DEPARTMENT: WATER AFFAIRS AND FORESTRY

GROUNDWATER RESOURCE ASSESSMENT II – TASK 3aE RECHARGE

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1. INTRODUCTION

This report (3aE) constitutes the final report of Project 3a: Groundwater Recharge.

1.1 Symbols and Conventions

1' X 1' =		one minute by one minute of a degree square
^{14}C	=	Carbon 14 isotope
^{18}O	=	Oxygen 18 isotope
^{2}H	=	Deuterium
$32^{o}S$	=	32 degrees south
^{3}H	=	Tritium
^{3}He	=	Helium 3 isotope
a	=	A Proportion of Precipitation
C_R	=	Regression Constant
Et_a	=	Actual evapotranspiration
Et_p	=	Potential evapotranspiration
K	=	Hydraulic Conductivity
mg/L	=	milligrams per litre
mm	=	millimetres
mm/a	=	millimetres per annum
mS/m	=	milliSiemens per metre
P	=	Precipitation
P_{av}	=	Average precipitation
P_{min}	=	Minimum precipitation
Q_s	=	Surface Run-off
R	=	Recharge
RE	=	Recharge
R_p	=	Percolation of Soil Moisture
S	=	Aquifer Storativity
SM	=	Soil Moisture
SM_m	=	Maximum Soil Moisture Capacity
Sm_r	=	Moisture retained by the soil matrix
SUST	=	Surface Water Accumulation

1.2 Applicable Documents

Project 3a, covering recharge, is being run in parallel with the groundwater/surface water interaction project (3b). The deliverables that are required for the Recharge project are also required for the groundwater/surface water project. Thus the final study report for project 3b (report 3bE) is directly applicable to this project report (report 3aE).

1.3 Acronyms And Abbreviations

Acronym/Abbreviation	Definition
"Geo-requests"	An e-mail address used for requesting data from the National Groundwater Archive or Open-National Groundwater Database
ACRU	Agrohydrological Model (Agricultural Catchments Research Unit)
ARC	Agricultural Research Council
CFC	Chlorofluorocarbon
CGS	Council for Geoscience
Cl	Chloride
CMB	Chloride Mass Balance
CRD	Cumulative Rainfall Departure Method
CWB	Channel Water Budget
DEM	Digital Elevation Model
DPE	Direct Parameter Estimation
DWAF	Department of Water Affairs and Forestry
EARTH	Extended Model for Aquifer Recharge and Moisture Transport through Unsaturated Hardrock
EV-SF	Equal Volume – Spiral Flow
GD	Groundwater Dating
Geosites	All features relating to groundwater, such as boreholes, springs, mines, drainage channels etc.
GIS	Geographic Information Systems
GIS	Geographical Information Systems
GIS	Geographic Information System
GM	Groundwater Modelling
GRA II	Groundwater Resource Assessment Phase II project
HS	Hydrograph Separation Method
IGS	Institute of Groundwater Studies
ISCW	Institute Soil, Climate and Water
ISCW	Institute of Soil, Climate and Water
LINRES	Linear Reservoir Module
MAE	Modified Amount Effect
MAP	Mean Annual Precipitation
MAR	Mean Annual Recharge
Maxil	Maximum Intercept Loss
NBI	National Botanical Institute
NGA	National Groundwater Archive
NGDB	National Groundwater Data Base
PDF	Portable document format
RQS	Resource Quality Studies
RTV	Recharge Threshold Value
SATFLOW	Saturated Flow Module
SIRI	Soil and Irrigation Research Institute
SOMOS	Soil Moisture Module
SRTM	Shuttle Radar Topography Mission
SVF	Saturated Volume Fluctuations
TDS	Total dissolved solids
UFM	Unsaturated Flow Modelling
VTI	Variable Time Interval
WGS84	World Geodetic System 1984
WM	Watershed Modelling
WMS	Water Management System
WQS	Water Quality Studies

Acronym/Abbreviation	Definition
WR90	Water Resource 1990 (a CD-ROM containing a synthesis of hydrological information, published by the Water Research Commission).
WRC	Water Research Commission
WTF	Water Table Fluctuation
ZFP	Zero Flux Plane

2. EXECUTIVE SUMMARY

South Africa is essentially an arid country and quantification of groundwater recharge is an essential task for water resource management. However, groundwater recharge can vary significantly across a catchment, both spatially and temporally, particularly so in the more arid parts of the country. There are numerous factors that influence 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, particularly in the context of the National Water Act of 1998.

The aim of this project is to develop a GIS based method for calculating groundwater recharge per quaternary catchment. The recharge rates will be determined as both mean annual values and values per calendar year. It must be noted that with the production of mean annual recharge rates, annual recharge as a recurring event is not implied.

The recharge method to be followed essentially comprises four main components. These components are to generate recharge values, based on

- the chloride mass balance (CMB) approach,
- empirical rainfall / recharge relationships,
- a layer model (GIS based) approach and then
- cross calibration of the results with field measurements and detailed catchment studies.

This report documents work completed toward definition and validation of a generic groundwater recharge algorithm. The data processing was carried out on a 1 km by 1 km grid cell size. The final results obtained from the grid modelling were then aggregated up to values at the quaternary catchment scale. The quaternary catchment is the “unit of measure” required by the client. The results obtained in this project are compared to the results obtained from earlier recharge studies. The algorithm used in this project does not differentiate between preferred path or matrix diffusion recharge. However, the advantage of the GIS based approach it that there is sufficient flexibility to include updated and new data sets and even to update the algorithm if need be.

The project also focussed on the calculation of a recharge threshold value (RTV) per quaternary catchment. This is a monthly figure, which indicates the monthly rainfall below which no direct groundwater recharge occurs. The RTV is an average value for the entire quaternary catchment and does not reflect the spatial variability within a catchment (due to varying geomorphology, soil characteristics, hydrogeological factors etc), nor does it take into account whether matrix or fracture flow occurs. Rainfall and recharge seasonality have been addressed, as far as possible, and the given RTV is applicable only in the rainfall season for that particular quaternary catchment. The

country has been divided into different rainfall zones and these are indicated on the table giving the RTVs per quaternary catchment.

This study calculated a national recharge volume of 30.52 km^3/a (5.2 % of mean annual precipitation), compared to a value of 33.82 km^3/a (5.8%) calculated by Vegter (1995).

3. BACKGROUND

To date Vegter (1995) has produced the only national data set on groundwater recharge (as part of his work on producing groundwater maps for the whole of South Africa). There is a need to enhance this work, particularly on a quaternary catchment scale, for the whole of South Africa. For the Department of Water Affairs and Forestry (DWAF) to assess applications for groundwater use, it is necessary to have the quantification of groundwater recharge on both a quaternary catchment scale and annual (hydrological year) basis.

A number of meetings were held with the project team to identify the most suitable approach as recharge determinations comprise many different methods, approaches and constraints. A key requirement of this project is that the approach to be followed is GIS based. To meet this requirement data sets used need to be spatially referenced, and if no geographically referenced data sets are available then they are problematic to use. The advantage with a GIS based method is that as new and updated data sets are generated they can easily be incorporated and the results updated. The algorithm that is developed must represent recharge as accurately as possible, taking into account spatial and temporal variability.

In order to try and get an accurate representation of recharge, the project team agreed that the chloride mass balance (CMB) approach should be followed. In addition, rainfall/recharge relationship, although not linear, may be easily applied in a GIS. Rainfall grids are generated by the Institute of Soil Climate and Water (ISCW) on a monthly basis for the entire country (on a 1 km by 1 km grid size). The third main approach discussed in this report is a “layered model” approach where the factors that are believed to impact groundwater recharge are taken into account. This approach then results in a recharge rating map, which still needs to be converted to a percentage recharge map for calculating recharge volumes. It is critical that the “layered model“ approach be calibrated with values obtained from the CMB and rainfall/recharge relationships. The above approaches are discussed in more detail later in the report. To carry out the above grid or raster analysis the country has been subdivided into 1407 rows and 1609 columns of 1km by 1km grid cells.

Running in parallel with this project is a project reviewing groundwater and surface water interaction. As part of this project recharge is calculated by first determining subsurface storage by reverse engineering the Pitman model. Once this is calculated the monthly recharge per quaternary catchment is determined according to the method proposed by Hughes (2004). This method uses a number of parameters defined in WR90 and is essentially based on hydrograph separations of monthly runoff data. To use this approach, for the entire country, would take approximately 200 man days (pers. comm., K. Sami, 2004) and it is not applicable in catchments where no surface water/groundwater interaction occurs. However, baseflow separation techniques do have value in defining a minimum recharge value per quaternary catchment. The quaternary catchment baseflow values obtained by Vegter (1995) will be checked against the recharge values obtained in this project.

Figure 3.1 shows the main components that play a role in determining the final amount of precipitation that eventually becomes groundwater recharge. The approach taken in this project, particularly the model layered approach has been to try and address each of the factors mentioned. Rainfall intensity, rainfall frequency, air temperature, wind speeds and humidity are difficult factors to obtain, but are being addressed by using rainfall seasonality.

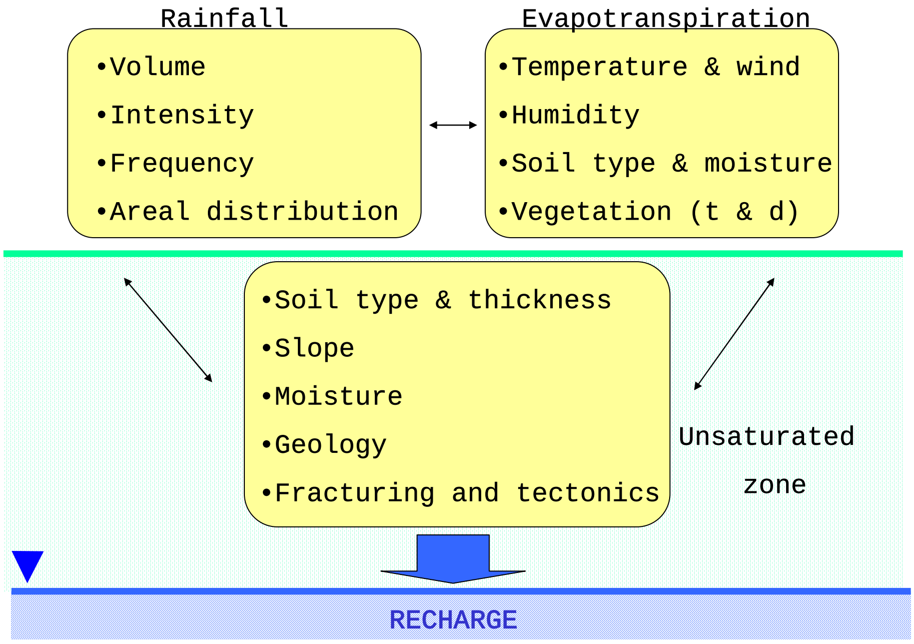

Figure 3.1: The main factors controlling groundwater recharge (Bredenkamp *et al.*, 1995)

This report discusses the three approaches followed in determining groundwater recharge. The findings from this method and the shortcomings are also discussed. The results obtained during this project will be compared to the results obtained during the earlier national scale recharge studies.

The Recharge Threshold Value (RTV) has also been calculated per quaternary catchment.

4. SELECTED RECHARGE LITERATURE

4.1 Groundwater Studies – Overview and introduction

Internationally, there is a lot of literature on groundwater recharge and, according to Simmers (1998) the key in recharge studies is the project objective. In this project, regional-based assessments are required, thus a combination of reliable local data, remote sensing, GIS and geostatistical techniques offers considerable promise for a better understanding and determination of recharge over extended areas.

Before discussing the literature review, a summary of groundwater recharge is presented. Lloyd (1986) provided a conceptual illustration of the elements involved in recharge (Figure 4.1). This figure has been included to provide an overview of the complexity of the recharge process.

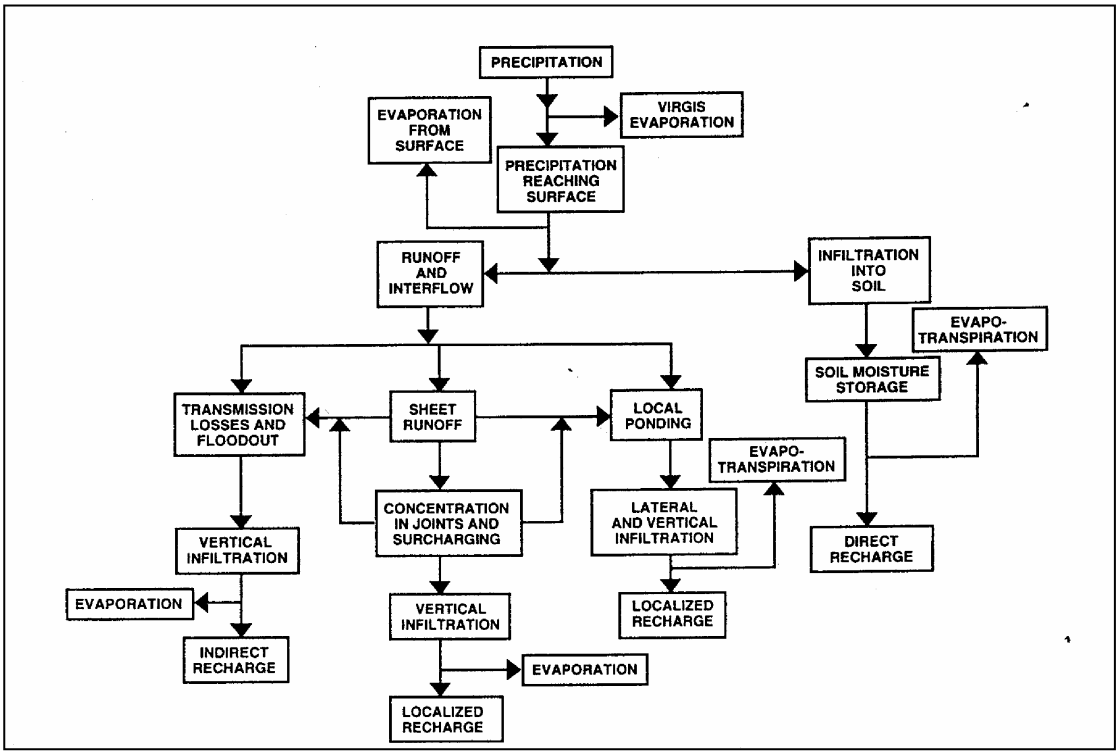

Figure 4.1: The various elements of recharge in a (semi-) arid area (Lloyd, 1986)

Recharge can occur in a number of ways. Lerner *et al*. (1990), in agreement with Lloyd (1986), have also categorized recharge as follows:

- Direct recharge: water added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration, by direct vertical percolation through the unsaturated zone.
- Localized recharge: an intermediate form of groundwater recharge resulting from the horizontal (near) surface concentration of water in the absence of well-defined channels.
- Indirect recharge: percolation to the water table through the beds of surface water courses.

The definitions in Figure 4.1 and above are of course a simplification of reality, since in many locations combinations of the various types of recharge will occur. Simmers (1998) makes it very clear that:

- Recharge occurs to some extent in even the most arid regions;
- As aridity increases, direct recharge is likely to become less important than localized and indirect recharge in terms of total aquifer replenishment;
- Estimates of direct recharge are likely to be more readily derived than those of either localized or indirect recharge.

When rain falls to earth, trees, plants and buildings intercept some portion of it. Most of this does not reach the ground and is subsequently lost by evaporation. This is known as interception loss. During frequent and brief low intensity events, interception loss may absorb a large fraction of the total rainfall. As a result, such events are the least effective from a water resource point of view.

During larger rainfall events, water that reaches the ground surface may follow several pathways. A component of it evaporates immediately from the soil surface while another infiltrates into the soil. Rainfall may enter the ground at a maximum rate defined as the infiltration capacity. This rate is controlled by soil texture and structure, as well as surface conditions and storm duration. Water entering the soil replenishes soil moisture if it is below field capacity. This capacity is defined as the maximum volume of water retainable by a soil against gravity. This water will subsequently be used by plants or evaporated directly. As field capacity is approached, soil water flow becomes increasingly important. Water may then flow laterally above a less permeable layer until it reaches a stream channel, or it may continue downward contributing to recharge. Since infiltration capacities and field capacities define thresholds, which control the movement of water through the soil, they are important attributes to consider in groundwater recharge studies.

In regions where soils are relatively thick and rainfall is low, soil moisture may rarely exceed field capacity, therefore, recharge though the soil seldom takes place. Recharge in such regions is dependent on isolated areas where soils may be shallow and field capacities are exceeded locally, or on areas where there are fractured rock outcrops at the surface. The existence of large macropores (large pore spaces such as animal burrows, root channels, worm and termite casts) may also provide an important pathway for rainfall to bypass the soil mass and contribute to recharge.

Numerous studies have shown that in semi-arid areas, which includes most of South Africa, very little flow percolates through the soil matrix to any significant depth, even with high rainfall (e.g. Lloyd, 1986; Sami, 1992; Kirchner *et al*., 1991). In such areas aquifers are recharged predominantly by indirect flowpaths and preferential pathways (Kirchner *et al*., 1991; Rushton, 1987; Sharma and Hughes, 1985).

If the intensity of rainfall exceeds the evaporation and infiltration rates, water will begin to collect on the surface in what is referred to as depression storage. Once these depressions fill and begin to run over, overland flow will then form in rills, small channels or as sheet flow. A fraction of overland flow may re-infiltrate into the soil if it runs over an area with a higher infiltration capacity. The portion of overland flow that enters stream channels is termed surface run-off. Even though surface run-off carries water away from a region it may still contribute to recharge. If run-off flows over permeable material in a stream channel, a component of it, termed transmission losses, may seep into the channel bed and contribute to recharge. The proportion of water that ultimately enters the aquifer will depend on the ability of the aquifer to accept it. This is a function of the aquifer's permeability and storage capacity.

It must be appreciated that groundwater recharge occurs as a result of differing mechanisms and associated with these mechanisms there is a high degree of spatial and temporal variability and most often high levels of uncertainty. Nonetheless groundwater recharge calculations are necessary for water resource management. Many techniques have been developed for calculating groundwater recharge. These techniques were mainly developed initially as point-estimate techniques. However, more recently many new techniques have been used to take into account spatial variability of groundwater recharge. In most situations it is not entirely valid to take a single point estimate value and then use this to calculate groundwater recharge across an entire catchment (which may have an area of a few hundred square kilometres).

For this project it is necessary to calculate groundwater recharge across the entire country (whilst taking into account spatial and temporal variability). In an attempt to determine the most suitable method for this task, a very preliminary review of

groundwater recharge studies in South Africa is given below. This is followed by a more detailed assessment of the selected references. In reviewing the selected references, certain key points from the references are highlighted. The selected references are not reviewed in their entirety, (as there would then be a fair amount of overlap on the topic of recharge from each reference) and the length of the review in this report is no indication of the literature's relevance to the current topic. Some of the literature is very comprehensive and detailed, containing numerous case studies and detail. This detail is not repeated in this report, but will play a valuable role in verifying (and calibrating) the method used for the national assessment of groundwater recharge. During the literature survey, all recharge results have been noted and plotted in a geographical information system.

The more detailed review of selected literature is listed chronologically and after each review, salient points (within the context of the GRAII project) from the particular review are given.

4.2 Recharge Studies carried out to date in South Africa

The first systematic recharge studies carried out in South Africa date back to the early 1970's in the western "Transvaal" (now the province of Gauteng) and in the Northern Cape. Recharge studies were mostly carried out at a local scale and not as part of larger groundwater resources assessment projects (Xu and Beekman, 2003). The growing need for reliable recharge estimation in South Africa is based on the need for improved management of limited water resources.

Verhagen *et al*. (1979) carried out extensive studies on the application of natural isotopes to the Kalahari region and to some semi-arid dolomitic areas.

Fleisher (1981) provided a major contribution to quantitative estimations of recharge in the West Rand dolomites based on water balance studies.

Connelly *et al*. (1989) investigated recharge of groundwater by rainfall. This study covered three different recharge areas and attempted to apply a conceptual model to infer recharge from the physical nature of the catchments and the characteristics of the aquifer. Although some results were obtained the study was abandoned due to the complexity of the systems to which the techniques had been applied.

Kirchner *et al*. (1991) studied recharge of the Karoo formations, incorporating water balance methods.

Sami (1991) provides a good summary and evaluation of the methods available and favours the use of natural chloride in semi-arid environments.

Gieske (1992) studied recharge in semi-arid regions and deals in detail with the chloride method as well as including new approaches.

Wright and Burgess (1992) have reviewed the hydrogeology of crystalline basement aquifers in Africa and include some useful quantitative estimates of recharge according to the baseflow from small sub-humid catchments in Zimbabwe and Malawi.

Vegter (1995) in his explanation of a set of national groundwater maps that he developed, describes the method he used to calculate national scale groundwater recharge. The approach he used is discussed in more detail later in this report (see Section 4.3).

Bredenkamp *et al*. (1995) produced a manual on recharge and storativity estimation, which includes many case studies and data. This manual is reviewed in this report (see Section 4.4).

Murray (1996), in the work he completed on assessing methods to determine sustainable borehole yields, also addressed the topic of recharge. In particular he assessed groundwater recharge and the relationship to precipitation. These relationships are discussed in more detail later in the report (see Section 4.5).

The publication by Xu and Beekman (2003) provides an overview of recharge methods and studies carried out in southern Africa, particularly within arid and semi-arid environments. It is considered in more detail in this report as well (see Section 4.6).

4.3 Review of Vegter, 1995 – National groundwater mapping, including recharge estimation

4.3.1 Direct and indirect recharge, estimates and a national map

Vegter (1995) states that groundwater recharge is dependent in the first instance on rainfall. He considers recharge to be involved in the absorption and addition of water to the zone of saturation. Effective rainfall is the rainfall on a given day minus interception loss, minus storm run-off (i.e. the part of rainfall that wets the soil). The distribution of rainfall, in particular effective rainfall, over South Africa provides a rough indication of the variation in recharge.

Of the effective rainfall only a small fraction infiltrates to the saturated zone. The major part is lost through evaporation from the soil and transpiration by vegetation. The determination of that fraction of the rainfall that ultimately becomes groundwater is one of the most difficult quantities to measure. Vegter acknowledges that although recharge is provided as millimetres per annum, it does not signify that recharge is an annual event throughout the country. Particularly in the western and drier parts of the country, recharge occurs periodically and not annually.

With regard to <u>direct recharge</u>, this is a highly complex process in which numerous factors and their interaction play a role, including:

- The amount, type, intensity, duration and temporal distribution of rainfall and evaporation;
- Surface slope and type of vegetation cover, stormwater run-off, interception and transpiration losses;
- Infiltration capacity of the materials at surface (be it rock, soil or sub-soil), the presence of so-called macropores and fractured rock is of major importance;
- Moisture retention capacity of the unsaturated zone.

<u>Indirect recharge</u>, particularly recharge from streams and rivers, is very difficult and often costly to assess. Infiltration from surface water occurs either directly into the saturated zone where the water table coincides with the stream bed, or through the unsaturated zone. Very few studies on recharge from rivers have been carried out in South Africa. It is considered that rivers, on a national scale, provide only localized sources of recharge, because of:

- The predominantly hard rock environment and lack of laterally extensive alluvial deposits below river bed level;
- The water table, for the greater part of South Africa, follows surface topography which inhibits the lateral expansion of the recharge mound that is built up below the river by infiltrating water;

- Rocky beds and silty channels limit infiltration.

In spite of their minor role, in terms of recharge, river valleys are generally more favourable for groundwater development, as a result of both groundwater flow toward them and augmentation by river recharge. In addition, some streams or river valleys follow fracture zones and thus provide favourable conditions for groundwater abstraction. Under arid conditions, where there is very little direct recharge from rainfall, ephemeral streams are important sources of replenishment and sand filled river beds are the only significant aquifers.

In determining a national scale map of groundwater recharge, the ACRU model was run for each of the 712 relatively homogeneous rainfall response zones, into which the country has been subdivided[1], to determine effective rainfall. Vegter (1995) collated the point recharge results from a number of studies, and these are listed in the table below.

Table 4.1: Groundwater Recharge Estimates (Vegter, 1995)

Locality (Reference)	Longitude (decimal degrees east)	Longitude (decimal degrees south)	Mean annual rainfall (mm)	Mean annual recharge (mm)	Percentage Recharge (%)
Dendron (17)	29.31	23.36	440	8.6	2.0
Limburg (10)	28.88	23.81	485	18.7	3.9
Dorpsrivier (8)	29.06	24.2	580	Range from 9.2– 17.8; mean 13.1	1.6 – 3.1 2.3
Sabie (15)	30.75	25.08	1250	288	23.0
Rietpoort (1)	25.95	25.70	530	Range from 48-67.2; mean 56.7	9.1 – 12.7 10.7
Pretoria Fountains (15)	28.13	25.83	675	74.3	11.0
Upper Molopo (6, 8)	25.88	25.88	570	Range from 46-49.3; mean 47.8	8.1 – 8.6 8.4
Steenkoppies (3, 11, 12 and 13)	27.63	26.05	650	Range from 70.4-87.5; mean 81.1	10.8 – 13.5 12.5
Schoonspruit (15, 18)	26.75	26.16	660	82.1	12.4
Vicinity Leandra (23)	28.92	26.38	700	35	5.0
Louwna-Coetzersdam (2)	24.23	26.85	450	12	2.7
Kuruman (7, 20)	23.63	27.63	460	15	3.3
Hlobane (21)	31.0	27.72	720	117	16.3
Marydale (19)	22.08	29.42	185	0.8	0.4
Bloemendal (15)	30.50	29.55	910	65.4	7.2
Dewetsdorp (14)	26.68	29.56	530	21.3	4.0
Reddersburg (15)	26.25	29.67	480	38.1	7.9
Trompsburg (15)	25.80	30.03	370	25.2	6.8
Kokstad (15)	29.42	30.55	760	55	7.2
De Aar (14, 22)	24.0	30.65	280	16.4	5.9
New Bethesda (15)	24.62	32.28	315	21.9	7.0
Bedford (15)	26.10	32.67	605	36.2	6.0
Bosberg (15)	25.95	32.73	700	50.4	7.2

[1] Based on the work of Dent *et al.* (1990) South Africa's rainfall has been subdivided geographically into 712 relatively homogeneous rainfall response zones

Locality (Reference)	Longitude (decimal degrees east)	Longitude (decimal degrees south)	Mean annual rainfall (mm)	Mean annual recharge (mm)	Percentage Recharge (%)
Klein Swartberg (16)	21.3	33.36	245	12.5	5.1
Atlantis (5, 8, 15)	18.40	33.56	375	Range from 32-70; mean 42.5	8.5 – 18.7 11.3
Koo (9)	19.85	33.68	535	47.7	8.9
Cape Padrone (15)	26.4	33.75	640	53	8.3
Bredasdorp (15)	20.12	34.52	460	22	4.8

References:

1 Botha (1993)
2 Botha and Bredenkamp (1992)
3 Bredenkamp (1986)
4 Bredenkamp (1993)
5 Bredenkamp and Vandoolaeghe (1982)
6 Bredenkamp, Janse van Rensburg, Van Tonder and Cogho (1987)
7 Bredenkamp, Botha and Esterhuyse (1992)
8 Bredenkamp, Janse van Rensburg and Botha (1993)
9 Dziembowski (1969)
10 Dziembowski (1975)
11 Enslin (1971)
12 Enslin and Kriel (1967)
13 Fleisher (1981)
14 Kirchner, Van Tonder and Lukas (1991)
15 Kok (1992)
16 Meyer (1984)
17 Orpen and Bertram (1991)
18 Polivka (1987)
19 Schumann (1970)
20 Smit (1978)
21 Van Wyk (1963)
22 Vegter (1992)
23 Vegter and Ellis (1968)

It must be noted that for a variety of reasons the reliability of many of the recharge estimates remains questionable. Interestingly, estimates for the same locality by different methods vary appreciably.

