GRDM
Software Design Document

Groundwater Resource Directed Measures (GRDM) methodology update, software enhancements and training

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DISCLAIMER

Acknowledgements and link to resources

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The software and associated videos can be found at the following link:
www.waterscience.co.za/grdm.html

Abstract

This report outlines the design of the second generation GRDM software, its associated components and implementation thereof. UML is used to describe the legacy and new generation of the software. A gap analysis was performed through the use of workshops where users of the second generation GRDM raised issues experienced when making use of the software. These issues were categorised in four categories relating to enhancing exiting functionality, creation of new functionality, out of scope functionality and functionality already supported. The design for the third generation GRDM software is then presented in the context of the first two categories mentioned. The report discusses some results and makes recommendations that came about during the course of the software update. Finally the report also documents all calculations associated with objects residing in the object tree which describes a scenario that is being assessed.

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Nomenclature

L/s	Litres per second
m	Meters
m^3	Cubic metres
mamsl	Metres above mean sea level
mbgl	Metres below ground level
mg/L	Milligram per litre
mm	Millimetre

Acronyms

AFYM	Aquifer Firm Yield Model
API	Application Programming Interface
BHN	Basic Human Need (25L/p/d)
CRD	Cumulative Rainfall Departure
DLL	Dynamic Linked Library
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EARTH	Extended model for Aquifer Recharge and soil moisture Transport in Hardrock
ET	Evapotranspiration
EWR	Ecological Water Requirements
GIS	Geographic Information System
GRAII	Groundwater Resources Assessment – Phase 2
GRDM	Groundwater Resource Directed Measures
GRIP	Groundwater Resources Information Project
GUI	Graphical User Interface
Gx	Generation where x represents the number 1,2,3 e.g. G3 = Generation 3
IT	Information Technology
MAP	Mean Annual Precipitation
MS	Microsoft
NWA	National Water Act
RDM	Resource Directed Measures
RQO	Resource Quality Objective
SVF	Saturated Volume Fluctuation
UML	Unified Modelling Language
WARMS	Water use Authorization & Registration Management System
WGS84	World Geographic System 1984
WISH	Windows Interpretation System for Hydrogeologists
WRx	Water Resources Project
WULA	Water Use Licence Agreement

Chapter 1 Introduction

1.1 Preamble

In 2005, a research study to develop the methods to assess the groundwater component of the RDM was initiated. This study was funded by the Department of Water and Sanitation (DWS), implemented by the Water Research Commission (WRC) and undertaken by a Professional Service Provider (PSP). As the methods of this study were applied and tested, gaps were identified, for example, the issue of scale i.e. regional scale versus local scale. Subsequently in 2011, a new project was conducted to build on the existing information, address the gaps identified in the methods and include new methods which could be applied to assess GRDM. The outcomes of the project were a revised methodology as well as updated GRDM software. This study was completed in 2013. There has been a gradual improvement in methodologies for groundwater modelling and protection thereof.

With the continuous use of the 2013 GRDM methodology and software version, some issues with the methodology have come up and gaps identified. Furthermore, the software presented serious short-comings in application by the users.

These issues include, among others, addressing the issue of quaternary catchments delineation whilst groundwater is not bounded by them; groundwater contribution to baseflow (or ecological water requirements – EWR); capability to update data used as new data becomes available; formatting of the quality component of groundwater Reserve; accommodating groundwater-surface water interaction in the assessment of the resource; and linking of GRDM to the existing databases of the DWS where possible. In addition to that, various review exercises by experts in the groundwater field, in studies commissioned by the WRC, have highlighted issues with the current GRDM methodology which need to be addressed in order to protect the groundwater resource effectively. All these have necessitated the updating of the GRDM methodology, which entails the enhancement of the software as well.

The DWS officials are the target users for the system when determining groundwater resource classes and the Reserve, and setting the RQOs. With challenges relating to staff turnover in the DWS and required training to DWS officials on the use of the GRDM methodology and software, it was deemed necessary that a formal training programme be developed as part of this project.

1.2 Software Evolution

The first version of the GRDM software was released in 2005 under WRC Project K5/1427. In 2010, FETWater sponsored various training workshops and at this time minor software changes were made compared to the first official release in 2005. In 2011, the WRC sponsored a project for the review of the GRDM methodology and software under WRC Project K8/891. After the update and release of the software only one training workshop was held at DWA at the time. After 2011, the GRDM component was moved into a software package called Aquiworx, which evolved from the Aquifer Management System which was developed through DWAF at the time. This decision was taken as no further projects were issued from DWAF to maintain any of the aforementioned software packages. Since the two packages complemented each other it was the logic step as only one software package required updating and bug fixes where required.

