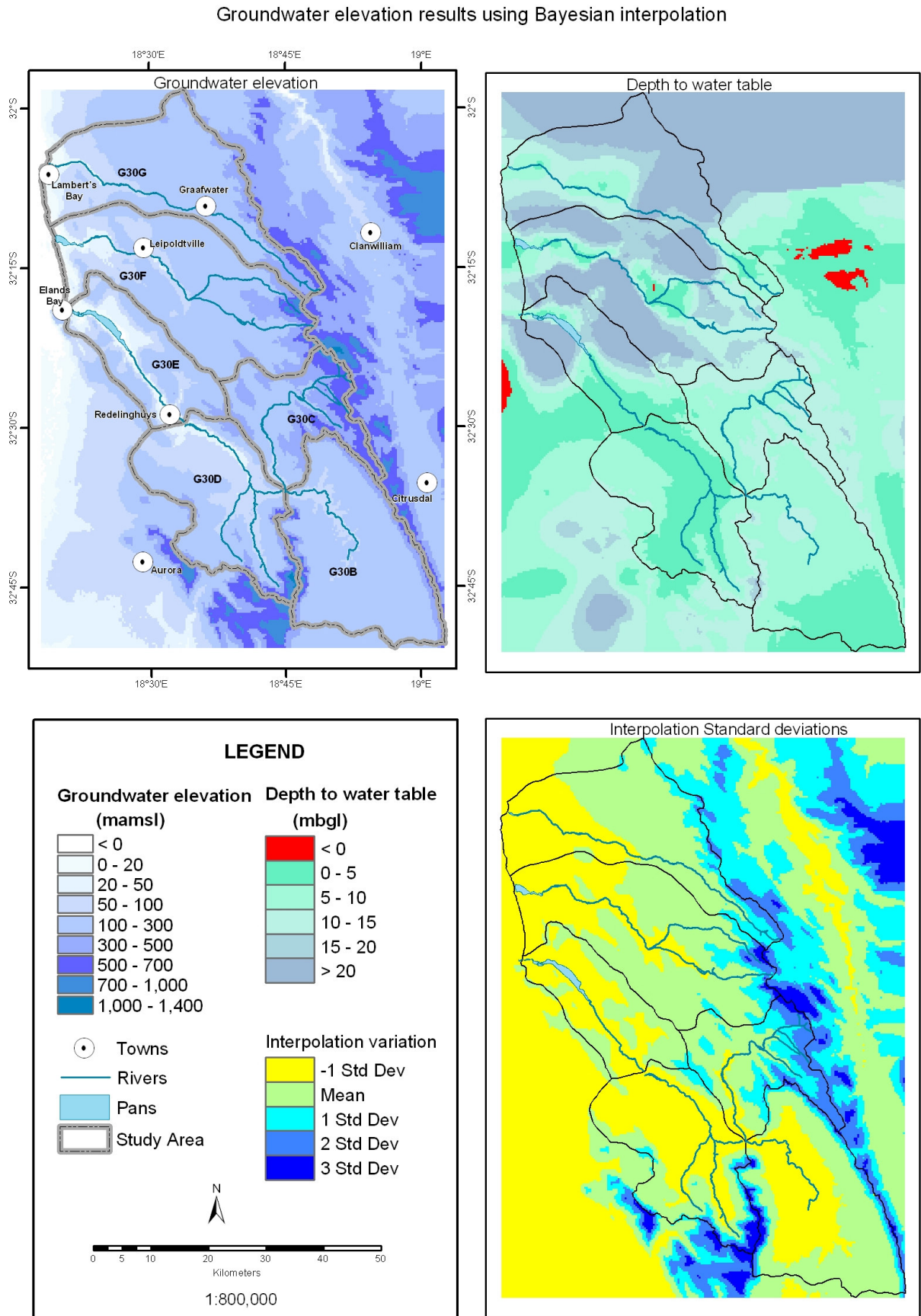


Figure 3.7 Results from Bayesian interpolation: Groundwater elevations and depth to water table

CHAPTER 4: GROUNDWATER RECHARGE

In this chapter on groundwater recharge, a simple overview will be given of groundwater recharge. Many studies have been devoted to the complex concept of how and when recharge occurs and which parameters may influence it. Readers wanting to know more about this topic can consult Bean (2003) who reviews recharge methods used in South Africa.

In this thesis a GIS approach is taken, using a ranking system based on the expert knowledge of groundwater consultants to devise recharge for the Sandveld study area and calibrating the recharge using the Chloride Mass Balance method (CMB). This recharge will be quantified for use in the groundwater Reserve determination.

Vegter (1995) describes recharge as “the process involved in the absorption and addition of water to the zone of saturation”. The quantification of groundwater recharge is an essential task for water resource management, however, groundwater recharge can vary significantly across a catchment and the estimates calculated can also be difficult to validate. There can be many factors that influence groundwater recharge and the interaction between these factors is also important. Nonetheless quantification of groundwater recharge is required on a catchment basis for assessing the sustainable use of groundwater in the context of the National Water Act (1998). Once the Reserve has been set and the existing lawful use determined, the amount of groundwater available for other activities can be allocated.

Various techniques to quantify recharge have been described in the past, summarising recharge for the South African environment, such as the work done by Bredenkamp *et al.* (1995). Many of the methods are dependent on detail information about a particular resource where long-term data sets are available. These types of data are not readily available on a regional scale. One of the techniques to determine recharge is the Chloride Mass Balance method (CMB). This method will be used to calibrate the GIS layer model. It is a site-specific method based on the Law of Mass Conservation which balances inflows with outflows. The water stored in the aquifer forms part of this equation (Fetter 1994). In its simplest form, the CMB method assumes that vertical recharge is derived entirely from rainfall and that recharge water has a consistent chloride concentration. Therefore the proportion of rainfall that enters the aquifer as recharge is given by the equation:

$$R = PCl_p / Cl_{gw}$$

Where R = Recharge, P = Precipitation (mm), and Cl_p and Cl_{gw} represent the chloride concentration (mg/l) of precipitation and recharge water percolating through the matrix of unsaturated zone, respectively (Bean 2003). Adams (2004) postulated that in the absence of measured values of rainfall chloride (Cl_p), the average of the following three formulas could be used:

$$Cl_p = 0.0042P + 1.1214$$

$$Cl_p = 170.84E^{-0.6511}$$

$$Cl_p = 23.107D^{-0.4615}$$

Where Cl_p = chloride concentration (mg/l) of precipitation, P = Precipitation (mm), E = Elevation (m) and D = Distance from the coast (km). It is important to note that these equations are only valid for the coastal areas of Southern Africa, in which the Sandveld study area lies.

The amount of water that can be abstracted from an aquifer is limited by the rate of recharge associated with precipitation or surface water bodies. A comprehensive study conducted by Bredenkamp *et al.* (1995) identified some main elements and their governing variables. Figure 4.1 is based on his approach but has been expanded.

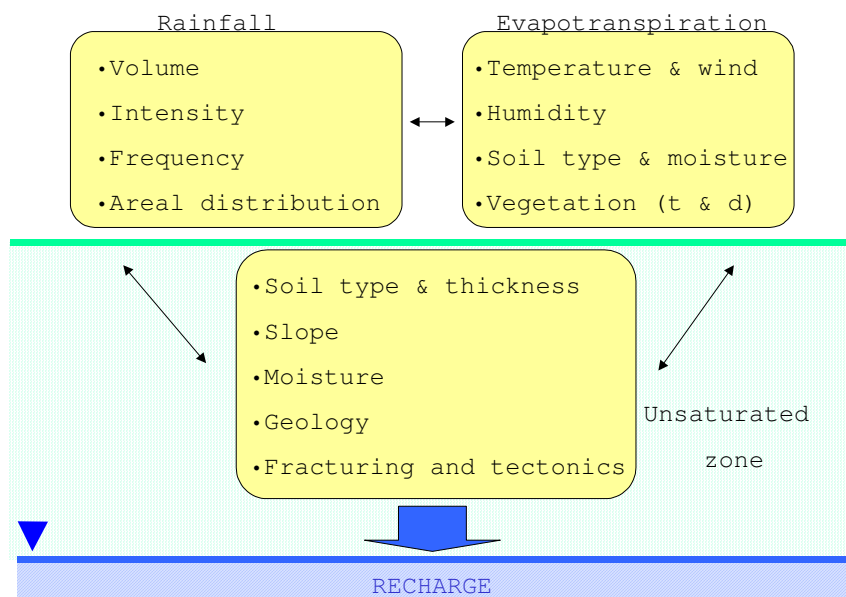


Figure 4.1 Main factors controlling groundwater recharge
[Adapted from Bredenkamp *et al.* (1995) (Source: Conrad 2004)]

The main “inputs” to an aquifer include:

- Recharge from rainfall;
- Recharge from river flow;
- Lateral inflow.

The main “outputs” from an aquifer include:

- Groundwater abstraction;
- Baseflow contributing to river flow;
- Springs;
- Lateral outflow from the aquifer;
- Evaporation and transpiration (taken into account when calculating vertical recharge).

The balance between inputs to the aquifer and outputs from the aquifer is known as the water balance. Figure 4.2 gives a graphical summary of these natural groundwater processes.

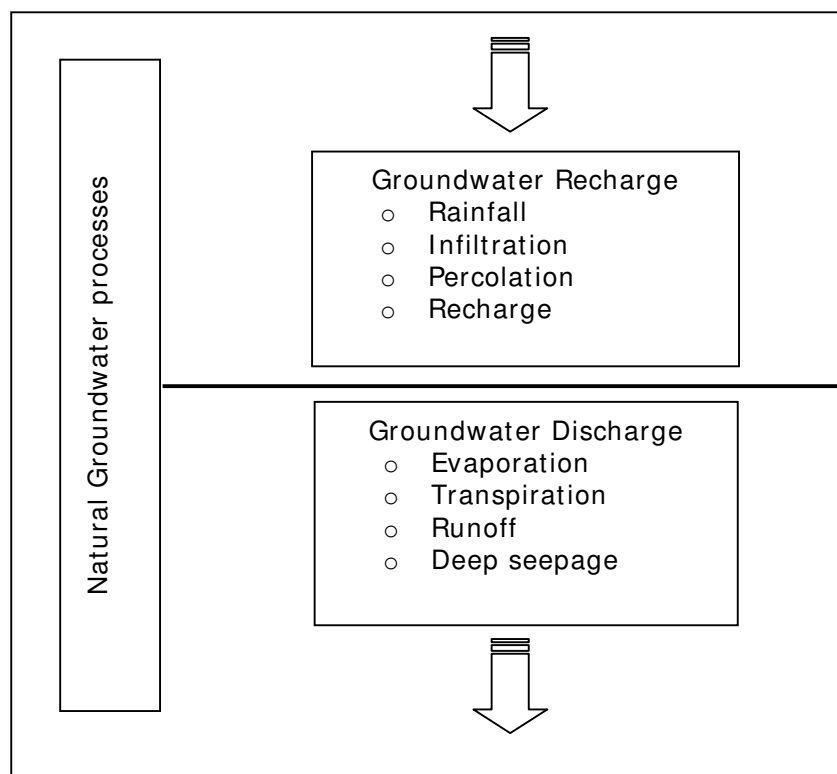


Figure 4.2 Natural groundwater processes

Based on the conceptual model developed for the area by Nel (DWAF In press) and Conrad & Munch in DWAF (2004b), it is assumed that groundwater input into the area is mainly made up of direct rainfall recharge and deep-seated inflow. The calculation of this recharge was

carried out using grid-modelling taking into account the following factors: land cover, geology, depth to groundwater, topography (slope) and rainfall. Selected output data sets from the interpolation experiments described in the previous chapters were used as input.

4.1 RECHARGE METHODOLOGY

The methodology used for this process, followed the classic approach of combining reclassified grids using different weights for different factors. Classification of the grids was done using a combination of literature and expert knowledge (Conrad 2004 (Pers com)).

The following section describes the data sets that were reclassified and combined. Ratings assigned to reclassified grids are subjective. Each data set was given an equal weight. The percentage recharge was defined by geology, while the other factors contributed to a recharge rating. Recharge percentage and ratings were combined and then calibrated using the chloride mass balance method. The Reserve calculation (DWAF 2004b) required volumes and so recharge volumes were calculated per quaternary catchment (G30B-G30F). To emphasise the difference made by a different interpolation technique, three different *rainfall* grids were used as input to the groundwater recharge model: Thiessen polygons (Figure 3.2, T3), Block Kriging with quadratic drift (Figure 3.5 (B3)) and Spatial prediction (Figure 3.5 (C)).

Conrad (DWAF 2003a) assigned a percentage recharge to different geological formations from literature. The geology data set was created for the Council for Geoscience (De Beer 2003). Table A.4 in Appendix A shows the recharge percentage assigned to the particular geological formations. Arcview 3.2 Spatial Analyst was used to create a percentage recharge grid from the *geology* data set. The National Land Cover data set was reclassified as described in Table A.1 in Appendix A and gridded. *Land cover* was used to assess the amount of precipitation interception and evapotranspiration.

A *slope* grid (percentage) was created from the SRTM90 DEM. Slope classes were assigned different recharge ratings with flat areas having the greatest probability of recharge. Table A.2 (Appendix A) summarises the recharge ratings based on slope. The *depth to water table* grid that was created as a product of the Bayesian interpolation of groundwater elevation was used as input. Recharge ratings were assigned to different classes of depth to water table. These ratings can be found in Table A.3 in Appendix A.

The input grids were combined using the following formula:

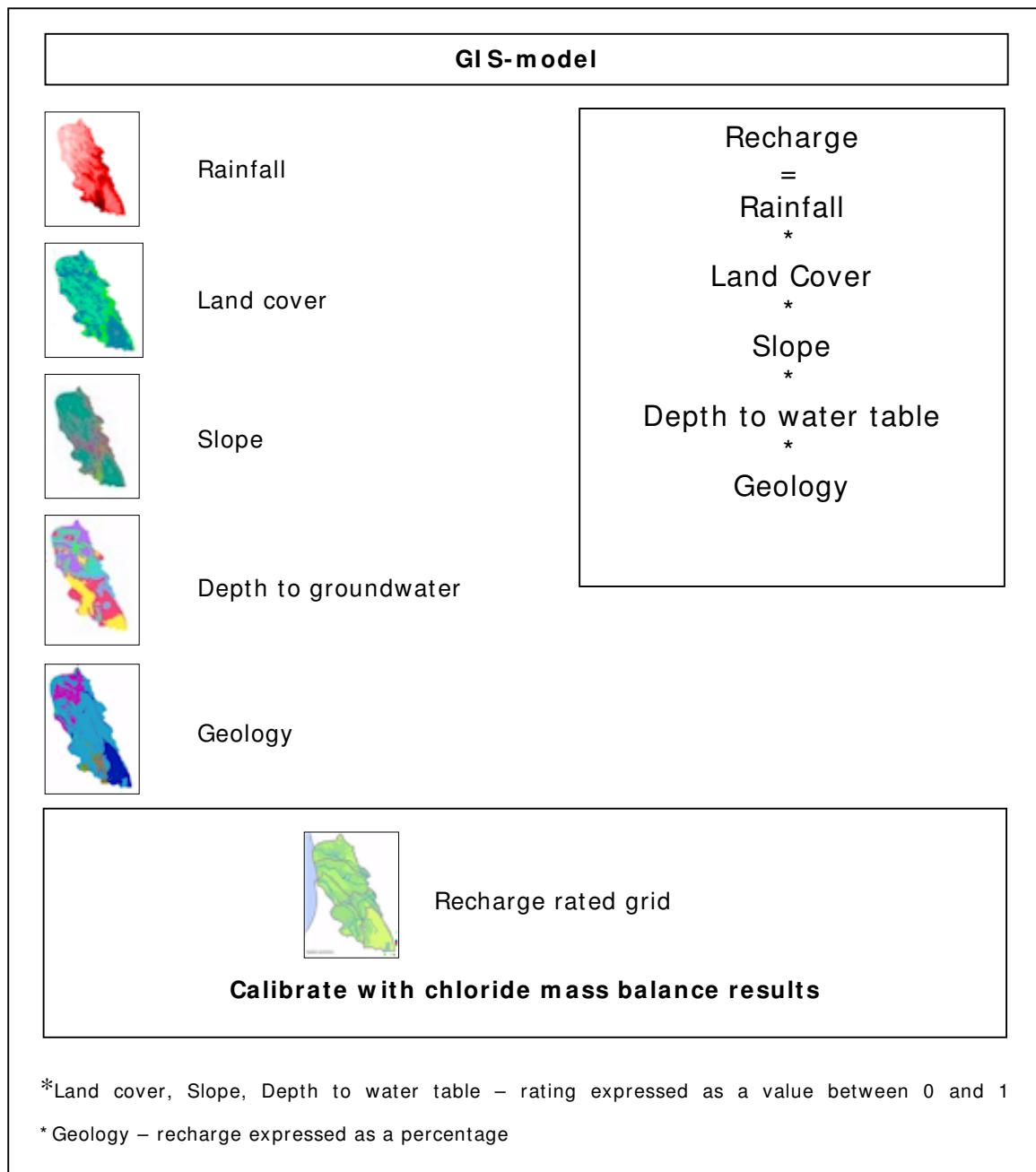


Figure 4.3 The GIS recharge model

The resultant recharge rated grid was calibrated using the CMB method for point values in the study area. The CMB method required the harmonic mean of groundwater chloride concentrations, rainfall chloride concentrations and precipitation amounts. The groundwater chloride values were obtained from *geoMon*. Rainfall chloride concentrations were calculated using the formulas suggested by Adams (2004). For precipitation three rainfall grids were used: Thiessen polygons (Figure 3.2, T3), Block Kriging with quadratic drift (Figure 3.5 (B3))

and Spatial prediction (Figure 3.5 (C)). The results from the calibration can be found in Figure 4.4.

