DEPARTMENT: WATER AFFAIRS AND FORESTRY

Groundwater Resource Assessment II

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1. INTRODUCTION

The main purpose of the GRA II Project is to provide assistance in allocating groundwater use. In doing so it needs to allow for reliability during droughts, above average availability after major recharge events, and policy requirements (environmental and social).

2. TASK 1 - APPROACHES TO QUANTIFYING GROUNDWATER

2.1 Task 1A - Literature review

Project 1 of GRA II is to provide an approach in the form of an algorithm to assess the volume of water available from a specific area over a particular period of time. The figure obtained will be the starting point from which deductions will be made depending on policy requirements and will form the best estimate with available data sets. In the more advanced approach to quantifying groundwater, the algorithm can be run with the most recent data in order to establish up-to-date groundwater availability.

Project 1 describes how aquifer storage and throughflow (inflow and outflow) is quantified and taken into account when assessing the volume of water theoretically available for abstraction from storage over a given period of time. It also describes how natural recharge affects the availability of a groundwater resource, but does not describe how to establish recharge values – this falls under Project 3.

The algorithm will be applicable to both small-scale and large-scale quantification of groundwater resources. Where little information on the area exists, generalised or default values will need to be used, and as a result, the confidence in the answer will be relatively low. By contrast, where an area has been studied in depth, the confidence level in the result will be high. Project 1 defines the algorithm for quantifying groundwater and recommends data sets depending on the level of confidence required.

The literature reviewed included local and international approaches to quantifying groundwater resources. Various estimates of groundwater availability in South Africa have been put forward over the past 30 odd years. They range from 2 500 million m^3 per annum (Enslin, 1970) to 19 100 million m^3 per annum (Baron *et al,* 1998). The latter figure comes from applying the Harvest Potential method (see Section 4). This approach does not take into account the “abstractability” of the resource and it also includes groundwater contribution to baseflow**.** WSM (2001) modified the Harvest Potential estimate to accommodate abstractability, and came up with an Exploitation Potential of 10 100 million m^3 per annum.

All approaches are based on the water balance equation (described in Section 4), although different authors have dealt with the problem of limited information in different ways. For example, there are various approaches put forward to estimate aquifer thickness. In cases where the base of the aquifer is fairly well defined, eg, in alluvial aquifers, estimating aquifer thickness does not pose a big problem, but in many fractured environments, generalising about aquifer thickness is problematic. Vegter (1995), for example, proposed that the saturated thickness of these aquifers be defined as the difference between the median regional water strike depth and the median rest water level.

In concluding the literature study, a method for quantifying groundwater is proposed. This has been called the Aquifer Assurance Method. It builds on the methods described in the literature study, but includes an assessment of the risk of resource failure. It is felt that some level of assurance of supply needs to be incorporated into the preferred method(s) – possibly in a similar way to surface water resource assessments. The proposed approach is thus similar to the simulation of dam storage levels, which are defined as the volume of water that can be drawn from a dam each year at a designated assurance level or risk level.

2.2 Task 1BC - Methodology report

The key objective of the GRA II project is to provide an approach to quantifying groundwater resources in South Africa. Together with the approach (or method), the project must provide generic data sets that can be used for rapid and regional-scale groundwater resource assessments. The main purpose for quantifying groundwater in the GRA II project is to provide guidance on how much water can be allocated for use.

The process of establishing this will follow the steps outlined in **Table 1** for any given area of interest, be it an aquifer, a catchment or a particular study area. **Table 1** also mentions where the information will come from out of the five GRA II projects.

Table 1 : Process for Groundwater Resource Assessment and Allocation

Step	Task	Project No
1	Establish the volume of groundwater held in storage	1
2	Establish the proportion of this that can feasibly be abstracted, and the proportion that should be abstracted in a single year in order to bridge drought cycles	2 with input from 3
3	Establish the proportion of 2 above that should remain behind in the aquifer in order to meet specific management criteria (eg the Reserve, prevention of land subsidence, maintain water quality in the aquifer, etc)	4 and Reserve Estimates
4	Establish the current abstraction	5
5	Establish the remainder that can be allocated for further use	-

In order for the approach to be practical and to meet the objective of supporting groundwater resource quantification per defined management unit, the following factors have been incorporated into the approach:

The data sets are spatially (GIS) based;
The data sets can easily be replaced once new data becomes available;
The approach is applicable at various scales;
The approach is easy to use (ie the answers can be obtained using a hand calculator and it is not necessary to have GIS-computer skills).

The outputs of the five GRA II projects are mostly in volumes of groundwater per grid area (**Table 2**).

Table 2: Output per GRA II project

Key output	Form of output for GRA II	Project No
Storage	Available storage in m^3 per grid area (this will take the form of rough estimates to be used as country-	1

	wide default values; and it will describe an approach to determining current storage should detailed, localized data be available)	
Natural recharge	Mean annual recharge in m^3 per grid area (from precipitation & surface water)	3
Natural discharge	Mean annual discharge to surface water in m^3 per grid area	3
Abstraction potential	Allocatable groundwater use in m^3 per grid area in order to bridge drought cycles and taking aquifer permeability into account	2
Groundwater use	Average usage in m^3 per quaternary catchment or grid area Method to determine annual usage in m^3 per quaternary catchment or grid area	5
Aquifer classification	Guide on aquifer status to serve as qualitative input into allocating groundwater use	4

Note: All key outputs will cover the entire country – ie default values will be provided should accurate figures not be available.