Since many previous versions of the GRDM exits, this report will refer to generations of the software rather than versions to avoid confusion. A summary of the software generations and version is presented Table 1. A feature matrix is presented in Table 2 to compare functionality between the G1 and G2.

1.3 Purpose

Currently the G2 is 12 years old and during this time various datasets were updated and research has revealed alternative methodologies for some of the subcomponents used in the GRDM methodology.

Chapter 3 of the National Water Act (Act 36 of 1998) (NWA) focuses on the protection of South Africa's water resources. This is meant to ensure that water is available for current and future use. Protection therefore involves the sustaining of a certain quantity and quality of water to maintain the overall ecological functioning of rivers, wetlands, estuaries and groundwater.

Since groundwater practitioners have a legal obligation to protect South Africa's water resources, the purpose of the GRDM update is to enhance the existing software with both methodological changes identified by the project team in consultation with DWS, as well as identified issues from the users to enable DWS to validate RDM studies as well as evaluate WULA applications.

Table 1: GRDM generations and versions

<table>
<tr><th>Generation</th><th>Year</th><th>Version</th><th>Splash Screen</th></tr>
<tr><td rowspan="2">G1</td><td>2005</td><td>v3.3.0.6</td><td>
</td></tr>
<tr><td>2010</td><td>V4.0</td><td>
</td></tr>
<tr><td rowspan="2">G2</td><td>2011</td><td>v2.5.x</td><td>
</td></tr>
<tr><td>2012</td><td>v2.5.3</td><td>
</td></tr>
</table>

Table 2: Software generation feature matrix

Feature	G1	G2
GIS based system supporting general vector and raster formats	✓	✓
Quaternary shape file with default values (GRA2 & WRx)	✓	✓
Auxiliary shape file library	✓	✗
Rainfall and flow database (WRx)	✓	✓
Present monitoring data in GIS with thematic rendering	✗	✓
Time series graphs of monitoring data	✗	✓
Water chemistry analysis (Piper, Pie and Radar diagrams)	✗	✓
Basic water balance calculation	✓	✓
Assured Aquifer Yield Model	✗	✓
Cooper-Jacob Wellfield Model	✗	✓
Protection zone calculations	✓	✓
Protection zone visualization	✗	✓
Reserve determination for single and multiple quaternaries	✓	✓
Reserve determination for custom delineations	✓	✓
Single Herold baseflow separation	✓	✓
Multiple Herold baseflow separation	✗	✓
Provide modelled baseflow values (Pitman, Hughes, Schultz)	✗	✓
Single recharge estimation (Cl, EARTH, SVF, CRD, Isotope)	✗	✓
Multiple recharge estimations (Cl, EARTH, SVF, CRD, Isotope)	✓	✓
Basic human need calculated making use of census data	✓	✓

Multiple scenario analysis (using different parameters)	✗	✓
Reserve determination roadmap	✓	✗
Providing descriptive input parameters	✓	✗
Generic RQO suggestions with examples	✓	✗

1.4 Objectives

The objectives of the software update as it relates to this report are outlined as follows:

- Make the software more user-friendly, improve functionality, and implement newly identified methodology.
- Update the underlying database with new data where available.
- Test the software against case studies conducted as part of the research component of the overall project.
- Provide documentation on the software development for future maintenance of the produced product.

1.5 Report Outline

The structure of this report is outlined in Table 3 with a summary description of each chapter.

Table 3: Chapter outline

Chapter	**Summary Description**
1. Introduction	Provides background to the history and purpose of the required software update.
2. Legacy System Design	This chapter discusses the G2 system design and associated functionality.
3. Gap Analysis	The gap analysis of the G2 is discussed and analysed in this chapter to obtain a list of software enhancements together with new features that are required for G3.
4. Updated System Design	In this chapter the updated system design is presented where differences between G2 and G3 is highlighted.
5. Results and Discussion	Discussion of gap analysis results.

6. Recommendations	Finally recommendations are made based on future features to be considered as identified in the gap analysis, but are out of scope for this project.
7. References	List of key references used in the report.
Appendix A	Unified Modelling Language (UML) used in the software design documentation.
Appendix B	Assured Aquifer Yield Model used in the 2nd generation GRDM as yield model.
Appendix C	Dual Layer Model used in the 3rd generation GRDM as yield model.
Appendix D	Formulation of objects for existing functionality in the 2rd generation GRDM carried over to the 3rd generation GRDM.
Appendix E	Formulation of objects for new functionality in the 3rd generation GRDM.