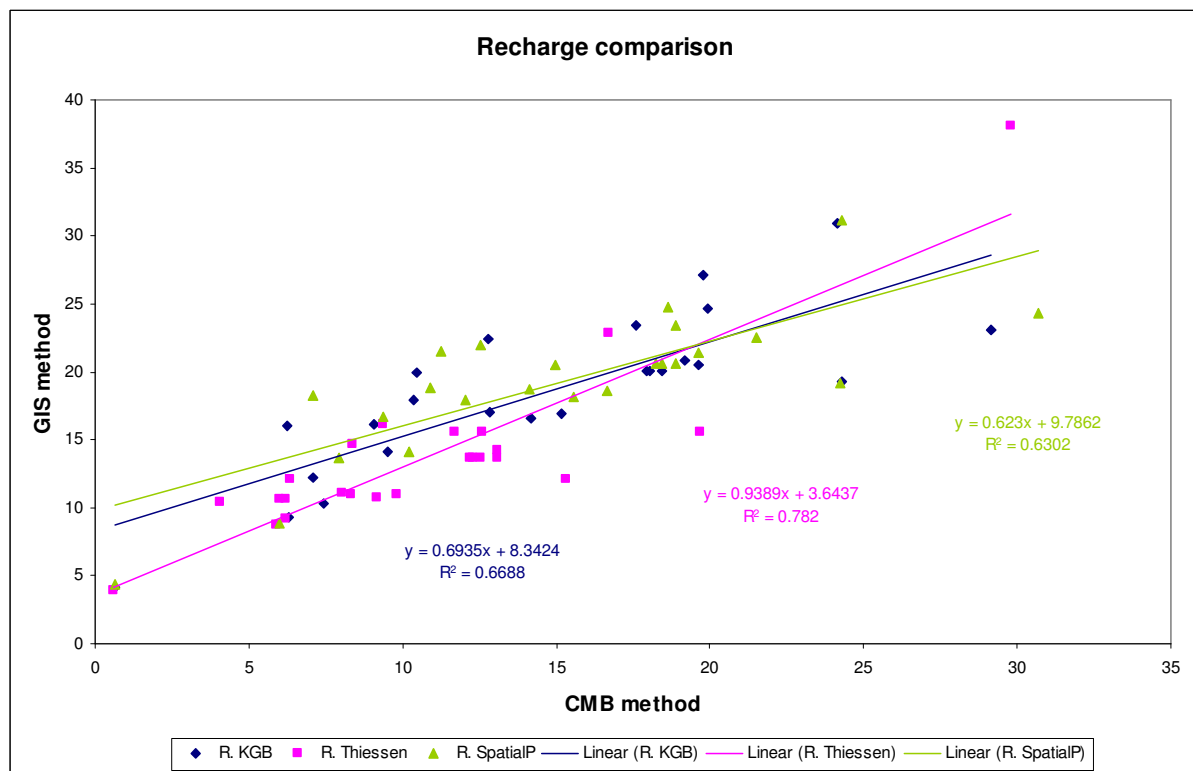


Figure 4.4 Recharge calibration

A final recharge grid was calculated for each rainfall grid using a derivative of the calibration equations from Figure 4.4. (Block Kriging recharge = $0.9644Rr - 3.2122$; Thiessen recharge = $0.8328Rr - 0.6976$; Spatial prediction recharge = $1.0117Rr - 4.3099$; where Rr = recharge rated grid). These grids were summarised per quaternary catchment and a volume calculation was done.

4.2 RECHARGE PER CATCHMENT

Figure 4.5 shows the results from the recharge calculations. For each rainfall grid, the calibrated recharge grid is shown, as well as the difference between the calibrated recharge grid and the recharge rated grid.

Table 4.1 contains the average rainfall calculated for each quaternary catchment using the different input rainfall grids, as well as the recharge associated with the particular rainfall figure, measured in Mm^3/a . The rainfall figures for the last five years derived through

interpolation, are lower than the values used in WR90 for the calculation of the mean annual precipitation (MAP). A lower recharge can be expected for this period.

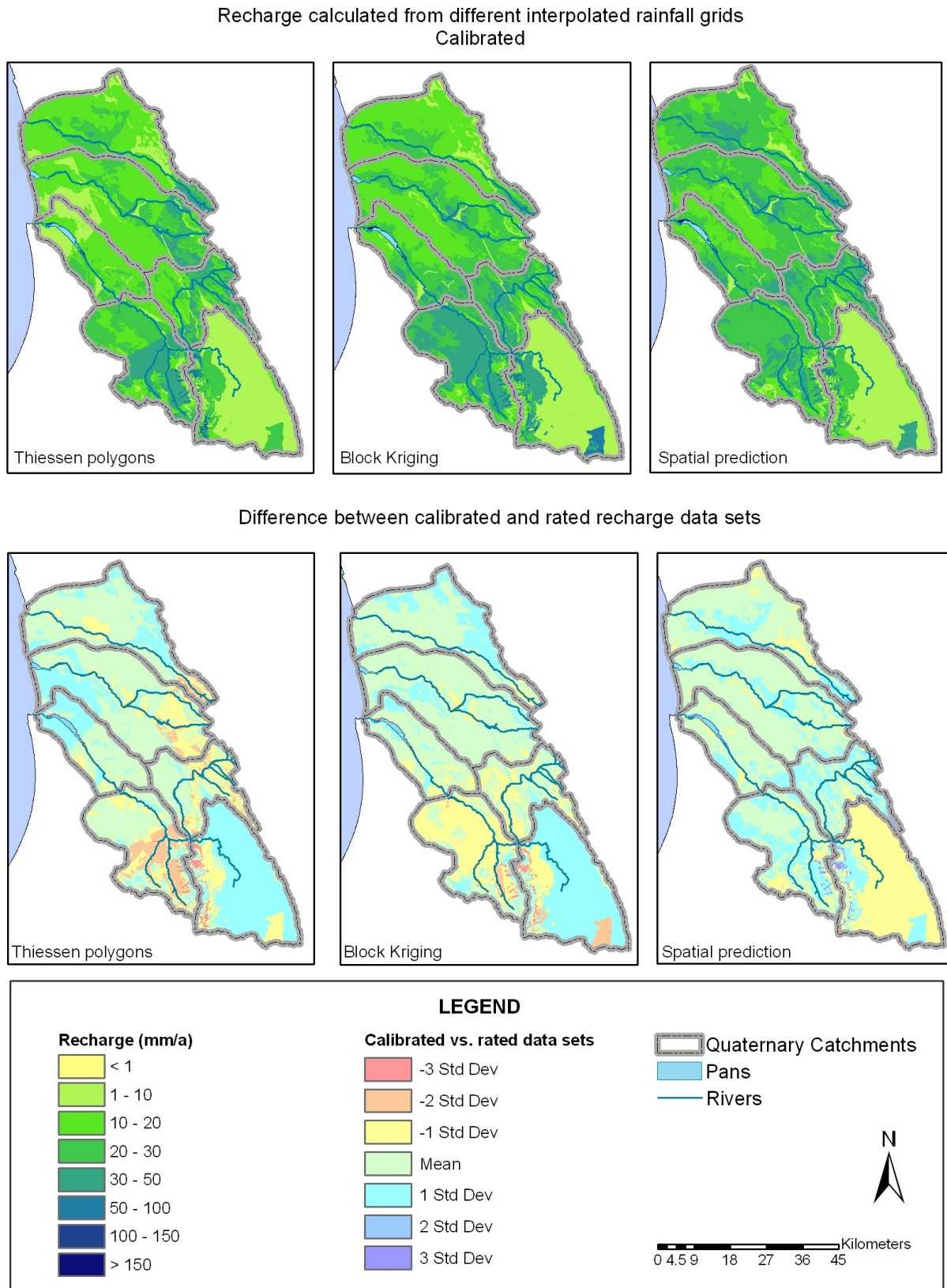


Figure 4.5 Recharge comparison

When comparing the total recharge obtained, it can be seen that, once calibrated, the rainfall grid from spatial prediction as well the rainfall grid derived through Block Kriging, provide similar volumes. Since the Block Kriging method provides the highest recharge, it is compared to each of the other methods using the analysis of variance. This is summarised in Table 4.2, which makes it clear that there is a significant difference between the results obtained using the input data set created with the local interpolator (Thiessen polygons) versus the data sets created using geostatistical techniques (Kriging and Spatial prediction).

Table 4.1 Recharge statistics per quaternary catchment

Catnum	Rainfall				Recharge		
	MAP WR90 mm/a	Thiessen polygons mm/a	Block Kriging mm/a	Spatial Prediction mm/a	Thiessen polygons Mm ³ /a	Block Kriging Mm ³ /a	Spatial prediction Mm ³ /a
G30B	394	339	419	297	6.78	9.53	7.05
G30C	410	368	345	351	8.06	9.01	9.44
G30D	384	340	347	285	13.11	15.97	13.23
G30E	249	204	261	264	6.33	9.60	9.86
G30F	285	271	260	290	13.35	15.13	17.51
G30G	253	249	215	291	10.66	10.53	14.74
<i>Sum</i>	1975	1772	1846	1778	58.28	72.34	71.83
			<i>Average</i>		9.71	11.63	11.97
			<i>Variance</i>		9.67	9.55	15.00

Table 4.2 Comparison of variance statistics for recharge calculated from different rainfall input data sets

Groups analyzed			<i>F</i>	<i>p-Value</i>
<i>Recharge calculated from rainfall data set created using:</i>				
Block Kriging	Vs.	Thiessen polygons	1.144300	0.309886
Block Kriging	Vs.	Spatial prediction	0.028972	0.868238
Spatial Prediction	Vs.	Thiessen polygons	1.240777	0.291378

CHAPTER 5: RDM - DEFINING MANAGEMENT CLASSES

Defining management classes gives one the opportunity to implement some of the findings of the interpolation comparison. Groundwater levels are once again required as input data set.

5.1 RESOURCE DIRECTED MEASURES

According to the National Water Act, water resources should be protected for their sustainable utilisation. Resource Directed Measures (RDM) forms the core of these protective measures and is comprised of the three aspects set out in Chapter 3 of the National Water Act: classification, the reserve and resource quality objectives. Figure 5.1 from Xu *et al.* (2003) neatly summarises the RDM for groundwater protection.

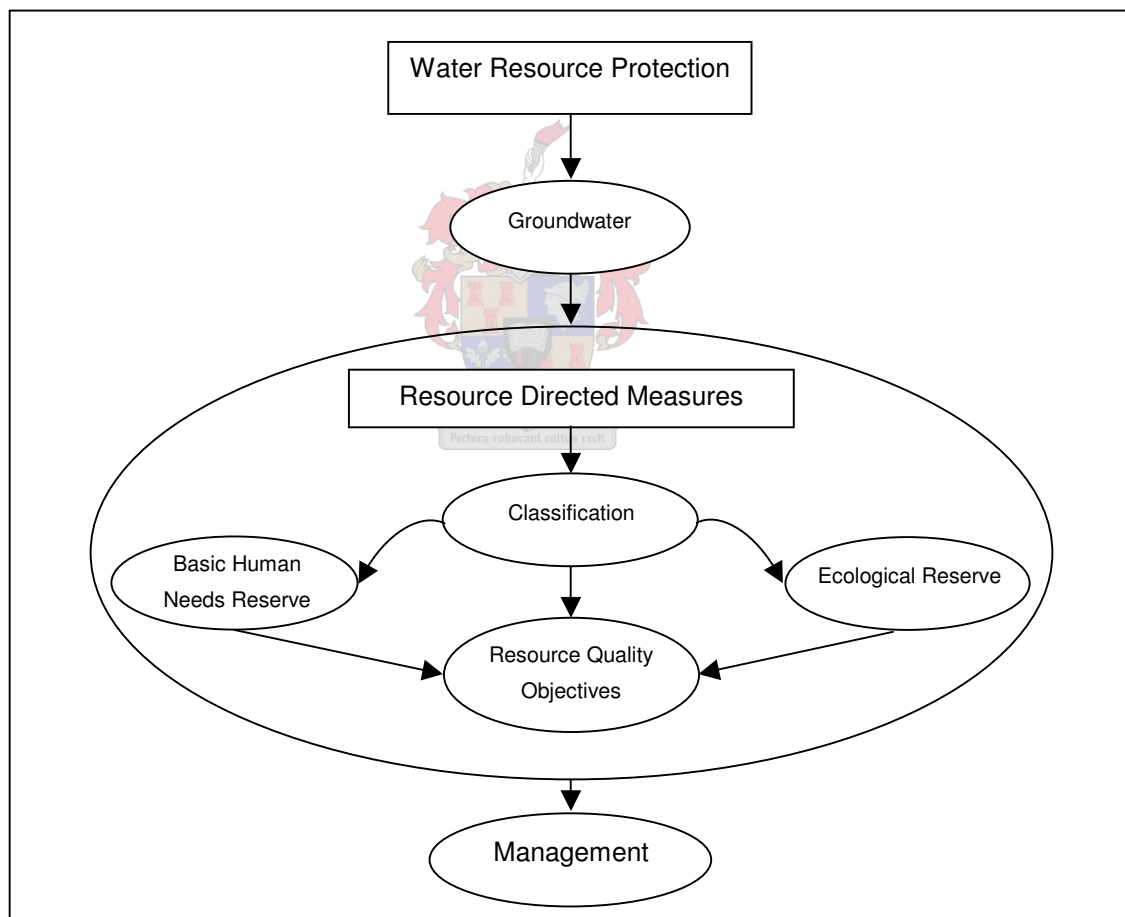


Figure 5.1 Resource directed measures for groundwater protection

[Source: Xu *et al.* 2003:7]

When there is a linked aquatic ecosystem that requires protection, and groundwater contributes, an **Ecological Reserve** is determined. The role of groundwater in supporting

terrestrial ecosystems and hypogean life is not provided for in the Reserve, but must be addressed by **Resource Quality Objectives (RQO)**. The **Basic Human Needs Reserve** is determined where people take water from or are being supplied from the groundwater resource whether the groundwater contributes to the Ecological Reserve or not. This is an essential reserve considering groundwater's role in domestic water supply.

The rest of this chapter will be devoted to Classification. Classification forms an integral part of RDM, along with the Reserve (Ecological and Basic Human Needs) and Resource Quality Objectives, in designing the final management plan to successfully protect a resource at risk.

5.1.1 Classification

The purpose of classification is to determine guidelines and procedures for decision making regarding water resources. It is necessary to assess the current status of a resource, determining the degree of modification. This will assist in establishing the associated risk of irreversible damage to the resource (Conrad & van der Voort 2000). The final classification process should have technical and scientific input from specialists but must happen in conjunction with stakeholders. Once a class has been established, consistent rules can be applied in determining the Reserve, procedures can be designed to satisfy water quality requirements of users and regulations can be drawn up to control activities that may damage water resources. In short, RQOs are drawn up and a management plan can be established for a particular class of resource. Through the classification system a groundwater management unit can be delineated and be classed as protected, good, fair or severely modified. These four management classes (Xu *et al.* 2003) imply different levels of resource protection and impact acceptable to stakeholders.

The concept of resource classification is not new and other classification systems have been designed, eg. groundwater contaminant vulnerability (Jolly & Reynders 1993; Parsons & Conrad 1998), classes of aquifers based on productivity and dependency of human users (Parsons & Conrad 1998) and classes of water suitability for different uses (DAAF, DOH, WRC 1998). This particular classification system is designed to tie in with the whole RDM process in classifying all components of the hydrologic cycle in an inclusive way, based on RDM principles.

Scientist will determine RDM scenarios, but the final setting of the management class must represent the needs of stakeholders in the particular catchment. A groundwater classification

methodology has been developed by the WRC's RDM program (Xu *et al.* 2003), which suggests following generic steps:

- a) Delineate the area
- b) Delineate groundwater regions
- c) Delineate the groundwater response units
- d) Describe the reference conditions and present status
- e) Describe the importance and vulnerability
- f) Delineate the groundwater management units
- g) Set the management class

The methodology was tested with a case study in the Pienaars River Catchment and presented at WISA 2000 by Conrad & van der Voort (2000).