The temporal variability of effective rainfall is least in the eastern, higher rainfall areas of the country and greatest in the western, semi-arid to arid parts of the country. Recharge, though variable from year to year, may be expected to occur every rainfall season in the east, in the area where baseflow occurs. However, in the western part of the country, recharge is not necessarily an annual event. In fact there is evidence that in certain parts of the country recharge is restricted to abnormally high rainfall events. Such events may be of short duration and not necessarily reflected in monthly rainfall values.

Vegter's groundwater recharge map depicts broad trends rather then accurate recharge figures. The recharge map is based on the following:

- The base flow map, which provides a regionalised, albeit somewhat underestimated, picture of recharge in the eastern and southern parts of South Africa.
- A comparison of base flow with recharge estimates within and just outside the base flow areas, yields a mean difference of about 30 mm/a for the underestimation of recharge by base flow.
- Base flow values were assigned the following recharge values, which were only used as a guide and were not strictly adhered to across the country.

Mean baseflow (mm/a)	Mean recharge (mm/a)
0 (edge of area)	25
10	37.5
25	50
50	75
100	110
150	160
200	200

- Where there is no base flow, recharge was based on effective rainfall.
- Where rainfall in excess of 15 mm/day occurs, the "De Aar model[2]" was applied. However, transpiration does play a significant role (values of 25 mm/a are reported).
- In the West Coast sand belt north of the Olifants River mouth, the Koa Valley and the western Kalahari, a value of 1 mm/a recharge was allocated, although it is noted that recharge is actually limited to the occasional event of abnormally high rainfall.
- Recharge values were contoured as follows: 1, 5, 10, 15, 25, 37.5, 50, 75, 110 mm/a on the national recharge map.

The national recharge maps produced provide a good starting point for this project, although a number of issues need to be addressed. Firstly, an objective of this project is to generate an actual recharge amount per annum (based on actual annual precipitation) per quaternary catchment, as well as a mean annual recharge map. Secondly, the approach of using river baseflow in the eastern portion of the country as an estimator of groundwater recharge will also be carefully considered. Further to the issue of calculating groundwater recharge, another dependency is the status regarding groundwater storage volumes. This is discussed in the following section.

4.3.2 The role of groundwater storage

With a high water table the available space between the water table and the surface may become replenished completely with the result that infiltration is halted and further rainfall is disposed of as run-off or evaporation. Under such conditions one has to distinguish between <u>rainfall dependent potential recharge</u> and <u>actual storage dependent recharge</u>.

A special case of storage-dependent recharge is that of so-called "dual porosity" formations such as Karoo sedimentary rocks. Permeable open fractures in these formations may fill up rapidly under favourable recharge conditions whilst the uptake of water from the open fractures into adjacent pores and micro-fractures is slow. The result is incomplete recharge of available storage space. Complete replenishment of the available space may only be realised during a prolonged period of rainfall, or after several abnormally high rainfall seasons.

4.3.3 Salient points from the work of Vegter (1995)

These can be summarized as follows:

- Recharge is derived from effective rainfall (effective rainfall = rainfall – interception – run-off)

[2] For more information on the "De Aar model", refer to Vegter (1992)

- Recharge = effective rainfall – soil evaporation – vegetation transpiration
- Mean annual recharge does not imply recharge every year
- Some factors that need to be taken into account when calculating direct recharge include:
    - Rainfall (amount, type, intensity and duration)
    - Evaporation
    - Surface slope
    - Vegetation type
    - Storm run-off
    - Interception
    - Transpiration
    - Infiltration capacity (macropores and fracturing)
    - Moisture retention capacity of the unsaturated zone
- Other factors that may have to be considered include:
    - Surface conditions after the previous season
    - Surface cover material (soil, vegetation, barren rock etc)
    - Pre-climatic conditions (moist / drought etc)
- Indirect recharge also occurs, but is only locally significant
- Recharge to an aquifer can vary according to its "storage status".

The above factors will have to be taken into consideration in this project. This project will most likely only determine direct recharge and aquifer storage status may have to be ignored.

4.4 Review of Manual on quantitative estimation of groundwater recharge and aquifer storativity (Bredenkamp *et al*., 1995)

4.4.1 Overview

This comprehensive manual provides an overview of recharge methods and results carried out in South Africa. The manual contains many case studies, which are of great value for this study. The manual is not reviewed in its entirety in this report. However, the results listed from the case studies will be documented and will be used when calibration and verification of the final results occurs. The manual was reviewed with the GRAII recharge project objectives in mind, i.e. to quantify groundwater recharge regionally.

Numerous methods are used to estimate recharge rates and all have their limitations. Both Simmers (1987) and Bredenkamp *et al*. (1995) note that no single estimation technique has been identified which does not give suspect results. For this reason, some form of averaging needs to be applied to several techniques when accurate values are required (Bredenkamp *et al*., 1995). In general, recharge estimation techniques can be divided into physical and chemical methods. Physical methods attempt to estimate recharge from water balances calculated either from hydrometeorologic measurements, direct estimates of soil water fluxes based on soil physics or changes in the aquifer's saturated volume based on water table fluctuations. Chemical methods are based on the distribution of a tracer (commonly ^{2}H, ^{3}H, ^{14}C, ^{18}O and Cl) in the saturated or unsaturated zone.

Water balances are of limited use in semi-arid regions since the recharge component is small in relation to errors in the measurement of evapotranspiration, run-off and precipitation. Gee and Hillel (1988) have shown that the accumulation of the error term in the recharge estimate of a water balance has been found to exceed several hundred percent. Methods which rely on the direct measurement

of soil water fluxes are problematic because fluxes are low and difficult to detect (Lerner *et al*., 1990). Kirchner *et al*. (1991) attempted to estimate recharge at Dewetsdorp and De Aar directly, and found that none of the techniques provided meaningful results. The drawback of these methods is that they assume that flow takes place through a soil matrix, rather than preferred pathways such as macro-pores and joints in rock outcrops. In arid areas, such localised recharge is likely to predominate. This is because large storm thresholds are required to overcome the substantial soil moisture deficits and initiate direct recharge through the soil matrix (Lloyd, 1986). A problem with water table fluctuation measurements is that they require accurate estimates of aquifer parameters in order to equate changes in saturated volume to recharge (Rushton, 1987). In fractured rock aquifers, these parameters are rarely uniform.

While there are numerous problems with physical recharge measurement techniques, equal concern needs to be expressed as to whether the values obtained from point measurements are representative for the specified area of interest. Allison (1988) expressed this concern when he concluded that the most important problem to overcome in the estimation of groundwater recharge is probably the assessment and prediction of this spatial variability.

Certain chemical recharge estimation techniques tend to overcome some of the spatial variability problems. For example, a tracer's concentration, like the chloride concentration in rainfall, should represent a spatially uniform concentration in the soil surface (Lerner *et al*., 1990). Their reliability in certain environments, however, may also be questionable. For example, the accumulation of chloride in the soil by evapotranspiration in dry areas, or its elevated concentrations in coastal areas could undermine the assumptions on which the method is based (Allison, 1988). The chloride concentrations in rainwater may be very low and therefore difficult to accurately quantify. Where aquifers store sufficient water, the chemical methods have the advantage in that data collected may represent many years of recharge from which a historical record can be derived (Allison *et al*., 1985). In contrast, direct physical methods only provide data over the duration of the monitoring period.

Recharge estimation methods, including both physical and chemical, can be grouped in the following manner (abbreviations and examples have been placed in brackets):

- **The unsaturated zone**
  - Lysimeter studies;
  - Soil moisture flow and balances;
  - Chloride profiles;
  - Radioisotopes (e.g. Tritium and ^{14}C);
  - Stable isotopes (e.g. ^{18}O and ^{2}H).

- **The saturated zone**
  - Analysis of borehole water level fluctuations (groundwater hydrographs; the cumulative rainfall departure method – CRD);
  - Aquifer water balances;
  - Analysis of spring flow;
  - Saturated volume fluctuations (SVF).

- **Numerical modelling** (of groundwater flow and the water balance)

- Inverse groundwater modelling to calibrate recharge so that simulated heads match observed heads;
- Hydrological models which consider groundwater recharge to be via porous media, rather than preferential pathways (e.g. ACRU);
- Mathematical regression models (e.g. Direct Parameter Estimation method – DPE).

➢ **Steady state flow approximation** (based on Darcy's Law)

➢ **Rainfall-recharge relationships**.

The wide range of methods used for calculating groundwater recharge indicates that it is essential to have a clearly defined objective when determining groundwater recharge. For the GRAII project, it is essential to calculate recharge on a regional basis and this objective limits the number of approaches that can be used.

The manual by Bredenkamp *et al*. (1995) introduces the topic of groundwater recharge, and then discusses a number of approaches to groundwater recharge calculations (such as the soil moisture balances, hydrological balances, and catchment balances). Methods relevant to the unsaturated zone are discussed (such as lysimeter usage; tritium profiles; soil moisture balances; Darcy flow; and chloride profiling). Next, methods relevant to the saturated zone are discussed (such as hydrograph interpretation; rainfall/recharge relationships; cumulative rainfall departure techniques; spring flow analysis; chloride balances; saturated volume fluctuation techniques; and modelling). The models include hydrological, regression type and flow models. Further to the above discussions complementary methods are also reviewed, such as geothermal gradients; natural (stable and radioactive) isotopes; and radioisotopes. Regional estimation of groundwater recharge; the role of aquifer storativity; groundwater management; groundwater monitoring; relationships to surface water hydrology and case studies are also included in the manual.

A selected number of comments, relevant to the GRAII project, from the work of Bredenkamp *et al*. (1995) are listed. Firstly, Sharma (1989) has highlighted the need for regional estimates, by possibly extrapolating results from a small area that has been studied in detail, to similar aquifers. The chloride method complies with this requirement but yields values of recharge that tend to exceed the effective recharge.

In the South African context, Enslin (1970) advocated the use of a rainfall/recharge relationship for the entire country. The use of low flow of rivers as a measure of the groundwater recharge in relation to precipitation has also been analysed. Bredenkamp *et al*. (1992) have shown a linear relationship between base flow and average annual precipitation for mountainous catchments, with a threshold rainfall of 500 mm below which the recharge would be zero. In addition, Bredenkamp (1978, 1990) has shown that for dolomitic aquifers, a linear rainfall/recharge relationship is obtained above an annual rainfall of 313 mm.

Regarding the results based on cumulative rainfall departures (CRD) it was clearly shown to correlate with groundwater fluctuations reliably, but the method needs to be investigated further to ascertain if it has potential for quantitative estimation of regional recharge.

A more acceptable procedure would be to infer the average recharge from the chloride relationship and then apply the CRD relationship to obtain the variability of recharge. This approach still has to be validated, but this may be a way of extrapolating a provisional estimate of recharge for a specific type of aquifer, to an aquifer of the same type in another region, based solely on the ratio of recharge to average rainfall.

Bredenkamp *et al*. (1995) clearly states that aquifer storativity (S) is a vital parameter in the assessment of aquifer recharge. It is a difficult parameter to estimate and results obtained from fractured aquifers has revealed that estimates of S obtained from pumping tests can be unreliable.

4.4.2 Salient points from the manual by Bredenkamp *et al*. (1995)

These are:

- Many methods have been tested and point recharge values are given for these studies which will be valuable when calibrating regional assessments;
- The proposed regional assessment method is to use rainfall/recharge relationships. The drawback with this approach, on a national scale, is that these relationships have only been determined for a limited number of type areas. The validity of national extrapolation needs to be carefully assessed.
- The report does not refer to spatial modelling techniques, as at the time of compiling the report, geographical information systems and remote sensing technologies were in a relatively early stage of development.

The manual by Bredenkamp *et al*. (1995) is a good reference for the GRAII recharge study. Included within the manual are numerous results from a wide range of recharge studies, carried out in South Africa. Numerous differing techniques have been reviewed and the pros and cons highlighted. The challenge remains in that many of the studies reviewed are “point estimates” and for this project regional values are required. Valid techniques of taking these point estimates and extrapolating them regionally need to be considered. The possibility does exist that this approach might be invalid and process-based modelling techniques may have to be followed, that will then take into account spatial variability. In the context of integrated water resource management it is also essential that the groundwater recharge values, that are determined, be associated with levels of confidence. Thus stochastic modelling techniques will also have to be used. As a follow on from the GRAII project, levels of risk associated with the recharge estimates should be determined so as to identify those catchments that require very accurate recharge estimations. With the recharge determination process being carried out in a Geographical Information System, it will be relatively easy to keep the national recharge values up to date.

4.5 Review of Groundwater Resource Evaluation based on Recharge (Murray, 1996)

Outlined in this section is a review of the work carried out by Murray (1996). He provides a good overview of recharge mechanisms and the methods used to determine recharge. Included below are sections taken directly from his work, as they provide a very good summary of groundwater recharge processes and may well be used later in the project.

4.5.1 Recharge values obtained from studies in Southern Africa

Table 4.2 summarises the findings of recharge studies that have taken place on a variety of secondary aquifers. Although a representative sample was not available for granitic aquifers, this summary includes results from two granitic aquifers located in northern South Africa. The same aquifer categories that were used in the recharge manual written by Bredenkamp *et al*. (1995) have been used in this report. While the high recharge values found in dolomitic aquifers can be attributed to their high degree of secondary porosity, in mountainous sedimentary aquifers, the high rainfall, shallow soils and outcropping fractured rocks (which facilitate flow in preferential pathways), contribute to their high recharge values. The low rainfall, high evapotranspiration, lack of widespread secondary porosity and, in places deep soils, contribute to the low recharge values found in the Karoo, granitic and Kalahari aquifers.

Table 4.2: Groundwater Recharge Estimates

Aquifer	Location	Map (mm/a)	Recharge (mm/a)	Recharge (% Map)	Method	Reference
Karoo:						
Fractured sedimentary rocks	DeWetsdorp	587	9.5 – 21.3	1.6 – 3.6	SVF	Kirchner *et al*., 1991
	De Aar	287	4.0 – 12.6	1.4 – 4.4	SVF	Kirchner *et al*., 1991
	Williston	176	2.5 – 3.2	1.4 – 1.8	Water balance	Woodford, pers comm.
	Bedford	483	1.4 – 12	0.3 – 2.5	VTI	Sami and Hughes, 1996
	Kat River	641	2.0 – 26	0.3 – 4.1	VTI	Sami, 1994
	Thornhill	470	4.5 – 8.6	1.0 – 1.8	MODFLOW	Sami and Murray, 1995
	Beaufort West	235	4.7	2.0	Water balance	Parsons, 1994
Basalt	Springbok Flats	571	5.5 – 99	1.0 – 17.3	CMB	Bredenkamp *et al*., 1995
Granite	Dendron	440	3 – 35.2	0.7 – 8.0	CMB	Bredenkamp, *et al*., 1995
	Coetzersdam	450	10 – 14	2.2 – 3.1	SVF	Bredenkamp, *et al*., 1995
Sedimentary hard rock aquifers in mountain catchments	Pretoria/ Rietondale	670	54 – 160	8.1 – 23.9	Various	Bredenkamp *et al*., 1995
	Die Hoek	1852	19.9–290	1.1 – 15.7	Various	Connelly *et al*., 1989
	Rustenburg	749	114	15.2	Hydrograph	Bredenkamp *et al*., 1995
	Zachariashoek	1061	319	30.1	Hydrograph	Bredenkamp *et al*., 1995
Dolomites	Grootfontein	560	26.7 – 48	4.8 – 8.6	Various	Bredenkamp *et al*., 1995
	Rietpoort	532	49.3 – 60	9.3 – 11.3	Various	Bredenkamp *et al*., 1995
	West Areas	700	54 – 175	7.7 – 25	Various	Bredenkamp *et al*., 1995
	Kuruman	460	36 – 44	7.8 – 9.6	Various	Bredenkamp *et al*., 1995
	Sishen	386	49	12.7	SVF	Bredenkamp *et al*., 1995
	Pering	460	84 – 146	18.3–31.7	Various	Bredenkamp *et al*., 1995
	Potgietersrus	573	9.2 – 34	1.6 – 5.9	Various	Bredenkamp *et al*., 1995
Kalahari/ Karoo	Bray	400	3.7	0.9	CMB	Bredenkamp *et al*., 1995
	Dimaje	400	2.6 – 2.9	0.7	CMB	GCS, 1991
	Jwaneng	400	0.2 – 6.2	0.1 – 1.6	Isotope	Bredenkamp *et al*., 1995
	Lethlhakeng	420	1.1 – 5.7	0.3 – 1.4	Various	Bredenkamp *et al*., 1995

KEY:

SVF	Saturated Volume Fluctuation	Various	These include more than one of the following: CMB, spring flow, Tritium profile, SVF, Hill method, CRD method, DPE method, Darcy flow/Dynamic model, Hydrological model. Very low values obtained from Carbon and Tritium age methods were excluded.
ACRUWAT	A moisture budget model		
CMB	Chloride Mass Balance		
VTI	A variable time interval rainfall/run-off model with groundwater components		
MODFLOW	Inverse modelling using a finite difference model		
Tritium	Tritium profile		
GCS	Groundwater Consulting Services	Woodford, A.	Geohydrologist, DWAF

The above summary relates groundwater recharge values to rock type across the whole of South Africa. From the table it is clear that there is significant variability in the values determined, and no single value can be applied to a particular rock type. This variability in values is important and needs to be taken into account when the stochastic modelling of regional recharge is carried out. The nature of groundwater occurrence is still a very important factor, particularly in that fractured aquifers predominate to such an extent in South Africa. This means that to apply a recharge value directly to a rock type will in many instances be very inaccurate.

4.5.2 Regional Recharge Estimates

Rainfall-recharge relationships

In order to extrapolate point recharge estimates to other areas, regional recharge estimation methods have been developed. The simplest empirical formula takes recharge as a proportion (a) of precipitation (P):

$$R = a \cdot P \qquad \text{eq. 1}$$

Equation 1 assumes that recharge is a constant fraction of rainfall. In some environments, particularly in arid and semi-arid areas, recharge may not be experienced after short, low intensity rainfall events (Parsons, 1994). Rather than considering recharge from rainfall events, it is commonly averaged over a year, and mean annual precipitation (MAP) is used as the P-value. For example, 5% MAP was commonly used to represent recharge to Karoo aquifers (Seward, 1988; Parsons, 1987; Vandoolhaeghe, 1985; Woodford, 1984).

The next set of equations includes a threshold (P_{min} or P_{av}) below which recharge is unlikely to occur.

$$R = a\,(P - P_{min}) \qquad P \geq P_{min} \qquad \text{eq. 2}$$

Or

$$R = (P - P_{av}) \qquad \text{eq. 3}$$

Where:

P_{min} = minimum precipitation

P_{av} = average precipitation

Kirchner *et al*. (1991) obtained a figure of 4.6% of MAP in excess of 263 mm, in a study of De Aar and Dewetsdorp, which focussed on saturated volume fluctuations. Taking soil thickness into account, Kirchner *et al*. (1991) produced the following formulae:

Thin soil cover:	$R = 0.06\ (MAP - 120)$ [mm]	eq. 3
Thick soil cover:	$R = 0.023\ (MAP - 51)$ [mm]	eq. 4
Alluvial cover:	$R = 0.12\ (MAP - 20)$ [mm]	eq. 5

Many rainfall-recharge relationships have been developed for dolomitic aquifers, and not all are linear. Bredenkamp (1978 and 1990) plotted recharge estimates from dolomitic aquifers in different areas, and showed that a linear relationship is obtained above an annual rainfall of 313 mm. This was adjusted to give the following general formula (Bredenkamp *et al*., 1995):

$$R = 0.32\ (MAP - 360)\ [mm] \qquad \text{eq. 6}$$

In the case of mountainous catchments, Bredenkamp *et al*. (1995) adopted the view that the base flow component of stream flow can be used to estimate groundwater recharge. This relies on assumptions, which may not necessarily hold true since it assumes that base flow can reliably be separated from total flow, and that all the recharge is derived from the delineated catchment. When relating base flow to MAP in mountainous catchments, representative rainfall data can be problematic. Because of steep slopes, orographic rainfall variations can be significant, and rain gauges are unlikely to reflect the true average precipitation over the catchments. Base flow studies in several mountainous catchments have been collated to produce the general formula (Bredenkamp *et al*. 1995).

$$R = 0.73\ (P_{av} - 480)\ [mm] \qquad \text{eq. 7}$$

Numerous other rainfall-recharge relationships have been developed from point studies of South African aquifers. Some of the more complex formulae do not necessarily preserve linearity, for example:

$$R = a\ (P / P_{av})P \qquad \text{eq. 8}$$

and

$$R = a\ .\ P_{av}\ (1 - b \times P_{av} / P) \qquad \text{eq. 9}$$

where
a and b are empirical parameters.

While equation 8 and 9 shows that recharge varies proportionally to the deviation of rainfall from the average value, equation 10 assumes that the ineffective portion of rainfall varies, depending on the extent of the rainfall deviation from the long-term average. DWAF has used the following relationship to obtain a first estimate of groundwater recharge (M. Smart and A. Woodford, pers comm.):

$$R = (MAP)^2/10000\ [mm] \qquad \text{eq. 10}$$

Equation 10 translates to using 1% of MAP where MAP = 100 mm; 2% of MAP where MAP = 200 mm; etc.

The three main criticisms of simple rainfall-recharge formulae are:

- Relationships may not be transferable to areas other than those in which they were derived; thus they are not applicable to regional assessments (E. van Wyk, pers. comm.)
- They ignore temporal distribution of rainfall;
- Their accuracy is dependent on the accuracy of the recharge estimates from which the relationship was derived.

The section on rainfall/recharge relationships is quite extensive but this approach is quite often used to determine groundwater recharge. In certain situations this may be valid and it is certainly an interesting approach. The applicability of this approach for the GRAII project will be considered. However, on a national scale it will probably be more accurate to take into account many more of the factors that control groundwater recharge.

4.5.3 A Comparison of Regional Recharge Estimation Methods

Regional recharge estimation methods are compared using the recharge values and ranges from Table 4.2 and these have been subdivided according to the prevalent geological conditions. The generalised recharge rates per particular geological formation are listed in Table 4.3. The aim of this comparison is to identify a recharge value per geological formation.

Table 4.3: Generalised recharge rates for certain aquifers

Aquifer	Recharge Rate
Karoo aquifers:	Where MAP is above 300 mm/a, 1.5% MAP for recharge is accepted (may not be applicable if MAP > 700 mm/a)
Granite aquifers:	The following equation is recommended: $R = (MAP)^2/20\ 000$ [mm]
Sedimentary aquifers:	The following equation is recommended: $R = 0.73\ (MAP – 600)$
Dolomitic aquifers:	Highly variable, and no generic equation is applicable
Kalahari aquifers:	Recommended is 0.8% MAP, although rainfall is episodic. Sand thickness may also play a role, and if sand thickness exceeds 6m no recharge may occur.

4.5.4 Salient points from the review by Murray (1996):

Some of the key points, in the context of the GRAII project, are given below:

- The existence of preferential flow paths is important in calculating groundwater recharge (this is very site specific and will be difficult to generalise at the regional to national scale),
- Rainfall characteristics (such as intensity) need to be taken into account,
- An aquifer's permeability and storage capacity are important characteristics in controlling groundwater recharge,
- Rainfall / recharge relationships that have been determined provide a useful means of calculating groundwater recharge,
- Recharge estimates for certain aquifer types are presented. However the rainfall / recharge relationships and recharge characterisation per aquifer are limited in terms of the objectives of this project.

4.6 Review of Groundwater Recharge Estimation in Southern Africa, (Xu and Beekman (eds.), 2003)

4.6.1 Introduction

This book provides a comprehensive review of recharge methods and studies have been selected that add significantly to the topic of recharge estimation. Recharge estimation methods can be classified according to:

- Hydrogeological provinces: regions of similar climate and geology with similar geomorphologic history (e.g. alluvial fans and riverbeds, sand and sandstone, volcanic, etc.; Lerner *et al*., 1990),
- Hydrologic zones: atmosphere, surface water, unsaturated and saturated zones (Bredenkamp *et al*., 1995, Beekman *et al*., 1999, Scanlon *et al*., 2002), or
- Physical and Tracer approaches: direct versus indirect, water balance and Darcian physical methods and chemical, isotopic and gaseous tracer methods (Lerner *et al*., 1990; Kinzelbach *et al*., 2002).

The ideal classification accommodates for all the above-mentioned criteria.

4.6.2 Commonly used methods

An overview of commonly used recharge estimation methods in Southern Africa is given in Table 4.4. The methods are grouped according to hydrologic zones and further sub-divided into physical and tracer approaches. A brief description of the principles and references is given for each method. Methods referring to surface water and unsaturated zones estimate potential recharge whereas methods referring to the saturated zone estimate actual recharge. A review of commonly used methods is given in Section 4.6.4. Methods excluded from the overview and review due to either a too qualitative nature, large inaccuracy or a too complicated nature for application in (semi-) arid environments are the rainfall-recharge relationships, soil-moisture/water budgets (Schulze, 1995), seepage meter, applied and heat tracers and (semi-) quantitative methods which involve ^{2}H, ^{18}O (Beekman *et al*., 1996) and ^{4}He (Selaolo, 1998). ^{36}Cl has not yet been applied in the field of recharge estimation.

Examples of integrated approaches, i.e. combining various methods, are:

"Combined chemical and isotope mass balance approach" (Beekman *et al*., 1999), and
"Recharge" Excel spreadsheet model (Van Tonder and Xu, 2000).