Chapter 2 Legacy System Design

The current G2 is considered the legacy system and which is to be updated. This chapter will present all components of the legacy system.

2.1 Software Deployment

The software executable is considered to be a self-contained executable (all dependencies reside within the executable) with the exception of the MS Access database driver required on some target computers and selected DLLs required for the GIS functionality. The required driver is deployed to the target computer through the *AccessDatabaseEngine2007* installer.

The advantage of a true self-contained executable is that the software does not have to be deployed by an installer which manages all the software dependencies during the deployment. This means the software can simply be copied to the target computer and the executable will run. The reason that this behaviour is attractive, is the fact that many companies and institutions, including DWS, cast an image on their employees computers which prevents the users to install any software without having administrator rights. Even though this is good practice from an IT point of view, it has caused a lot of frustration during past training sessions as the attendees cannot install the software on their computers and the self-contained executable has circumvented this problem.

Since the software consists of more files than just the executable e.g. database files, the installer consists of a self-extracting executable (Figure 1) which contains all required files and will create the directory structure shown in Figure 2 on the target computer where the software is deployed.

The self-extracting executable (Figure 1) has the option to automatically start the software once deployed, but in the absence of the correct MS Access driver an error message may appear as shown in Figure 3. To resolve this problem the correct MS Access driver can be installed by running *AccessDatabaseEngine2007.exe* contained in the *3rd Party* directory (Figure 2). Note the screenshots referred to relates to Aquiworx as the GRDM is contained in Aquiworx since the final G2.