5.1.2 Setting the Reserve

The Reserve consists of two components (the basic human needs reserve and the ecological reserve) (see Figure 5.1) and refers to both the quantity and the quality of the particular class of water resource. The basic human needs reserve includes water for drinking, food preparation and personal hygiene, i.e. provides for the essential needs of individuals, while the ecological reserve relates to water necessary to protect aquatic ecosystems. If a resource has not yet been classified, a preliminary determination of the Reserve may be made and later superseded by a new one. Much work has gone into drawing up guidelines for setting the reserve, whether it is a desktop, rapid, intermediate or comprehensive Reserve determination (Xu *et al.* 2003).

5.1.3 Resource Quality Objectives

The purpose of resource quality objectives (RQOs) is to set clear goals for protection within a management class. RQOs may be numerical in nature or merely describe an improvement or threshold for a particular impacted resource. The RQO must represent a balance between the need for protection and sustainability on the one hand and the need for development and use on the other. Provisional classifications may be done, but once the class of water resource and associated RQOs have formally been determined, they are binding. RQOs are particularly important for groundwater as they are not just limited to the aquatic ecosystems, but can represent the importance of aquifers to the wider environment. RQOs may relate to

the Reserve, instream flow, water levels, water quality, the characteristics and distribution of aquatic biota or the regulation or prohibition of activities which may affect the quantity or quality of the water resource.

5.2 DETERMINE THE RESERVE USING RDM

RDM comprises three aspects set out in Chapter 3 of the National Water Act: classification, the reserve and resource quality objectives. This document discusses the first of these components namely classification. The “Reserve” calculation is described in detail in DWAF (2004b). Resource Quality Objectives need to be defined in collaboration with stakeholders.

5.2.1 Classification

Different classes are assigned to water resources to represent different levels of acceptable risk of modification from natural conditions. Classification is intended to be legally and scientifically defensible, simple and should contain a limited number of classes (Xu *et al.* 2003).

5.2.1.1 Delineating groundwater response units (GRUs)

Although quaternary catchment boundaries do not form groundwater divides, groundwater response units have been selected largely within catchment confines, yet with relatively good homogeneity in groundwater characteristics and behaviour. Consultation with DWAF (Nel 2004 (Pers com); DWAF In press) lead to the definition of six major GRUs of which some have been subdivided. Fault lines with a Northwest trend, determined via aeromagnetic geophysics probably indicates preferential groundwater flow paths (DWAF In press), which caused some units to be delineated over catchment boundaries.

5.2.1.2 Level of modification

To assess **level of modification**, the present state must be compared to reference conditions. Measurable factors that contribute towards modification reviewed in this document are the effect of agriculture, drop in groundwater levels and change in water quality. For each of the factors a grid was created, which was reclassified as specified below. Each factor was weighted. The weights and ratings are described in Table 5.1.

Table 5.1 Summary of ratings per factor influencing level of modification

Factor		Rating					Weight
		1	2	3	4	5	
Abstraction density	A	0 – 6,500	6,500 – 13,000	13,000 – 19,500	19,500 – 26,000	> 26,000	1
Water level drop (m)	M	No drop	0 – 1	1 – 2	2 - 5	> 5	3
Water level drop (%)	P	0 – 20	20 – 40	40 – 60	60 – 100	> 100	5
EC slope	S	0 – 0.04	0.04 – 0.08	0.08 – 0.12	0.12 – 0.17	> 0.17	2
EC change	E	< 0	0 - 10	10 – 30	30 - 80	> 80	4
Geology	R	Q*, Tv					1
Well-field development	B			Redelinghuys Leipoldville	Elands Bay	Lamberts Bay	1

i. Effect of agriculture

The extent of land cleared for agriculture as identified by centre pivot circles was captured into a shape file from satellite images of a summer (February) and winter (July) scene of the study area. The digitised irrigation circles were categorized as actively irrigated (I), cover crop (C) or dry, previously irrigated circles (D) from the satellite images. Actively irrigated (I) circles were selected for processing. A centre pivot can abstract 1000mm/ha groundwater per season for irrigation in summer and 600mm/ha for irrigation in winter. The total abstraction per season (summer and winter) was calculated from the area of the irrigation circles plus the abstraction rate. An abstraction density grid was created. The equal interval method was used to reclassify the grid into 5 classes with lowest concentration as 1 and highest as 5. The letter A was used to identify this parameter in later processing.

ii. Drop in water levels

A dataset was created representing the drop in water level in the area in meters by using the latest water level grid and subtracting the earliest water level grid from it. The drop in water level in the area was reclassified (grid labelled M).

The modification of water level in the area was also calculated by deriving the percentage change in water level from available time series data (labelled P). This was to balance the effect of a large drop in water level in a deep borehole vs. a smaller drop in water level in a borehole close to the surface. A grid was interpolated from these percentages using the IDW

method to highlight local variation and honour the points. The water level change grid was reclassified (labelled P).

iii. Change in water quality

The change in water quality was analysed by gridding the slope of the electrical conductivity (EC) change from time series data. Ordinary Kriging was used for interpolation to determine the trend in change. The EC change grid was reclassified (labelled S). A negative slope was assigned a rating of zero. The change in water quality was also assessed by comparing the latest EC grid with the earliest. The EC change grid (labelled E) was reclassified as described in Table 5.1.

iv. Geology

The level of modification is associated with the underlying geology and this factor was taken into account by creating a grid rating all quaternary sands (Geological Formation Codes Q* and Tv – see Table A.4 in Appendix A and Table C.5 in Appendix C) as 1 and bedrock as 0. The reclassified grid was labelled R.

v. Well-field development

The areas in and around the well-fields responsible for supplying towns and industries experience a greater degree of modification. This was accounted for by the inclusion of the following grid labelled B. Importance was rated on the population supplied by the well-field: Wadrif well-field (Lamberts Bay) = 5; Graafwater and Elands Bay = 4; Redelinghuys and Leipoldtville = 3.

The derived data sets created as input to the level of modification grid, are shown in Figure 5.2. Levels of modification for the whole study area was classified by evaluating all the grids in the Arcview 3.2 map calculator, using the ratings and weights assigned to the particular parameters, by the following formula:

$$A_r A_w + M_r M_w + P_r P_w + S_r S_w + E_r E_w + R_r R_w + B_r B_w$$

The resultant grid was reclassified according to the values in Table 5.2 and represents a quantifiable level of groundwater modification for the area.

Factors influencing level of modification

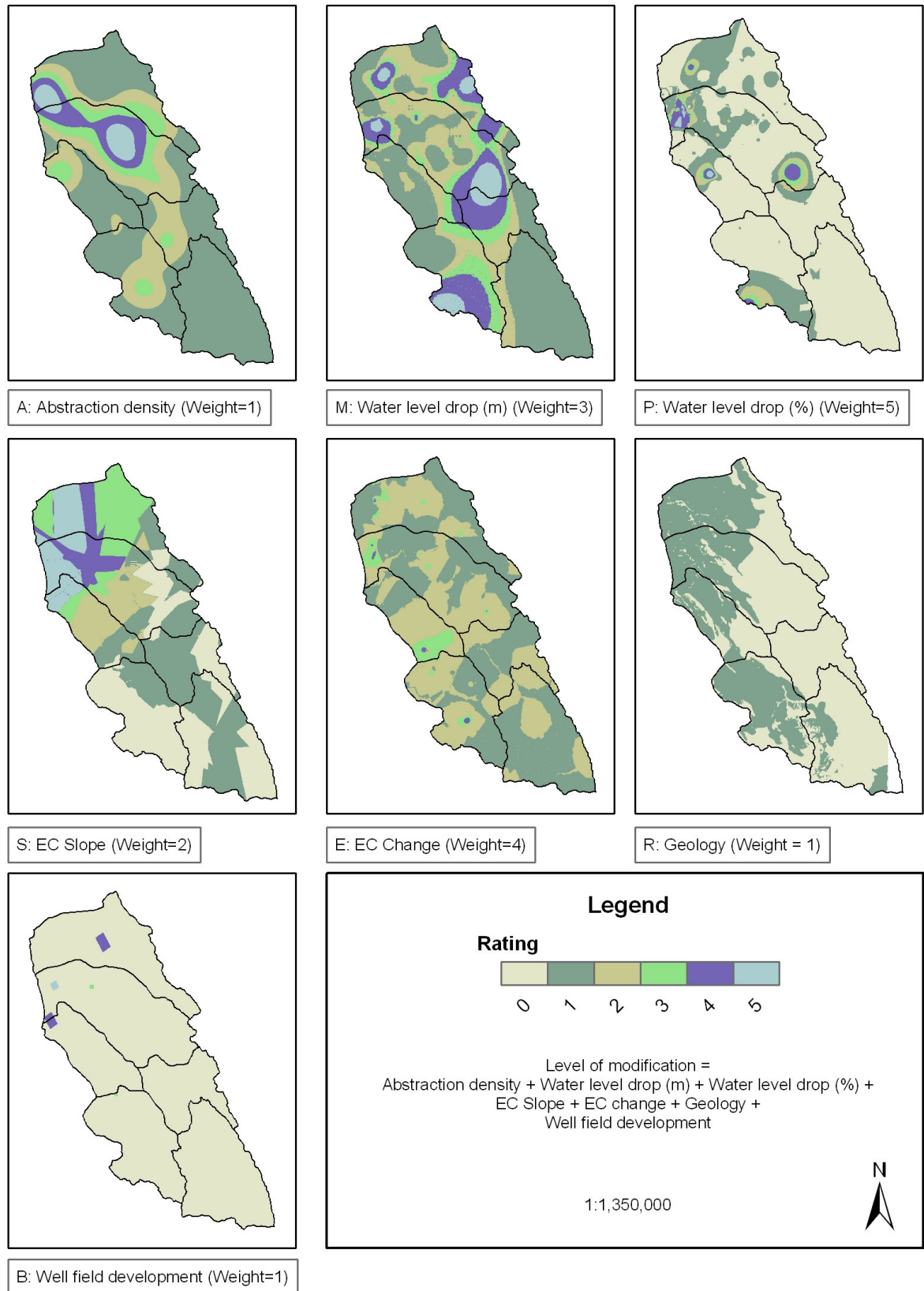


Figure 5.2 Derived data sets used as input to level of modification classification

Table 5.2 Final level of modification classification

Value	Classification
8 – 20	Natural
21 – 33	Good
34 – 46	Fairly Modified
47 - 59	Poor
60 - 72	Severely Modified

This level of modification grid was used in conjunction with an importance output grid and a vulnerability grid (DRASTIC) to derive the final management units for the area. The steps taken to create the importance output grid are discussed in the next section (5.2.1.3), followed by a summary of the DRASTIC process (5.2.1.4).

5.2.1.3 Importance

The importance of the resource units must be defined with respect to ecological importance, social importance and economic importance. These values are difficult to quantify, but an attempt was made to do so to provide input to stakeholders with the ultimate responsibility for RQOs. Especially in the case of a groundwater resource, stakeholders need to be educated as to the important role of this resource (Xu *et al.* 2003).

According to Xu *et al.* (2003) ecological importance indicates the ability of a resource to maintain its ecological diversity and functioning on a local and wider scale. For the Sandveld, areas of groundwater and surface water interaction as well as springs were considered. For social importance the basic human needs supplied by the well-fields and springs as well as Verlorenvlei as recreation were considered. Agriculture was considered under economic importance as well as the groundwater supply to industry in the main urban areas. For each factor a weighted grid was created. Factors were summed to the particular category, i.e. ecological, social or economic and the resultant grid reclassified. Finally the three components were summed with equal weight to provide an overall importance output. This grid was again reclassified into low, medium and high importance. Table 5.3 describes the factors, weighting and reclassification while Figure 5.3 shows these input data sets.

Table 5.3 Factors and weighting for calculation of importance output grid

Importance Factor	Input grids			Sum grid		Importance Output			
	Name	Value	Wt	Reclassified					
Ecological	Groundwater-Surface water interaction (A)	None	0	(X) = (A) + (B)		Old X	New X		
		Interaction	5						
	Springs (B)	None	0	0	1				
		Springs	5	5	4				
Social	Basic Human Needs (C)	Background	0	(Y) = (C) + (D)		Old Y	New Y		
		Leipoldtville	3						
		Redelinghuys	3						
		Elands Bay	4						
		Graafwater	5						
		Wadrif	5						
	Recreation (D)	Background	0	0	1				
		Verlorenvlei	5	5	4				
Economic	Industrial activity (E)	Background	0	(Z) = (X) + (Y) + (Z) + (X)					
		Leipoldtville	3						
		Redelinghuys	3						
		Elands Bay	4						
		Graafwater	5						
		Wadrif	5						
	Agricultural activity (F)	m³/a/km²						(Z) = (E) + (F) + (G) + (H)	
		0	1						
		0 - 3,500	2						
		3,500 - 7,000	3						
		7,000 - 13,000	4						
	>13,000	5							
	Borehole yield (G)	L/s						Old Z	New Z
		<1	1					3 - 5	1
1 - 7		2	6 - 7	2					
8 - 15		3	8 - 9	3					
16 - 22		4	10 - 11	4					
> 22		5	12 - 18	5					
Borehole density (H)	number/m²		Reclassified as:						
	< 0.1	1			3	Very low			
	0.1 - 0.2	2			4 - 5	Low			
	0.2 - 0.3	3			6 - 10	Moderate			
	0.3 - 0.4	4			11-14	High			
	> 0.4	5							

5.2.1.4 Vulnerability (DRASTIC)

Groundwater vulnerability was considered in terms of the DRASTIC method of assessment of the intrinsic vulnerability of an aquifer to contamination from the surface (Aller *et al.* 1987). The method considers the following factors which control the vulnerability of an aquifer to contamination from surface: depth to water table (D), recharge (R), aquifer material (A), soils (S), topography and slope (T), impact of the vadose (unsaturated) zone (I) and hydraulic conductivity (C).

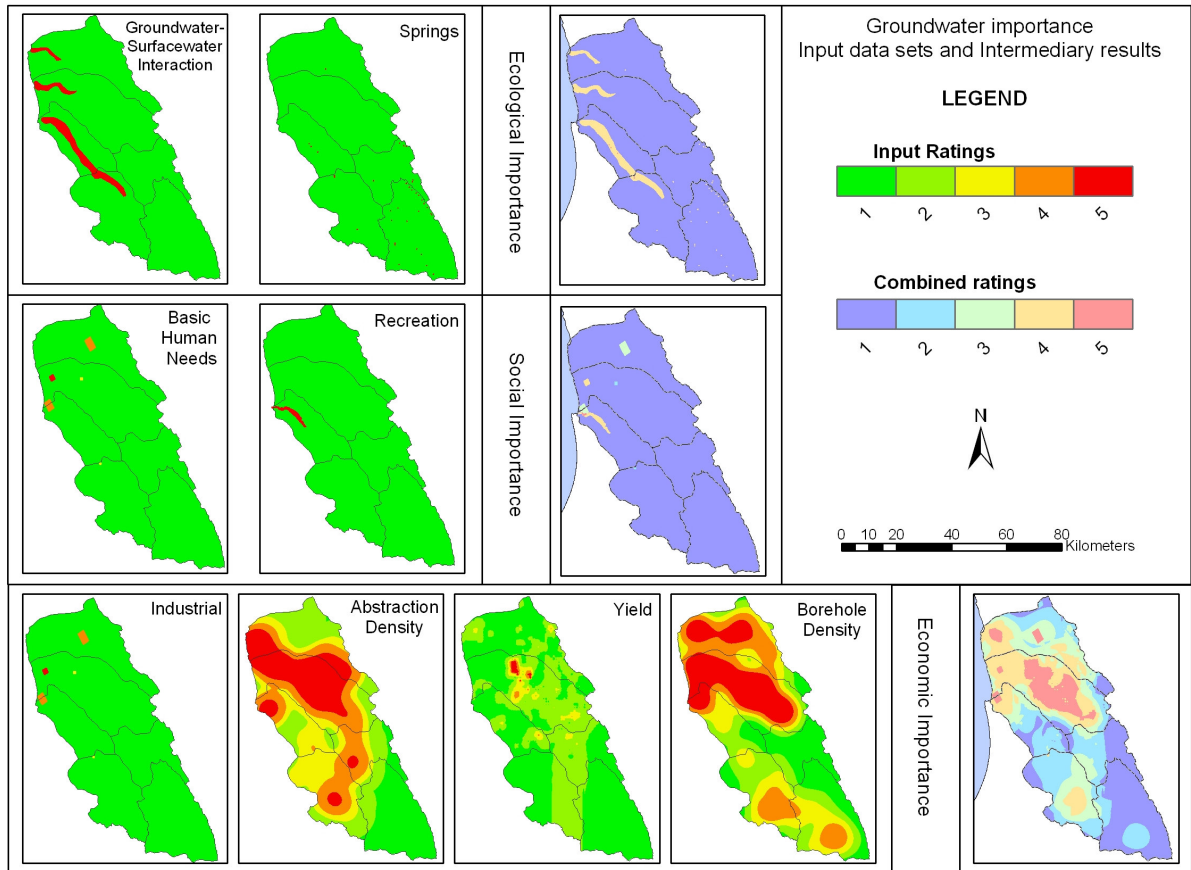


Figure 5.3 Inputs to the groundwater importance rating showing intermediary results: Ecological, social and economic importance

The DRASTIC method is widely accepted even though it is subjective due to the selection of classes and weights for characteristics. The outcome of the DRASTIC method shows the relative vulnerability of the aquifer (Xu *et al.* 2003; DWAF 2004a). The ratings and weights used were based on the categories and values defined by Aller *et al.* (1987) and are shown in Appendix C, Tables C.1 to C.5. Figure 5.4 shows the reclassified DRASTIC input layers.