The combined chemical and isotope mass balance approach is based on dating moisture and groundwater using the Chloride Mass Balance and ^{14}C groundwater dating methods. The "Recharge" spreadsheet model enables analysis of hydrogeological data by commonly used estimation methods from Table 4.4 and gives an opportunity to calculate a weighted average recharge rate after having assigned weighting factors to each of the methods used.

A quantitative approach has been applied to crystalline basement aquifers of Central Namaqualand in South Africa to define the recharge potential (Conrad *et al.*, 2003). The approach is based on integrating spatial climatic and (hydro-) geologic datasets in a GIS environment.

Table 4.4: Recharge estimation methods applied in (semi)-arid Southern Africa

Zone	Approach	Method	Principle	References
Surface Water	**Physical**	HS	Stream Hydrograph separation: outflow, evapotranspiration and abstraction balances recharge	10
		CWB	Recharge derived from difference in flow upstream and downstream accounting for evapotranspiration, in- and outflow and channel storage change	4
		WM	Numerical rainfall-run-off modelling, recharge estimated as a residual term	5
Unsaturated	**Physical**	Lysimeter	Drainage proportional to moisture flux/recharge	2
		UFM	Unsaturated flow simulation e.g. by using numerical solutions to Richards equation	2, 4
		ZFP	Soil moisture storage changes below ZFP (zero vertical hydraulic gradient) proportional to moisture flux/recharge	2, 3, 6
	Tracer	CMB	Chloride Mass Balance – Profiling: drainage inversely proportional to Cl in pore water	1, 2, 3, 6
		Historical	Vertical distribution of tracer as a result of activities in the past (^{3}H)	1, 2, 3, 6
Saturated – Unsaturated	**Physical**	CRD	Water level response from recharge proportional to cumulative rainfall departure	2, 9
		EARTH	Lumped distributed model simulating water level fluctuations by coupling climatic, soil moisture and groundwater level data	3, 7
		WTF	Water level response proportional to recharge/discharge	2
	Tracer	CMB	Amount of Cl into the system balanced by amount of Cl out of the system for negligible surface run-off/run-on	1, 2, 3, 6
Saturated	**Physical**	GM	Recharge inversely derived from numerical modelling groundwater flow and calibrating on hydraulic heads / groundwater ages	2, 3
		SVF	Water balance over time based on averaged groundwater levels from monitoring boreholes	2
		EV-SF	Water balance at catchment scale	2
	Tracer	GD	Age gradient derived from tracers, inversely proportional to recharge. Recharge unconfined aquifer based on vertical age gradient (^{3}H, CFCs, $^{3}H/^{3}He$); Recharge confined aquifer based on horizontal age gradient (^{14}C)	1, 6, 8

HS:	**Hydrograph Separation – Baseflow**	**EARTH:**	**Extended model for Aquifer Recharge and Moisture Transport through Unsaturated Hardrock**
CWB:	Channel Water Budget		
WM:	Watershed Modelling	**WTF:**	Water Table Fluctuation
UFM:	Unsaturated Flow Modelling	**GM:**	Groundwater Modelling
ZFP:	Zero Flux Plane	**SVF:**	Saturated Volume Fluctuation
CMB:	Chloride Mass Balance	**EV-SF:**	Equal volume – Spring Flow
CRD:	Cumulative Rainfall Departure	**GD:**	Groundwater Dating

[1]Beekman *et al*. (1996)
[2]Bredenkamp *et al*. (1995)
[3]Gieske (1992)
[4]Lerner *et al*. (1990)
[4] Sami and Hughes (1996)
[6]Selaolo (1998)
[7]Van der Lee and Gehrels (1997)
[8]Weaver and Talma (1999)
[9]Xu and Van Tonder (2001)
[10]Xu *et al*. (2002)

4.6.3 Recharge forecasting

Forecasting groundwater recharge has become increasingly important, particularly with regard to the envisaged climate change impacts on Southern Africa's limited water resources (Kirchner, 2003; Cavé *et al*., 2003). Methods that have great potential to forecast recharge are those that have established relationships between rainfall, abstraction and water level fluctuations, such as the CRD, EARTH, Auto Regression Moving Averages and empirical methods. Critical in reliable forecasting of recharge is the accuracy of forecasting rainfall in terms of frequency of events, quantity and intensity. In Southern Africa there is a wealth of rainfall records, often dating back to the beginning of the previous century and this should form a sound basis for future predictions. Note that the accuracy of forecasting recharge is further complicated by the non-linearity of groundwater resources in their response to rainfall. Forecasting should accommodate for the propagation of uncertainty in input parameters.

4.6.4 Review of recharge estimation methods

A review of commonly used recharge estimation methods in (semi)-arid Southern Africa is presented in Table 4.5. Methods are evaluated in terms of limitations, applicability (range of fluxes, spatial and temporal scales) and ratings (accuracy, ease of applications, cost).

Table 4.5: Review of commonly used recharge methods for (semi)-arid Southern Africa

Zone	Method	Limitations	Applicability[2]			Rating[3]		
			Flux (mm/a)	Area (km^2)	Time (yrs)	Acc.	Ease	Cost
SW	HS	Ephemeral rivers	400-4000 (0.1-1000)	10^{-4}-1300 (10-1000)	0.3-50 (1-100)	2-3	1-2	1-2
	CWB	Inaccurate flow measurements	100-5000	10^{-3}-10	1d-1yr	2-3	2	3
	WM	Ephemeral rivers	1-400	10^{-1}-5*10^{5}	1d-10yr	2	2-3	3
Unsaturated[1]	Lysimeter	Surface run-off	1-500 (0-200)	0.1-30m^2	0.1-6	2	3	3
	UFM	Poorly known relationship hydraulic conductivity – moisture content	20-500	0.1-1m^2	0.1-400	3	2	2
	ZFP	Subsurface heterogeneity; periods of high infiltration	30-500	0.1-1m^2	0.1-6	3	2	2
	CMB	Long-term atmospheric deposition unknown	0.1-300 (0.6-300)	0.1-1m^2	5-10000	2	1	1

Zone	Method	Limitations	Applicability[2]			Rating[3]		
			Flux (mm/a)	Area (km^2)	Time (yrs)	Acc.	Ease	Cost
	Historical	Poorly known porosity; present ^3H levels almost undetectable	10-50 (10-80)	0.1-1m^2	1.5-50	2-3	2-3	3
Sat. – Unsat.	CRD	Deep (multi-layer) aquifer; sensitive to specific yield (S_y)	(0.1-1000)	(1-1000)	(0.1-20)	1-2	1-2	2
	EARTH	Poorly known S_y	(1-80)	(1-10m^2)	(1-5)	1-2	2	1
	WTF	In/Outflow and S_y usually unknown	5-500	$5*10^{-5}$->10^{-3}	0.1-5	2	1	1
	CMB	Long-term atmospheric deposition unknown	0.1-500	$2*10^{-6}$->10^{-2}	5->10000	2	1	1
Saturated	GM	Time-consuming; poorly known transmissivity; sensitive to boundary conditions	(0.1-1000)	(10^{-6}-10^{6})	(1d-20yr)	1-2	3	3
	SVF	Flow-through region; multi-layered aquifers	(0.1-1000)	(0.1-1000)	(0.1-20)	1-2	1-2	2
	EV-SF	Confined aquifer	(0.1-1000)	(1-100)	(1-100)	1-2	1-2	1-2
	GD	^{14}C, $^3H/^3He$, CFC: poorly known porosity / correction for dead carbon contribution	^{14}C: 1-100 $^3H/^3He$, CFC: 30-1000	^{14}C, $^3H/^3He$, CFC: $2*10^{-6}$->10^{-3}	^{14}C: 200-200000 $^3H/^3He$, CFC: 2-40	3	2-3	3

1 All methods for estimating fluxes through the unsaturated zone assume diffuse vertical flow whereas in reality flow along preferred pathways is the rule rather than the exception. These methods therefore tend to overestimate the diffuse flux.
2 Data in brackets are estimates from Southern Africa. Rainfall may be up to 2000 mm/ in a year; other data represent global values and are taken from Scanlon *et al*. (2002).
3 Ratings for methods applied to semi-arid Southern Africa.

The aim of rating is to advance an on-going discussion among a wide range of stakeholders on the selection of appropriate methods for recharge estimation. The ratings are based on the authors experience and on ratings given by Bredenkamp *et al*. (1995), van Tonder and Xu (2000), Kinzelbach *et al*. (2002) and a recent workshop on the "Framework for recharge estimation in Southern Africa" project (Beekman *et al*., 2003).

With regard to the applicability of methods, data have been adopted from Scanlon *et al*. (2002). Regarding ratings, the approach of *accuracy* rating is adopted from Kinzelbach *et al*. (2002): Class 1: difference from true value within a factor of 2, Class 2: within a factor of 5 and Class 3: within a factor of 10 or more. *Ease of*

application is related to data requirements and data availability and is rated from 1: easy to use to 3: difficult to use. *Cost* is rated from 1: inexpensive to 3: expensive.

The authors conclude that the following methods can be applied with greater certainty in the arid and semi-arid regions: CMB, CRD, EARTH, GM, SVF and WTF methods. From these methods CB is the easiest and least expensive to apply whereas GM is the most difficult and expensive method.

4.6.5 Salient points from review of the book.

Some relevant comments pertaining to the book are given below:

- The book provides a very good summary of recharge work carried out in the arid and semi-arid regions of Southern Africa over the past 30 years.
- It provides a good overview of all recharge methods and approaches. These approaches are also classified according to suitable scale and geohydrological settings. It provides a good guide on which methods should be used under which circumstances.
- The book also has included recent research into the topic of groundwater recharge and addresses many of the relevant topics in groundwater in the light of the National Water Act (such as groundwater / surface water interaction, recharge and stream flow etc). The book also addresses recharge estimates in fractured rock environments.
- A very relevant reference, which is well compiled and will have great value for this project.

4.7 Groundwater recharge maps

The Directorate of Geohydrology in DWAF has produced a series of 21 1 : 500 000 general hydrogeological maps covering South Africa which include 1 : 2 000 000 inset groundwater recharge potential maps. The recharge values used come from a compilation of various estimation methods. For example, equations 4 and 5 were used in the Queenstown map, and base flows and equation 1 were used in the Cape Town map (Baron, pers comm.). In the Pietersburg map, a rating system was developed which was calibrated against recharge estimates (Haupt, pers comm.). The rating system was based on factors that affect recharge, such as rainfall, topography, soils and depth of water table.

The Department of Agricultural Engineering, University of Natal, Pietermaritzburg, with support from the Water Research Commission, produced a net recharge map of South Africa based on the physical conceptual model, ACRU. The ACRU model considers moisture movement in the vertical dimension, and provides a means of estimating the amount of water leaving the root zone at a specific site. A major drawback with the model, with respect to its application on a regional level, is that it was designed for use in areas where recharge occurs via porous media, and therefore it cannot account for direct recharge via preferential pathways. As discussed earlier, flow via macro pores, joints, fissures and the like is believed to be of major significance in areas characterised by deep soils or a semi-arid climate (Lloyd, 1986; Sami, 1992; Kirchner *et al*., 1991; Rushton, 1987; Sharma and Hughes, 1985).

4.8 Recharge Threshold Values

If time series data of rainfall and groundwater level fluctuations can be obtained in close proximity, then an analysis of these data can be carried out. Ideally, these data can be collected on a daily basis. The results of the analysis will provide an RTV for an individual rainfall event. The Cumulative Rainfall Departure (CRD) method is a good analytical method if the above-mentioned data (including the specific yield of an aquifer) are known.

Bean (2003) mentions that recent work undertaken in semi-arid Central Australia by Harrington *et al*., (2002) suggests that the recharge threshold can be predicted through an understanding of stable isotopes abundances in rainfall and groundwater. Bean (2003) developed a new stable isotope- based technique, called the Modified Amount Effect (MAE) Method. This technique provides insight into episodic recharge processes by estimating the proportion of preferential pathway-to-matrix-derived flow entering an aquifer, and the amount of rainfall required to initiate recharge via the respective flow paths. Significantly, the proportion of bypass flow can be determined without undertaking expensive and time consuming unsaturated zone studies, both factors often of primary concern when undertaking recharge investigations in developing countries.

Bean (2003) states that four recharge thresholds can be identified using the MAE Method; the low and high recharge thresholds that must be exceeded before recharge occurs via preferential pathways or the matrix, respectively. These represent threshold limits, the low value only of importance following successive months of wet weather, the high value representing the rainfall that must be received to restore an aquifer system to equilibrium after prolonged dry spells. Once these thresholds are known, the recharge history of a site can be modelled using available rainfall data by adapting the Cumulative Rainfall Departure (CRD) method. An important finding of modelling undertaken during this investigation is that in those semi-arid to arid areas where most recharge water enters the aquifer via the matrix, the period of time that elapses between successive rainfall events that exceed the matrix recharge threshold often extends to scores of years.
Thus, through understanding the episodic nature of recharge in semi-arid and arid areas, and therefore the thresholds that must be exceeded before recharge occurs, geohydrologists are better able to provide predictive advice for their clients.

In terms of aquifer management, it is therefore important to know whether the suggested recharge is actually occurring, and if so, the recharge threshold, particularly in semi-arid and arid environments where recharge is episodic in character. In the absence of long-term site rainfall or water level data, an understanding of environmental tracers present in recharge waters can be of some benefit, particularly when investigating aquifers containing young groundwater, and receiving significant recharge (Cook *et al*., 2001)

The limitations of the MAE method, in the context of the GRA II Project, is that the isotope data available is of limited geographic spread, and it will not be valid to extrapolate these point values to a national scale. However, this method does highlight the importance of collecting isotope data for recharge and RTV assessments.

5. DATA SET EVALUATION

5.1 Background

5.1.1 Project Overview

The purpose of this section is to document the data sets identified as being relevant to groundwater recharge calculations and then to obtain these data sets and validate them. The validification process entails checking the data in terms of relevance and accuracy. This project is aimed at carrying out recharge estimations per quaternary catchment for the entire country using a GIS-based approach. The GIS approach will also be supported by components from the other sub-projects being carried out, applicable to recharge estimates. Recharge calculations, at best, have moderate to high levels of uncertainty, and a notable element of subjectivity. An important consideration when carrying out this project is that two products are required.

- The first is a national scale map of groundwater recharge per quaternary catchment as a long-term average value, and
- The second is recharge per quaternary catchment as an annual value. This latter product means that recharge will have to be determined for each calendar year.

This requirement of generating two products has important bearing on the methodology to be used for this project.

A fundamental requirement of this project is that the recharge calculations are GIS based. This means that all data must have a spatial reference to be of value in this project. A number of factors that are relevant to recharge are difficult to use in a spatial environment, because they are not compatible with GIS processing. In addition, there may be very limited data, which are just point values, and thus cannot be extrapolated to the catchment scale. Examples of these data sets include preferential flow paths, aquifer transmissivity and aquifer storage. Thus a number of components that play a role in groundwater recharge will have to be assigned default values to be used in the calculations. As the quantification and delineation of these components improves, so they can be incorporated into the recharge calculations.

Groundwater recharge has been determined by Vegter (1995) on a national scale. This is the only known study of groundwater recharge at this scale. The method used by Vegter (1995) has been documented in the previous progress report for this project (DWAF, 2004). The recharge map generated by Vegter (1995) provides reference values for this assessment. A basic difference from the Vegter (1995) approach will be to carry out the assessments on a quaternary catchment basis as opposed to a geohydrological response unit approach and this study will address more of the factors involved in controlling groundwater recharge, than used by Vegter (1995). However for comparison purposes the results from this study will also be aggregated to geohydrological response units. This will then also enable the checking of Vegter’s recharge values to the values obtained in this project. In addition, as already mentioned, this project is to generate both long term average recharge estimates and annual recharge values. Vegter (1995) only provided a longer-term average recharge value. This project also needs to determine recharge cut-off values per quaternary catchment, i.e. rainfall values below which recharge does not occur.

5.1.2 Identified data sets

Carrying out a literature survey and holding a workshop to collectively discuss recharge assessment methods initiated the project. In addition, Prof. Gerrit van Tonder and Dr Ingrid Dennis of the Institute for Groundwater Studies, University of the Free State, were consulted for their input into appropriate data sets and methods for recharge estimates.

From the abovementioned process the following data sets were identified as being important for groundwater recharge estimations (listed below in no particular order):

- National Groundwater Recharge (Vegter, 1995)
- Baseflow per quaternary catchment (Schulze, 1995 and Pitman, 1995)
- Rainfall chloride concentration
- Groundwater chloride and total dissolved solids concentration
- Surface topography (slope)
- Soil cover (texture and thickness)
- Vegetation (type and density)
- Geology (lithological and structural data)
- Satellite imagery (particularly to identify recharge and fracture zones)
- All point estimates obtained from recharge studies
- Extent and type of riparian vegetation
- Depth to groundwater
- Groundwater level fluctuations, and
- Rainfall per annum.

There are many other data sets that could be considered important, such as rainfall intensity and duration, evapotranspiration, alluvial extent within valley floors, isotope results, etc. However, many of these data sets are either difficult to obtain or will be too detailed to contribute meaningfully to the final result.

5.1.3 Data processing method

The data obtained for this study was processed using a raster or grid based approach. The cell size used for the project was 1 km x 1 km, using Albers Equal Area project with a 1st standard parallel of 32°S, 2nd standard parallel of 18°S, and with a central meridian of 24°E. Once the data processing is complete, the data will be converted to Geographic (WGS84) coordinates and provided to DWAF. The results obtained from the cell-based processing will be aggregated up to a single value of recharge per quaternary catchment. Both long-term recharge values, as well as recharge values per year (for the past 5 years) will be generated.

5.2 DataSet Evaluation

The following discussion in this chapter reviews each of the data sets listed in Chapter 3.2. The usability of the data is evaluated, however not all data sets have been received by the consultant for evaluation at the time of writing this report. The data sets are not discussed in any particular sequence of importance, however just according to a “flow path”, i.e. from precipitation through to flow to the saturated zone, via intercepting factors.

5.2.1 Rainfall

After making enquiries with the South African Weather Service, it was learnt that an annual rainfall grid is not produced. However, what is available is the total rainfall for 100 automatic weather stations for the past 5 years. The distribution of these rainfall stations is shown in Figure 5.1. The data have been obtained from the South African Weather Service and imported into a GIS format.

It was recently learnt that the Agricultural Research Council (ARC) compiles rainfall data on a regular basis and that these results are gridded on a national basis. The details regarding this data are currently being followed up.

Gridded rainfall has been compiled for the whole of South Africa by Schulze (1997). Schulze (1997) explains that in creating this gridded surface of mean annual precipitation (MAP), Dent, Lynch and Schulze (1989) [in Schulze, 1997] divided South Africa, Lesotho and Swaziland into 34 regions, each of which was considered relatively homogeneous in relation to “controls” of rainfall distribution. These controls include altitude (and its influence on orographic lifting), distance from sea (as an index of continentality), aspect, terrain roughness and direction of prevailing rain bearing winds. Using data from over 6 000 rainfall stations, equations for MAP were developed for each region, from which 1’ x 1’ of a degree gridded values of MAP were generated in 1989. There appear to be no MAP gridded surfaces produced since 1989. The South African Atlas of Agrohydrology and Climatology was produced in 1997 and it includes the 1989 data as the most recent data.

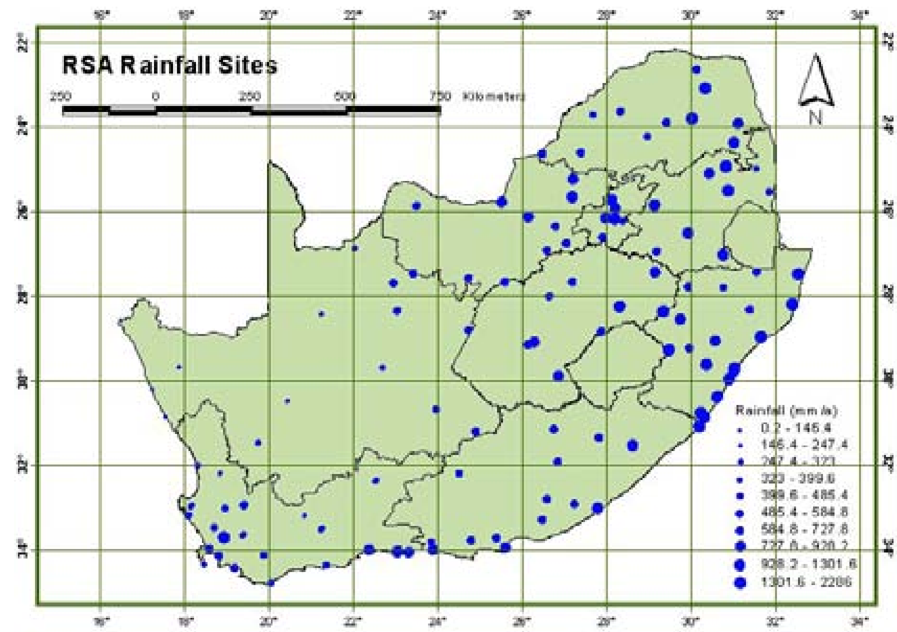

Figure 5.1: Distribution of automatic rainfall stations (Source: Weather Services)

In order to address this data gap, the project team proposed to extrapolate the data received from 100 automatic rainfall stations, as shown in Figure 5.1. The most appropriate extrapolation technique and the factors that need to be taken into account still needs to be researched. Feedback from the ARC on the rainfall data processing they do is also pending.

5.2.2 Rainfall chloride concentration

For a national scale assessment of groundwater recharge a chloride mass balance calculation will provide a good first approximation. In order to carry this out the chloride concentration of rainfall is required. It is acknowledged that chloride concentration does vary with rainfall, almost with each rainfall event. This finding was measured and documented by the Institute for Groundwater Studies. However, if a harmonic mean value is calculated it will provide an adequate first approximation. DWAF have set up a number of rainfall sampling stations through South Africa. The distribution of the rainfall sampling stations, as provided by the Weather Services, is shown in Figure 5.2. This does not include the DWAF weather station sites.

Firstly, the distribution of the stations is such that extrapolation of results to areas where no measuring is taking place, will be highly uncertain, to the extent that results obtained will be misleading and thus cannot be used. However, the values obtained from the stations can be applied to the localized area nearby the rainfall stations. Secondly, after receiving the data following on from a “Geo-requests” submission to the National Groundwater Archive, the results obtained are summarized in Table 5.1: Thus only seven values can be used for carrying out a chloride mass balance.

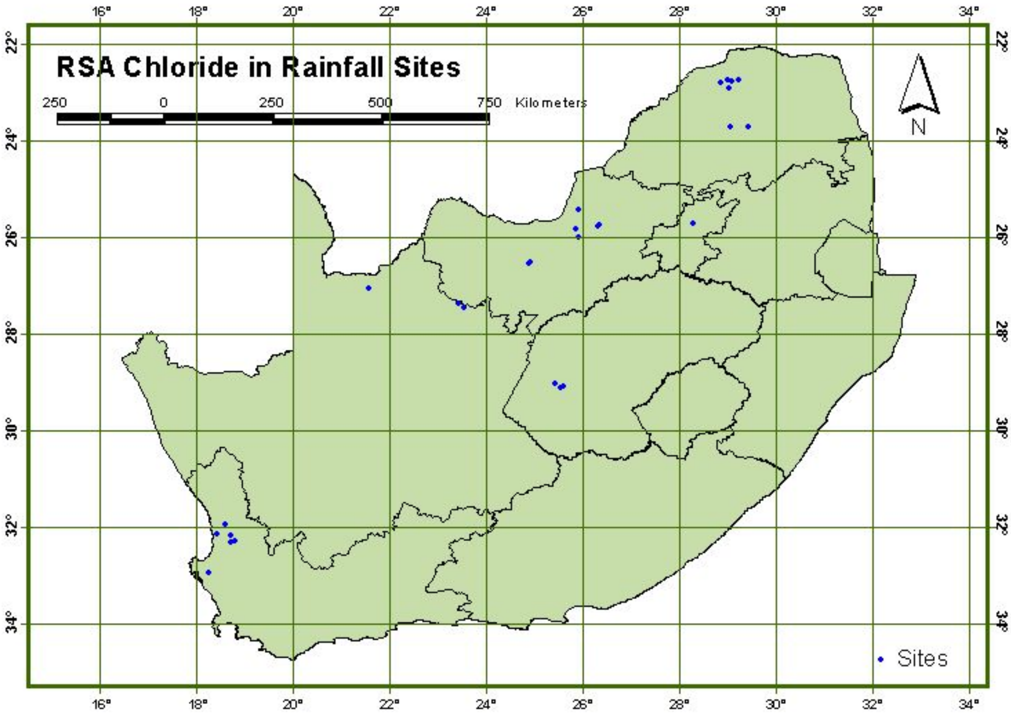

Figure 5.2: Rainfall event sampling stations (Source: DWAF)

Table 5.1: Summary of rainfall chloride measurements obtained from the NGA

32 results received for 27 rainfall stations	
Rainfall Chloride Value[*]	**No of stations**
(mg/L)	-
“<10”	5
“<5”	18
“<3”	1
Actual values between 14.746 & 5.057	7

Prof. Van Tonder of the IGS, has a database containing 14 rainfall chloride values for sites distributed throughout southern Africa. Interestingly the highest chloride value from this IGS database is 8.4 mg/L.

In summary, there are only 21 rainfall chloride values throughout southern Africa. These values cannot be extrapolated and will need to be used only in the immediate vicinity of the rainfall sampling station. The position of the sampling station can be related to the geological conditions as well and possibly a recharge percentage (as a range of values) can be assigned to that geological formation in that area. This will be explored in due course.

DWAF have a programme in place for sampling rainfall and then having the samples analysed chemically, including chloride concentration, by the Atmospheric laboratory at the CSIR, Pretoria. Subsequent to the data assessment section being written, a lot more rainfall chloride data were obtained (refer to Section 6.2).

5.2.3 Baseflow per quaternary catchment

The most recent base flow values are available from the WR90 database. A time series of monthly flows for each of the quaternary catchments exists and each time series covers the period 1920 to 1989 (sixty nine years). Vegter (1995) favours use of the Herold method for determining surface and groundwater components of monthly flows. Vegter (1995) grouped the quaternary catchments according to their hydrological characteristics and derived base flow values for the entire country. The results of this exercise are shown in Figure 5.3.

[*] As reported.