The approach adopted in Project 1 (Methodology for Groundwater Quantification) is summarized in Section 4 of this report. It was initially intended that two separate reports would be written to describe "the methodology" and the "rapid approach". It is, however, preferable to combine these reports into one, since a single method has been developed. What is different between the more detailed approach and the rapid approach is that the input data for the rapid approach are the generic values that have been developed for the entire country, whereas for the more detailed approach, site specific values will be used.

A considerable portion of the work done on the project to date has been on developing the default values (and at this stage, they have not been finalized). GIS layers based mostly on a 1 km by 1 km grid have been developed for the various "levels" within an aquifer. These levels are grouped into static storage, which is the volume of groundwater available in the permeable portion of the aquifer below the zone of natural water level fluctuation, and dynamic storage, which is the volume of groundwater available in the zone of natural water level fluctuation. The levels are listed below:

Static storage {
- Level 1 - bottom of the aquifer
- Level 2 - bottom of the natural dynamic groundwater elevation

Dynamic storage {
- Level 3 - current groundwater elevation
- Level 4 - average groundwater elevation
- Level 5 - top of the aquifer

The volume of aquifer material bound between the layers reduced by an appropriate storage coefficient gives groundwater storage (V). The mathematical expression for groundwater storage is:

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Where

$\sum$ is a summation sign
A is the area of each grid
S is the storage coefficient
Δh is thickness between any two layers of interest.

By taking different Δh values, various storage volumes can be computed. Project 2, which provides the groundwater planning potential map, will use one or more of these storage values, together with drought cycles and aquifer permeability to determine the practical groundwater resource that should be available for use in any given area on an annual basis.

The process required to establish the volumes is summarized in **Table 3**.

Table 3: Steps to quantify groundwater storage

Steps	Method	Result
Step 1	Delineate the area to be studied.	Area of groundwater unit
Step 2	Establish the coefficient of storage for the aquifer	S-value
Step 3	1. Establish aquifer thickness by taking the difference between the top of the aquifer (Level 5) and the bottom of the aquifer (Level 1). 2. Apply the coefficient of storage to the aquifer volume.	The maximum groundwater storage
	1. Establish the base of the natural dynamic storage (Level 2) and take the difference between this and the bottom of the aquifer. 2. Apply the coefficient of storage.	The static storage
	1. Establish the average water level (Level 4) and take the difference between this and the bottom of the aquifer. 2. Apply the coefficient of storage.	The average total storage
	1. Take the difference between the average water level (Level 4) and base of the natural dynamic storage (Level 2). 2. Apply the coefficient of storage.	The average dynamic storage
	1. Establish the average current water level (Level 3) and take the difference between this and the base of the natural dynamic storage. 2. Apply the coefficient of storage.	The current available dynamic storage

2.3 Task 1D - Final Report

The key objective of the GRA II project is to provide a generic approach or methodology for quantifying the groundwater resources of South Africa. Together with this approach, the project should also establish the required datasets for verifying the methodology developed at both the national and the aquifer scale. The main purpose for quantifying the groundwater resources in the GRA II project is to provide guidance on how much water can ultimately be allocated for use.

The process of establishing the groundwater resources for any given area of interest will follow the steps outlined in Table 1, be it an aquifer, a catchment or the entire country. Table 1 also indicates which of the five GRA II projects will provide the various outputs.

Table 4 : Process for Groundwater Resource Assessment and Allocation

Step	Task	Project No
1	Establish the volume of groundwater held in storage in the aquifer system. This involves defining various aquifer levels such as the thickness of the aquifer system.	1
2	Establish the rate of aquifer replenishment from rainfall and the proportion of groundwater that can feasibly be abstracted, whilst taking into account the effects of droughts.	2 with input from 3
3	Establish the proportion of 2 above that should remain behind in the aquifer system in order to meet specific management criteria (e.g. the Reserve, prevention of land subsidence, maintain water quality in the aquifer, etc)	4 and Reserve Estimates
4	Establish the current abstraction	5
5	Establish the 'surplus' groundwater resources that can be allocated for further use.	-

In order for the methodology to be practical and to meet the objective of quantifying the groundwater resources within various management units (i.e. Quaternary Catchments), the following factors have been incorporated into the approach:

- The data sets are spatially (GIS) based;
- The data sets can easily be replaced once new data becomes available;
- The approach is applicable at various scales;
- The approach is easy to use (i.e. the answers can be obtained using a hand calculator and it is not necessary to have specialised GIS-computer skills).

The outputs of the five GRA II projects are mostly in volumes of groundwater per square kilometre (Table 2).