The overall DRASTIC equation is shown below:

$$Pollution\ potential = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w$$

Where: R = rating and w = weighting

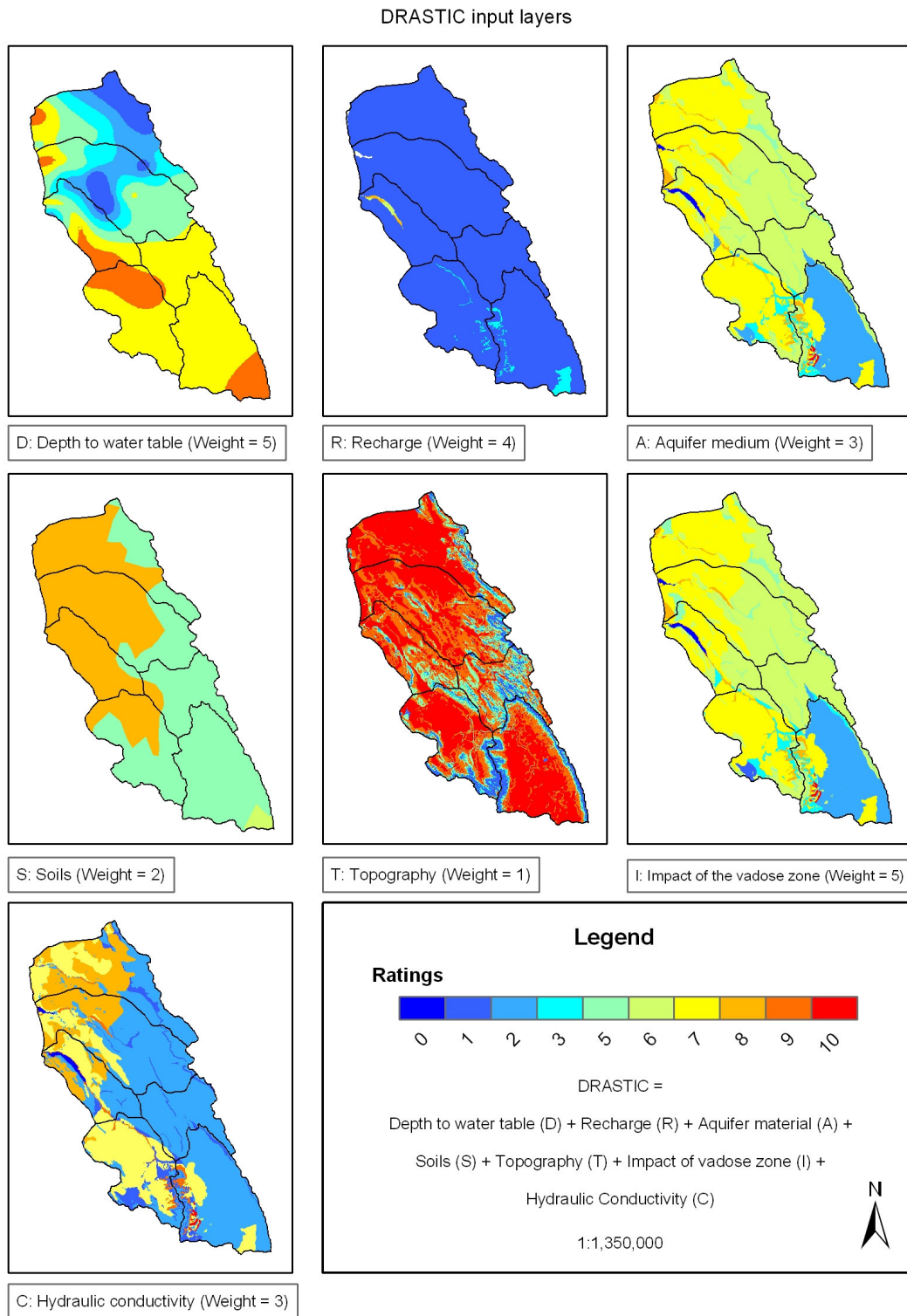


Figure 5.4 Reclassified DRASTIC input layers

5.2.1.5 Defining management classes

Management classes are currently subdivided into four classes, namely: Protected, Good, Fair and Severely Modified. The management classes and associated descriptions as listed in

Table 5.4 have relevance. Each management class will be assigned specific management objectives once RQOs have been determined.

Table 5.4 Future Management classes and descriptions

Class	Description
Protected (Reference condition)	Human activity has caused no or minimal change to the geohydrology (groundwater levels and piezometric levels). Chemical concentrations are not significantly different from background concentration levels, or ranges for naturally occurring substances. Concentration levels of artificial substances do not exceed detection limits of advanced analytical methodologies.
Good	The resource is slightly to moderately altered from the protected reference conditions.
Fair	The resource has been significantly changed from reference conditions. The class "Poor" is sometimes also applied if the conditions are worse than "Fair".
Severely modified	A water resource that has been severely and permanently physically modified that rehabilitation to anything approaching a natural ecosystem would be impossible or prohibitively expensive.

[Source: Xu *et al.* (2003:22)]

From the level of modification grid, the importance output grid and the vulnerability grid, a present ecological status was derived, which will enable selecting a future management class. This output grid was reclassified into four classes representing suggested management classes. However, setting of management classes remains a management and stakeholder decision. Implementation of the Class, Reserve and RQOs will not necessarily tell water managers how much groundwater is available for allocation. Individual license applications must be assessed in the context of the Class (Xu *et al.* 2003).

5.3 CLASSIFICATION – THE OUTPUTS

5.3.1 Geohydrological response units (GRUs)

These units were based on quaternary catchments and geology and follow the so-called block faults as described by Nel (2004). The location of these areas can be found in Figure 5.5. The GRUs were separated into primary and secondary response units based on aquifer characteristics. This was reflected in the naming convention e.g. GRU1 which was split into GRU1P along the coast and GRU1S along the mountain ranges east. The quaternary catchments were overlaid, with the topography as background to the map. GRU1E and

GRU2E are part of the E10 catchments and fall outside of the study area, but were considered to be contributing to the groundwater recharge in the area.

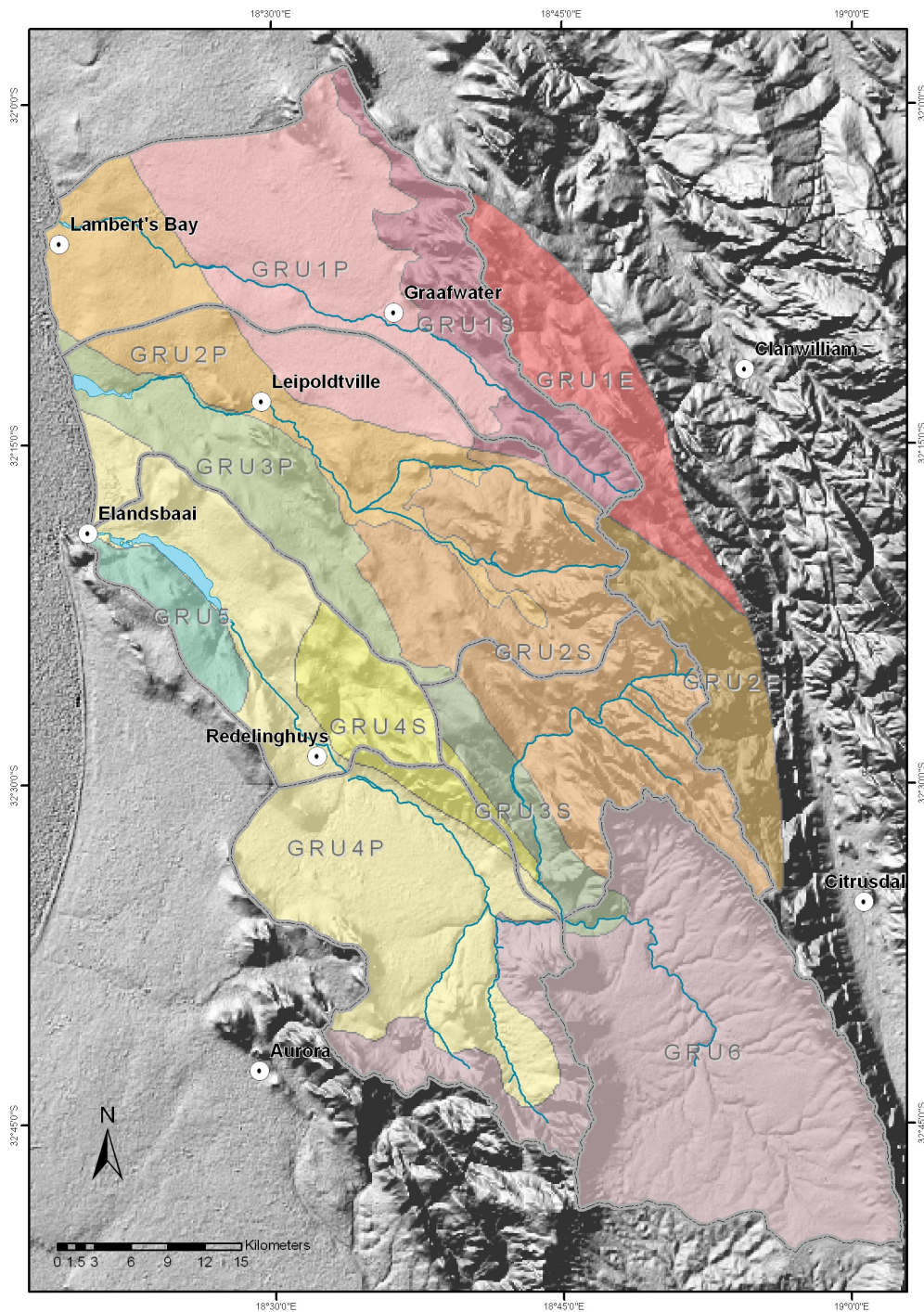


Figure 5.5 Geohydrological response units

A detailed description of the GRUs is quoted from DWAF (2004a:5-2).

“A total of six GRUs were defined for the study area. The major GRUs have been subdivided, as deemed necessary and in total there are ten GRUs including sub-units.

GRU1P: The northern most GRU, comprising both primary and secondary aquifers. It straddles the Jakkals River, contains the Graafwater wellfield and receives inflow from the inland recharge area. The northern part of this GRU comprises the Sandlaagte area.

GRU1S: This northern GRU comprises only secondary aquifer and the mountains above the town of Graafwater. It receives significant inflow from the eastern neighbouring area, which is part of the E10 catchments.

GRU2P: This unit contains a geologically complex region, which hosts the secondary aquifer, as well as a primary aquifer, and the town of Lamberts Bay. It contains the major portion of the upper Langvlei, Lambertshoek and Alexanderhoek Rivers. The northern boundary of the unit is defined according to the position of dolerite dykes and associated geological structures.

GRU2S: This unit is the secondary aquifer unit that extends into the mountains in the eastern portion of the study area. It contains significant geological faults and would provide significant inflow into GRU2P. GRU2E is a recharge area and will provide inflow into this unit.

GRU3P: The primary aquifer unit containing the Wadrif saltpan, Wadrif wetland, Wadrif well-field and is drained by the Langvlei River. It also contains the Wadrif aquifer. It is underlain by a complex geology and associated secondary aquifer.

GRU3S: The secondary aquifer unit, which provides significant inflow into unit GRU3P.

GRU4P: Is the largest unit and contains Verlorenvlei and extensive primary and secondary aquifers.

GRU4S: The secondary aquifer unit that is coupled to the unit GRU4P.

GRU5: The unit to the southwest of Verlorenvlei, which consists of a very different hydrogeology as GRU4S and is treated as a separate unit.

GRU6: This is the unit located between Piketberg and the N7, characterised by poor groundwater conditions.”

5.3.2 Level of modification

Following the steps set out above in section 5.2.1.2 in combining the intermediate derived data sets found in Figure 5.2, the map in Figure 5.6 was generated. The combination of weighted grids accentuates areas with compounded parameters that may have a causative effect in modification.

The IDW method of interpolation, with the “duck-egg” patterns highlighting outlier data with relative few samples in the neighbourhood, was used with success in this classification process. The classification was particularly sensitive to the change in groundwater level grid. Pumping groundwater levels, incorrectly captured in the database, were responsible for the “Poor” classification in GRU2S. Higher degrees of modification were found associated with urban and agricultural development. Assigning values to the final classification remains a subjective process.

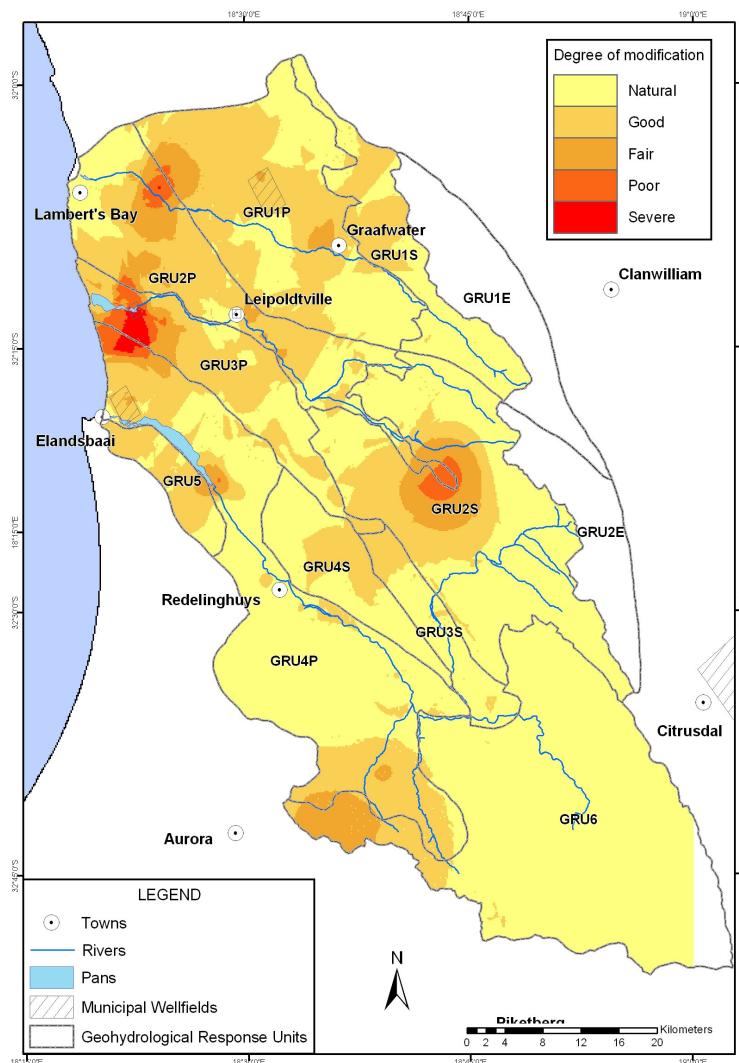


Figure 5.6 Level of groundwater modification

5.3.3 Importance

Figure 5.3 shows the three combined inputs to the groundwater importance rating, namely ecological, social and economic importance grids. The input grids were summed without attaching weights. These grids can be used for public participation in educating the stakeholders and gaining support for the classification, which needs to be ratified by the stakeholders. The final groundwater importance grid (Figure 5.7) highlights the municipal well-fields as well as the Verlorenvlei and Wadrif saltpan as most important. DWAF has suggested that additional input grids be added especially in the social importance and basic human needs area (Pienaar 2004(Pers com)).