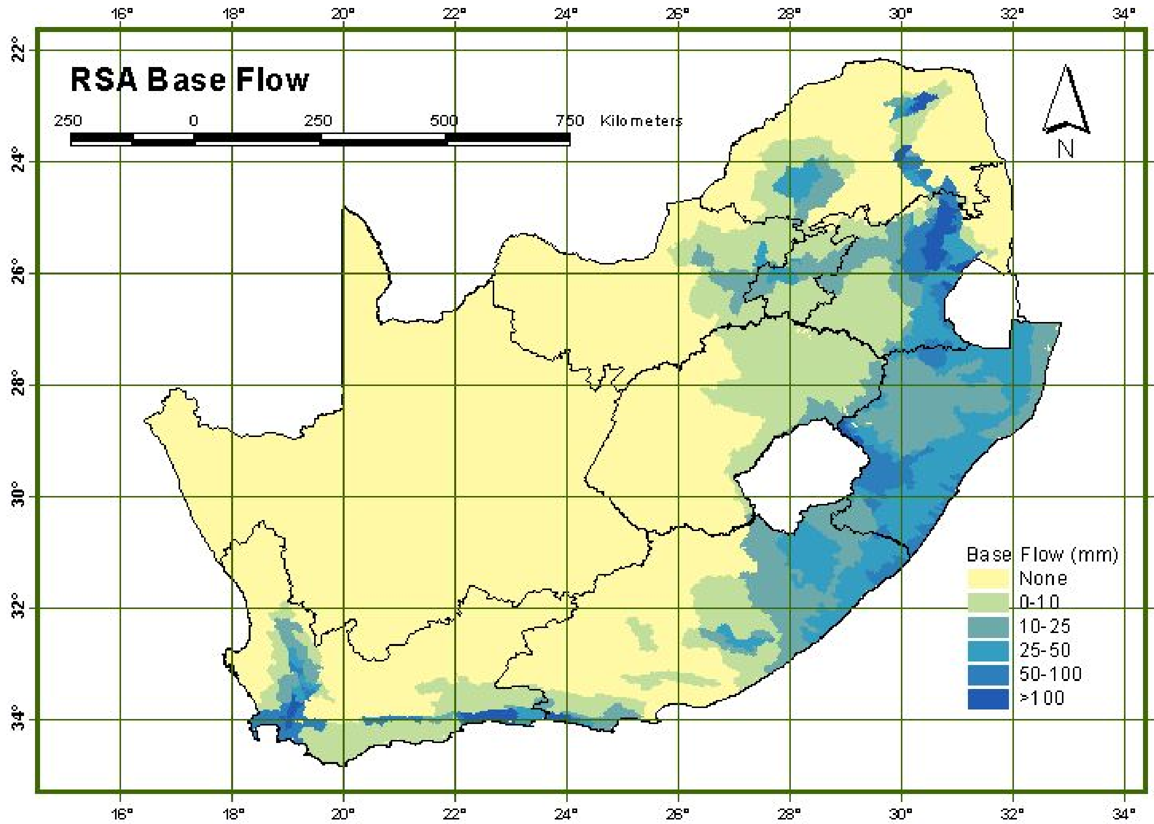

Figure 5.3: Groundwater component (baseflow) of river flow (Source: Vegter, 1995)

A number of other specialists have also calculated baseflow per quaternary catchment. These include Schulze (1997), Hughes (2003) and Pitman [in Vegter, 1995]. Further research is required into which is the most appropriate data to use for this project. Bearing in mind the objectives of this project, and as a result of discussions with Prof. Van Tonder, the baseflow results generated by Schulze (1997) appear most applicable at this stage, however, the most suitable data will be researched.

Baseflow is considered to represent a minimum value for groundwater recharge.

5.2.4 Surface topography slope

There is correlation between ground surface slope and groundwater recharge. The steeper the slope, the greater the surface water run-off and the lower the groundwater recharge. If a slope is very shallow, the recharge potential will be higher. Slope is considered a significant factor for recharge calculations. DWAF have invested in obtaining a hydrologically corrected digital elevation model. This DEM was supplied to the project team (13.0 Gbytes). An example of the results obtained from the DEM is shown in Figure 5.4. This dataset covers the whole of South Africa.

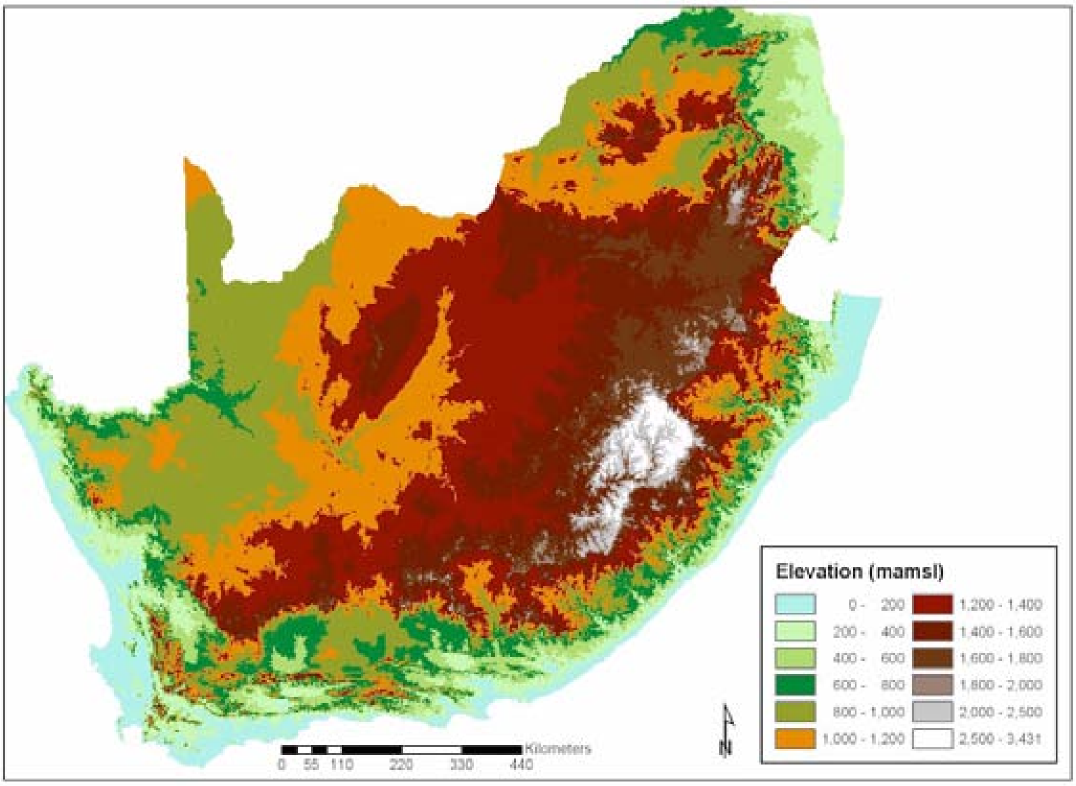

Figure 5.4: An example of the DWAF supplied DEM

Subsequent processing of the DWAF provided DEM by the project team has resulted in the DEM being corrected and usable. For the groundwater recharge project the DWAF DEM is to be used. The entire DEM has been evaluated by GEOSS and in places elevation anomalies corrected. A slope grid (1 km x 1 km) has been generated.

5.2.5 Vegetation

Vegetation also plays a role in controlling groundwater recharge. Different types of vegetation transpire at different rates, thus varying the amount of precipitation available for groundwater recharge. The National Botanical Institute (NBI) has produced the most suitable vegetation data set for the whole of South Africa. A map showing the vegetation coverage is included in Figure 5.5.

The vegetation mapping was carried out to provide floristically based vegetation units of South Africa, Lesotho and Swaziland, at a greater level of detail than has been available before. There are 440 zonal and azonal vegetation types mapped at a working scale of 1:250 000. The units are identified by number with a linked table of names. The map is the result of a collaborative project involving about 60 individual contributors from a number of organizations. The final product was scheduled to be published, together with descriptions, in a book in late 2004.

In the next phase of the project, the processing of this vegetation data, will be carried out and optimal rankings determined.

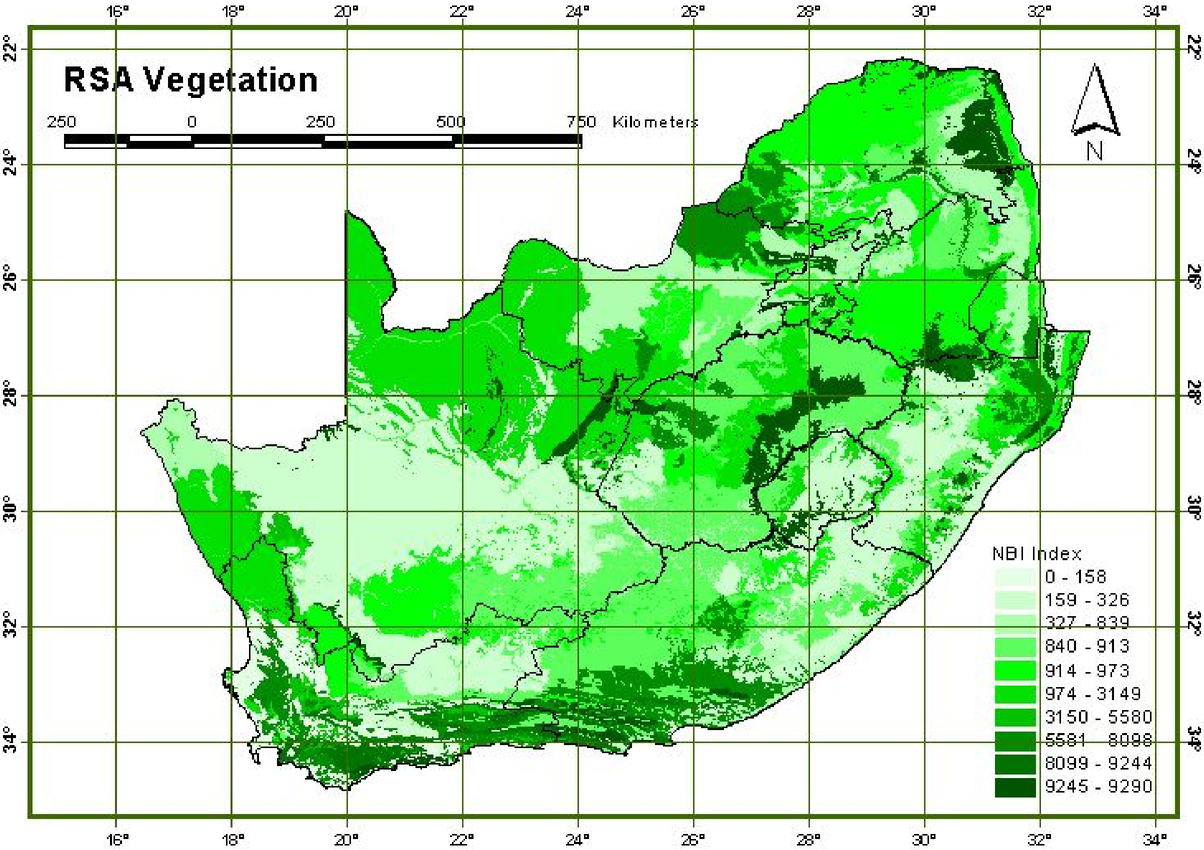

Figure 5.5: The botanical map produced by the NBI (Source: Muccina and Rutherford, 2004).

5.2.6 Soil cover

Soil conditions are also considered an important factor in controlling groundwater recharge. Important characteristics of soil, with respect to groundwater recharge include, soil thickness and soil texture. The only type of data available for this purpose is the Institute for Soil, Climate and Water (ISCW) Land Type data. This data was mapped at a scale of 1:250 000 and the Land Type polygons are determined according to microclimate, terrain and soil forms. Within the Land Types the percentage of soil types, thicknesses, etc. is given, however, the actual soil conditions (such as thickness) are not mapped. Currently discussions are under way with the ISCW as to the availability of the Land Type data for this project. The ISCW normally sells the Land Type data per 1:250 000 scale map sheet.

The other source of soil data is available from the WR90 CD-ROM. This soil data is very generalised and shown in Figure 5.6.

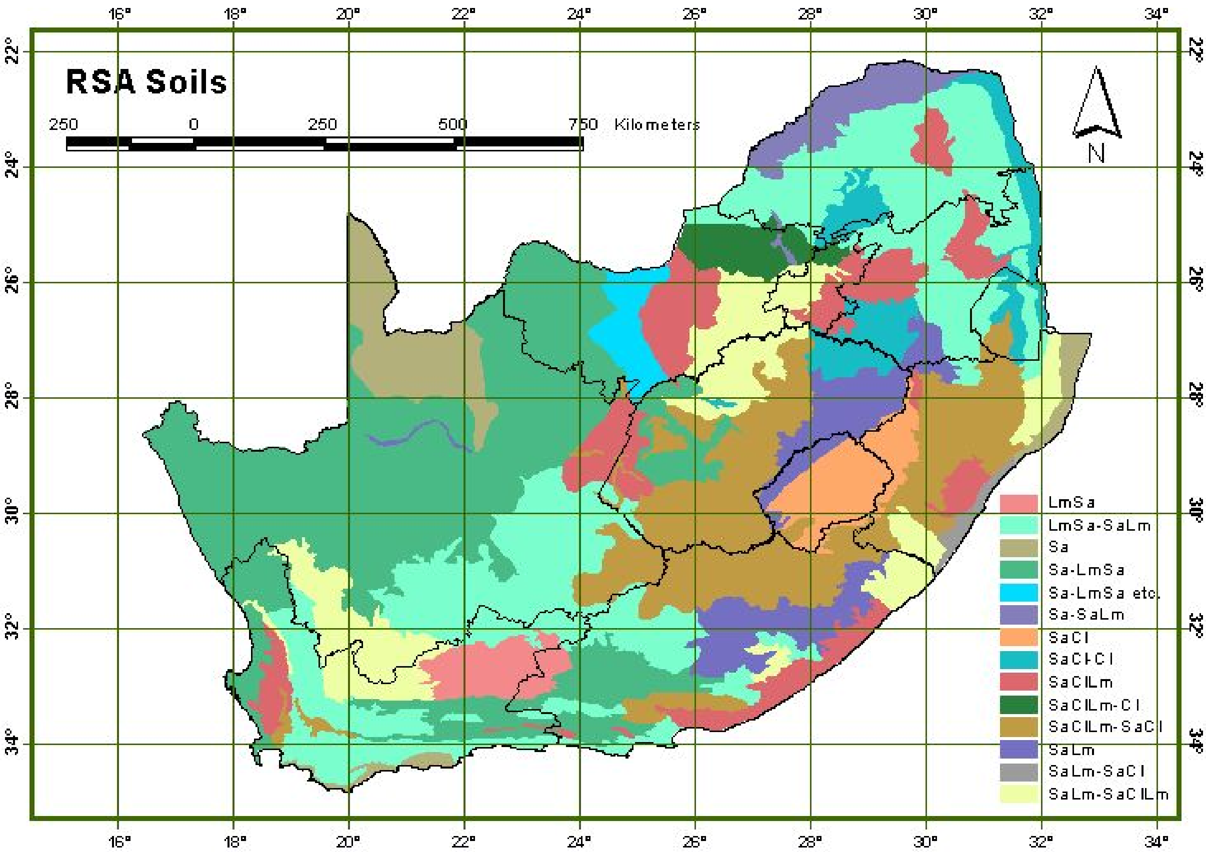

Figure 5.6: Generalised soil map (Source: WR90)

The soil coverage is based on the 1989 Revised Broad Homogeneous Natural Regions map produced by the Department of Agricultural Engineering, University of Natal, Pietermaritzburg. WR90 created soil classifications that contain depth, texture and relief. Associated with the soil polygons are the following data fields: Average soil depth (mm); WR90 soil classification; dominant soil series; the name of the dominant series, percentage of the name of the dominant series, dominant soil texture, dominant series texture, percentage of dominant series texture; highest point; lowest elevation; range of elevation; and broad SIRI soil mapping units.

Knowing the complexity and large spatial variability associated with soil types, it would be better for the project if the 1:250 000 scale Land Type data were obtained. It is appreciated that certain processing will be required of the Land Type data to obtain the soil data required for this project, however this is currently being negotiated with the Institute for Soil, Climate and Water.

5.2.7 Satellite imagery

The satellite imagery will play a role in assisting with the definition of recharge zones, and the delineation of riparian zones and alluvial valley floor deposits. DWAF provided GEOSS with 1998 Space Maps (11.5 Gbytes). The space maps were generated for the 1:250 000 National Land Cover mapping project, and are

authorectified and clipped/mosaiced according to the 1:250 000 scale map outlines. The space maps for the entire country have been provided. The space maps comprise Landsat TM5 data, with a 25 m by 25 m cell size. The resolution of the imagery is coarse for the delineation of riparian zones, which typically can be in the region of 5 to 10 m wide, however, the major riparian zones can be mapped. This project will be carried out in conjunction with the national rivers data set, recently supplied by DWAF. The satellite data will also be useful for characterising broad recharge zones, indicated by rock outcrops, and mountainous regions.

5.2.8 Geology (lithology and structural data)

South African hydrogeology is characterized by predominantly secondary aquifer conditions, with groundwater occurrences being controlled by geological settings and structural features, such as faults, and fractures. It is an important requirement of this project to take into account the hydrogeological setting of aquifers and thus structurally controlled recharge events need to be predicted where possible. One of the concerns regarding the use of the ACRU model, for example, is that this model, which does predict groundwater recharge, does not take into account geological complexity and preferred flow paths along which groundwater recharge occurs.

For this project it is considered important that detailed geological data be used. The Council for Geoscience (CGS) has released a 1:1 million scale data set for the geology of the whole of South Africa (Figure 5.7). The Council have however recently released a 1:250 000 scale geological coverage for the whole of South Africa. This coverage was derived from merging the individual 1:250 000 geological data sets. The national 1:250 000 scale data set is not entirely complete and there is an area in the northern Cape that has not yet been completed. This is not seen as being problematic as the 1:1 million scale data will be used to fill in these “gaps”. A structural geology data set has also been completed at the scale of 1:250 000 and will also be beneficial to this project. A request has been submitted to the Council for Geoscience for the use of the 1:250 000 scale data sets (both lithological and structural data) and at the time of writing this report, the data had not yet been received from the Council for Geoscience.

A subset of the 1:250 000 scale geological coverage has been tested in a pilot study area and it will definitely be of great value to this project, due to its more detailed accuracy. The liaison person for obtaining the 1:250 000 scale geological data from the Council for Geoscience is Dr. Manie Brynard.

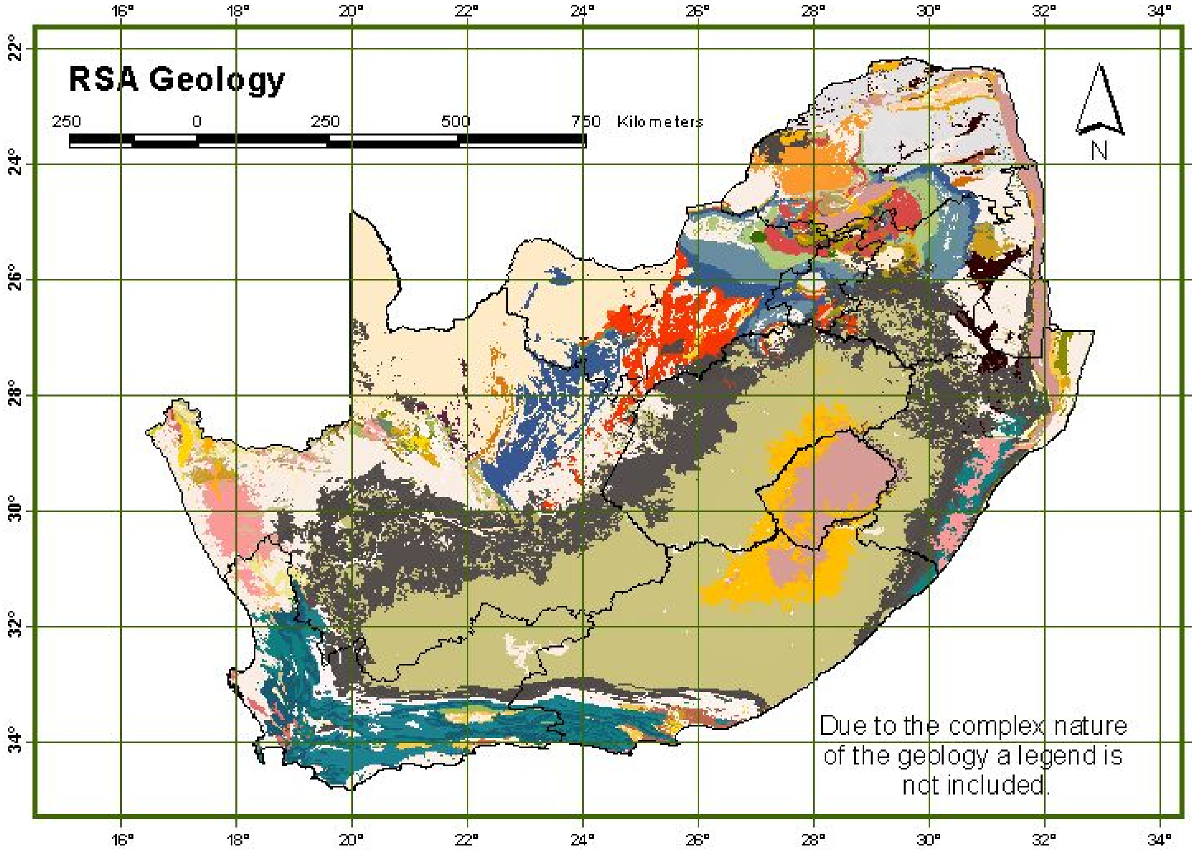

Figure 5.7: Geological map of South Africa, scale 1:1 million (Source: Council for Geoscience)

5.2.9 Groundwater quality

Regarding the chloride mass balance method, which is going to be carried out for this project, it is necessary to have the chloride concentration of groundwater (as well as the chloride concentration of rainwater, which has already been discussed). The Water Research Commission (WRC) has funded studies into characterization of the chemistry of South African groundwater. The chemistry data were obtained from the Water Research Commission. However, the compilation of chemistry maps was delivered in Adobe® pdf format. On enquiry, although the data were analysed in a GIS, the resultant GIS data and maps were not provided to the WRC, only pdf files of the maps. The person responsible for the work (Milo Simonic) has left South Africa and the GIS files are not available. As the analysis for this project is to be carried out in GIS, it is essential that GIS format data be obtained. In order to do this, a "GEO-request" was submitted to DWAF for all the latest chloride values per borehole throughout the country. These data have been received and the distribution of boreholes is shown in Figure 5.8.

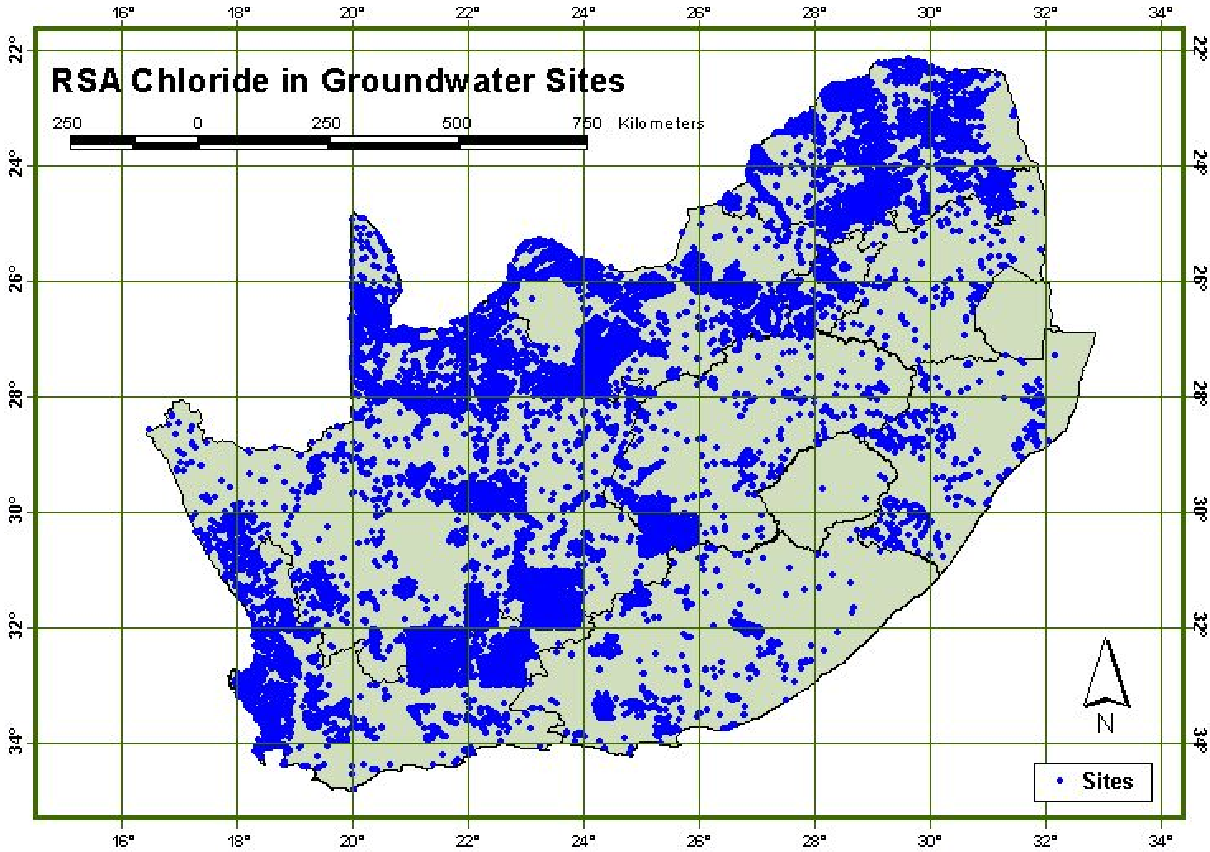

Figure 5.8: Distribution of boreholes with chloride measurements (Source: DWAF)

The chloride data are still to be filtered, analysed and extrapolated into a gridded file format.

In the coastal area, the chloride mass balance method can be quite inaccurate due to higher salinity levels in the rainfall and possible saline intrusion of groundwater. For these reasons, the total dissolves solids (TDS) content of groundwater will also be evaluated. For this reason, the TDS values were also obtained for these boreholes, shown in Figure 5.8. This data also still needs to be filtered, analysed and extrapolated into a gridded file format. Chloride ion groundwater time series data has also been obtained.

The concern does remain that the chloride mass balance method can only be applied for very localised areas due to the limited distribution of rainfall chloride samples.

5.2.10 Depth to groundwater

A factor also to be considered when carrying out groundwater recharge estimations is the depth to groundwater. For this reason, a "Geo-request" was submitted and the results of boreholes with water level data, including water level time series data, is shown in Figure 5.9.