Table 5: Output per GRA II project

Key output	Form of output for GRA II	Project No
Aquifer Storage	Groundwater storage in m^3 per km^2.	1
Rainfall Recharge	Mean annual recharge in m^3 per km^2.	3
Natural Discharge	Mean annual discharge to surface water bodies in m^3 per km^2	3
Abstraction Potential	Volumes of groundwater in m^3 per km^2 that can be abstracted on a sustainable basis under various constraints (i.e. aquifer permeability, water quality).	2
Groundwater Use	Average usage in m^3 per quaternary catchment.	5
Aquifer Classification	Guide on aquifer status to serve as qualitative input into allocating groundwater use	4

<u>Note</u>: *All key outputs will cover the entire country, excluding Lesotho and Swaziland, i.e. default values will be provided should accurate figures not be available.*

The approach adopted in Project 1 (Methodology for Groundwater Quantification) is summarized in **Section** Error! Reference source not found. of this report. A single methodology has been developed for more detailed as well as rapid estimations of storage. For the rapid approach, the generic input datasets were developed for the entire country, whereas for the more detailed approach, site specific values at an aquifer level are used.

A considerable portion of the work carried out during this project has been on developing the default values for verification of the methodology on a national scale, where it was decided to generate inputs and outputs at a spatial resolution of 1km by 1km (1 km^2). Raster-based GIS layers or ‘Grids’ were developed for various ‘levels’ within a conceptual aquifer system (Figure 1). These aquifer levels are grouped into two broad zones; namely (i) ‘static’ storage zone, which is the volume of groundwater available in the permeable portion of the aquifer below the zone of natural water level fluctuation (level 2), and (ii) ‘dynamic’ storage zone, which is the volume of groundwater available in the zone of natural water level fluctuation.

The levels are listed below (Figure 1):

Static storage {
- Level 1 - base of the aquifer
- Level 2 - base of the natural dynamic groundwater elevation

Dynamic storage {
- Level 3 - current groundwater elevation
- Level 4 - average groundwater elevation
- Level 5 - top of the aquifer

A 6th level (Management Waterlevel Restriction) was introduced to take into account environmental, legal or other constraints placed on the volumes of water that may safely be abstracted from an aquifer system, e.g. restrictions to ensure that DWAF ‘Reserve’ requirements are met, restrictions on maximum waterlevel drawdown in dolomitic aquifers due to the hazard of sinkhole formation, avoidance of intrusion of saline water into an aquifer.

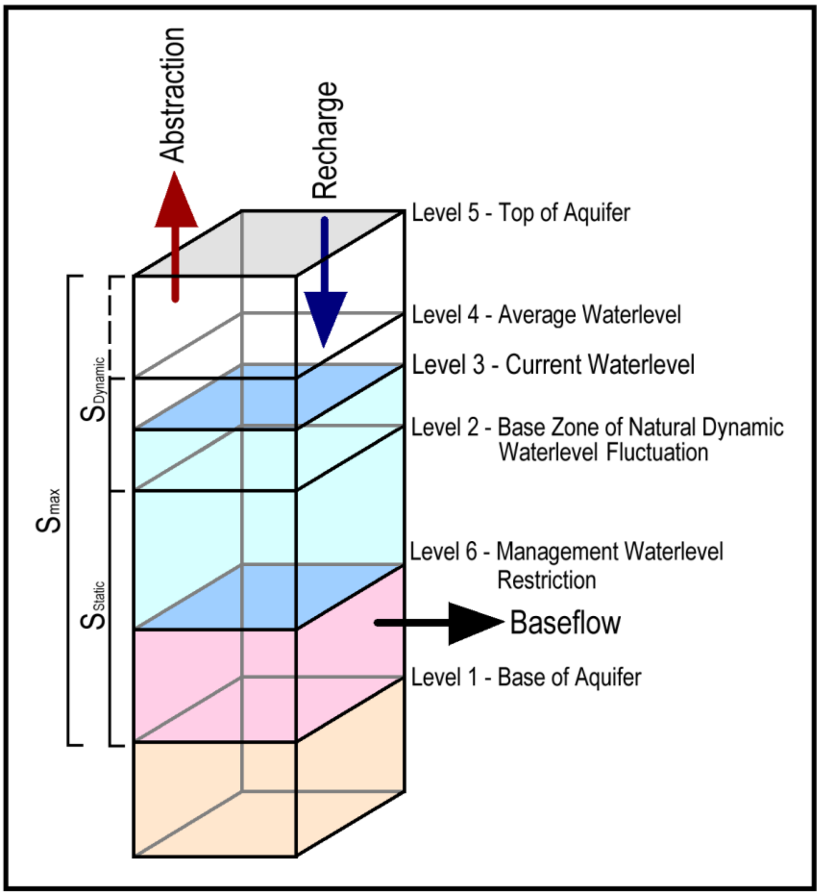

Figure 1: Six Levels in Aquifer System used to assess Volumes of Groundwater held in Storage

The volume (*V*) of water stored between any two aquifer levels or zones is estimated as the volume of aquifer material reduced by an appropriate storage-coefficient or specific yield. The mathematical expression for groundwater storage is:

$$V = \sum AS\Delta h$$

Where

$\sum$ is a summation sign
A is the area of each grid (i.e. 1 km^2)
S is the storage coefficient / Specific Yield.
Δh is thickness between any two layers of interest.