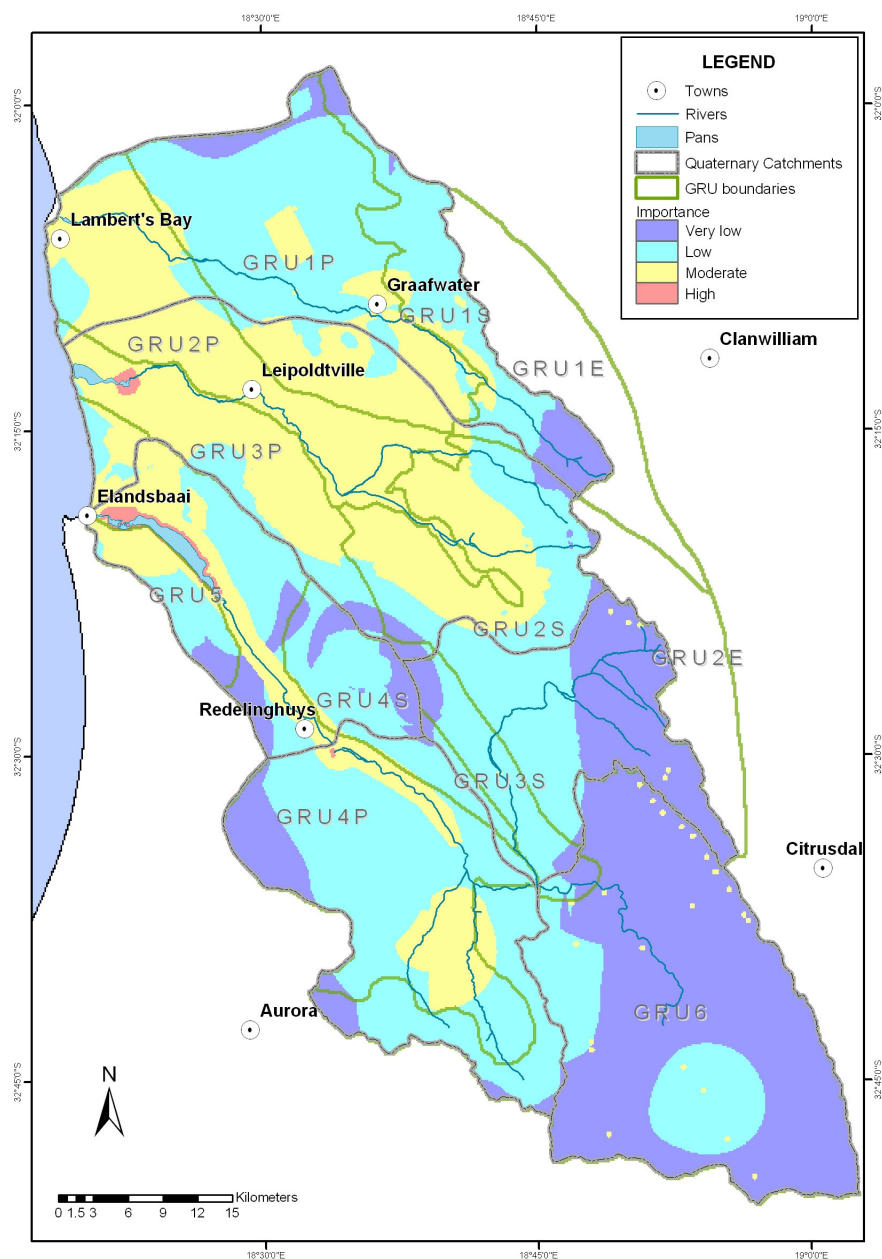


Figure 5.7 Overall groundwater importance

5.3.4 Vulnerability

The DRASTIC process was carried out and the resultant grid classified as shown in Figure 5.8. DRASTIC shows the vulnerability based on the physical characteristics of the aquifer.

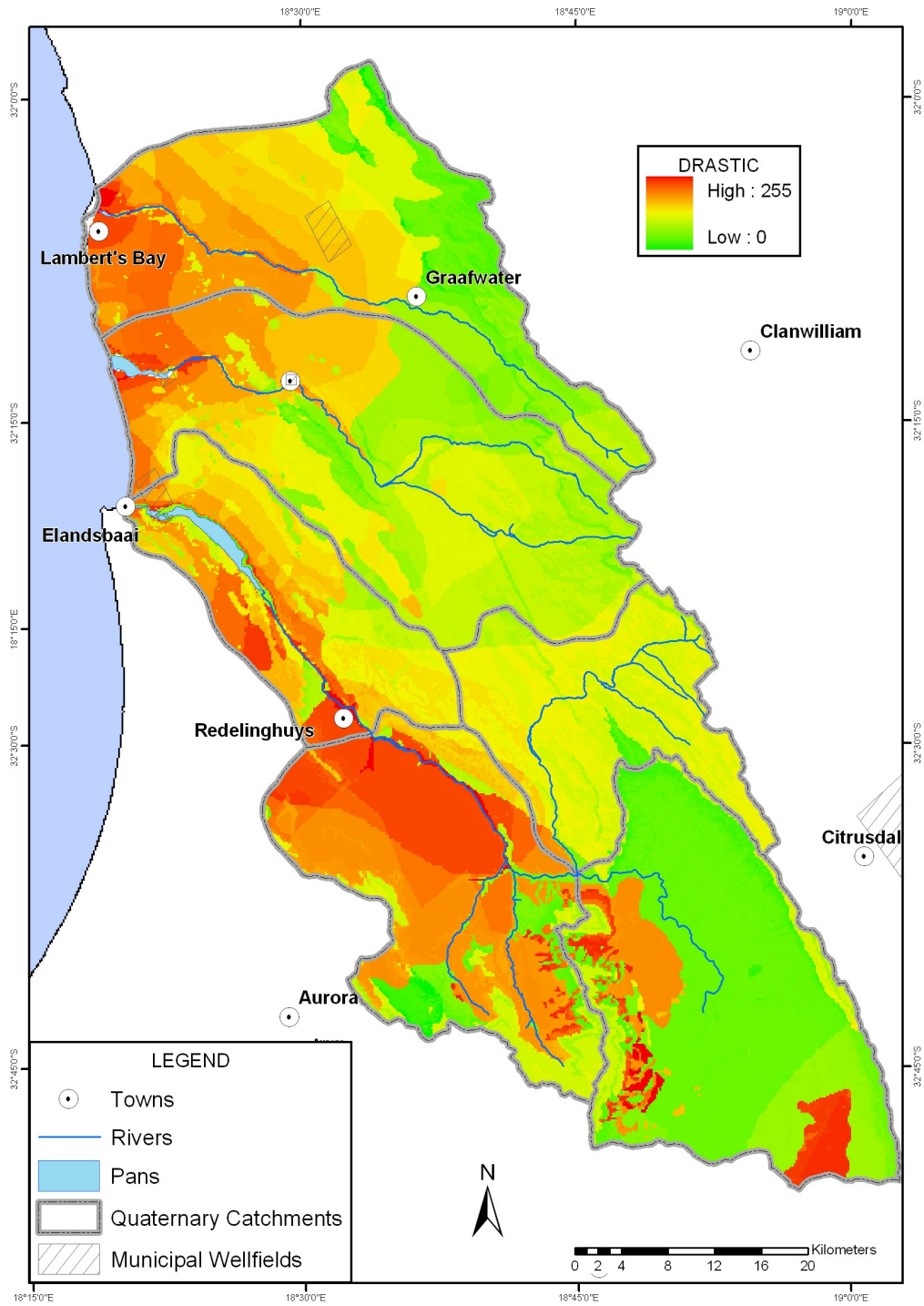


Figure 5.8 DRASTIC result showing relative groundwater vulnerability

5.3.5 Management classes based on present ecological status

Combining the vulnerability, importance and level of modification grids led to the creation of a data set that captured the current status (level of modification) of the area while looking forward to the future (importance), not forgetting the frail framework of the underlying landscape (vulnerability). Management classes are intended to show a future desired status by managing an area to an achievable state based on the current status. While a large part of the Sandveld remains undisturbed, hot spots were defined within particular GRUs. These stressed areas need particular attention.

Table 5.5 shows the management classes for the Sandveld. Graphically the management units are displayed in Figure 5.9 against the setting of the present ecological status (the combined grid). The well-fields have emerged as the areas most in need of attention. A management plan for the Sandveld has become an essential requirement.

Table 5.5 Present status and management units per GRU

GRU – Management Units	Importance	Vulnerability	Nature of modification	Present Status Category	Desired management class
GRU1P_WF (Graafwater)	Very high	Moderate	Fairly modified	Poor	Good
GRU1P	Moderate	Moderate	Modified	Fair	Good
GRU1S	Low	Very Low	Fairly unmodified	Natural	Good
GRU2P_WF (Leipoldtv.)	Very high	Very high	Fairly modified	Poor	Good
GRU2P	High	High	Modified	Fair	Good
GRU2S	Low	Low	Fairly unmodified	Good	Good
GRU3P_WF (Wadrif)	Very high	High	Severely modified	Severe	Fair
GRU3P	High	Moderate	Fairly modified	Fair	Good
GRU3S	Low	Low	Fairly unmodified	Natural	Good
GRU4P_WF (Elands Bay)	Very high	Very high	Fairly modified	Poor	Good
GRU4P	Moderate	Very high	Fairly unmodified	Fair	Good
GRU4S	Very Low	Moderate	Fairly unmodified	Good	Good
GRU5	Moderate	High	Modified	Fair	Good
GRU6	Very Low	Very Low	Fairly unmodified	Good	Good

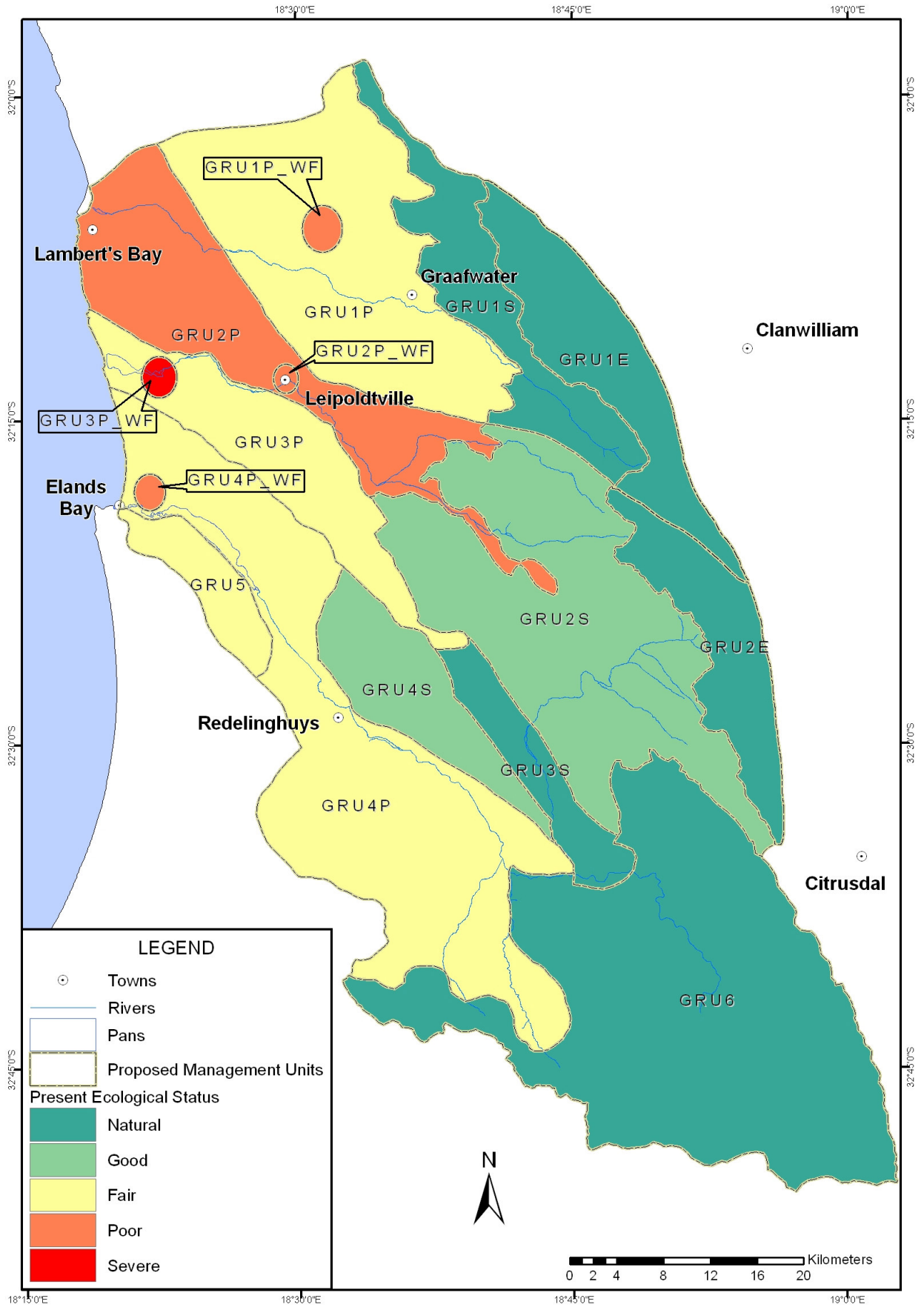


Figure 5.9 Proposed management units shown against present ecological status

5.4 RAINFALL AND RECHARGE CALCULATIONS PER GRU

A reserve calculation which requires information per GRU forms the final step of the analysis. This follows on from the classification. The same procedure used to calculate recharge per catchment (Section 4.2, Table 4.1) is followed to calculate the rainfall and recharge per GRU. The results from the calibrated recharge grids are presented in Table 5.6.

Table 5.6 Rainfall and recharge per GRU

GRU	Recharge Mm ³ /a				Rainfall mm/a			
	TH	KGB	SPP	DWAF	TH	KGB	SPP	MAP
GRU1P	7.28	7.42	10.04	4.80	245	216	280	251
GRU1S	3.10	2.67	3.92	8.50	316	248	354	355
GRU2P	5.06	5.94	7.21	3.90	219	221	256	206
GRU2S	11.99	11.83	13.25	29.4	385	321	350	393
GRU3P	2.33	3.51	4.08	2.30	189	239	267	221
GRU3S	1.70	2.38	2.17	4.60	289	344	294	381
GRU4P	14.18	19.13	16.66	3.80	265	304	256	301
GRU4S	2.39	3.51	3.61	7.10	239	302	298	355
GRU5	0.92	1.39	1.54	0.60	178	244	258	189
GRU6	9.34	12.01	9.36	17.30	359	413	307	410
<i>Sum</i>	58.28	69.77	71.84	82.30	2683	2853	2921	3062

Key:

TH – Thiessen polygons; KGB – Block Kriging; SPP – Spatial prediction; DWAF – Comprehensive reserve; MAP – WR90

From Table 5.6, just as in Table 4.1, it can be seen that the rainfall grid derived from Thiessen polygons provides a much lower recharge to the area. The value labelled DWAF in Table 5.6 refers to the figure used in the comprehensive Reserve document (DWAF 2004a). These numbers were based on the MAP value from WR90 which refers to a wetter climatic period. Conservatively one can see from the rainfall that the total recharge to the area is very low and serious measures will have to be taken to manage this stricken area.

CHAPTER 6: DISCUSSION AND CONCLUSION

In reviewing the data collection steps and methodologies used to extract information for the groundwater Reserve determination in the Sandveld, four objectives were set: reviewing the use of a relational database, comparing spatial interpolation techniques, quantifying recharge using a calibrated GIS-based calculation and setting management classes according to RDM.

The relational database, *geoMon*, provides an easily updateable data capture facility with a reliable repository, easy access and simple analysis capabilities. The strength of the database lies in the power of creating dynamic relationships and implementing them spatially, as well as reporting on newly added data in a timeous and accurate manner. Future enhancements include a dynamic process to update previously created surfaces with current groundwater level data.

For the environmental scientist, the challenge is always to obtain the most reliable data set available. Generating data for unsampled points poses a challenge despite advances in software. The mathematics involved in an interpolation technique such as Kriging remains the domain of the mathematician and statistician. The spatial variability of environmental data is not easily represented by a mathematical function. Kriging techniques may provide erroneous and biased results in the presence of strong trends in the variables being analysed. Choice of a different operator at a different scale may produce a completely different result from the same data. The environmental scientist is confronted with a black box which magically generates groundwater levels or rainfall grids.