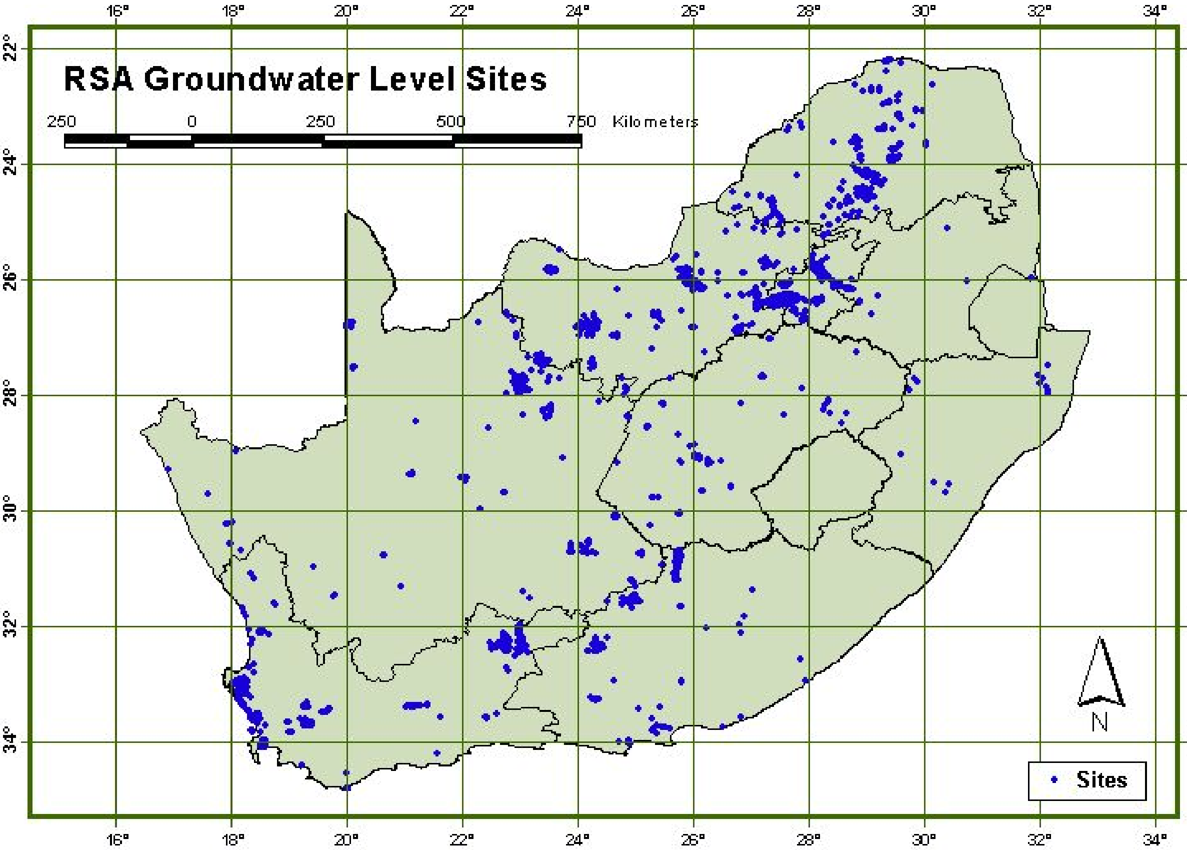

Figure 5.9: Boreholes with time series water level data (Source: DWAF)

It is considered necessary to obtain time series water level data as well, so as to be able to determine the rainfall/recharge cut-off values per quaternary catchment. The approach is to evaluate rainfall patterns in close proximity to boreholes with time series water level data. The time series water level data will have to be scrutinized for groundwater abstraction impacts on the water levels, as essentially only naturalized fluctuations are required. Where valid groundwater level fluctuation data is available, time series rainfall data will be requested from the South African Weather Services and compared to the water level graphs. This will require detailed and time consuming analysis, however is considered one of the best ways for assessing the cut-off amount of rainfall, below which no groundwater recharge occurs.

5.2.11 Groundwater recharge

Vegter (1995) produce a map presenting a countrywide picture of groundwater recharge.

Although recharge is expressed quantitatively, the map is to be considered as depicting broad trends rather than laying claim to accurate regional recharge figures. Nevertheless, it is considered to provide a fair estimate of the wide range of values. The recharge map is based on: a regionalised baseflow map in the eastern and southern parts of SA; effective rainfall; rainfall and recharge estimates for certain areas (where recharge is only considered if > 15 mm rainfall occurs per day); and results obtained from literature studies.

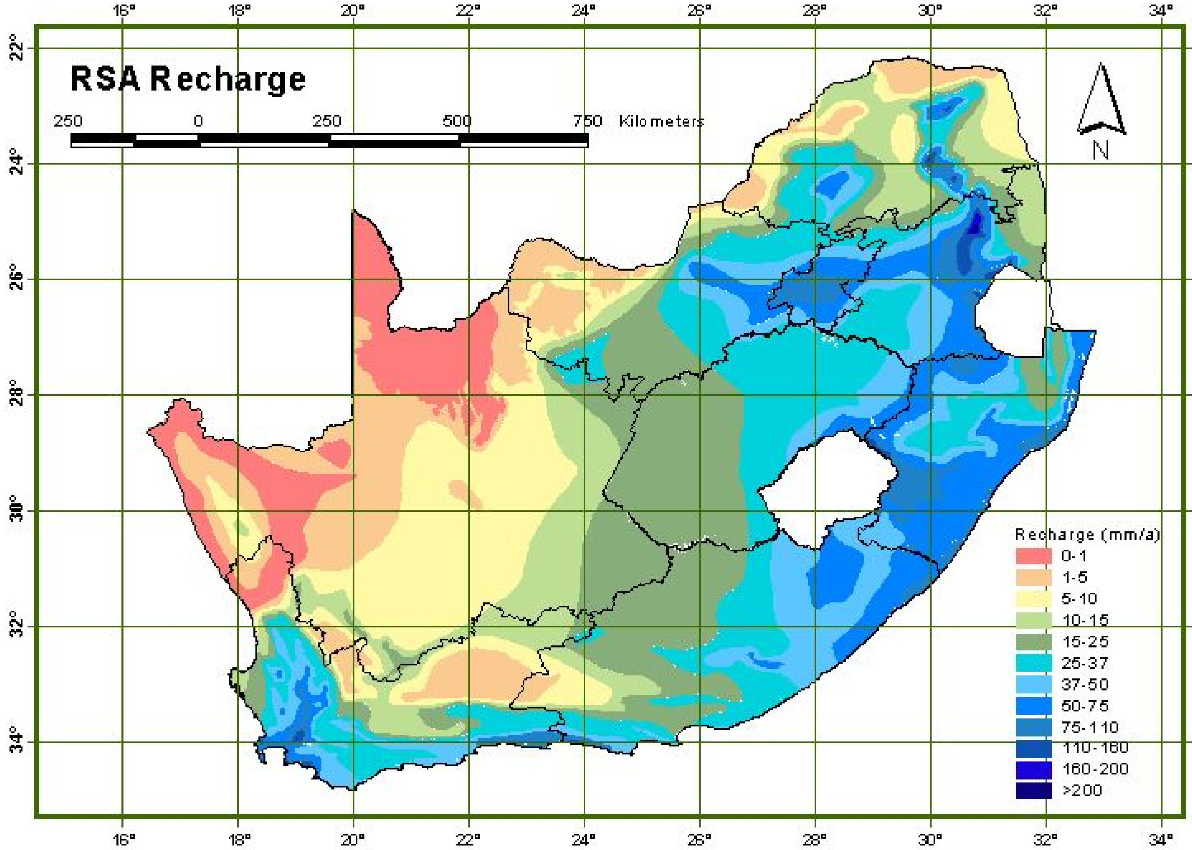

Figure 5.10: Groundwater Recharge (Source: Vegter, 1995)

The recharge map produced by Vegter (1995) does not take into account many of the factors that control groundwater recharge, and this project will attempt to do so. However, it must be noted, that although Vegter (1995) did not take into account these factors, his results must be taking into account when assessing revised recharge values.

Further to producing the recharge map, Vegter (1995) also produced a table of actual sites where recharge studies have been carried out. Fortunately, these studies have geographic coordinates and can be used for this project. The distribution of these study sites is shown in Figure 5.11 below.

It is anticipated that this database showing where point recharge estimates have been calculated will be expanded, as all the results of the literature study carried out, will be added to this database.

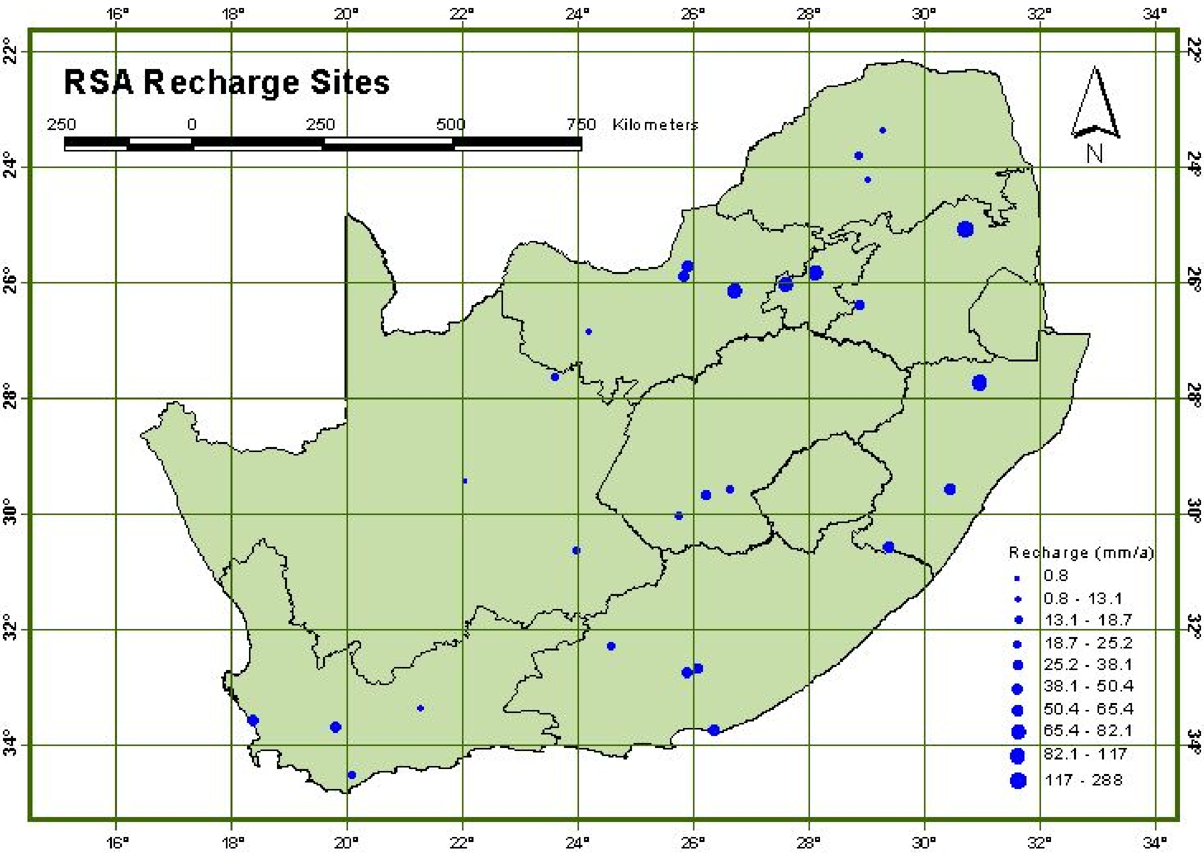

Figure 5.11: Distribution of point recharge values (Source: Vegter, 1995)

6. METHDOLOGY

6.1 Overview

Using the simplified CMB method as proposed by Bean (2003), the following equation applies to calculating recharge:

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

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).

In this project, recharge was calculated as a percentage, excluding precipitation, to enable the calculation of recharge depth using various different precipitation grids, monthly or annually. Figure 6.1 gives an overview of the process followed. Each step in the process will be described along with its input and output datasets.

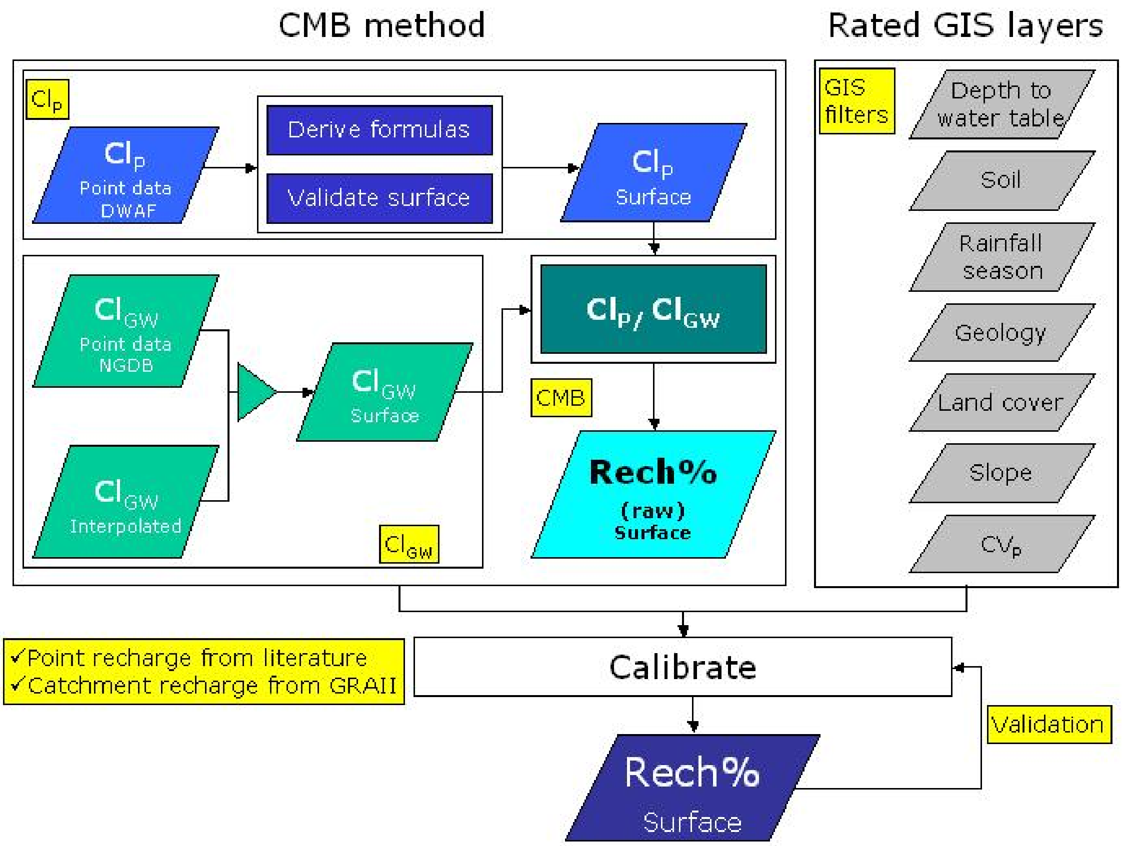

Figure 6.1: Overview of the recharge calculation process used in this project

6.2 CMB method

6.2.1 Cl_p: Chloride in rainfall

Rainfall chloride values were obtained from DWAF, Shafick Adams and the NGDB. Time-series data for 74 stations specifically equipped for Cl_p collection were supplied by DWAF. Table 6.1 outlines the data with its data sources.

Table 6.1: Data sources for rainfall chloride

Data Source	No of data locations	Time-series data from	Location of values	
Adams	18	Adams (one value per point)	Coast	10
			Inland	8
DWAF	74	DWAF	Coast	44
			GW	5
			Inland	151
		NGDB (one value per point)	Coast	5
			Inland	2

Significant spatial and temporal variations have been observed in Cl_p concentrations during other studies (Beekman *et al*., 1997; Beekman and Sungaro, 2000). According to Bean (2003), "it is the observed partitioning of

precipitation chloride concentration data that is of importance from a recharge estimation perspective". In his case studies at Bloemfontein and Hotazel (Table 6.2), Bean (2003) suggested that values > 5mg/L represent site-specific enrichment within the given sampling period and would result in an over-estimation of recharge (Bean, 2003).

Bean (2003) suggests that concentrations with values ≤ 5 mg/L represent background conditions, as also assumed by Beekman *et al*. (1997).

This principal (excluding values 5 mg/L) was applied to data for stations found inland (i.e. not within the defined coast). For the coast, all values were considered since very high values have been reported, e.g. 26 at Struisbaai by Weaver & Talma (2002). Five stations (DWAF) appeared to have excessively high values for rainfall chloride (varying between 80 and 1885). These values were not considered in the analysis, the assumption being that these values were more in line with groundwater chloride values. Data from Adams without directly reported coordinates, were not used to derive the equations, but were used later for the validation of the final rainfall chloride surface. Coordinates from the nearest town were taken. Seventy-nine rainfall chloride locations (16 from Adams, 63 from DWAF) were selected for processing and are indicated on the map (Figure 6.2).

Table 6.2: Chloride concentration of precipitation, and rainfall at sites in Bloemfontein and Hotazel for the period 2002-2003. (Source: Bean, 2003)

Month	**Bloemfontein**		**Hotazel**	
	Rainfall	**Chloride**	**Rainfall**	**Chloride**
February	36.1	0.80	70.0	1.72
March	51.0	0.53	80.0	3.55
April	40.4	1.23	29.5	12.22
May	31.0	0.49	42.5	16.26
June	6.0	0.58	14.0	2.21
July	0.0	0.00	0.0	0.00
August	99.0	0.49	30.0	1.98
September	10.0	3.12	6.0	19.78
October	35.5	10.22	8.0	12.76
November	20.0	10.37	27.5	11.63
December	98.1	0.24	92.5	1.97
January	50.0	0.22	19.0	29.23
Total rainfall (mm)	477.1		419.0	
Weighted average - All data	1.7		6.7	
Weighted average <5mg/L	0.6		2.4	

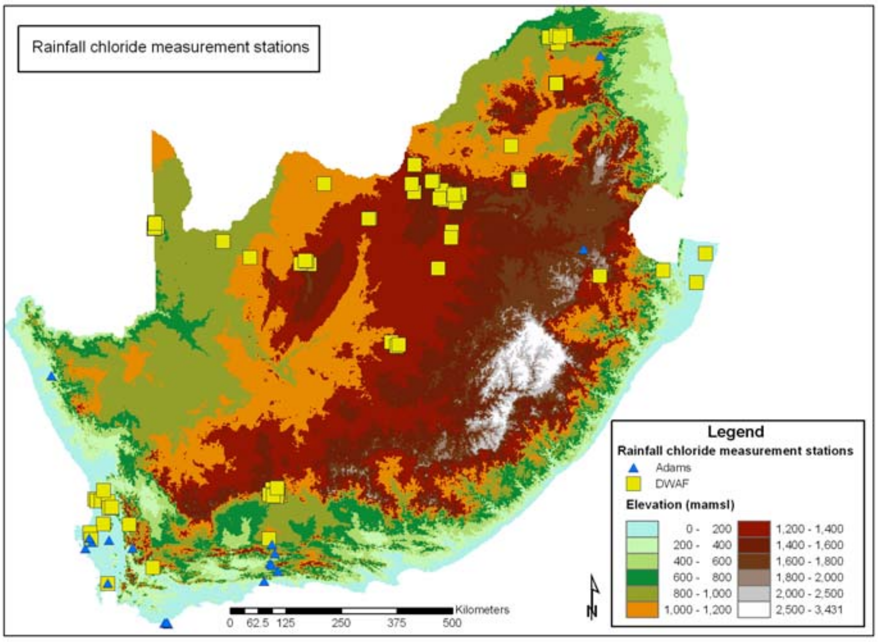

Figure 6.2: Location of rainfall chloride collection stations

These data, in combination with the following input data sets, were used to derive equations for chloride in rainfall (Cl_p) as done by Adams (2004).

- Mean Annual Precipitation
- Elevation
- Distance to coast

6.2.1.1 *Mean Annual Precipitation*

Precipitation was calculated from the MAP grid (Figure 6.3) produced by Schulze (1997) and worked to a 1 X 1 km grid.

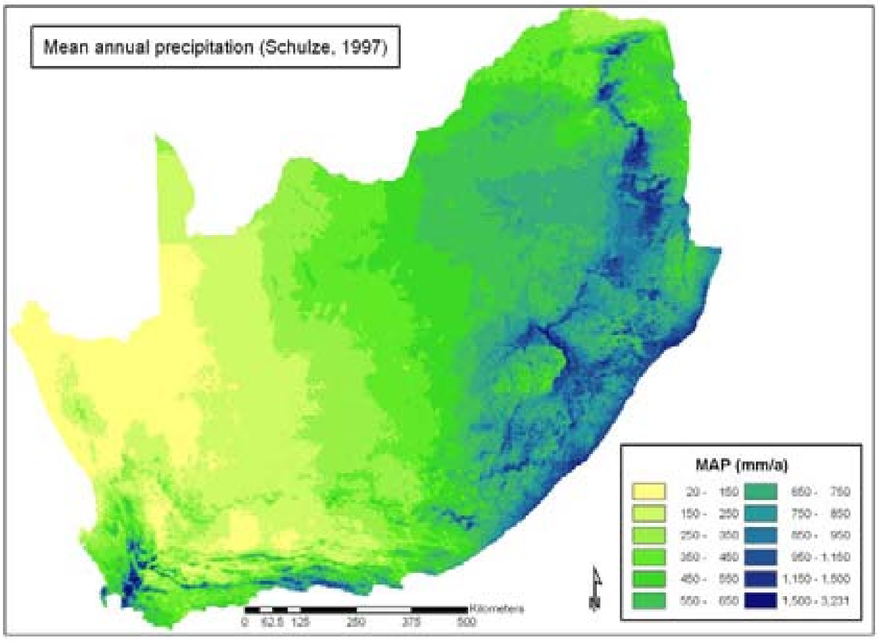

Figure 6.3: Mean Annual Precipitation (Schulze, 1997)

6.2.1.2 *Elevation*

The 20m DTM was obtained from DWAF and reworked to a 1 X 1 km grid (Figure 6.4). With the jagged coastline, areas less than half of the $1km^2$ grid cell were not included. The processed data was extended to cover the outline by extracting information from the original DTM.

6.2.1.3 *Distance to coast*

For the centre point of each $1km^2$ cell in the RSA grid, the Euclidian distance to the coast was calculated (Figure 6.5).

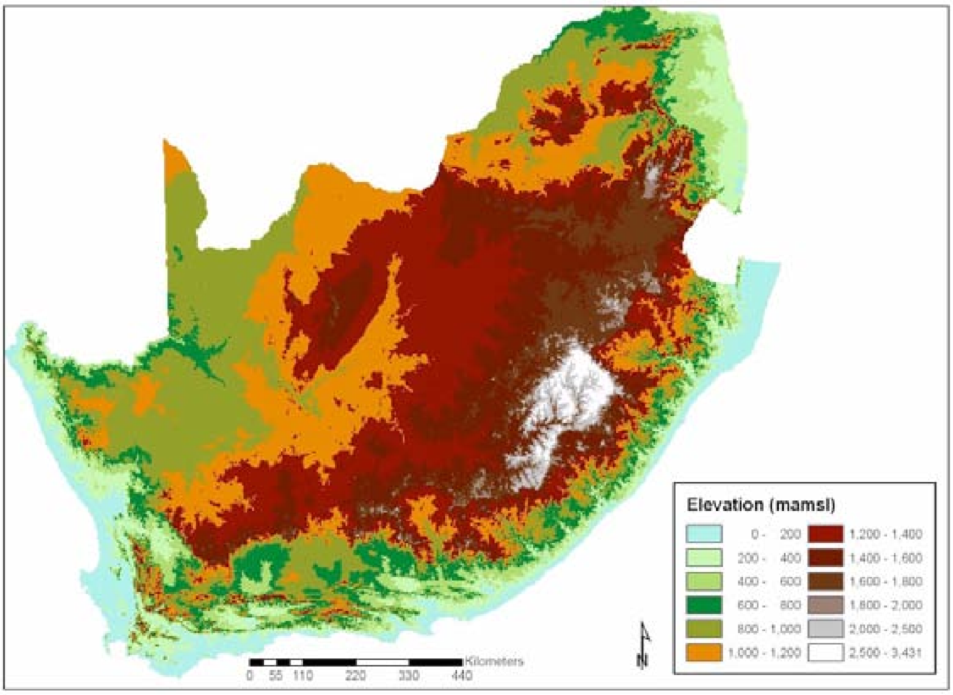

Figure 6.4: The DWAF DTM reworked to 1km^2 grid

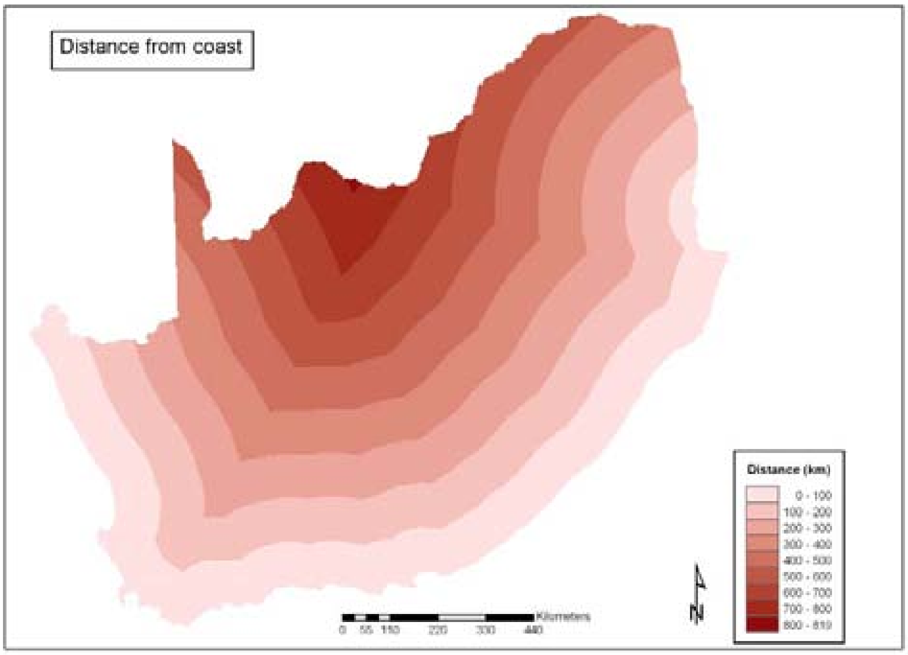

Figure 6.5: Distance to the coast

6.2.1.4 *Defining the coast*

Adams (2004) described a process of deriving rainfall chloride values for the coastal regions within 100km of the sea. Using a GIS terrain-modelling approach, the Topographic Position Index (TPI) was defined as seen in Figure 6.6. Valid values for TPI can be found in Table 6.3. Upper slopes and ridges were used to delineate the coast.