By taking different Δh values, various storage volumes can be computed. Project 2, which provides the groundwater resource ‘planning potential’ datasets, makes use of a number of these potential storage volumes (*V*) together with parameters such as rainfall recharge and baseflow to determine the annual volumes of groundwater available for utilisation on a sustainable basis.

This project indicates that some 235 x 10^9 m^3 of groundwater may be stored in aquifers in South Africa. The approach involved defining the thickness and storativity of two aquifer zones, (i) the upper ‘weathered-jointed’ or WZ and (ii) the underlying ‘fractured’ zone or FZ. It is estimated that 79% of this water is stored in the WZ which is on average only 33m thick, as opposed to an average FZ thickness of 121m –

providing a mean aquifer thickness of 154m. The mean storativity of the WZ and FZ is estimated at 2.62×10^{-3} and 1.52×10^{-4}, respectively.

3. TASK 2 - GW PLANNING POTENTIAL

Project 2 of this study deals with the so-called 'Planning Potential' maps that will be produced essentially using inputs from the other 4 projects, namely Groundwater Quantification (1), Recharge and Surface Water Interactions (3), Aquifer Classification (5) and Groundwater Use (5).

The Water Research Commission funded JR Vegter (1995a & b) to produce the first GIS-based set of maps depicting the groundwater resources of South Africa, aptly entitled 'Groundwater Resources of the Republic of South Africa'. Seymour and Seward (1997) used Vegter's work as a basis to produce the so-called 'Harvest Potential' map, which provides preliminary annual estimates on a national scale of the maximum volume of groundwater that can be abstracted from a unit area on a sustainable basis without depleting the aquifers. This information was used to compile the Department of Water Affairs and Forestry's (DWAF) National Groundwater General Authorisations dataset, in accordance with Section 39 of the 1998 National Water Act.

Water Systems Management (2001) further refined the Harvest Potential estimates of the groundwater resources potential, by taking into consideration the variable yield potential within and between various aquifer systems. This information was summarised per Quaternary drainage region as part of DWAF's national Water Resources Situation Assessment. Other more localised GIS-based groundwater resource assessment studies have been carried out in Southern Africa. The pertinent methods and outcomes of these projects are discussed in this document.

3.1 Task 2A - Literature study

3.2 Task 2B – Methodology

3.3 Task 2C – Final

The Average Groundwater Resource Potential (m3/km2/a) of aquifers in South Africa was estimated under normal rainfall conditions at 49.249,x,109 m3/annum, which decreases to 41.553,x,109 m3/annum during a drought. These estimates are regarded as the maximum volumes that could be abstracted on a sustainable basis, if and only if, an adequate and even distribution of production boreholes can be developed over the entire catchment or aquifer system – which in most fractured-rock aquifer is considered to be highly improbable.

The Average Groundwater Exploitation Potential (m3/km2/a) of aquifers in South Africa is estimated at 19.073 x,109 m3/annum, which declines to 16.253 x,109 m3/annum during a drought. It is likely that, with an adequate and even distribution of production boreholes in accessible portions of most catchments or aquifer systems, these volumes of groundwater may be annually abstracted on a sustainable basis.

The Potable Groundwater Exploitation Potential (m3/km2/a) of aquifers in South Africa is estimated at 14.802 x,109 m3/annum, which declines to 12.626 x,109 m3/annum during a drought. Nationally, this represents almost a 30% reduction in the annual volumes of available groundwater for domestic supply due to water quality constraints.

The Utilisable Groundwater Exploitation Potential (m3/km2/a), under normal rainfall conditions, and the UGEPDRY, under drought conditions, of aquifers in South Africa is estimated at 10.353 x,109 m3/annum, which declines to 7.536 x,109 m3/annum during a drought. The UGEP represents a management restriction on the volumes that may be abstracted based on the defined 'maximum allowable water level drawdown' and therefore it is always less than or equal the AGEP. It is likely that, with an adequate and even distribution of production boreholes in accessible portions of most catchments or aquifer systems, these volumes of groundwater may be annually abstracted on a sustainable basis.

The annual total volume of the Average Groundwater Exploitation Potential (AGEP) is slightly greater than the Harvest Potential or HP, whilst the AGEPDRY is slightly less than the Harvest Potential. The AGRP is more than double the Harvest Potential. When compared to the AGEP, the HP is higher for large parts of South Africa, except in large parts of the Central and Eastern Karoo, as well as Northern Province. During droughts the situation is similar, except that the areas where the HP is greater than the AGEP increases slightly. The HP is significantly greater than the AGEP along the northern Kwazulu-Natal coast, whilst the AGEP is anomalously higher than the HP in groundwater region 10 (Zeerust-Delmas Karst Belt).