A number of different techniques were investigated to assess the sensitivity of the predictive models. The quantitative result from the rainfall and recharge grids, shows that in the final analysis an acceptable result may be achieved through consistent data management even though the interpolation techniques produce different input values. The rainfall grids interpolated through the various methods provided lower rainfall values per catchment as compared to the MAP obtained from WR90. The lower values can be ascribed to three possible reasons. The first one being the decreasing trend of rainfall amounts over the last five years which is easily discernable in Figure 1.4. The second reason may be ascribed to the subtle underestimation of values by the interpolation techniques, which cannot adequately predict the full range of variations within the environmental data. A third possible reason may be found in the possible rain shadow effect, since all available rain gauge data were

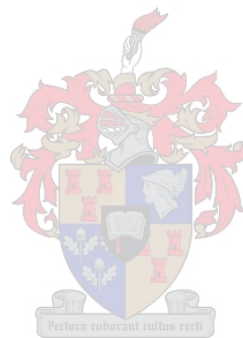
included in the interpolation. The Bayesian interpolation technique (not used for rainfall in this experiment) does seem to provide a reasonable estimate for data that is highly correlated with other variables, such as groundwater levels and topography. Block Kriging also produced a total value very close to the expected WR90 MAP. As suggested by Genton & Furrer (1998), local knowledge of the environmental variables being modelled is essential in selecting an appropriate interpolation technique. Genton & Furrer (1998) found their “guestimate” for rainfall in Switzerland to be within the same range as when using a sophisticated interpolation method and their question “Is spatial statistics worth the trouble”, is worth considering (Genton & Furrer 1998:13).

Rather than venturing into the process of deriving a current rainfall grid, many groundwater studies make use of the tried and tested MAP rainfall grid (Schulze 1997) or WR90 MAP per quaternary catchment. These data sets may not make provision for the current climatic period the world is in, and consequently not alert catchment water managers timeously of the serious overallocation in some areas. As our knowledge and understanding of environmental processes increase, so our ability to create interpolated surfaces to model real life scenarios will improve. Future research could focus on classification of data in a spatial context before applying interpolation techniques in order to provide for the possible rain shadow effect experienced.

Following the classic approach of combining reclassified grids using different weights for different factors and then calibrating the resultant surface using the chloride mass balance method provided input to the groundwater reserve determination process. When calculating the total water balance per quaternary catchment, the accuracy of the recharge calculations will be determined. The fact that no chloride in rainfall (Cl_p) was available for the area against which correlations for the CMB method could be checked, is a shortcoming which could be addressed by a rainfall sampling program in the area.

Classification and setting of management classes according to the principles of RDM provided a challenge in ensuring that all relevant aspects were evaluated. Basic human needs and social importance need to be re-evaluated in participation with stakeholders. The well-field feeding Lambert’s Bay situated in the Wadrif wetland area has emerged as the area most impacted and in need of management.

Using the tools available, sufficiently accurate information could be generated to be used for determining a Reserve with acceptable validity (DWAF 2004a). This process will ensure that areas that were identified as severely modified from physical data, and extremely important from subjective data, are treated fairly so that the aims of the National Water Act (Act 36) which states “some, for all, forever...” will be honoured.



REFERENCES

- Adams S 2004. Groundwater recharge assessment of the basement aquifers of central Namaqualand. PhD dissertation. Cape Town: University of the Western Cape.
- AI-GEOSTATS 2004. AI-GEOSTATS: the main information server for geostatistics and spatial statistics. [Online]. Available: <http://www.ai-geostats.org> [17.09.2004]
- Aller L, Bennett Y, Lehr JH & Petty RJ 1987. *DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeological settings*. (Report 600/2-85/018). Washington, DC: United States Environmental Protection Agency.
- Aquimon (In press). Sustainable development of groundwater sources under the community water supply and sanitation programme in South Africa (2000-2003). DWAF project. Pretoria: Department of Water Affairs and Forestry.
- Atkinson PM & Lloyd CD 1998. Mapping precipitation in Switzerland with ordinary and indicator Kriging. *Journal of Geographic Information and Decision Analysis* 2, 2: 65-76.
- Bean JA 2003. A critical review of recharge estimation methods used in South Africa. PhD dissertation. Bloemfontein: University of the Free State, Department of Geohydrology.
- Bredenkamp DB, Botha LJ, van Tonder GJ & van Rensburg HJ 1995. *Manual on quantitative estimation of groundwater recharge and aquifer storativity*. (Report no. ISBN 1 86845 176 3). Pretoria: Water Research Commission.
- Burrough PA & McDonnell RA 1998. *Principles of geographical information systems*. New York: Oxford University Press.
- Canter LW, Chowdhury AKMM & Vieux BE 1994. Geographic information systems: A tool for strategic ground water quality management. *Journal of Environmental Planning and Management* 37, 3: 251–266.
- Cogho VE, Kirchner J & Morris JW 1989. *A national ground-water data base for South Africa. Development of the data base*. (WRC Report No. 150/1/89).
- Conrad JE & van der Voort I 2000. Classifying Groundwater under the National Water Act: A case study. Paper delivered at the Water Institute of South Africa conference, Sun City.

- Conrad JE 2001. *Assessment of spatially distributed relative groundwater recharge potential for an area in Namaqualand, South Africa*. Stellenbosch: GEOSS.
- Cressie N 1991. *Statistics for spatial data*. New York: John Wiley and Sons.
- CSIR 1983. Report on a geophysical and geohydrological investigation of the groundwater potential between Lambert's Bay and Graafwater and the coastal region between Lambert's Bay and Eland's Bay. (Report No KON/GF/79/1). Pretoria: CSIR.
- De Beer CH 2003. *The geology of the Sandveld area between Lambert's Bay and Piketberg (Project 5510)*. (Report No. 2003-0032). Bellville: Council for Geoscience, Western Cape Unit.
- Dubois G 1998. Spatial Interpolation Comparison 97: Foreword and Introduction. *Journal of Geographic Information and Decision Analysis* 2, 2: 1-11.
- DWAF 1992. *The geohydrology of the Eland's Bay primary aquifer*. Report by J. Jolly. (Report No GH 3581). Pretoria: Directorate of Geohydrology, Department of Water Affairs.
- DWAF, DOH, WRC, 1998. *Quality of domestic water supplies, Volumes 1 – 5*. Pretoria: Department of Water Affairs and Forestry, Department of Health, Water Research Commission.
- DWAF 2003a. *Sandveld preliminary (Rapid) reserve determinations. Langvlei, Jakkals and Verlorenvlei Rivers, Olifants-Doorn WMA G30, Volume 1: Reserve Specifications*. Prepared by JE Conrad, GEOSS, in association with Southern Waters. DWAF Project Number: 2002-227. Pretoria: Department of Water Affairs and Forestry.
- DWAF 2003b. *Sandveld preliminary (Rapid) reserve determinations. Langvlei, Jakkals and Verlorenvlei Rivers, Olifants-Doorn WMA G30, Volume 2: Specialist Reports*. Prepared by JE Conrad, GEOSS, in association with Southern Waters and Coastec. DWAF Project Number: 2002-227. Pretoria: Department of Water Affairs and Forestry.
- DWAF 2003c. *Integrated water reserve management, trial implementation and testing of groundwater guidelines (Olifants-Doorn Water Management Area, 5 December 2003)*.

Prepared by JE Conrad, GEOSS, in association with SRK. Pretoria: Department of Water Affairs and Forestry.

DWAF 2004a. *Completion of high confidence ecological reserve for the groundwater, wetland and salt pan components: Groundwater reserve determination required for the Sandveld*. Prepared by JE Conrad & Z Munch, GEOSS. DWAF Project Number: 2003/03/08. Pretoria: Department of Water Affairs and Forestry.

DWAF 2004b. Information Systems. [Online]. Available: http://www.pwv.gov.za/geohydrology/InfoSystem/info_system.htm [17.09.2004].

DWAF (In press). *Assessment of the Groundwater Potential of the Langvlei catchment with special emphasis on the protection of the water resources and management options*. (Report No. GH4000). Prepared by JM Nel. Pretoria: Department of Water Affairs and Forestry.

Dyason B 1991. *Hidrosensus resultate in die Wadrif ondergrondse akwifer*. Pretoria: Department of Water Affairs and Forestry.

Englund EJ 1990. A variance of geostatisticians. *Mathematical Geology* 22: 417-455.

Fetter CW 1994. *Applied hydrogeology*. Sydney: Maxwell Macmillan International.

Gatrell AC 1983. *Distance and space – Contemporary problems in geography*. New York: Oxford University Press.

Genton MG & Furrer R 1998. Analysis of rainfall data by simple good sense: Is spatial statistics worth the trouble? *Journal of Geographic Information and Decision Analysis* 2, 2: 12-17.

GEOSS 2001. *Groundwater assessment in the potato growing regions of the Sandveld, Western Cape*. Prepared by JE Conrad. (Report No G 2001-02). Stellenbosch: GEOSS.

Havenga PL 1989. *Geohidrologiese opname in die Langvlei – Opvang gebied in die Sandveld*. (Technical Report No GH 3646). Cape Town: Directorate Geohydrology, Department of Water Affairs and Forestry.

- Hoeksema RJ & Kitanidis PK 1984. An application of the geostatistical approach to the inverse problem in two-dimensional groundwater modelling. *Water Resources Research* 20, 7: 1003–1020.
- Hutchinson MF 1998. Interpolation of rainfall data with thin plate smoothing splines - Part II: Analysis of topographic dependence. *Journal of Geographic Information and Decision Analysis* 2, 2: 152–167.
- Isaaks E & Srivastava M 1989. *An introduction to applied geostatistics*. New York: Oxford University Press.
- IWQS 2003. Institute for Water Quality Studies website. [Online]. Available: <http://iwqs.pwv.gov.za/wg/waterlaw/rdm/terminology.htm> [24.11.2003].
- Jolly JL 1992. *Geohydrology of the Graafwater government subterranean water control area*. (Report No GH 3778). Cape Town: Directorate Geohydrology, Department of Water Affairs and Forestry.
- Jolly JL & Reynders AG 1993. The protection of aquifers – a proposed aquifer classification and protection zoning for South African conditions. Paper delivered at International groundwater convention of Groundwater Division of the Geological Society of South Africa (“Africa needs groundwater”), Johannesburg.
- Li B & Yeh T-CJ 1999. Cokriging estimation of the conductivity field under variably saturated flow conditions. *Water Resources Research* 35,12: 3663-3674.
- MacKay HM 1999. *Towards a classification system for water resources in South Africa*. Pretoria: Institute for Water Quality Studies, Department of Water Affairs and Forestry.
- Maclear LGA 1994. *A groundwater hydrocensus and water quality investigation of the Eland's Bay primary aquifer – Verlorenvlei*. (Technical Report GH 3835). Cape Town: Department of Water Affairs and Forestry.
- Malan A 1998. *Leipoldville eksterne watervoorsiening*. (CMIP Technical Report Project No J80397A). Bellville: Gibb Africa.

- McNoleg O 1996. The integration of GIS, remote sensing, expert systems and adaptive co-kriging for environmental habitat modelling of the Highland Haggis using object-oriented, fuzzy-logic and neural-network techniques. *Computers and Geosciences* 22, 5: 585-588.
- Midgley DC, Pitman WV & Middleton BJ 1994. *Surface water resources of South Africa 1990*. Pretoria: Water Research Commission.
- NLC 1999. The South African national land-cover database. [Online]. Available: http://www.csir.co.za/plsql/ptl0002/PTL0002_PGE015_PRODUCT?PRODUCT_NO=1600858 [25.09.2004].
- Pannatier Y 1996. *VarioWin - Software for spatial data analysis in 2D*. New York: Springer-Verlag.
- Parsons R & Conrad JE 1998. *Explanatory notes for the aquifer classification map of South Africa*. (WRC Report No KV 116/98). Pretoria: Water Research Commission.
- Potatoes 2004. Potatoes South Africa. [Online]. Available: <http://www.potatoes.co.za> [09.08.2004]
- Rasmussen J 1999. *Leipoldville bulk water supply, groundwater development*. (Report No 990205). Wynberg: Toens and Partners.
- Saayman I, Colvin C, Cave L, Moseki C, Braune E, Toksvad T & Conrad J 2002. National guidelines to enable Integrated Groundwater Resource Management in Water Management Areas. Paper delivered at Western Cape Groundwater Conference, Groundwater Division of the Geological Society of South Africa (“Tales of a hidden treasure”), Somerset West.
- Schulze RE 1997. *South African atlas of agrohydrology and -climatology*. (Report No TT82/96). Pretoria: Water Research Commission.
- Schultz RE, Maharaj M, Lynch SD, Howe BI & Melvil-Thomson B 2002. *South African atlas of agrohydrology and climatology*. Data on CD ROM.
- Shine JA & Krause PF 2000. Exploration and estimation of North American climatological data. *Computing science and statistics Volume 32*. [Online]. Available:

<http://www.galaxy.gmu.edu/interface/I00/I2000Proceedings/JShine/jshinePaper.pdf>
[27.05.2004].

South Africa (Republic of) 1998. *National Water Act, Act No. 36 of 1998*. Government Gazette, 19182. Pretoria: Government Printer.

SRK 1985. *Proposal to develop the groundwater resources of Eland's Bay, Phase I*. Cape Town: SRK.

SRK 1986. *Investigation into the groundwater resources of the Eland's Bay area, Phase II*. (Report KP 4934/4). Cape Town: SRK.

SRK 1998. *Wadrif groundwater investigation for water supply to Lambert's Bay*. (Report 253 068/1). Prepared by G Maclear. Cape Town: SRK.

SRTM30 2004. Shuttle radar topography mission. [Online]. Available: <http://www2.jpl.nasa.gov/srtm/cbanddataproducts.html> [03.09.2004].

Surfer 2002. *Surfer Version 8.02*. Surface Mapping System. PLACE: Golden Software, Inc.

Tobler W 1979. Smooth pycnophylactic interpolation for geographical regions. *Journal of the American Statistical Association* 74,357: 519-535.

Todini E 2001. A Bayesian technique for conditioning radar precipitation estimates to rain-gauge measurements. *Hydrology and Earth System Sciences* 5,2: 187–199.

Umvoto – SRK 2000. *Reconnaissance investigation into the development and utilization of the Table Mountain group artesian groundwater, using the E10 catchment as a pilot study area*. Cape Town: Umvoto.

Van Doolaege MAC 1981. *Pumping test on production well G 31350 Wagendrift – Lambert's Bay*. (Technical Report GH 3178). Cape Town: Department of Water Affairs and Forestry.

Van Kleef HA 1997. *'n Aanvullende grondwater opname binne die Wadrif ondergrondse staatswaterbeheergebied: Effek van grootskaalse onttrekking op die grondwatervlakke en kwaliteit*. (Technical Report GH 3179). Bellville: Department of Water Affairs and Forestry.

- Van Sandwyk L, van Tonder GJ, de Waal DJ & Botha, JF 1992. *A comparison of spatial Bayesian estimation and classical Bayesian kriging procedures*. (WRC report no. 271/3/92). Pretoria: Water Research Commission.
- Van Tonder GJ, Van Sandwyk L & Buys J 1996. Program TRIPOL, version 1.0, Institute for Groundwater studies, and Water Research Commission.
- Vegter JR 1995. *An explanation of a set of national groundwater maps*. (WRC report no. TT74/95). Pretoria: Water Research Commission.
- Visser D 2002a. *Graafwater – Groundwater monitoring report No. 2. (Period April 2002 to June 2002)*. (Report No. 2002284). Cape Town: Toens & Partners.
- Visser D 2002b. *Graafwater – Groundwater monitoring report No. 3. (Period July 2002 to October 2002)*. (Report No. 2002295). Cape Town: Toens & Partners.
- Visser D 2003. *Graafwater – Groundwater monitoring report No. 4. (Period November 2002 to March 2003)*. (Report No. 318529 A-4). Cape Town: SRK Consulting.
- Visser D & Esterhuysen CJ 2002. *Graafwater – Groundwater monitoring report No. 1. (Period 1989 to March 2002)*. (Report No. 2002272). Cape Town: Toens & Partners.
- Xu Y, Colvin C, van Tonder G, Hughes S, le Maitre D, Zhang J, Mafanya T & Braune E 2003. *Towards the Resource Directed Measures: Groundwater Component (Version 1.1)*. (WRC Report No. 1090-2/1/03). Projects K5/1090, 1091 & 1092. Pretoria: Water Research Commission.

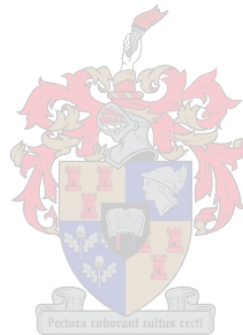
PERSONAL COMMUNICATIONS

Conrad JE 2004. Principal member, GEOSS. Stellenbosch. Interview on 11 March about classification parameters for recharge input. Personal communication.

Nel J 2004. Geohydrologist, DWAF Head office. Stellenbosch. Meeting on 16 February regarding the definition of GRUs.

Pienaar H 2004. Director, DWAF RDM office. Pretoria. Feedback meeting on 23 March regarding Report 2003/08/03.

Silberbauer M 2004. Institute for Water Quality Studies, DWAF, Pretoria. E-mail on 28 July regarding SRTM data set.