Table 6.3: Topographic Positional Index values

Relative slope position	TPI value
Upper slopes	1
Ridges	2
Mid-slopes	3
Foot slopes	4
Valleys / Flat areas	5

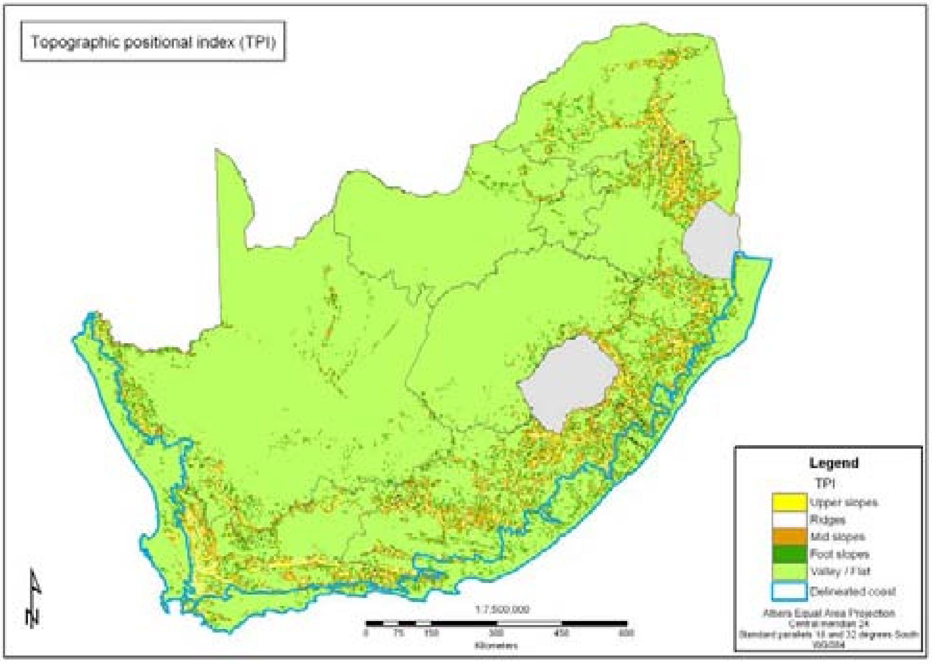

Figure 6.6: The topographic positional index used to delineate the coast

Cut-off values were implemented. The highest empirical value determined in RSA, was 26 at Struisbaai by Weaver and Talma (2002). So a value of 30 for the coast was regarded as a suitable cut-off (Beekman, pers comm.). Highest recorded value from DWAF stations was 31 mg/L. A low value of 0.2 mg/L was implemented since it was the lowest measured value for chloride in rainfall obtained from DWAF. For inland rainfall chloride, Beekman (pers comm.) suggested a high of 1.5 mg/L as cut-off value. Table 6.4 describes the equations, R^2 values and cut-off values implemented. For each of the elements a grid was calculated in ArcView 3.2 using the input dataset and the derived equation. The coast was treated separately from inland.

Table 6.4: Equations used to derive chloride in rainfall values for the country

Input dataset (x in equation)	Equations	R^2	Output grid values	Comments
COAST				
MAP (Schulze, 1997)	$Cl_p = -5.9079Ln(x) + 42.056$	0.724	-3.983 – 24.358	Cl_p<0 ----> 0.01
Elevation (DWAF DTM)	$Cl_p = -3.158Ln(x) + 24.693$	0.5338	0.681 – 53.779	Cl_p>30 ----> 30
Distance to coast	$Cl_p = 20.223e^{-0.046x}$	0.6598	0.038 – 20.223	Cl_p<0.2 ----> 0.2
INLAND				
MAP (Schulze, 1997)	$Cl_p = 1.4322e^{-0.0017x}$	0.2689	0.006 – 1.384	Cl_p<0.2 ----> 0.2
Elevation (DWAF DTM)	$Cl_p = 2.1677e^{-0.001x}$	0.2637	0.07 – 2.108	Cl_p<0.2 ----> 0.2 Cl_p>30 ----> 30

The three coastal grids were summed and the mean value calculated (Output grid values were 0.577 – 23.829). The two inland grids were summed and the mean value calculated (Output grid values: 0.2 – 1.442). The resultant coastal and inland grids were combined to create the final Cl_p grid. Values ranged from 0.2 – 23.829. The Cl_p grid was smoothed using a 5X5 circular filter calculating the mean (Values 0.205 – 18.838). This Cl_p grid was validated against the chloride in rainfall values supplied by DWAF. The correlation obtained (R^2 =0.7867) is shown in Figure 6.7. The smoothed grid was calibrated using the formula y= 1.3412x - 0.082 (R^2=0.7867). The range of values obtained were 0.192 – 25.183 (Figure 6.8).

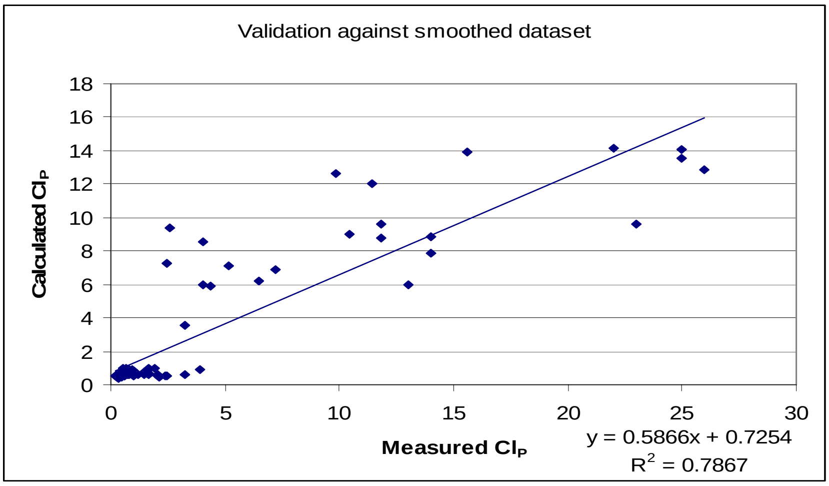

Figure 6.7: Correlation between measured and calculated rainfall chloride

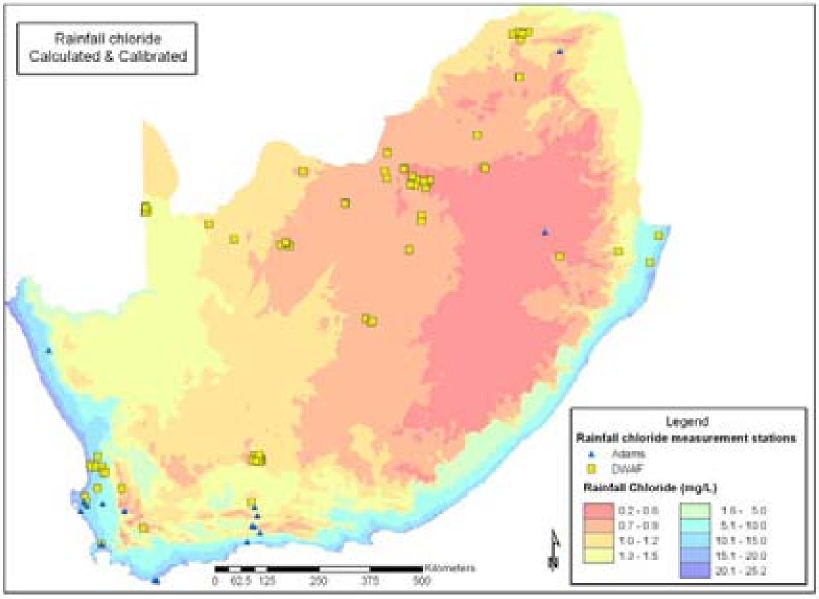

Figure 6.8: Rainfall chloride

6.2.2 Cl_{gw}: Chloride in groundwater

The NGDB was trawled for all available chloride values. ZQM monitoring data was obtained from DWAF. Many outliers were identified with values varying between 1.5 mg/L and 98 625 mg/L. All values higher than seawater (19 000mg/L) were eliminated. Values then ranged from 1.5 to 18 943.1 mg/L. Other outlier data pre-1980 were also eliminated if the values were greater than 3 Standard Deviations above the mean. Cl_{gw} values for saltpans in the Northern Cape and on the West Coast were left intact.

The harmonic mean of 42 662 data points of time-series data were calculated giving 28 465 locations with chloride values. The harmonic mean for each 1km^2 grid cell in the RSA grid was calculated from these locations giving 21 795 populated cells. These 21 795 groundwater chloride points were interpolated using the Kriging method. A groundwater chloride surface was generated with values ranging from 2.587 to 5 855.737 mg/L. The interpolation technique smoothed the data eliminating very high and very low values for groundwater chloride. For this reason the 21 795 cells with actual groundwater chloride values were superimposed onto the interpolated groundwater chloride surface (values 1.5 – 18 943.1 mg/L) (Figure 6.9).

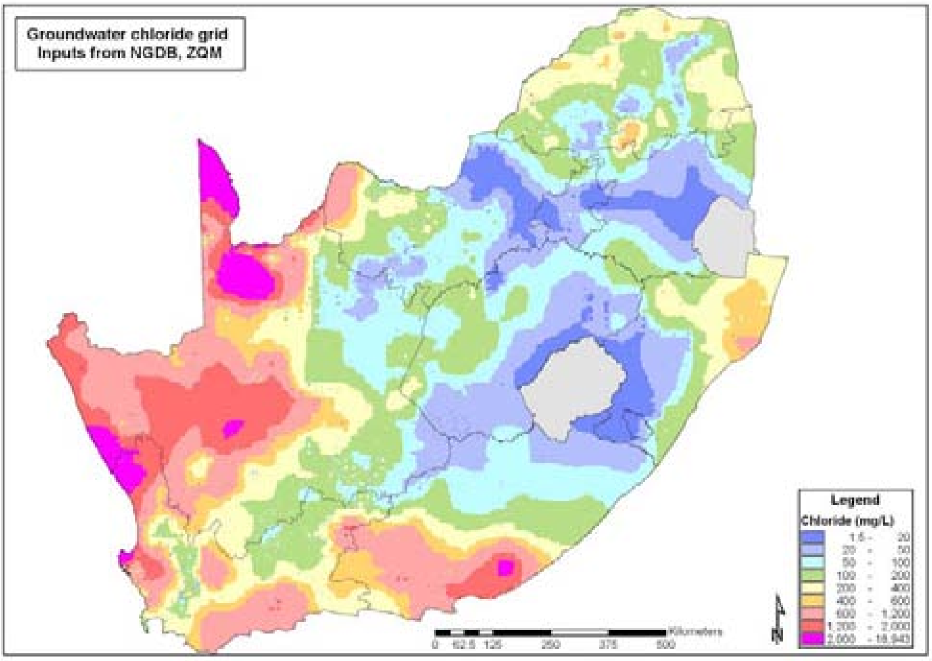

Figure 6.9: Groundwater chloride values

6.2.3 The result of the CMB method

The following equation was used to calculate the recharge percentage:

$$R\% = 100 \times Cl_p / Cl_{gw}$$

The calculation provided values between 0.006 and 79.586%. This raw recharge grid was smoothed with a mean circle with radius 5km giving a recharge percentage surface with values between 0.02 and 21.803% (Figure 6.10).

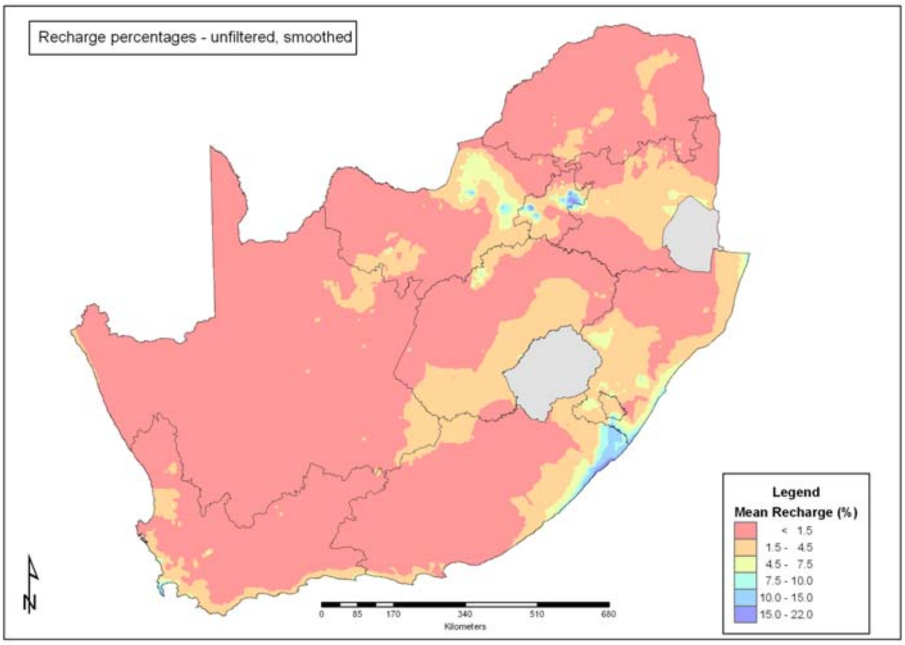

Figure 6.10: Smoothed uncalibrated recharge percentage grid

The correlation of this data set with values from literature was low as seen in Figure 6.11.

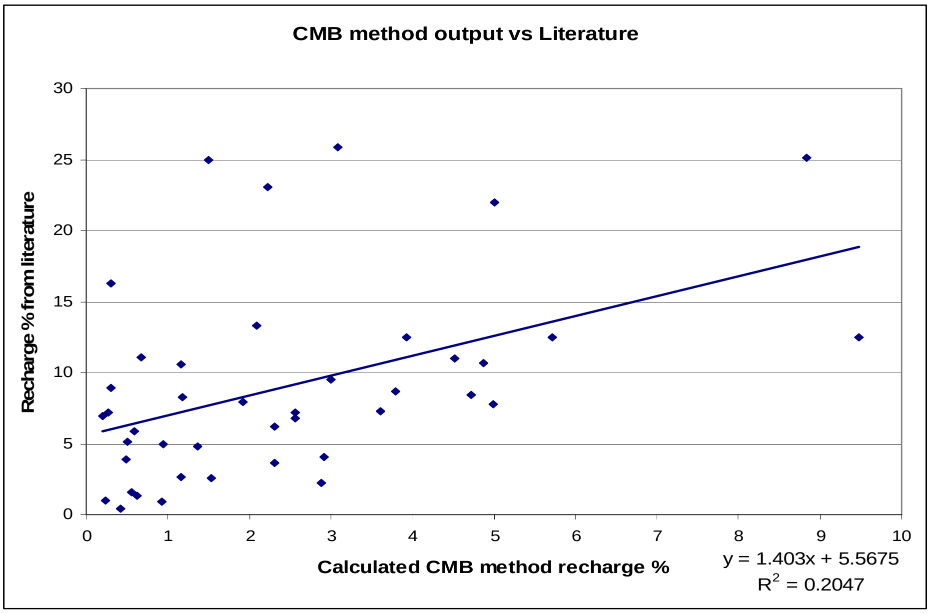

Figure 6.11: Comparing calculated CMB method output to literature

6.3 GIS filters

Several GIS layers were suggested as filters to remove anomalies and introduce local variation. In each case the layer was rated according to recharge probability. These layers include:

- Saturated thickness
- Soil drainage rate
- Rainfall seasonality
- Geology
- Land cover
- Topography as represented by slope
- Coefficient of variation of annual precipitation

6.3.1 Saturated thickness

A total of 126 263 groundwater levels from the NGDB (for 4 280 of these, the mean groundwater level was calculated from time-series data) were interpolated to a groundwater level grid. The resultant grid (Figure 6.12) was reclassified according to Table 6.5, based on the aquifer classification map of South Africa (Parsons & Conrad, 1998):

Table 6.5: Rating the saturated thickness grid

Range (m)	Rating
0 – 2	10
2 – 5	9
5 – 10	7
10 – 17	5
17 – 25	3
25 – 33	2
> 33	1

6.3.2 Soil drainage rates

The drainage rate index from Schulze (1997) was used. The drainage rates, governed by the soil texture of the subsoil, are expressed as fractions of the excess water per day (Schulze, 1997). These fractions, multiplied by 10 to give a value between 0 and 10, can be seen in Figure 6.13.

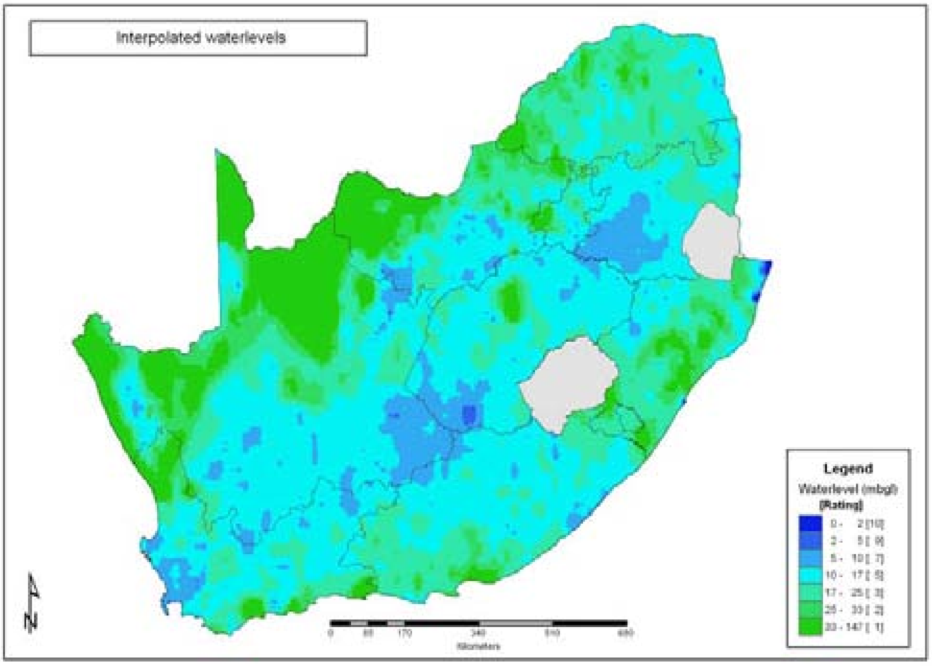

Figure 6.12: Groundwater levels interpolated from NGDB data

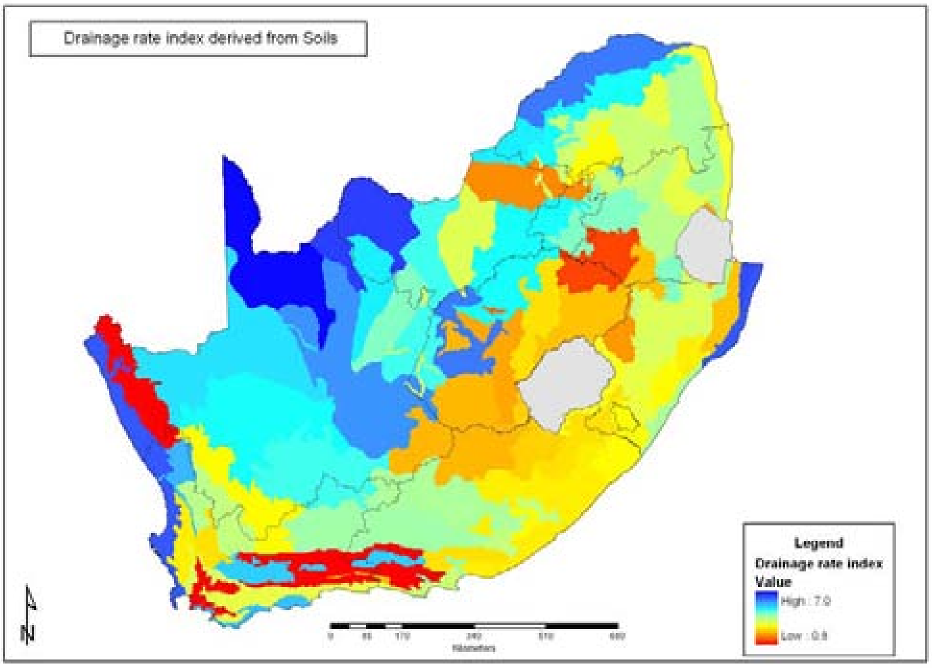

Figure 6.13: Drainage rate index derived from soils

6.3.3 Rainfall seasonality

Rainfall seasons were described by Schulze (1997). These seasons were rated as described in Table 6.6 and shown in Figure 6.14.

Table 6.6: Rating rainfall seasons (from Schulze, 1997)

Description	Value	Rating
All year	1	8
Winter	2	9
December	3	6
January	4	5
February	5	4
March – May	6	7

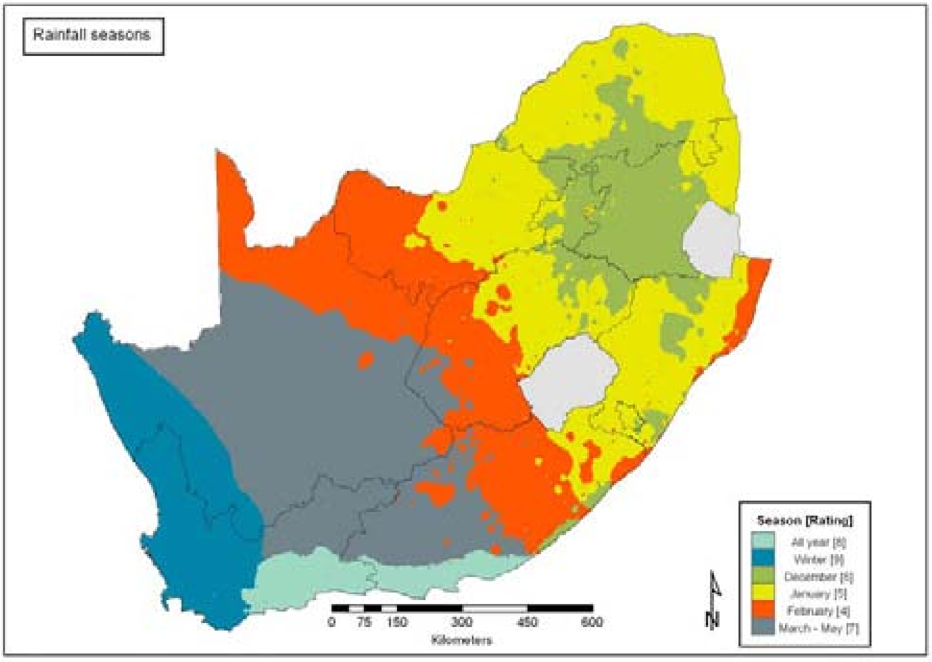

Figure 6.14: Rainfall seasonality

6.3.4 Geology

The 1:1 million geological map produced by the Council for Geoscience was used and rating was done using Chronology, Litho_1, Litho_2 and Litho_3. Three hundred and sixty seven classes were identified. The ratings can be found in Appendix A.1. The rated geological grid is shown in Figure 6.15.

6.3.5 Land cover

The land cover data set was created as part of the National land cover project run by a number of organisations directed by the CSIR. The recharge probabilities were assigned by Conrad (Table 6.7). The rated land cover data set was shown in Figure 6.16.

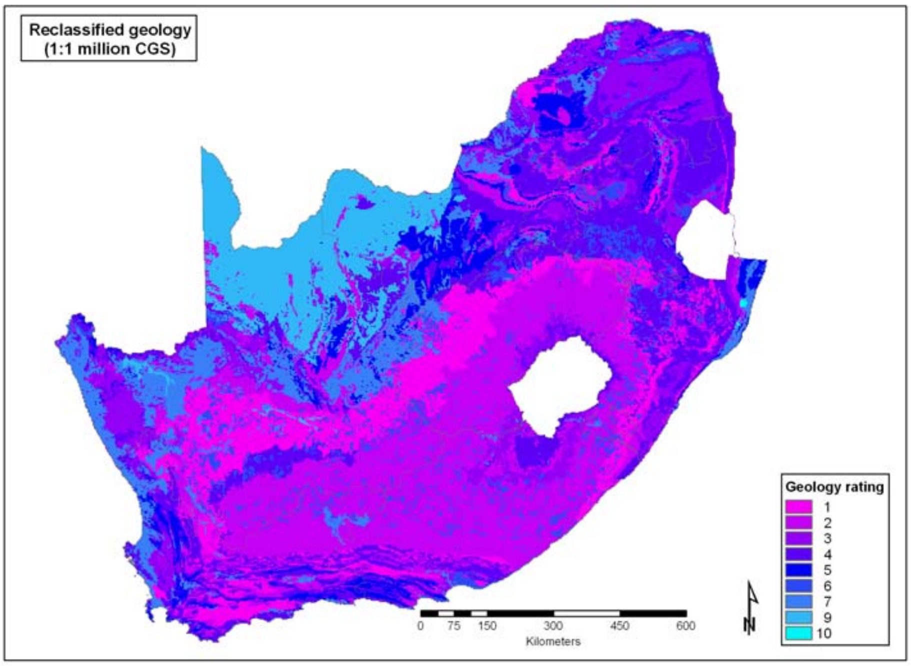

Figure 6.15: Geology rating with regards to recharge (as defined by Conrad, 2004).

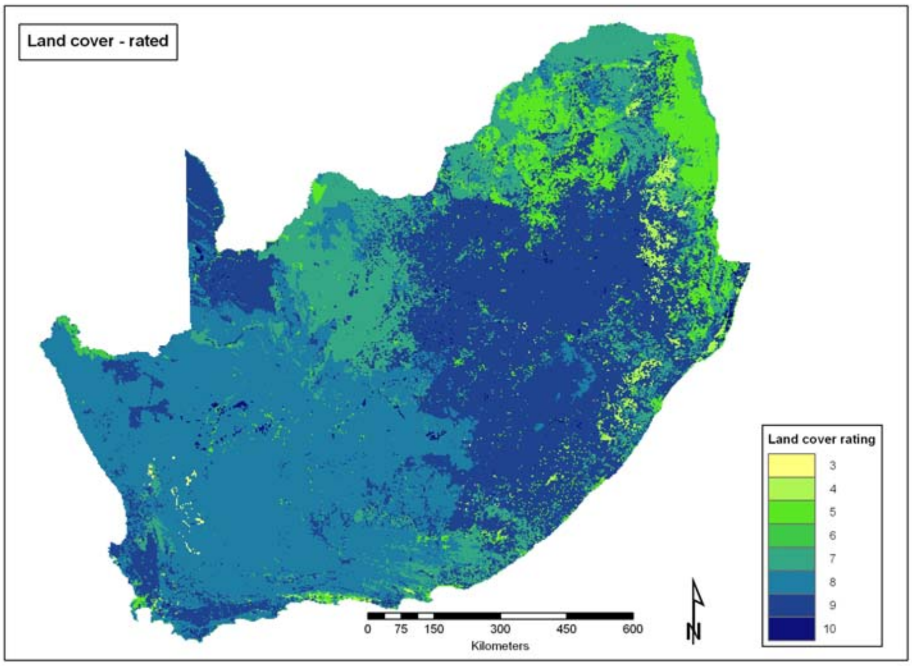

Figure 6.16: Rated land cover dataset

6.3.6 Topography as represented by slope

Slope was calculated from the 20m DTM obtained from DWAF. The percentage slope (Figure 6.17) was rated (Table 6.8) according to the ratings assigned in the aquifer vulnerability classification for South Africa carried out by Parsons & Conrad (1998).