Estimates of the available groundwater resource potential of South Africa range from a maximum of 47.727,x,109 to as low as 7.536,x,109 m3/km2/a. For general planning purposes, it is recommended that the so-called 'Average Groundwater Exploitation Potential' or AGEP be adopted where the total volume of groundwater available for abstraction under normal rainfall conditions is estimated at 19.073 x,109 m3/a, which declines to 16.253 x,109 m3/annum during a drought. It is likely that, with an adequate and even distribution of production boreholes in accessible portions of most catchments or aquifer systems, these volumes of groundwater may be annually abstracted on a sustainable basis. Only approximately 6% by volume of the AGEP is currently being abstracted on an annual basis.

4. TASK 3A - RECHARGE

4.1 Task 3aA - Literature Review

Within South Africa 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.

In order to carry out a meaningful assessment of groundwater recharge, geographic information systems, remote sensing and geostatistical techniques will be used. It is proposed that a deterministic model approach be initially followed, such as the EARTH model, which will be modified later in the project according to South African conditions, including a stochastic approach to assess levels of uncertainty.

This report constitutes the first deliverable for the Recharge project. It includes:

- A very brief overview of groundwater recharge. As mentioned, recharge is a complex process including many factors and high levels of uncertainty. There are a number of very good publications on the topic and these are referred to in this report, (but not repeated).
- A review of the more commonly referenced recharge studies in southern Africa,
- A more detailed review of selected references (this review includes the work of Vegter (1995), Bredenkamp *et al*., (1995), Murray (1996), and Xu and Beekman (Eds.) (2003)). This section does not review each reference mentioned above in its entirety, but rather focuses on selected portions of the references, thereby bringing differing aspects of recharge to the fore.
- A proposed method for carrying out the work. The method proposed is still to be finalised as one of the following project tasks. However, at this stage of the project, a deterministic type model is to be considered, such as the EARTH model, developed by Van der Lee and Gehrels (1990). Later in the project stochastic analysis will also be included.

4.2 Task 3aB - Data Set Identification and Validation Report

This report is the second deliverable for the recharge project, which is a component of the larger Groundwater Resource Assessment, Phase II project, funded by DWAF. The first deliverable was a report reviewing the literature relevant to groundwater recharge assessments.

In order to identify which data sets are to be used for this project, it was necessary to establish, in a preliminary way, possible methods and approaches to determining groundwater recharge. Once that had been established the required data sets were identified. The data sets that were identified as being relevant include: rainfall volumes and distribution; chloride concentration of rainfall, ground surface slope, vegetation cover (type and density), soil type (texture and thickness), geological data (lithology and structure), riparian zone vegetation (type and extent), depth to groundwater, groundwater chemistry (particularly chloride and Total Dissolved Solids), and groundwater level fluctuations. Satellite imagery is considered important for verifying structural geological information, identifying riparian zones and recharge zones.

Following on from the identification of required data sets, a process was followed of writing letters and requesting data from various sources and organisations. The data that has been obtained is not as complete as the list given above, for a number of reasons. These reasons are discussed to a limited extent in the report. Each data set is reviewed in the report outlining its status, usability and applicability for determining groundwater recharge values.

It is clear that although there are many methods for calculating recharge on a national scale, the limiting factor is the availability and validity of data sets. Examples of such methods are the chloride mass balance, water balance or EARTH models. It is not possible to obtain all the data sets required for these methods. A hybridised method will have to be used, based on available and valid data sets. However, there have been many detailed recharge studies carried out throughout South Africa and these point estimates will be used, as far as possible, to validate the GIS based, national scale methods used.

4.3 Task 3aC – Methodology

This report constitutes the third deliverable of the Groundwater Recharge component of the Groundwater Resources Assessment Phase II project. This report focuses on the method to be followed in determining groundwater recharge. Groundwater recharge is to be determined both as a long term average value and a value per hydrological year. The more detailed title of this “Method” report is “Definition and validation of generic algorithm". This deliverable builds on earlier work completed which includes a literature study and identification of available data sets for carrying out national scale recharge assessments.

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

- the chloride mass balance (CMB) approach,
- on empirical rainfall / recharge relationships,
- a layer model (GIS based) approach and then
- cross calibration of the results obtained, ensuring as close as possible, that the results obtained correlate with field measurements and results.

This report documents work completed toward definition and validation of a generic algorithm. However, during the validation process results were obtained that were questionable and thus revision of the algorithm was carried out. Thus the process of algorithm definition and validation is an iterative one, and at the time of writing this report the process had not been entirely finalised, as a few data sets were still outstanding. However, the algorithm to be used will be finalised in the near future.

The data processing is being carried out on a 1 km by 1 km grid cell size. Once the final results have been obtained at this resolution, they will be aggregated up to the quaternary catchment scale. The quaternary catchment is the "unit of measure" required by the client. The results obtained in this project will be compared to the results obtained from earlier recharge studies. It appears that the algorithm that will be used in this project will not take into account rainfall duration or intensity nor will fracture dominated flow be differentiated from matrix dominated flow processes. However, the advantage of the GIS based approach is that there is sufficient flexibility to include updated and new data sets and even to update the algorithm if need be.