ADDITIONAL SOURCES

- Allard D 1998. Geostatistical classification and class Kriging. *Journal of Geographic Information and Decision Analysis* 2, 2: 77-90.
- Daly C, Neilson RP & Phillips DL 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology* 33: 140–158.
- DWAF 1999. *Resource directed measures for protection of water resources*, Volume 2: *Integrated manual version 1.0*. Pretoria: Department of Water Affairs and Forestry.
- Goovaerts, P 1997. *Geostatistics for natural resources evaluation*. New York: Oxford University Press.
- Kitanidis PK & Vomvoris EG 1983. A geostatistical approach to the inverse problem in groundwater modeling (steady state) and onedimensional simulations. *Water Resources Research* 19, 3: 677–690.
- Kitanidis PK 1995. Quasi-linear geostatistical theory for inversing. *Water Resources Research* 31, 10: 2411–2419.
- Kitanidis PK 1997. *Introduction to geostatistics - Applications in hydrogeology*. New York: Cambridge University Press.
- Parsons R 1995. *A South African aquifer system management classification*. (WRC Report No KV 77/95). Pretoria: Water Research Commission.
- Parsons R (In press). *Surface water – Groundwater interaction in a Southern African context – A geohydrological perspective*. Pretoria: Water Research Commission.
- Wessels F 1992. Variogram identification and parameter estimation for the Kriging interpolation technique – An overview. MSc thesis. Port Elizabeth: University of Port Elizabeth.

APPENDIX A : RECHARGE RATINGS

Table A.1 Land Cover reclassification for recharge rating

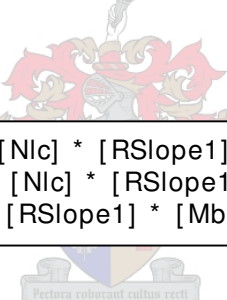
Land Cover description	Recharge rating
Barren rock	1
Cultivated: permanent - commercial dryland	9
Cultivated: permanent - commercial irrigated	9
Cultivated: permanent - commercial sugarcane	9
Cultivated: temporary - commercial dryland	9
Cultivated: temporary - commercial irrigated	9
Cultivated: temporary - semi-commercial/subsistence dryland	9
Degraded: forest and woodland	6
Degraded: herbland	7
Degraded: shrubland and low Fynbos	9
Degraded: thicket & bushland (etc)	8
Degraded: unimproved grassland	9
Dongas & sheet erosion scars	10
Forest	5
Forest and Woodland	5
Forest plantations	4
Herbland	6
Improved grassland	8
Mines & quarries	10
Shrubland and low Fynbos	8
Thicket & bushland (etc)	7
Unimproved grassland	9
Urban / built-up land: commercial	5
Urban / built-up land: industrial / transport	5
Urban / built-up land: residential	5
Urban / built-up land: residential (small holdings: bushland)	6
Urban / built-up land: residential (small holdings: grassland)	6
Urban / built-up land: residential (small holdings: shrubland)	6
Urban / built-up land: residential (small holdings: woodland)	6
Waterbodies	10
Wetlands	10

Table A.2 Recharge rating classification according to slope

Slope (degrees)	Recharge rating
0-5	10
5-10	9
10-20	7
20-50	5
50-90	2

Table A.3 Recharge rating reclassification for depth to water level

Depth to water level	Recharge rating
0-5	9
5-10	8
10-15	7
15-20	6
20+	5



```

([Rain_calce.shp] * [Geol1] * [Nlc] * [RSlope1] * [Mbgl_bayes])/100000.AsGrid
([Rain_kg_blk.shp]* [Geol1] * [Nlc] * [RSlope1] * [Mbgl_bayes])/100000.AsGrid
([Thiessen]* [Geol1] * [Nlc] * [RSlope1] * [Mbgl_bayes])/100000.AsGrid

```

Figure A.1 Map calculator equations for calculating recharge

Table A.4 Recharge percentage based on geology

Symbol	Formation	SubGroup	Group/Suite	SuperGroup	% Recharge
Qa					20
Qt					30
Qg					18
Qg					18
Qb					5
Qf					5
Qq					10
Qc					10
Qtg					15
Qw	Witzand				20
Qs	Springfontein		Sandveld		15
Qv	Veldrif				10
Tv	Varswater				15
Jd			Karoo Dolerite		5
Do	Osberg				1
Dk	Klipbokkop	Bidouw			1
Dwu	Wuppertal				1
Dw	Waboomberg				1
Db	Boplaas		Bokkeveld		1
Dt	Tra-Tra				1
Dh	Hex River	Ceres			1
Dv	Voorstehoek			Cape	1
Dga	Gamka				1
Dg	Gydo				1
	Lamberts	Bay			
Tm	Breccia Basalt	Nardouw			5
	Not yet subdivided				
Sn	on sheet 32	Winterhoek	Table		5
	Pakhuis	&			
Ow	Cedarberg		Mountain		1
Ope	Peninsula		Group		15
Og	Graafwater				2
Op	Piekenierskloof				15
Cp	Populierbos		Klipheuwel		2
Cm	Magrug				5
Np	Piketberg				7
Nm	Moorreesburg				5
Npo	Porterville				2
Et	Bridgetown		Malmesbury		5
Nk	Klipplaat*				5
Nb	Bergrivier*				5
Nd**	Porterville				5
Nf**	Porterville				5
Nat	Aties*		Gifberg	Gariiep	7

APPENDIX B : INTERPOLATION DATA

Table B.1 Rainfall stations with rainfall values obtained through interpolation

Rainfall Station	Source	Y-Coord	X-Coord	Elev	Ctrl Data	5yr Avg	Point Kriging			Block Kriging			Regression
							None	Linear	Qd	None	Linear	Qd	
107396 Vanrhynsdorp	SAWS	-31.60	18.73	135	142	152	189	113	145	193	113	146	267
107759 Sandvlei	SAWS	-31.65	18.93	214	184	194	204	166	172	207	166	173	283
107869 Kanolvlei	SAWS	-31.98	18.98	210	172	176	230	245	234	233	245	234	279
108311 Lokenburg	SAWS	-31.68	19.18	662	245	253	229	186	213	231	186	213	307
20019 Citrusdal (NIVV)	Infruitec	-32.57	18.98	175	372	400	390	387	394	389	387	395	355
20036 Pools	G30	-32.80	18.88	154	322	296	415	436	444	412	436	445	336
20052 Nooitgedacht, Ceres	Infruitec	-33.22	19.33	1058	779	736							509
20066 Moorreesburg Ko-op	Infruitec	-33.15	18.68	192	417	404	446	447	427	445	447	427	372
20068 Porterville Ko-op	Infruitec	-33.02	19.02	180	775	522	487	513	532	481	513	532	507
20069 Graafwater	G30	-32.17	18.60	179	298	250	247	237	238	250	237	238	327
20087 Nortier, Lambertsbaai	G30	-32.03	18.33	100	223	221	210	168	170	213	168	171	298
20100 Heldervue	Infruitec	-32.82	18.72	744	851	741	433	421	419	429	421	419	536
20124 Middeltuyn	Infruitec	-32.30	18.83	590	507	382	322	300	315	322	300	314	406
20127 Stagmanskop	Infruitec	-32.50	18.90	560	499	456	376	360	373	374	360	373	403
20131 Sneeuwkop	Infruitec	-32.92	19.45	995	352	466							347
20133 Lorraine	Infruitec	-32.05	19.05	327	244	223	254	267	258	257	267	258	306
20145 H.L.S.Augsburg	Infruitec	-32.17	18.90	146	283	194	264	278	268	267	278	268	321
20147 Afgunst	Infruitec	-32.50	18.60	36	293	234	310	319	313	311	319	314	325
20159 Eendekuil	Infruitec	-32.68	18.88	93	282	304	386	403	415	385	403	415	321
30012 De Keur	Infruitec	-32.98	19.30	940	509	608	512	539	554	506	539	554	407
30175 Riviera	Infruitec	-32.68	18.68	76	394	405	382	380	379	381	380	380	363
62444 Piketberg - SAPD	SAWS	-32.90	18.75	265	411	408	439	449	437	435	449	437	369
62671 Eendekuil	SAWS	-32.68	18.88	104	287	291	385	402	413	384	402	414	323
63005 Citrusdal	SAWS	-32.58	19.02	218	301	326	395	396	401	393	396	402	328
63807 Ceres Excelsior	SAWS	-32.95	19.45	949	306	418							330
83515 Lambert's Bay	G30	-32.08	18.30	22	156	173	212	178	180	216	178	180	273
83618 Elandsbaai	G30	-32.30	18.35	5	190	145	237	234	213	240	234	213	286
84059 Redelinghuys	SAWS	-32.48	18.53	18	263	242	294	299	287	296	299	287	313
84159 Graafwater	SAWS	-32.15	18.60	164	240	250	244	234	230	247	234	230	305
84558 Elandsfontein	SAWS	-32.30	18.82	460	508	461	321	299	313	320	299	313	406
84701 Clanwilliam	SAWS	-32.18	18.90	92	222	155	268	281	274	271	281	275	298
85112 Algeria - Bos	SAWS	-32.37	19.07	646	476	675	384	352	371	382	352	370	394
85309 Mertenhof	SAWS	-32.15	19.18	471	266	197	295	304	300	296	304	300	315
E1E004 Andriesgrond	DWAF	-32.18	18.88	151	246	206	266	277	271	269	277	271	307

Table B.2 Comparison of interpolated values for boreholes

BH_NO	Elevation	WL (mamsl)	BAYES Kriging	Ordinary Kriging	Kriging with Breakline	Kriging with River pts
102/3	100	98.3	98.7	217.7	212.2	199.5
225/14	119	91.4	102.0	109.5	111.1	85.0
230/8	19	1.5	11.1	21.6	21.7	13.0
238/1	100	99.7	99.1	110.7	110.0	102.0
254-1	440	433.7	447.9	274.4	322.8	489.0
3218BC 23	115	111.1	110.0	125.6	125.3	117.7
3218BD BH1	128	126.5	142.7	174.6	218.9	311.4
3218CB/CA 22	64	57.0	63.3	64.3	64.0	63.8
3218CB/CA 34	60	59.7	61.4	73.5	76.0	90.6
3218CB/CA20	30	25.2	31.3	38.3	38.0	42.4
3218CB/CA9220	30	26.5	31.3	38.3	38.0	42.4
3218DB 53	95	83.1	85.5	152.1	129.5	82.4
3218DD 79	179	177.8	181.1	209.1	199.2	175.6
3219CA 53	210	187.7	195.7	184.7	198.4	228.1
3219CA 54	190	187.2	175.2	183.2	198.7	227.9
3219CA 61	190	185.9	191.0	187.4	188.1	212.6
3219CA 62	200	196.9	206.6	187.4	190.5	215.9
37/1	860	848.7	895.6	445.9	421.7	352.4
37/2	850	843.8	858.0	442.3	419.4	352.3
481/1	200	195.7	205.2	193.9	188.7	167.1
88/9	40	39.4	32.7	57.8	55.2	34.8
92/4	21	-5.5	2.6	16.5	16.6	6.7
BG11	180	179.5	177.4	160.6	162.1	164.6
BG23	190	184.9	187.6	162.8	164.6	170.7
B'HOLE A	6	-5.2	8.8	16.9	17.0	7.8
B'HOLE B	8	-4.0	7.6	17.9	18.1	7.8
B'HOLE C	8	-6.7	6.4	18.9	19.2	8.0
BT10	124	93.7	108.3	70.8	68.8	48.0
BT9	28	25.1	20.8	39.6	39.3	23.8
DR13	111	107.4	110.2	125.3	124.9	117.0
G31019	8	2.2	3.8	19.0	19.7	8.3
G31262	6	-3.1	8.8	16.9	17.0	7.8
G31263	15	14.8	6.6	18.9	19.2	8.0
G31293	16	15.7	2.6	19.0	19.6	8.4
G31350	15	1.9	6.4	18.9	19.2	8.0
G33568	40	29.3	29.9	46.1	40.7	21.2
G33652	40	13.6	7.4	12.1	12.0	6.6
G33654	12	-14.5	1.7	12.0	11.9	6.1
G33658	40	13.8	7.3	12.0	11.9	6.6
G33658A	40	13.8	7.5	12.0	12.0	6.7
G33726	167	161.8	165.8	141.5	139.5	122.2
G33747	177	160.0	178.1	178.3	177.6	169.5
G33748	165	104.6	129.6	155.4	154.8	151.4
G33921	150	132.4	136.0	117.3	116.6	102.0
G33922	209	195.1	192.4	199.8	199.7	191.4
G33923	194	178.1	129.6	155.4	154.8	151.4
G33928	145	127.6	128.9	110.3	109.5	97.9
G33941	155	119.0	109.1	105.5	103.0	95.8
G33942	168	127.3	138.2	102.3	97.2	89.8
G33943	111	106.4	100.9	96.2	95.2	85.5
G33944	68	64.9	65.6	67.6	66.8	60.8
G33945	82	63.8	71.0	66.9	65.8	59.9
G33945A	82	69.0	70.6	66.9	65.7	59.9

Table B.2 Comparison of interpolated values for boreholes (*cont.*)

BH_NO	Elevation	WL (mamsl)	BAYES Kriging	Ordinary Kriging	Kriging with Breakline	Kriging with River pts
G33946	101	58.6	60.4	62.0	58.3	54.9
G33947	62	48.9	47.8	50.8	48.2	45.6
G33948	24	1.2	3.8	10.9	10.9	6.7
G33989	21	2.4	7.0	11.2	11.2	7.6
G40144	133	125.9	145.6	174.8	218.7	310.1
G44061	5	1.4	-0.5	10.6	10.4	5.3
G44065	10	5.2	5.4	14.3	13.9	5.1
G47798	4	1.1	3.2	9.3	9.5	3.5
G47799	2	1.1	3.5	9.5	9.8	3.5
G47800	4	0.6	1.6	18.2	18.7	8.3
G47801	4	1.1	1.6	18.2	18.7	8.3
G47802	5	1.1	1.9	18.6	19.2	8.2
G47803	1	-0.7	0.9	16.6	17.2	6.9
G47804	28	25.1	27.1	31.9	32.9	22.8
G47805	35	27.0	27.4	31.8	32.7	23.8
G47806	33	28.3	30.0	33.4	34.1	24.9
G47807	4	1.1	4.8	9.3	9.5	3.4
G47811	24	21.2	22.4	36.2	37.0	23.3
G47812	97	94.9	93.6	110.6	109.4	100.2
G47813	57	55.7	89.7	78.7	78.2	62.9
G47814	158	155.2	180.2	158.5	159.7	163.5
G47815	164	162.6	177.5	160.7	162.3	165.0
G47816	127	122.7	116.9	140.3	140.5	134.7
G47817	119	117.2	118.7	132.2	133.4	125.4
G47818	73	66.5	56.4	103.9	100.8	83.9
G47819	48	44.6	67.9	65.7	65.0	53.5
G47820	132	119.0	120.9	116.9	116.3	107.0
G47821	127	115.8	112.7	105.3	102.9	96.8
G47822	127	116.3	112.8	105.3	102.9	96.9
G47823	113	70.9	77.8	95.3	94.2	83.0
G47824	83	64.1	66.7	84.3	86.6	69.2
G47825	83	64.2	66.7	84.3	86.7	69.2
G47826	161	142.5	142.8	122.7	124.3	96.3
G47827	117	112.3	117.7	130.1	129.5	113.5
G47828	180	166.7	164.7	162.7	162.8	160.2
G47829	268	227.9	255.5	203.2	202.4	190.4
G47830B	111	104.2	108.2	114.2	116.2	105.7
G47831	225	119.6	140.5	107.4	103.8	98.3
G47832	183	73.8	73.2	103.9	101.7	86.1
G47833	196	120.8	125.1	93.9	92.1	82.3
G47834	322	201.1	216.3	105.8	104.2	90.0
G47835	36	13.0	18.0	15.5	16.2	7.6
G47836	63	42.3	52.3	36.2	35.4	24.5
G47837	57	55.3	65.0	78.8	78.5	63.2
G47838	186	110.6	122.6	58.2	52.3	46.1
G47839	20	11.9	18.5	16.1	17.5	7.6
G47840	2	1.1	4.2	9.5	9.8	3.5
G47841	30	28.6	33.1	57.9	55.4	36.5
G47842	63	61.7	62.3	83.5	80.5	68.0
G47843	130	122.0	125.0	133.1	131.0	126.2
G47844	190	160.5	160.7	168.3	172.6	170.5
G47845	259	191.3	201.5	190.1	195.0	190.4

Table B.2 Comparison of interpolated values for boreholes (*cont.*)