Table 6.7: Recharge ratings per land cover class description

Description	Rech_Prob
Barren rock	5
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	3
Forest	5
Forest and Woodland	5
Forest plantations	4
Herbland	6
Improved grassland	8
Mines & quarries	8
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 6.8: Recharge ratings per slope (%)

Slope(%)	Rating
0 - 2	10
2 - 6	9
6 -12	5
12 -18	3
>18	1

6.3.7 Coefficient of variation of annual precipitation

This layer was added to improve the quality of the calibration. Coefficient of variation of annual precipitation was obtained from Schulze (1997), and rated into 10 classes (Figure 6.18); a lower percentage CV was given a higher recharge rating.

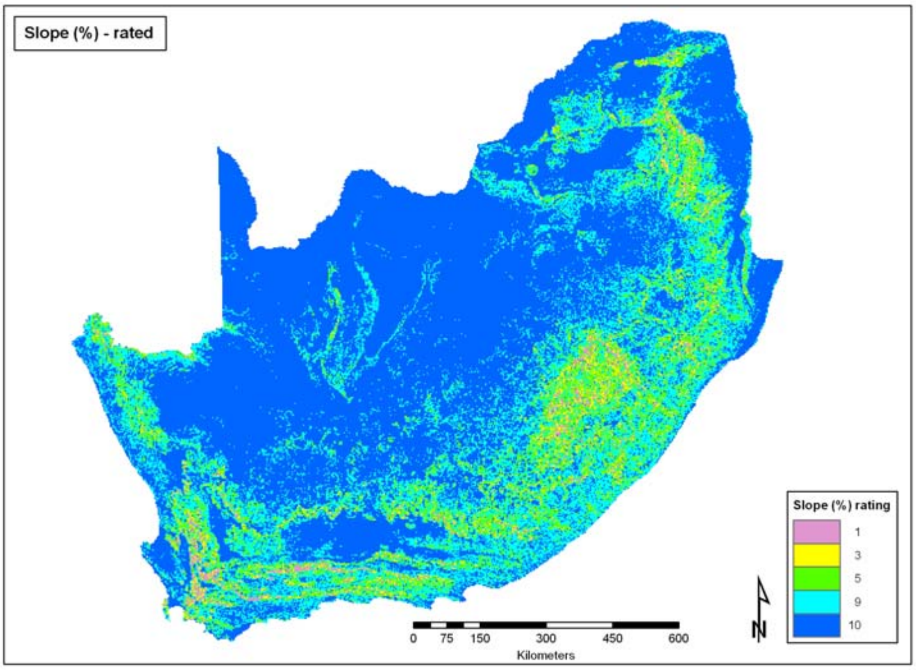

Figure 6.17: Slope (%) rated

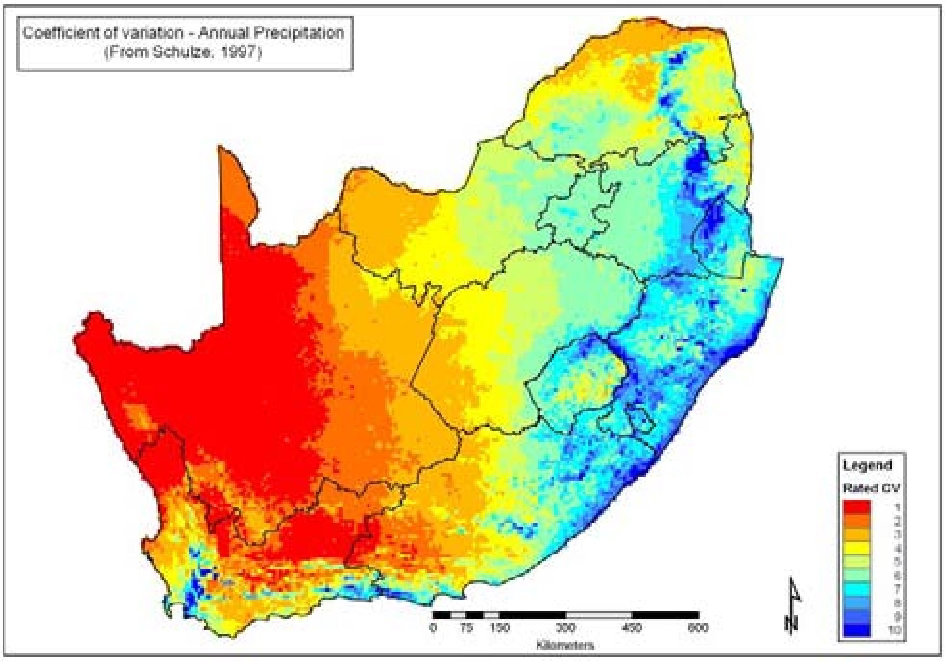

Figure 6.18: Recharge rated coefficient of variation of annual precipitation

6.4 Filter and calibrate

6.4.1 GIS filtering

The CMB calculated recharge grid was filtered using the various GIS layers described previously. As suggested by Bean (pers comm.), saturated thickness (mean groundwater level (mbgl)); soil drainage as described by Schulze (1997); and rainfall seasons were used. Geology and land cover (rated by Conrad) as well as topography and coefficient of variation of annual precipitation were added as filter layers.

Recharge values from the literature were supplied by Alan Woodford (Table A.2). Using multiple regression, the CMB output and GIS filter layers were calibrated against known recharge points only where recharge had been calculated by the CMB method (42 points). The coefficients for the regression equation are given in Table 6.9. The R^2 was 0.4519.

Table 6.9: Coefficients for regression equation

Layer	Coefficient
Intercept	-7.97225
Recharge (calculated)	1.013994
Land cover	0.194155
Geology	0.291186
Saturated thickness	0.853438
Soil drainage rates	1.287624
Rainfall seasonality	0.40496
Topography	-0.76121
CV of annual precipitation	1.500128

The relationship of CMB calculated recharge after being calibrated with the GIS filter layers with point recharge values from literature is given in Figure 6.19.

The final recharge grid was smoothed using a 5km circular function. Values for the calibrated recharge percentage grid were in the range –4.056 – 31.828. Values less than 0.01 were set to 0.01 and the grid was clipped to RSA boundaries (Figure 6.20). The total recharge volume per quaternary catchment was calculated using mean annual precipitation (Schulze, 1997) and summed for the country. A value of 52.7 kMm^3 was calculated which equates to a mean recharge of 9% over the whole country. This appears to be higher than expected, due to the low number of calibration input data points (42).

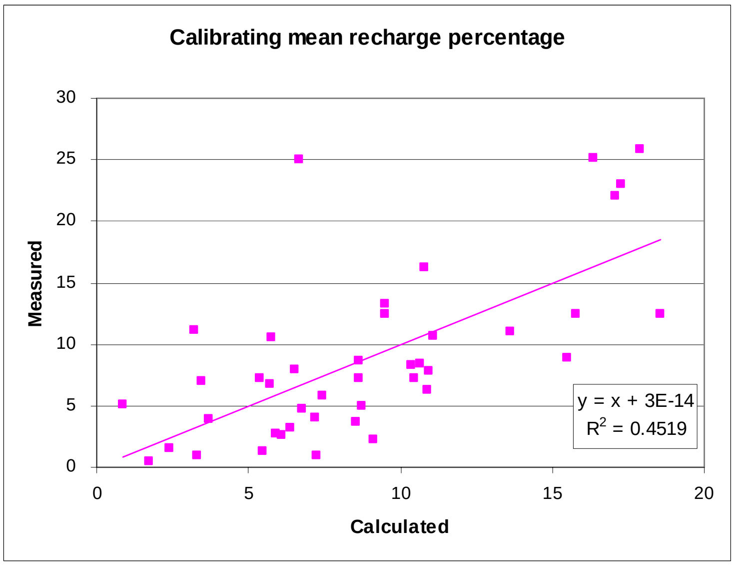

Figure 6.19: GIS-filtered recharge % vs. recharge values from literature

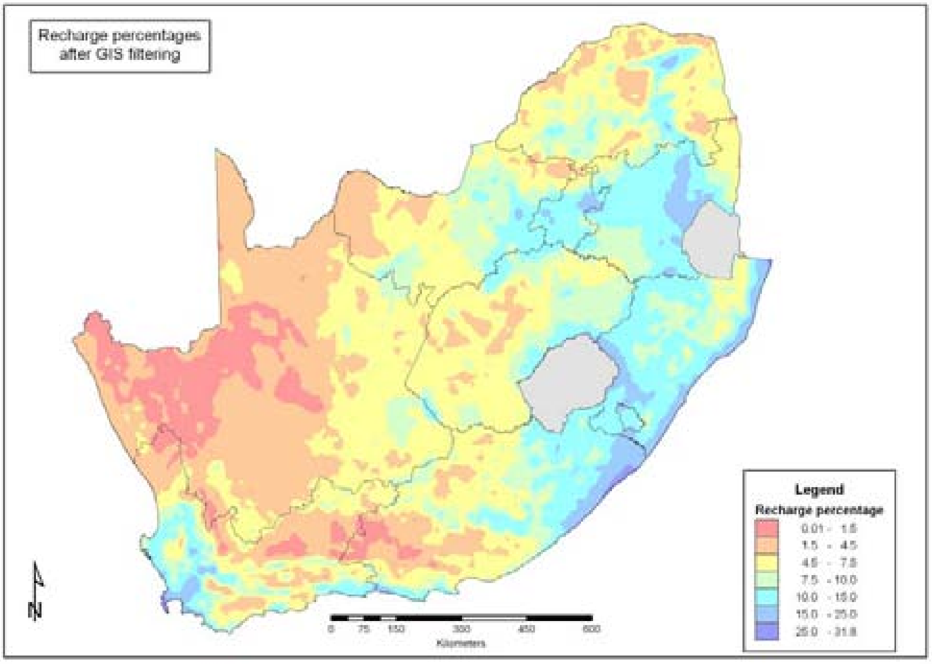

Figure 6.20: Filtered recharge percentage grid

Values per quaternary catchment were available from the GRAII GW/SW interaction project, but were unsuitable to use in the GIS linear regression calibration process, since the seven filter parameters described in the GIS filtering process would have to be smoothed per catchment, reducing their specificity. The further calibration required for the GIS filtered recharge grid was done using the available set of values per quaternary catchment.

6.4.2 Calibrating with regression output from GRAII GW/SW interaction

Recharge values per quaternary catchment were modelled as part of the GRAII GW/SW interaction project. A relationship was established between rainfall and

recharge values for all quaternary catchments-were derived from this equation (Figure 21).

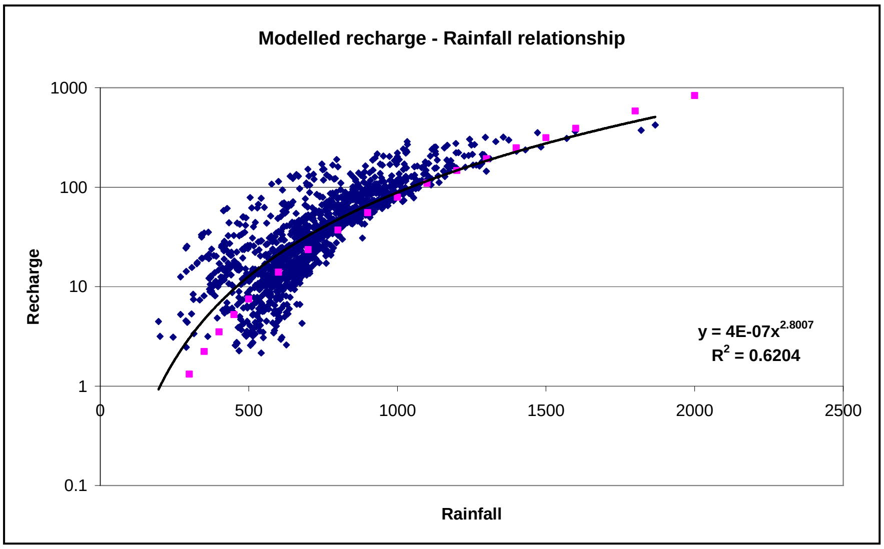

Figure 6.21: Rainfall-recharge relationship from GW/SW interaction

When comparing the GIS-filtered recharge grid (57kMm^3) summarized per catchment with the GW/SW interaction values, the correlation found in Figure 6.22 was obtained. The R^2 value of 0.6947 was most promising.

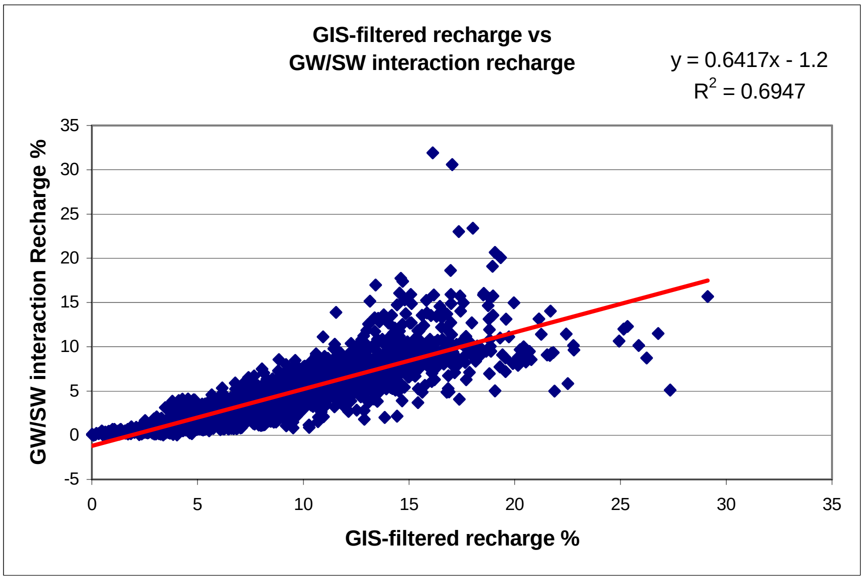

Figure 6.22: GIS-filtered recharge per catchment correlated with recharge from GW/SW interaction

The correlation equation was applied to the GIS-filtered recharge grid. Values ranging between -1.193583 and 19.223885 were obtained. Negative values were set to 0.00001. The resultant recharge percentage grid can be found in Figure 6.23.

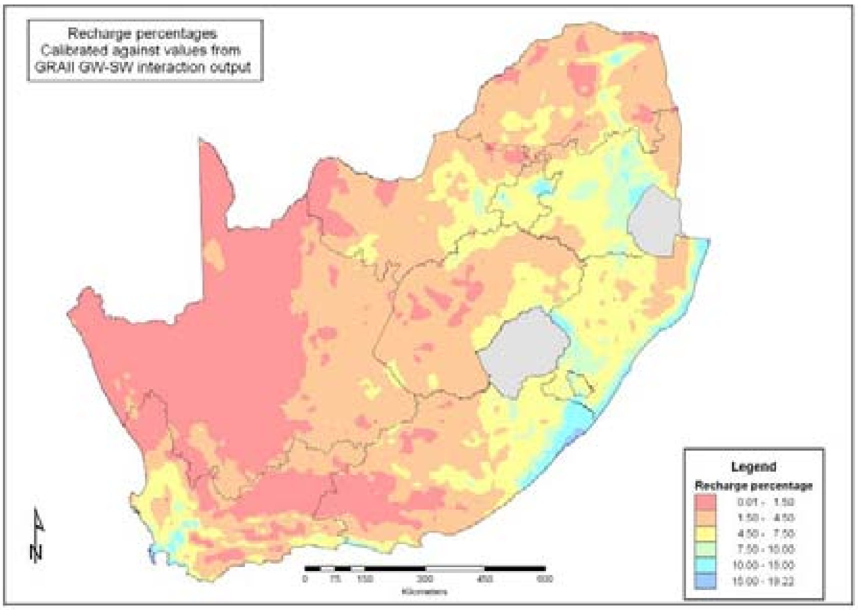

Figure 6.23: Calibrated GIS-filtered recharge percentage grid

Summarizing the recharge percentage grid per quaternary catchment, thereby obtaining a mean value per catchment, with WR90 MAP values for rainfall per catchment, a volume of 27.2396 kMm^3 was calculated for the 1946 catchments (See Table A.3).

6.4.3 Adjusting to minimum baseflow per catchment

Upon examination of the volumes per catchment, it was found that in certain catchments, the volume of recharge was less than the baseflow calculated during the GRAII GW/SW interaction project. It was suggested that the recharge per catchment be adjusted upward to match baseflow (G. van Tonder, pers. comm.). The problem arose that a mean value per catchment would be derived for certain catchments and the spatial variation represented by the 1km^2 grid would be lost. The upward adjustment for 413 catchments was applied to the recharge percentage grid. The adjusted recharge grid computes to a volume of 30.5187 kMm^3 (Figure 6.24). Values for the recharge percentage grid range from 0.0001 to 35.6947. Values for the recharge depth grid, created as the product of the mean annual precipitation grid (Schulze, 1998), range between 0.000002 and 810.521 mm/a with a mean value of 24.006mm/a. Correlating the values obtained in the adjusted recharge grid with the regression output from the GRAII GW/SW interaction project, a R^2 value of 0.7039 was obtained (Figure 6.25).

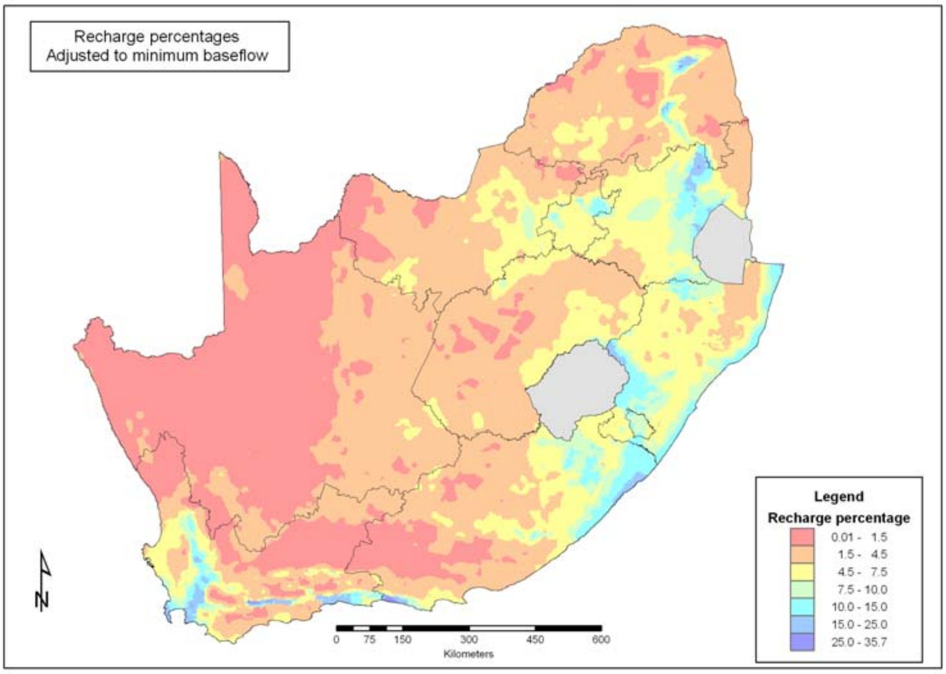

Figure 6.24: Recharge percentage grid adjusted for minimum baseflow per catchment

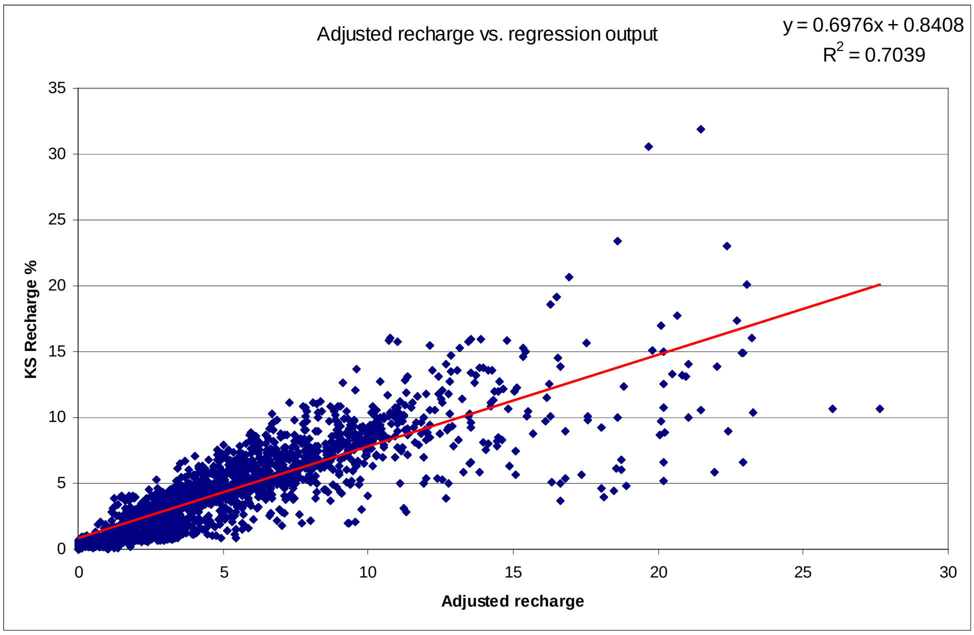

Figure 6.25: Adjusted recharge percentage grid correlated with GW/SW interaction output

The values of the adjusted recharge percentage grid were also compared to the 42 points from literature obtained via the CMB method. In Figure 6.26 the correlation is displayed graphically with an R^2 value of 0.5676. Figure 6.27 depicts the recharge depth grid obtained using this calibration.

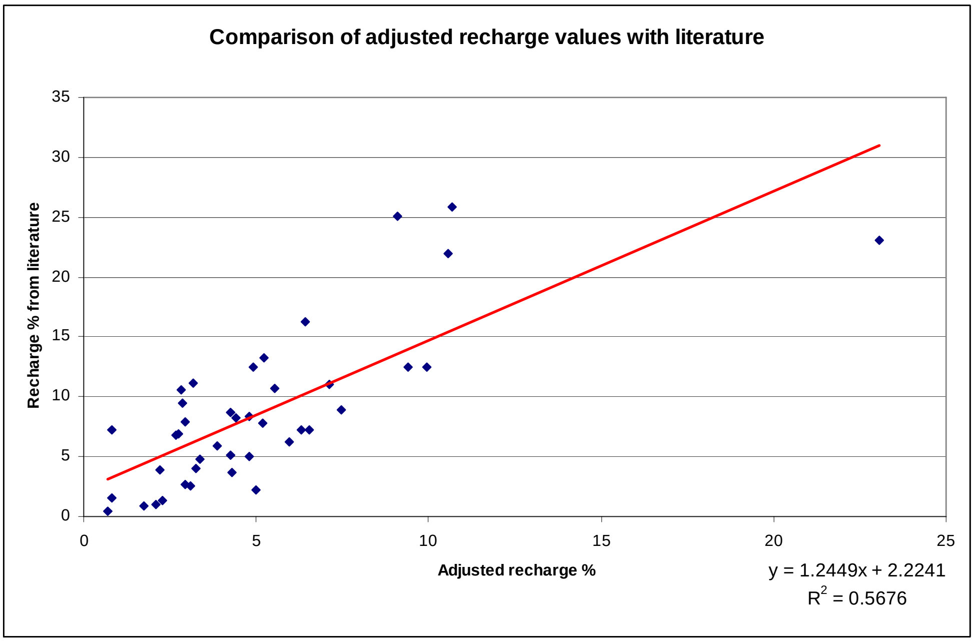

Figure 6.26: Adjusted recharge percentage grid correlated with values from literature

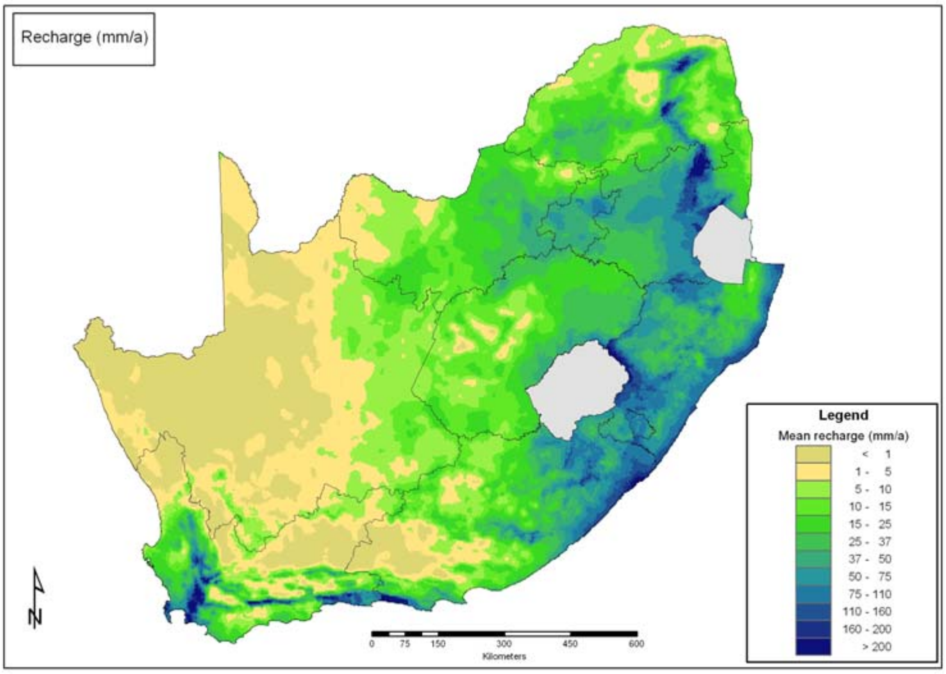

Figure 6.27: Adjusted recharge depth grid

6.5 Validation

The recharge volumes from recharge grids derived via various methods were compared. The various recharge grids were summarised for the 1946 quaternary catchments in the WR90 dataset. If recharge depth was not given, the recharge was quantified using the WR90 MAP as rainfall input.