4.4 Task 3aD - Recharge Threshold Values

This report is the fourth delivered for the Groundwater Recharge Study. It focuses on establishing the most suitable method to calculate an annual recharge threshold value (ARTV) per quaternary catchment. This is an annual figure, which indicates the annual rainfall below which no direct groundwater recharge occurs. It is an approximate figure, as it does not take into account spatial variability within a quaternary catchment (such as differing geomorphology, soil characteristics and hydrogeological factors). Also it does not take into account temporal variability, such as rainfall intensity, duration and antecedent conditions. There is a link between ARTV and climate zones, in that in the winter rainfall regions the ARTV will be lower than for summer rainfall regions.

Although Project 3b (groundwater/surface water interaction) has generated a time series recharge value per quaternary catchment, it does not generate an ARTV. Based on the GIS modelling carries out for this Recharge Project (3a), it is proposed that for each quaternary catchment the final recharge values obtained are plotted against the mean annual precipitation. From these data an ARTV is obtained. It is fully acknowledged that a threshold value should be obtained by assessing time series data, of rainfall and borehole water levels. However, due to paucity of such data, this is not possible. To obtain an ARTV the spatial distribution of Mean Annual Precipitation and Mean Annual Recharge were compared on a semi-log plot and the intercept where Mean Annual Recharge equals zero was used as the ARTV. This approach does take into account rainfall seasonality.

The ARTV is not subdivided into whether matrix or fracture flow occurs. It is a generalized value, essentially to guide planning and resource management, to assess whether the groundwater within a catchment is being recharged or not.

4.5 Task 3aE – Final

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).

5. TASK 3B - GROUNDWATER-SURFACE WATER INTERACTIONS

5.1 Task 3bA - Literature review

In 1995, the Department of Water Affairs and Forestry (DWAF) initiated a national hydrogeological mapping programme at 1:500 000 scale. This was completed in 2003 and is known as the Phase I Groundwater Resource Assessment.

The DWAF are now embarking on the Phase II Groundwater Resource Assessment. The main objective of the programme is to develop methodologies and data that will support groundwater resource quantification per defined management unit. This programme will also be in support of integrated water resources management, whose portfolio is to deliver relevant information on groundwater resources in support of Integrated Water Resources Management.

The Phase II programme was designed to address this need and comprises 11 projects, of which this project, Project 3B, Groundwater-Surface Water Interactions, is one. The objective of this project is to review methods to quantify groundwater-surface water interactions and to develop a generic algorithm that can be applied to estimate groundwater-surface water interaction on a national scale.

Project 3b is divided into phases whereby:

- the international literature on assessing surface groundwater interactions is reviewed,
- existing data sets available in South Africa will be identified,
- an algorithm to quantify interactions will be developed,
- and a data base populated.

This report summarises the findings of the literature review. Pertinent international literature and methodologies were reviewed in terms of their suitability for national scale modelling of surface-groundwater interactions. The literature reviewed can be classified as follows:

- stream flow classification methods
- geomorphologic classification of streams
- hydrograph separation techniques
- technical details required for determination of the groundwater component of the Reserve as required by the National Water Act, with specific reference to groundwater / surface water interactions.
- approach used in WR90 and other numerical models

5.2 Task 3bB - Data sets

This report identifies national scale data sets available for assessing groundwater/surface water interactions. Data sets identified include sources of data and digital coverages for:

- Rainfall data: data to categorise inputs to catchments at point and spatial scales
- Surface and groundwater abstraction and return flow data: data on actual and estimated surface and groundwater use
- Sources of data on streamflow reduction activities, e.g. afforestation and alien invasive vegetation: location of streamflow reducing activities and methodologies to estimate water consumption
- Baseflow estimates: data on estimated baseflow by Quaternary catchment
- Borehole yield: Data on borehole yield that can be used to derive aquifer permeability relationships
- Topography and rivers: The location of streams and catchment topography that can be used to prepare piezometric maps and identify zones of potential interactions
- Depth to groundwater: data on depth to groundwater that can be used to establish hydraulic connection between rivers and aquifers
- Flow gauging stations: data on actual streamflow
- Geology: lithological units to derive groundwater response zones
- Groundwater recharge: estimates of inputs to groundwater
- Potential groundwater-surface water interaction regions, Potential zonations that can be used to identify zones of similar groundwater interactions
- Soils: Data on soil depth, texture, slope and distribution

In general, sufficient data exist to consider the use of the VTI, ACRU and Pitman models to simulate baseflow. The international models (MIKE-SHE, HSPF, and SWAT) cannot utilise existing data directly and would require extensive calibration of empirical parameters. The number of parameters requiring calibration suggests that non-unique solutions would be possible. Insufficient data exist to set up MODFLOW; it would require a time series of recharge to simulate inputs, distributed aquifer hydraulic parameters and stream channel parameters.