BH_NO	Elevation	WL (mamsl)	BAYES Kriging	Ordinary Kriging	Kriging with Breakline	Kriging with River pts
G47846	216	170.0	176.6	169.0	173.1	171.3
G47847	134	109.0	108.4	103.1	101.2	89.9
G47848	134	108.7	108.5	103.1	101.2	89.9
G47849	113	98.4	94.4	109.1	106.2	99.1
G47850	113	97.8	94.4	109.1	106.2	99.1
G47851	210	173.6	173.2	169.2	172.1	171.0
G47852	216	174.2	179.7	171.6	174.9	172.1
G47853	240	188.4	191.2	198.7	206.5	198.4
G47854	228	215.3	229.3	218.8	218.3	213.5
G47855	385	293.5	294.3	223.1	223.0	206.7
G47856	176	140.5	146.0	152.9	152.9	127.3
G47857	154	119.7	121.3	116.8	116.2	99.9
G47858	164	133.4	132.5	137.6	137.3	121.8
G47859	164	133.4	132.6	137.6	137.3	121.7
G47860	38	7.7	15.1	18.3	17.8	15.9
G47861	152	33.3	55.7	22.6	21.4	14.6
G47862	59	23.8	22.1	21.2	19.8	10.1
G47863	59	29.7	31.8	55.4	52.1	10.6
G47868	206	205.3	208.8	210.1	210.6	212.4
GEOSS-A1	46	39.6	3.1	22.2	21.7	20.5
GEOSS-A10	134	118.6	96.3	162.5	160.1	162.8
GEOSS-A11	94	76.4	38.6	127.7	124.6	129.5
GEOSS-A12	75	26.5	34.9	122.4	120.1	132.2
GEOSS-A13	96	82.1	41.9	130.6	126.9	132.8
GEOSS-A3	32	28.2	6.9	25.8	25.0	25.1
GEOSS-A5	96	91.8	63.7	73.4	73.2	72.7
GEOSS-A6	134	115.7	70.4	99.7	98.5	98.0
GEOSS-A7	179	164.1	144.9	185.7	177.8	169.4
GEOSS-A8	125	124.6	102.7	215.3	209.7	197.0
GEOSS-A9	130	129.4	102.7	216.1	210.5	197.2
GEOSS-J1	58	56.0	19.8	52.9	49.7	28.4
GEOSS-J2	42	31.8	28.7	53.3	50.4	29.8
GEOSS-J3	102	84.7	65.0	75.1	72.5	57.4
GEOSS-J5	212	196.8	163.5	189.0	187.6	183.4
GEOSS-J6	271	266.5	238.9	232.1	238.4	253.1
GEOSS-L1	21	8.0	2.5	16.3	16.4	6.5
GEOSS-L10	199	187.0	169.0	174.6	174.0	175.8
GEOSS-L11	189	182.2	176.8	173.7	173.1	175.9
GEOSS-L12	191	168.5	177.5	174.9	174.2	180.8
GEOSS-L13	78	72.5	37.8	59.2	59.1	45.4
GEOSS-L2	26	20.0	3.6	16.1	16.2	7.5
GEOSS-L3	42	30.0	10.3	16.6	16.6	7.9
GEOSS-L4	74	68.1	37.9	58.6	57.9	45.9
GEOSS-L5	113	108.4	64.8	90.8	93.3	70.2
GEOSS-L6	105	99.7	65.7	98.4	99.4	77.4
GEOSS-L7	120	113.6	68.3	112.3	108.0	89.6
GEOSS-L8	141	140.9	109.9	121.6	123.2	111.1
GEOSS-L9	162	131.6	116.8	140.2	140.3	134.7
GEOSS-V10	14	13.3	15.5	38.4	33.1	9.4
GEOSS-V11	40	38.7	4.0	38.5	33.4	9.7
GEOSS-V12	71	68.4	37.1	74.2	69.2	43.1
GEOSS-V13	61	56.9	38.3	74.5	69.7	43.9

Table B.2 Comparison of interpolated values for boreholes (*cont.*)

BH_NO	Elevation	WL (mamsl)	BAYES Kriging	Ordinary Kriging	Kriging with Breakline	Kriging with River pts
GEOSS-V14	78	71.0	49.1	79.0	75.5	48.2
GEOSS-V15	32	31.0	6.4	48.3	42.9	18.8
GEOSS-V16	29	28.4	4.6	49.8	44.1	19.6
GEOSS-V20	72	70.2	42.5	99.7	90.7	46.5
GEOSS-V21	68	67.3	37.2	99.2	89.5	43.6
GEOSS-V22	42	39.3	39.7	98.7	89.2	44.7
GEOSS-V3	6	0.9	-0.3	13.9	13.6	5.1
GEOSS-V5	9	4.5	4.9	14.2	13.9	5.1
GEOSS-V8	39	37.1	5.0	37.4	33.3	14.5
GEOSS-V9	15	13.7	13.3	40.2	34.8	11.2
LPM01	68	61.3	64.3	87.2	89.7	69.7
R1	17	-4.4	7.8	11.1	11.0	7.1
R2	21	1.9	6.9	11.2	11.2	7.6
R3	40	12.6	7.3	12.0	12.0	6.6
R4	10	5.1	5.2	14.3	13.9	5.1
R5	4	-1.6	0.4	13.9	13.6	5.1
R6	8	3.7	9.7	15.5	15.0	4.9
R7	9	6.3	7.6	15.1	14.6	5.1
SRK1	9	4.2	6.7	19.3	20.1	8.2
SRK1c	9	3.5	4.3	18.9	19.7	8.3
SRK2	6	-3.8	1.8	18.8	19.4	8.4
SRK3	6	-15.1	3.9	18.5	18.8	8.1
SRK4	8	4.3	7.8	18.9	19.8	7.8
SRK4A	8	5.2	7.3	18.8	19.7	7.8
SRK5	6	4.4	2.6	17.4	17.9	8.0
SRK6	5	4.1	2.5	17.4	17.8	8.0



APPENDIX C : DRASTIC RATINGS AND WEIGHTS

Table C.1 Depth to groundwater ratings used in the DRASTIC method

Range (m)	Rating
0 – 1.5	10
1.5 – 4.5	9
4.5 – 9.0	7
9.0 – 15.0	5
15.0 – 22.5	3
22.5 – 30.0	2
> 30	1
Weight	5

Table C.2 Recharge ratings used in the DRASTIC method

Range (mm)	Rating
0 – 50	1
50 – 100	3
100 – 175	6
175 – 250	8
> 250	9
Weight	4

Table C.3 Soils ratings used in the DRASTIC method

Range – Sandveld	Rating
SaCILm (Sand Clay Loam)	5
SaLmSa (Sand Loam Sand)	8
LmSa-SaLm	6
SaLm-SaCILm	5
Weight	2

Table C.4 Topography (slope) ratings used in the DRASTIC method

Range (%)	Rating
<2	10
2 – 6	9
6 – 12	5
12 – 18	3
> 18	1
Weight	1

Table C.5 Ratings used in the DRASTIC method based on underlying geology: aquifer media, impact of vadose zone and hydraulic conductivity

Symbol	Lithology	Ratings		
		Aquifer media (A)	Impact of vadose zone (I)	Hydraulic conductivity (C)
Qa	Alluvium	8	8	9
Qt	Scree and gritty sand	8	8	9
Qg	Sandy loam soil	7	7	8
Qb	Brackish, calcareous soil	7	7	7
Qf	Ferricrete	6	6	6
Qq	Silcrete	6	6	6
Qw	Calcareous beach and dune sand	8	8	8
Qs	Sandy soil (unvegetated)	7	7	7
Qs/v	Sandy soil (vegetated)	6	6	7
Qv	Consolidated to unconsolidated marine shells, sand and gravel	7	6	9
Tv	Consolidated to unconsolidated phosphatic sand, clay and shelly gravel	6	5	8
Tm	Basalt and volcanic breccia	3	9	1
Ope	Thick bedded quartzose sandstone with minor shale and small-pebble conglomerate	6	6	2
Og	Thin bedded, red and brown sandstone, subordinate mudrock, small-pebble conglomerate and grit	5	5	1
Op	Thick bedded quartzose sandstone and conglomerate	6	6	2
Cp	Maroon to purple shale, arkose, small-pebble conglomerate and grit	2	3	1
Np	Feldspathic grit, greywacke, quartz schist, conglomerate and limestone beds with thin lenses of phyllite	3	3	1
Nm	Greywacke, phyllite and quartzite with thin bands of schist	2	1	1
Npo	Phyllite, schist, shale and greywacke	2	2	2
Qtg	River terrace gravel	10	10	10
Et	Greenstone	3	3	2
	Weight	3	5	3

APPENDIX D: *geoMON* TABLES

Table D.1 BHBASE

Field Name	Data Type	Size	Description
IDNUM	Long Integer	4	Internal Use
ENTDATE	Date	8	Internal Use - Date Entered
BHNUM	Text	30	Unique Borehole Number - Primary Key
COORDTYP	Text	20	Coordinate Accuracy
BHTYPE	Text	10	Borehole, well-point, etc
LATITUDE	Double	8	Borehole Latitude WGS84 (must be negative)
LONGITUDE	Double	8	Borehole Longitude WGS84
LAT_CAPE	Double	8	Borehole Latitude Cape (must be negative)
LONG_CAPE	Double	8	Borehole Longitude Cape
ELEVATION	Double	8	Elevation (metres above mean sea-level)
ELEV_O	Double	8	Elevation (metres above mean sea-level) previous
COLLAR	Double	8	Collar Elevation (metres above mean sea-level)
DATUM	Double	8	Datum (metres)
MAPSHEET	Text	10	1:50 000 Mapsheet Reference Number on which Borehole is Located
DRNREG	Text	10	Drainage region WR90
RAINSTAT	Text	60	Unique Identifier to link to Monthly Rainfall Data
DWAFNUM	Text	50	Department Water Affairs & Forestry Borehole Number
WARMLNUM	Text	50	DWAF WARMS Number
SITEID	Text	50	Site Identifier
OPID	Text	30	Borehole name with Consultant
OPNAME	Text	50	Name of Consultant
OID	Text	30	Other ID from NGDB
B_B_No	Text	20	BB_No from NGDB
Danida	Text	50	BH Name in Danida study
MUNICIPAL	Text	80	Name of District Municipality
COUNCIL	Text	80	Name of Local Council
COMMUNITY	Text	80	Name of Village or Community
FARMNO	Text	20	Farm Number
OWNER	Text	60	Farm Owner
CONTACTDETAILS	Text	60	Phone or fax
FARMNAME	Text	50	Farm Name (Portion)
AQUIFER	Text	80	Aquifer Name or Description
AQ_TYPE	Long Integer	4	Aquifer Type

Table D.1 BHBASE (cont.)

Field Name	Data Type	Size	Description
LITH	Text	10	Lithology from NGDB
BHDEPTH	Double	8	Depth (metres below ground-level) of Borehole
BHSAND	Double	8	Sand thickness
BHDIAM	Long Integer	4	Diameter (mm) of Borehole
CASETYPE	Text	30	Type of Casing
CASEDIAM	Long Integer	4	Diameter (mm) of Casing
CASEDEPTH	Double	8	Depth (metres below ground-level) of Casing
PUMPDEPTH	Double	8	Depth (metres below ground-level) of Pump Intake
EQUIPMENT	Text	20	Type of Pump Equipment
RWLEVEL	Double	8	Original Rest-Waterlevel at time of Drilling or Pump-Testing
MAINSTRIKE	Double	8	Depth (metres below ground-level) of Main Water Interception
ORD2STRIKE	Double	8	Depth (metres below ground-level) of 2nd Order Water Interception
ORD3STRIKE	Double	8	Depth (metres below ground-level) of 3rd Order Water Interception
BLOWYIELD	Double	8	Yield (l/s) of Borehole at end of Drilling
EC	Double	8	Original Electrical Conductivity (mS/m) of Water (i.e. after Drilling or Pump-Testing)
STATUS	Text	30	Status of Borehole - either Production or Monitoring
BHCOMMENT	Text	200	General Comments related to Borehole Information
BHDESCRIPTION	Text	200	General Borehole Description
PUMPRAT1	Double	8	Present Pumping Rate (litres per second) of Production Borehole
PUMPRAT2	Double	8	Present Pumping Rate (m ³ per hour) of Production Borehole
PUMPTIME	Long Integer	4	Average Daily Duration of Pumping in Hours
DAILYABS	Double	8	Average Daily Abstraction (m ³ /day)
MAXVOL	Double	8	Recommended Maximum Monthly Abstraction Volume (m ³) - Long-Term Sustainable Potential
MAXRWL	Double	8	Maximum Recommended Rest-Waterlevel (m.bgl)
RWLDATE	Date	8	Date of Rest-Waterlevel Measurement
REPINST	Text	50	Reporting Institution from NGDB
APPLICATION	Text	20	Application eg stock watering, irrigation etc.
USERNAME	Text	50	Name of User Editing MDB Database
SOURCE	Text	100	Source of BH data

Table D.2 BImage

Field Name	Data Type	Size	Description
ImageID	Long Integer	4	Internal use
IDNUM	Long Integer	4	Foreign key to BHBASE
bhNAME	Text	50	Borehole name
Image	Long Binary		Image data

Table D.3 WLMON

Field Name	Data Type	Size	Description
IDNUM	Long Integer	4	Internal use
BHNUM	Text	60	Foreign key to BHBASE
WLDATE	Date	8	Measurement date
WLTIME	Date	8	Measurement time
WL	Single	4	Raw data captured
WLMBD	Single	4	WL MBD
WLMBGL	Single	4	WL MBGL
WLPUMP	Single	4	Pump WL Flag: Values 0=Rest, 1=Pumped
YIELD	Single	4	Yield in L/s
WATERMETER	Single	4	Watermeter reading
ABSTRACTION	Single	4	Abstraction
HOURLMETER	Single	4	
WLCOMMENT	Text	255	Comment
SOURCE	Text	20	Data source

Table D.4 CHEMMON

Field Name	Data Type	Size	Description
IDNUM	Long Integer	4	Internal use
BHNUM	Text	50	Borehole Number (NB) - Foreign key
CHEMDATE	Date	8	Date of Sampling
CHEMTIME	Date	8	Time of Sampling
SAMPLER	Text	50	Name of Sampler
LAB	Text	50	Name of Laboratory
PRES	Text	50	Preservative Added
CHEMDEPTH	Single	4	Depth of Water Sample
PH_FLD	Double	8	pH Field
PH_LAB	Double	8	pH Lab
PH_SAT	Double	8	pH Satutrated
TEMP	Double	8	Groundwater Temperature (C)
TURB	Double	8	Turbidity in NTU
EC	Double	8	Electrical Conductivity (mS/m)
TDS	Double	8	Total Dissolved Solids (mg/l)
SODIUM	Double	8	Na (mg/l)
CALCIUM	Double	8	Ca (mg/l)
MAGNESIUM	Double	8	Mg (mg/l)
SILICA	Double	8	Si (mg/l)
POTASSIUM	Double	8	K (mg/l)
CHLORIDE	Double	8	Cl (mg/l)
SULPHATE	Double	8	SO4 (mg/l)
NITRATE	Double	8	NO2 as N (mg/l)
NO3_NO2	Double	8	NO3+NO2 as N (mg/l) (NITRITE in AQUIMON)
AMMONIA	Double	8	NH4 as N (mg/l)
FLOURIDE	Double	8	F (mg/l)
TOTALK	Double	8	Total Alkalinity (mg/l)
PHOSPHATE	Double	8	PO4 as P (mg/l)
IRON	Double	8	Fe (mg/l)
MANGANESE	Double	8	Mn (mg/l)
ZINC	Double	8	Zn (mg/l)
COPPER	Double	8	Cu (mg/l)
CADMIUM	Double	8	Cd (mg/l)
ARSENIC	Double	8	As (mg/l)
HARDNESS	Double	8	Total Hardness (mg/l)
DEUTERIUM	Double	8	Deterium %SMOW
O18	Double	8	O18 % SMOW

Table D.4 CHEMMON (cont.)

Field Name	Data Type	Size	Description
CARBON13	Double	8	Carbon13 %PDB
CARBON14	Double	8	Carbon14 PMC
C14_MAXAGE	Double	8	Max C14 Age
C14_MINAGE	Double	8	Min C14 Age
TOTCOLIFORM	Double	8	Total Coliforms (CFU/100/ml)
FACCOLIFORM	Double	8	Faecal Coliforms (CFU/100/ml)
BE	Double	8	Be-Diss-Water (mg/l)
B	Double	8	Boron
AL	Double	8	Al-Diss-Water (mg/l)
TI	Double	8	Ti-Diss-Water (mg/l)
V	Double	8	V-Diss-Water (mg/l)
CR	Double	8	Cr-Diss-Water (mg/l)
CO	Double	8	Co-Diss-Water (mg/l)
NI	Double	8	Ni-Diss-Water (mg/l)
SR	Double	8	Sr-Diss-Water (mg/l)
ZR	Double	8	Zr-Diss-Water (mg/l)
MO	Double	8	Mo-Diss-Water (mg/l)
BA	Double	8	Ba-Diss-Water (mg/l)
HG	Double	8	Hg-Diss-Water (mg/l)
PB	Double	8	Pb-Diss-Water (mg/l)
Li	Double	8	Lithium
Radon 222	Double	8	Radon 222
CHEMCOMMENT	Text	255	Add Comments
SOURCE	Text	20	Data source