The SRECH dataset of Vegter (1995) was extrapolated over Swaziland and then converted to a grid. The recharge depth was summarised per quaternary catchment and total volumes calculated.

Total rainfall was computed using the WR90 MAP (mean annual precipitation). The comparison can be found in Table 6.10.

Table 6.10: Comparison of rainfall volumes with recharge volumes using different calibration methods

Recharge	Recharge (km^3/a)		
	Mean	Min	Max
GIS filtered recharge grid	52.75 9.0%	41.30 7.1%	66.53 11.4%
GIS recharge grid calibrated with GRAII GW-SW output (unmodified)	27.24 4.7%	20.03 3.4%	36.12 6.2%
Adjusted recharge grid	30.52 5.2%	22.55 3.9%	40.55 6.9%
Recharge according to Vegter (1995)	33.82 5.8%	27.39 4.7%	42.88 7.3%
Rainfall volume (WR90)	**585.46 km^3/a**		

The values found in the adjusted recharge grid were also correlated with the values obtained by Vegter (1995). The comparison can be seen in Figure 6.28. The R^2 for the correlation is 0.6651.

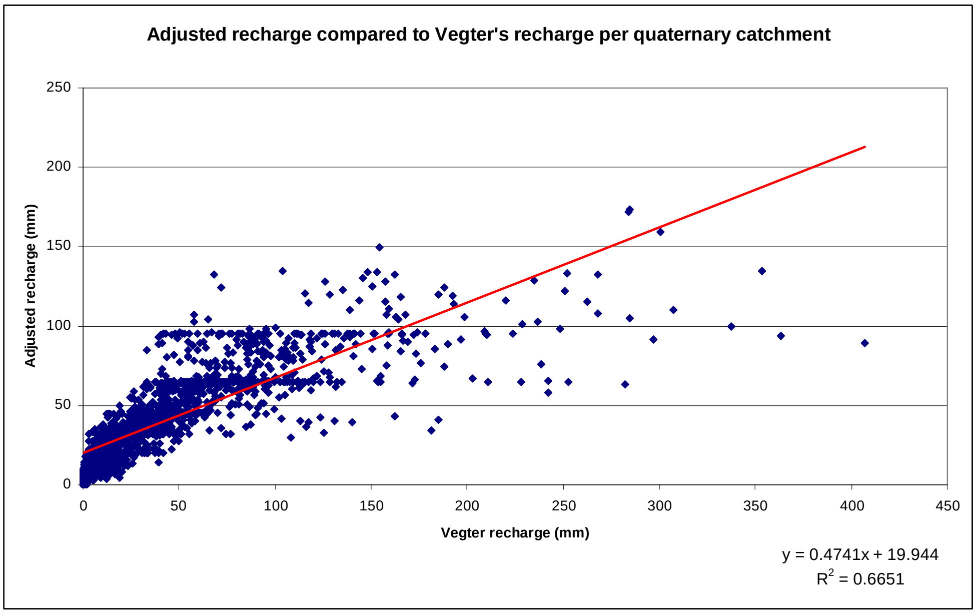

Figure 6.28: Adjusted recharge depth grid correlated with Vegter's recharge

7. RECHARGE THRESHOLD VALUES

7.1 Introduction

This chapter describes the groundwater recharge threshold values calculated per quaternary catchment.

7.2 Background

This chapter addresses the issue of "Recharge Threshold Value" (RTV). This is the value, which relates to precipitation and indicates a cut-off or threshold value, below which no direct groundwater recharge is likely to occur. In other words, the RTV is the minimum amount of rainfall required to initiate recharge. A low RTV means that recharge occurs rapidly in most years, and is associated with the wetter temperate areas. A high RTV indicates longer periods of no recharge, with associated lower and more variable rainfall patterns. If precipitation does not meet the RTV in a catchment, then necessary steps and precautionary measures will have to be taken to ensure groundwater depletion or "mining" does not occur, assuming groundwater abstraction is occurring. Or, if mining is occurring, then it is done on a managed basis.

It is important to stress that the RTV is a generalized and approximate figure, with large embedded uncertainty. This is due to the inability to quantify, both on a temporal and spatial scale, the many factors that influence the RTV. These factors include the rainfall season and characteristics, the climate conditions, the geomorphological and soil characteristics, the hydrogeological parameters, and antecedent soil moisture conditions. The algorithm used in this national scale project should optimally include hourly rainfall data in close proximity to hourly measured groundwater levels. However, we do not have hourly rainfall and groundwater level data for each and every quaternary catchment across the country. Thus a modelled approach is adopted in this project. However, for a more detailed, small area study such detailed data is most relevant.

There have been a few references to RTV in the literature and the most comprehensive review of RTV is by Bean (2003). Prior to discussing the results Bean obtained, Bredenkamp *et al* (1995) commented that chloride profiles indicated that regional recharge falls into two categories, namely:

- Areas where recharge occurs regularly
- Areas of sporadic recharge in the interior parts of the country, where recharge only occurs if the average annual rainfall exceeds a threshold value of about 290 mm (and average annual rainfall does not exceed 600 mm per annum).

It is reasonable to expect the RTV to be lower and for recharge to occur more quickly, if recharge water enters aquifers via preferential pathways as opposed to the matrix. Bean (2003) confirms, using isotopic data, that preferential flow path and matrix derived recharge does differ. Thus, RTVs can be sub-divided into the following components:

RTV_{ave}: Average threshold to be exceeded before recharge occurs.

RTV_{pp} Threshold to be exceeded before preferential flow recharge occurs.

RTV_{mat}: Threshold to be exceeded before matrix recharge occurs.

Detailed analysis is required to differentiate between matrix and preferential flow path recharge and such detail is not possible to obtain for this project.

From case studies carried out by Bean (2003), he suggests an annual RTV of:

- 150 mm for the Hotazel area,
- 150 mm for the Petrusburg area,
    - RTV_{pp} being 15 mm
    - RTV_{mat} being 200 mm
- Not given for Kriel, however the following is noted:
    - RTV_{pp} of 60 mm
    - RTV_{mat} being 135 mm.

In De Aar, Vegter (1992) compared daily rainfall information with water level fluctuations and found that recharge occurred only when daily rainfall exceeded 15mm.

7.3 Methodololgy

If time series data of rainfall and groundwater level fluctuations can be obtained in close proximity, then an analysis of these data can be carried out. Ideally these data need to be collected on a daily basis. The results of the analysis will provide an RTV for an individual rainfall event. The Cumulative Rainfall Departure (CRD) method is a good analytical method if the above-mentioned data (including the specific yield of an aquifer) are known.

Bean (2003) mentions that recent work undertaken in semi-arid Central Australia by Harrington *et al*., (2002), suggests that the recharge threshold can be predicted through an understanding of stable isotopes abundances in rainfall and groundwater. Bean (2003) developed a new stable isotope-based technique, called the Modified Amount Effect (MAE) Method. This technique provides insight into episodic recharge processes by estimating the proportion of preferential pathway-to-matrix-derived flow entering an aquifer, and the amount of rainfall required to initiate recharge via the respective flow paths. Significantly, the proportion of bypass flow can be determined without undertaking expensive and time consuming unsaturated zone studies, both factors often of primary concern when undertaking recharge investigations in developing countries.

Bean (2003) states that four recharge thresholds can be identified using the MAE Method; the low and high recharge thresholds that must be exceeded before recharge occurs via preferential pathways or the matrix, respectively. These represent threshold limits, the low value only of importance following successive months of wet weather, the high value representing the rainfall that must be received to restore an aquifer system to equilibrium after prolonged dry spells. Once these thresholds are known, the recharge history of a site can be modelled using available rainfall data by adapting the Cumulative Rainfall Departure (CRD) method. An important finding by Bean (2003) is that in those semi-arid to arid areas where most recharge water enters the aquifer via the matrix, the period of time that elapses between successive rainfall events that exceed the matrix recharge threshold often extends to scores of years.

Thus, through an understanding of the episodic nature of recharge in semi-arid and arid areas, and therefore the thresholds that must be exceeded before recharge occurs, geohydrologists are better able to provide scenarios of recharge status.

In terms of aquifer management, it is therefore important to know whether the suggested recharge is actually occurring, and if so, the recharge threshold, particularly in semi-arid and arid environments where recharge is episodic in character. In the absence of long-term site rainfall or water level data, an understanding of environmental tracers present in recharge waters can be of some benefit, particularly when investigating aquifers containing young groundwater, and receiving significant recharge (Cook *et al*., 2001)

The limitations of the MAE method, in the context of the GRA II Project, is that the isotope data available are of limited geographic spread, and it will not be valid to extrapolate these point values to a national scale. However, this method does highlight the importance of collecting isotope data for recharge and RTV assessments.

One of the methods considered for this study was to use the generated 1km by 1km gridded recharge values and to compare these to the Mean Annual Precipitation values per quaternary catchment. The method used to obtain these recharge values is contained in Report 3aC. However, this is not a time series based approach, but rather an assessment of these long term values for each quaternary catchment. Included in the recharge values, are factors such as rainfall seasonality. Figure 7.1 shows the results of plotting the data for a particular case-study quaternary catchment (G30F). The x-axis intercept is then considered the RTV for that particular catchment. For catchment G30F, an RTV of 100 mm is obtained. Catchment G30F is considered as it is a catchment currently being studied in detail as part of an RDM project (Nel, 2005 and DWAF, 2004e). Referring to Figure 7.1, the concern is the wide distribution of the data, relating to different geological terrains and rainfall patterns within a catchment and the low correlation coefficient obtained between the rainfall and recharge relationship. For these reasons additional approaches to calculating RTV were considered and adopted.

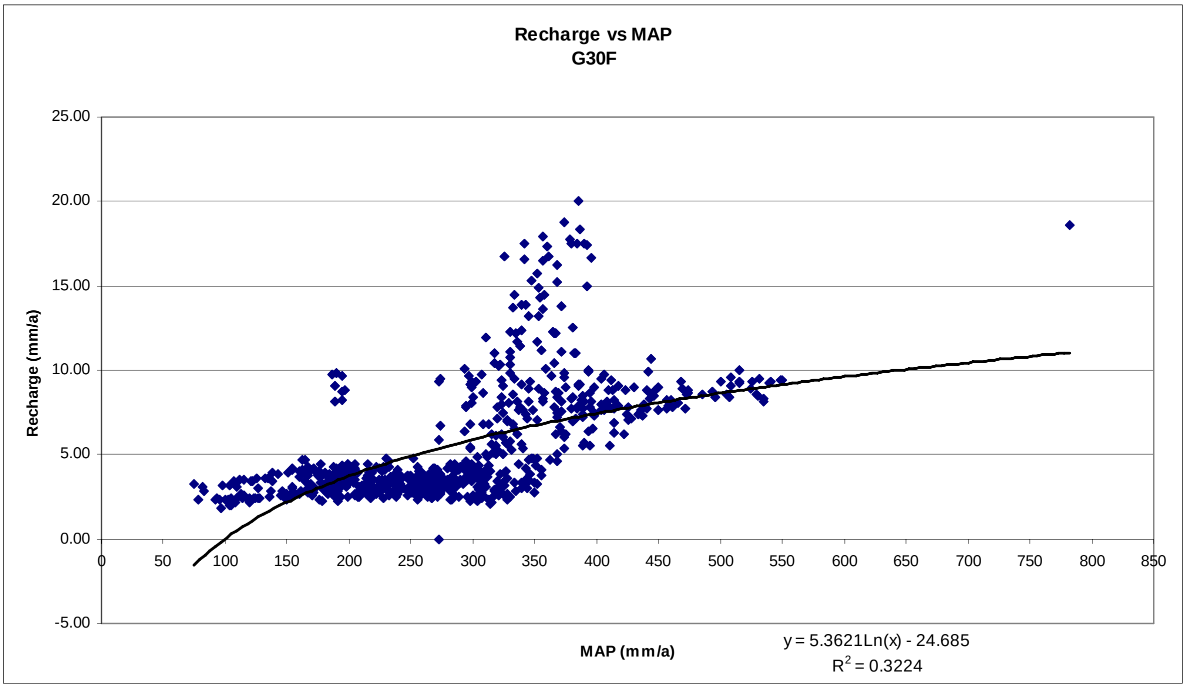

Figure 7.1: Recharge threshold value calculated for G30F

Bean (2003) noted that based on 98 years of rainfall for Petrusburg, the average monthly rainfall is 35.7mm, and importantly this value also represents the long term recharge threshold for an aquifer in equilibrium if seasonal conditions are ignored. In theory therefore, there would be no change in water levels if 35.7mm of rain fell at the site every month. However, in nature this does not occur and prolonged periods of below average rainfall are evident throughout the Petrusburg data set. Thus, in order to restore equilibrium conditions such that the average recharge threshold again decreases to 35.7mm/month, a given catchment must receive above average rainfall. This observation is significant because it indicates that, for a given aquifer in semi-arid and arid areas, multiple thresholds will be represented in site water level data.

Besides the added complexity of suggesting that multiple RTVs exist for a given aquifer, the above suggestion is interesting in that the Mean Annual Precipitation value can possibly be used as an indicator of RTV, assuming the catchment is not stressed and over-exploited. For comparison purposes the example given in Figure 1 indicates an RTV of 100mm and the WR90 data indicates a MAP of 123mm. Thus in the delivery of the final results (Appendix A), the MAP per quaternary catchment is given as well as the monthly RTV. Please note the MAP is an annual value and the RTV given is a monthly value.

Following on from the discussion above it was felt by the project team that another and more accurate approach should be considered in calculating RTV per quaternary catchment. Thus monthly rainfall data was purchased from the Agricultural Research Council for the time period January 2000 to August 2004. This data is provided for the entire country on a 1km by 1 km grid. Based on the modelling carried out to determine groundwater recharge, the rainfall data and groundwater recharge data was then aggregated up to the quaternary catchment scale and compared. The results, plotted on a semi-log graph, of the comparison are shown for a single catchment quaternary catchment in Figure 7.2.

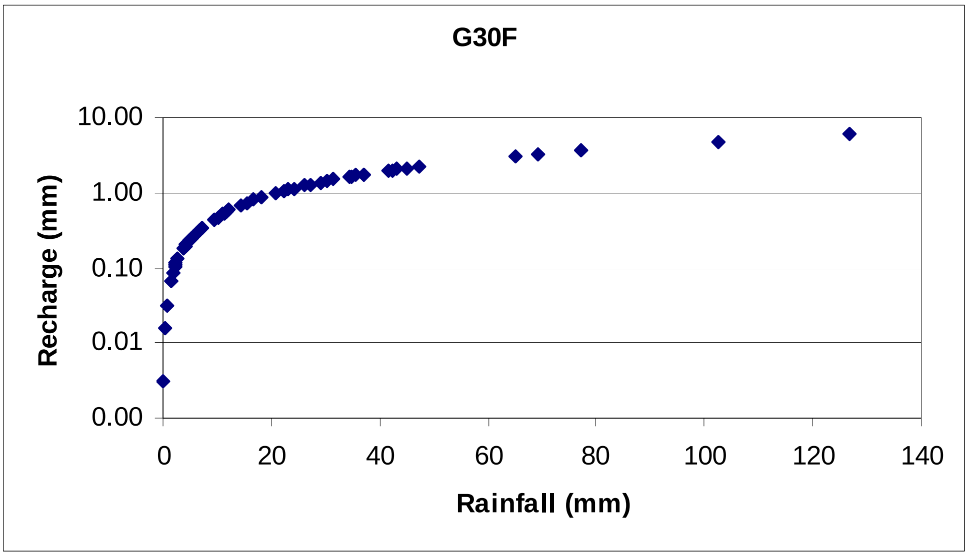

Figure 7.2: A semi-log plot of monthly rainfall versus recharge for catchment G30F, plotted for 56 months

The cumulative distribution of monthly recharge, together with a probability distribution based on a presumed normal distribution, indicating percentage non-exceedence, was then used, at the 98% confidence interval to determine a recharge value (Figure 7.3). This value indicates when recharge is likely to occur (at the 98% level of confidence) and is then related to a monthly rainfall value, which is the threshold value for that particular catchment.

Thus for the example of catchment G30F, a MAP of 285 mm is noted, which can be considered the annual RTV and from the analysis of monthly data a value of 102 mm is obtained, which is considered the monthly RTV. If more than 102 mm falls per month in the rainy season (winter) recharge will most probably occur. If more than 102 mm of rain fell in the summer months (improbable) recharge is still likely not to occur due to the high evapotranspiration rates and soil temperatures. The distribution of rainfall categories is shown in Figure 7.4.

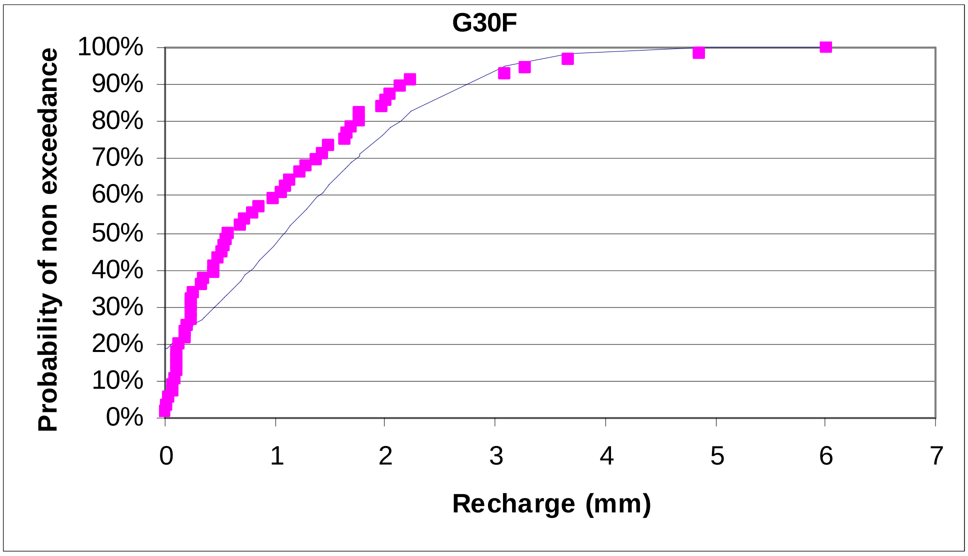

Figure 7.3: A probability plot indicating a recharge value of 5mm at the 98% confidence limit.

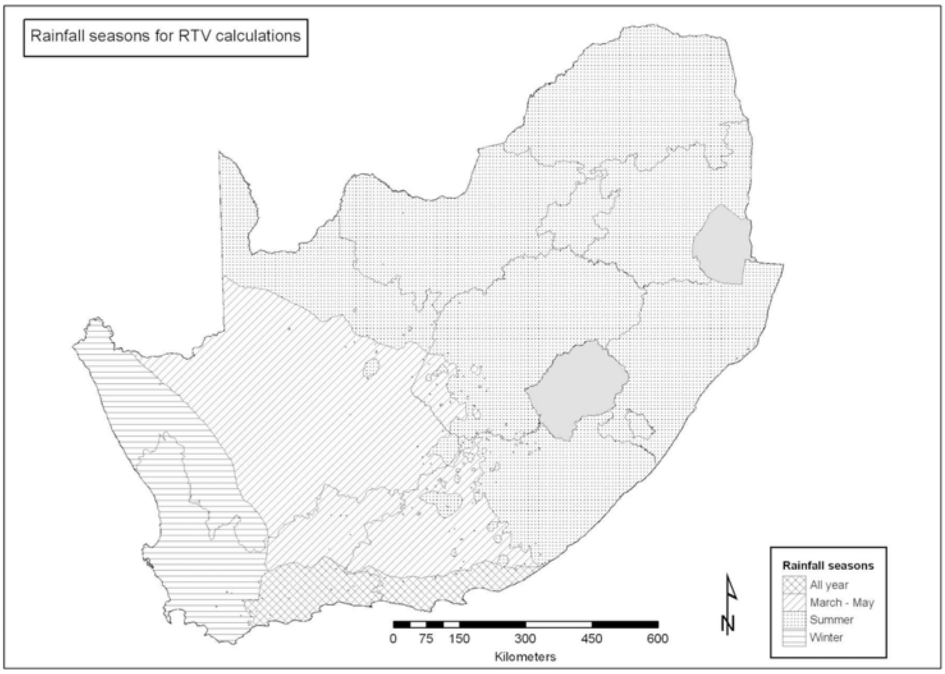

Figure 7.4: Rainfall seasons for South Africa (Schulze, 1997)

8. CURRENT SHORTCOMINGS

An increase in the number of rainfall chloride values will improve the accuracy of the calibration of the recharge grid. In addition calculation of actual evapotranspiration will be beneficial.

For assessment of an RTV, it is preferable to have daily time series data of rainfall and groundwater levels (in close proximity). However, for this project an RTV has to be calculated for each quaternary catchment and there are insufficient time series data sets across the country to support this type of analysis. Thus the current method of calculating RTVs is not based on time series data of rainfall and groundwater levels, but rather on an aggregated statistical value, based on "recharge probability non-exceedence". It must be noted that an additional incentive of monitoring rainfall and groundwater levels across the country would be to enable the improved assessment of RTVs. This benefit should be included when the New National Groundwater Monitoring Network is addressed (pers. comm., E van Wyk, 2005).

9. RECOMMENDATION

For calculating recharge and RTV, a more detailed approach is suggested in that stressed catchments should be determined and the modelling of recharge processes could be significantly refined if long term rest water levels and stable isotopes data is available for the aquifer. It is strongly recommended that monthly rainfall, rest groundwater levels, stable isotopes and chemistry data be collected. This data should be collected from rainwater, surface and groundwater if possible. In addition, stressed aquifer should be addressed and then sites selected on the basis of land use, climate zone, and aquifer type, with a view to extrapolating the results elsewhere across the country. The data needs to be stored and managed using the DWAF centralized databases.

Another recommendation is from the work Bean (2003) carried out. In semi-arid to arid areas where most recharge water enters the aquifer via the matrix, the period of time that elapses between successive rainfall events that exceed the recharge threshold often extends to many years. This has significant resource management implications, as it indicates that the current approach of basing allocations on average recharge estimations is only justified if sufficient groundwater is available for use over the entire period between recharge events. In many instances it may be more realistic to base groundwater allocations on the proportions of bypass flow-derived recharge (i.e. preferential flow) entering site aquifers initially, the allocations increasing once aquifer storage, recharge threshold, and recharge event return period characteristics are better understood.

10. CONCLUSION

Of the many methods available for determining groundwater recharge, the project team, including discussions with Prof van Tonder, Dr Beekman and Dr Bean concur that the chloride mass balance approach must be used, even though it has limitations. This method provides a starting point and calibration values for the layered model approach. Rainfall / recharge relations have limited value in this project. The results from rainfall / recharge relationships however are valuable in calibrating the CMB equations and the layered model. The layered model shows good potential, as long as it is carefully calibrated. Sensitivity analysis has indicated which factors need to be adjusted to calibrate the layered model. The method proposed does not include all factors determining groundwater recharge, however it

does include the main factors and a recharge values are obtained with a fair degree of certainty.

The determination of a Recharge Threshold Value (RTV) per quaternary catchment is beneficial for groundwater management and planning. It provides an indication of the amount of rainfall that is required to initiate recharge. Thus, if annual rainfall is below the RTV, then groundwater use and groundwater levels should be closely monitored as groundwater over-abstraction is a possibility.

However, a recharge threshold value is an uncertain value, with quite a high associated degree of uncertainty. Firstly, should the threshold value be a daily, monthly or annual figure? If an annual figure is given, it is possible that there are rainfall events within the year that generate recharge, yet on an annual basis the rainfall may be below the threshold value. The same applies to a monthly value, in that a rainfall event of short duration (e.g. 24 hours) may produce recharge but on a monthly basis the rainfall is below the monthly threshold value. Ideally, a daily threshold value should be calculated and used. However, this approach is data intensive and importantly many factors need to be taken into account, such as flow paths, antecedent soil moisture conditions etc. Taking into account the data available for this project, an approach has been followed, based on the rainfall seasons across the country, and groundwater recharge and rainfall relationships. Calculating the probability of “recharge non-exceedence” then provides a modelled value of an RTV. It must be noted that this is a monthly value applicable in the wet season of the catchment.

Secondly, different recharge thresholds should be calculated for preferential flow path or matrix diffusion recharge rates. These calculations are data intensive and also require stable isotope data. This is beyond the scope of this project.

Thirdly, the threshold value will also vary spatially across a catchment. This effect will be more pronounced in catchments with a diverse geomorphology and range of elevations, as opposed to relatively flat homogeneous catchments. Using a GIS based approach it may be possible to determine a spatially variable threshold value per catchment. However, for this project a single value is provided per quaternary catchment.

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GLOSSARY

TERM	DEFINITION
Aquifer	A geological formation (or one or more geological formations) that is porous enough and permeable enough to transmit water at a rate sufficient to feed a spring, provide baseflow to rivers, or a borehole.
Baseflow	Streamflow derived mainly from groundwater seepage into the stream. The base-flow in this study is defined as the annual equivalent of the average low flow that is equalled or exceeded 75% of the time during the 4 driest months of the year.
Chloride Mass Balance	This method of calculating groundwater recharge takes into account precipitation amount and the chloride concentration of both precipitation and groundwater.
EARTH model	Extended model for Aquifer Recharge and Moisture Transport through Unsaturated Hardrock
Effective rainfall	Effective rainfall is the rainfall on a given day minus interception loss, minus storm run-off.
Evapotranspiration	Loss of water from a land area through transpiration of plants and evaporation from the soils.
Groundwater	Underground water that is generally found in the pore species of rocks or sediments and that can be collected with boreholes, wells, tunnels or drainage galleries, or that flows naturally to the earth's surface via seeps or springs.
Hydraulic conductivity	Factor of proportionality in Darcy's equation defined as the volume of water that will move through a porous medium in a unit time under a unit hydraulic gradient through a unit area at right angles to the direction of flow.
Interception	The process by which water from precipitation is caught and stored on plant surfaces and eventually returned to the atmosphere without having reached the ground.
Isotopes	Isotopes of a particular element have the same atomic number but different atomic weights due to varying numbers of neutrons.
Recharge	The replenishment of groundwater in an aquifer. It can be either natural, through the movement of precipitation into an aquifer, direct stream recharge or artificial (the pumping of water into an aquifer).
Run-off	The total amount of water flowing in a stream. It includes overland flow, return flow, interflow and baseflow.
Storativity	Volume of water released per unit area of aquifer and per unit drop in the potentiometric surface. It is the product of the saturated thickness and the specific storage.
Storm run-off	Run-off reaching streams channels immediately after rainfall.