SWAT, HSPF, VTI, ACRU and the Pitman model treat groundwater as a lumped system and cannot directly simulate the impacts of groundwater abstraction and its location on surface-subsurface interactions without modifications
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5.3 Task 3bC - Methodology

5.4 Task 3bD - Database

The Water Service Act of South Africa 108 stipulates the importance of maintaining an adequate water reserve in watershed systems for human basic needs and for ecological stability. Since water resources contributing to this reserve include both surface and groundwater, the integrated and sustainable management and development of water resources requires an understanding of the interactions between groundwater and surface water. One of the goals of the DWAF groundwater resources assessment programme is designed to address this need and one of its component projects is related to Groundwater-Surface Water Interactions. The objective of this project is a review of methods to quantify groundwater- surface water interactions and to develop a generic algorithm that can be applied to estimate groundwater-surface water interaction nationally on a quaternary catchment scale.

A methodology and algorithm have been developed whereby the effects of groundwater abstraction and its proximity to river channels are incorporated to simulate impacts on baseflow. These have been incorporated into a computer programme in an MS-EXCEL environment (Report 3bC). These algorithms have also been coded into a multi worksheet MS-EXCEL data base set up by Quaternary catchments and has been used to estimate interactions over large parts of the country.

5.5 Task 3bE - Final

The Water Service Act of South Africa 108 stipulates the importance of maintaining an adequate water reserve in watershed systems for human basic needs and for ecological stability. Since water resources contributing to this reserve include both surface and groundwater, the integrated and sustainable management and development of water resources requires an understanding of the interactions between groundwater and surface water.

In 1995, the Department of Water Affairs and Forestry (DWAF) initiated a national hydrogeological mapping programme at 1:500 000 scale. This was completed in 2003 and is known as the Phase I Groundwater Resource Assessment.

The DWAF then embarked on the Phase II Groundwater Resource Assessment. The main objective of the programme is to develop methodologies and data that will support groundwater resource quantification per defined management unit. This programme will also be in support of integrated water resources management, whose portfolio is to deliver relevant information on groundwater resources in support of Integrated Water Reserve Management.

The Phase II programme is designed to address this need and comprises 11 projects, of which this project, Project 3B, Groundwater-Surface Water Interactions, is one. The objective of this project is to review of methods to quantify groundwater- surface water interactions and to develop a generic algorithm that can be applied to estimate groundwater-surface water interaction nationally on a quaternary catchment scale.

A methodology and algorithms have been developed whereby the effects of groundwater abstraction and its proximity to river channels are incorporated to simulate impacts on baseflow. These have been incorporated into a computer programme in an MS-EXCEL environment (Report 3Bc). These algorithms have also been coded into a multi worksheet MS-EXCEL data base set up by Quarternary catchments and has been used to estimate interactions over parts of the country where baseflow occurs.

6. TASK 4 - CLASSIFICATION

6.1 Task 4A - Literature study

This inception report documents a literature survey of relevant published material on the classification of groundwater resources under the NWA. This review, along with discussions with DWAF RDM personnel and their consultants, completes the inception phase of Project 4 (Classification) of the Groundwater Resource Assessment Phase II (GRAII) project. The understanding of current approaches to Classification will inform and guide the next phase of this project: to develop a Classification system for groundwater resources in South Africa.

This report provides the deliverables for the inception phase of Project 4, namely:

- Refined approach to the project, including a schedule that takes into account any changes in time lines of dependent projects.
- Detailed agreement of outputs for the second phase.

6.2 Task 4B - Methodology

This document follows report 4A, the groundwater Classification Inception report, produced as part of the same project within the GRA II suite of projects. It outlines the approach developed thus far for the Classification of groundwater resources under the National Water Act (NWA). This approach has been developed within the inception phase for the integrated National Water Resources Classification System (NWRCS) (DWAF, 2005).

Section 3 provides an overview of the legal background to Classification and the generic principals of the NWRCS. Section 4 outlines the approach developed by the full team for the NWRCS (C. Brown, C. Colvin, E. Dollar, J. Goldin, D. Grobler, J. Hallowes, D. Hughes, A.Joubert, S Mallory, S, Manyaka, C. Nicolson, J. Turpie, A, Turton), with guidelines for specific application to groundwater resources. National scale datasets that support Classification of groundwater are presented to give an indication of current present status, vulnerability, etc. A basic algorithm introducing national and regional-scale constraints is given and applied to the national scale (median) groundwater level according to the principals of Classification. This is presented to inform future planning and prioritisation of RDM implementation. It is intended that actual Classification will be carried out a quaternary or Water Management Area scale with stakeholder input.

Section 5 discusses the short comings of the data sets currently available. Recommendations for further work are given in section 6.

7. TASK 5 - GROUNDWATER USE

7.1 Task 5A – Literature Review

This report deals with the Literature Study element of the Groundwater Use task of the Groundwater Resource Assessment II project. It will endeavour to review the few studies that have been carried out in this arena and comment on related material found during the literature search.

7.2 Task 5B - Data Dictionary

This report is intended to summarise all of the data sets identified during the development of the methodology for Task 5: Groundwater Use determination under the Groundwater Resource Assessment II (GRA II) project. The data sets described herein have been gathered from numerous sources, but primarily from different directorates and sub-directorates of the Department of Water Affairs and Forestry (DWAF). The main thrust of this project is to define an up to date methodology to quantify groundwater use in South Africa but, as can be seen from the following report, much of the data are either outdated or incomplete.

As will be described in the Methodology report (Report 5D), several alternative methods were put forward, such as developing algorithms around the relationship between electricity consumption and groundwater abstraction, but these have been rejected due to insufficient data.

Attempts were also made to access numerous data sets at organisations such as mining houses and industries. However, this was unsuccessful due either to resistance to share data or a lack of data management. Although initially forthcoming and helpful, AngloAmerican's South African headquarters were restricted by head office in the UK from providing a comprehensive and detailed database of groundwater use.

As an overall comment, most of the data discovered during this initiative is outdated and / or incomplete. Even if a study was performed recently, it generally used old or incomplete information as its basis. This problem could be solved by the WARMS database but, at this stage, WARMS only describes registered use, not actual use. This could be improved if the registration was in some way related to billing, hence encouraging registering and current users to be realistic and or truthful about their water use. However, this will only happen once buy-in from all water users is obtained. The methodology to be submitted in Report 5D will, where possible, utilise WARMS data, but will use existing data sources with factors such as population growth to correct the date issues where WARMS is currently lacking.

7.3 Task 5C - Data Gaps

In South Africa, there appears to be a distinct need for improvement of databases of information related to **Groundwater use** at a national scale. As outlined in Report 5B, the Data Dictionary, the existing available data sets related to groundwater use, have limitations. There are issues relating to completeness, accuracy, out-dated information and even existence of key information.

This report summarises areas where data are missing and makes recommendations. Although not directly applicable in this project framework, these could assist in dealing with data challenges for groundwater use determination in the future. If these major challenges are not addressed, assessments such as this will continue to be made with sub-standard data sets, resulting in low confidence level results. This will also continue to impact on the potential security of valuable natural resources such as groundwater.

The limited timeframe for the project has necessitated that team members rely heavily on published or readily available sources of information, with particular emphasis on work that has been carried out by or for the DWAF in the recent past.

It is assumed that all the data summarised here are needed but are either available or are not available in the required format or at an appropriate scale to be of use in this study. In order to meet stakeholder expectations for groundwater use assessment, key sectors need to be addressed. As stated in previous reports, these sectors are:

- Municipal
- Rural
- Irrigation
- Livestock
- Industry
- Mining

Through the process of data exploration undertaken in this project, an assessment of available applicable data sets and sources was made. With an understanding of what is required to determine groundwater use, the team has identified a set of crucial gaps in available data. These gaps were expanded into a set of recommendations that can be used to inform future data acquisition and capture initiatives. These recommendations can also be used in combination with Report 5B to ensure realistic expectations in the development of future project terms of reference.

7.4 Task 5D - Methodology

It is important, for many aspects of Integrated Water Resource Management (IWRM) that the DWAF is equipped with a proper understanding of how much water, and more specifically groundwater, is being used nationally.

Report 5C has outlined, identified gaps and limitations of existing data and made recommendations for solving these issues. In doing so it has defined the layers that should be available groundwater use assessments in future. This report presents a principle method for implementation in a future where the recommendations made in Report 5C have been implemented along with a standardised groundwater use information capture and management framework has been implemented.

This document describes this Principle Method for groundwater use estimation in some detail and then proposes a Current Method utilising currently available data for estimating groundwater use at a national scale.

The Principle Method is a new simplistic approach to groundwater use estimation that relies on direct groundwater use monitoring and measurement data to create higher confidence estimates of use. It reaffirms stated needs within the DWAF for groundwater use data and aims to apply it directly to the problem rather than inference and extrapolation.

The Current Method builds on work previously carried out by the DWAF and their consultants and adds value to and updates pre-existing methods. Some methods used existing methods but added additional steps to apply new datasets to the problem. Where possible it utilises the information in the Water Authorisation and Registration Management System (WARMS).

The report will describe the need for a CMA and WMA level national groundwater use reporting framework and database for collecting and managing groundwater use information. A description of how the different data sets outlined in Report 5B will be applied to calculate a low confidence sectoral and total groundwater use follows. The major sectors of groundwater use addressed in this sub-project of the Groundwater

Resource Assessment II project are Municipal, Rural, Agricultural-Irrigation, Agricultural-Livestock watering, Industry and Mining.

7.5 Task 5E - Final

This report comprises two main sections. Firstly a description of the groundwater use maps generated using the Current Method described in Report 5D as part of the groundwater resource assessment II – groundwater use project. There are seven maps in the series, comprising individual sectoral groundwater use maps and a total groundwater use map. This is followed by summary of the findings of the project. This section includes sectoral and total groundwater use estimates comparisons with previous estimates and makes a number of observations drawn from validation datasets and sources.

Appendix B of this report includes a summary of expert inputs gathered during this project.