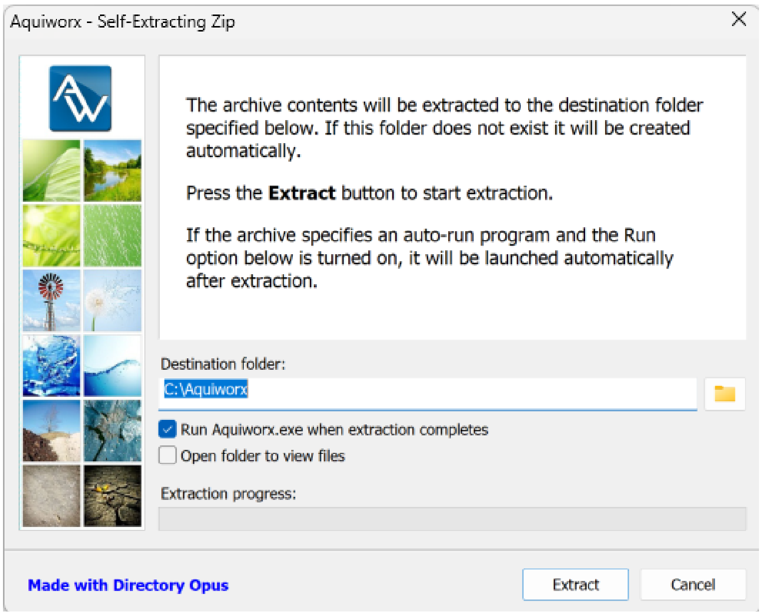

Figure 1: G2 self-extracting executable used for software deployment

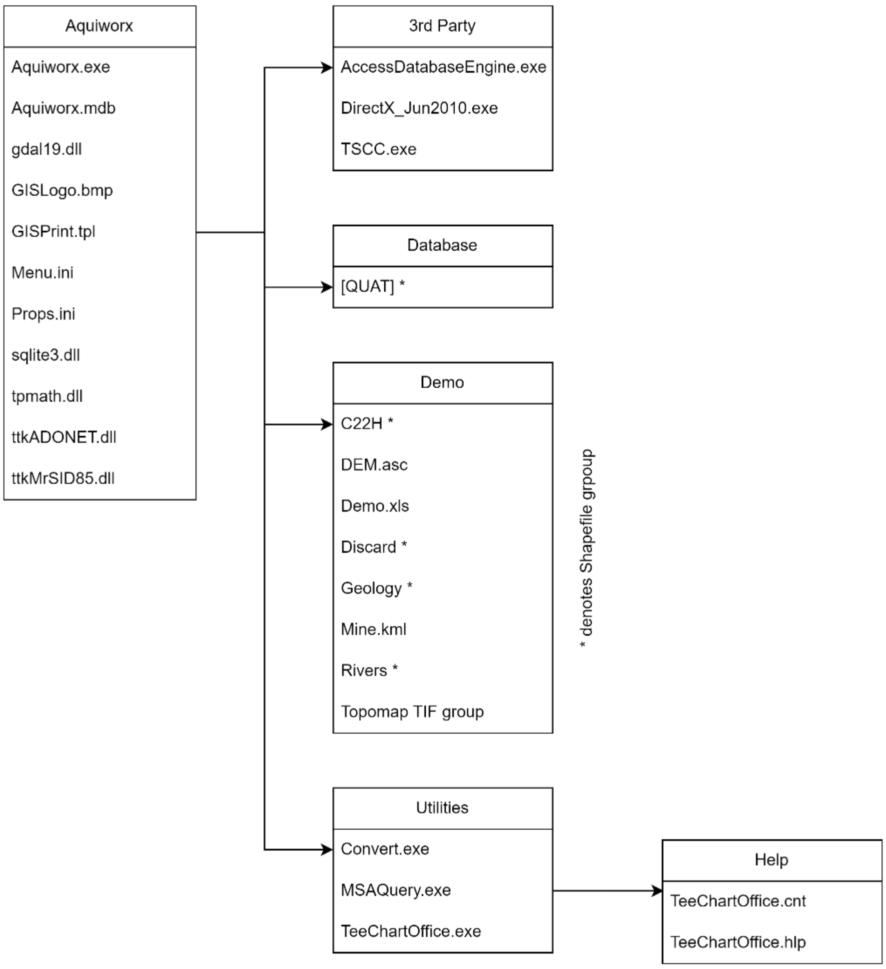

Figure 2: G2 deployment directory structure

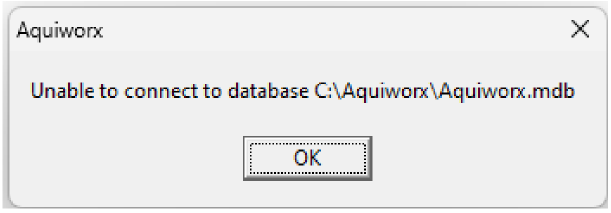

Figure 3: G2 error message related to missing MS Access driver

As summary of the deployed directory structure and associated content is presented in Table 4.

Table 4: G2 folder structure summary

Directory	**Contents**
Aquiworx	Aquiworx.exe → Main executable Aquiworx.mdb → Local database housing WR2005 data GISLogo.bmp → Logo displayed on printed GIS map GISPrint.tpl → GIS printing template *.ini → Ribbon component settings *.dll → Library files required for GIS component
3rd Party	AccessDatabaseEngine2007.exe → MS Access Driver DirectX_Jun2010.exe → Drivers for 3D functionality of GIS TSCC.exe → Installation of screen capture Codec for video help
Database	[QUAT] Shapefile group → Quaternary shape file used as spatial database for GRAII and WR2005 selected data.
Demo	Demo.xls → Excel user database The remainder of the files are GIS files related to the C22H quaternary catchment.
Utilities	Convert.exe → Unit conversion utility MSAQuery.exe → Access Database Utility used to open *mdb* files created from the Excel user database. TeeChartOffice.exe → Charting component allows for saving of layouts and the TeeChartOffice allows for configuring saved chart layouts.
Help	TeeChartOffice help files.

2.2 Overview of the GUI

2.2.1 Layout of the Main Form

The high level architecture for the current GUI presented in Figure 4 and consists of the following main components:

- *Main Form* – Parent component for all other GUI components.
- *Quick Access Toolbar* – Popup menu that provides access to file functions (project and user database) as well as 3rd party utilities and the help file.
- *Ribbon Style Toolbar* – Main menu for software categorising the software into the following categories:
  - *Spatial* – The spatial toolbar relates to the *GIS Interface* and provide access to map elements, search and export functions.
  - *Monitoring* – The monitoring toolbar relates to the loaded user database and provide access to parameter and date selections as well as evaluation and charting types to visualise the selected parameter in the context of the specified criteria.
  - *Aquifer Yield* – The aquifer yield toolbar provide access to the yield model execution as well as the various output stages in graph format.
  - *Well Field* – The well field toolbar relates to the Cooper-Jacob well field model and provides access to execute the model and visually evaluate the results in a few formats.
  - *Options* – The option toolbar provides access to the settings used in the evaluation functionality mentioned in the preceding bullet points as well as specifying the units in which volumes are expressed.
- *Tab Sheets* – Represents the different data views of the system and they are summarised as follows:
  - *GIS Interface* – This interface allows for the display and thematic rendering of all GIS files. In addition it also allows for creating and editing of both vector and associated attributes. The base layer containing all required in formation on quaternary level is automatically loaded on application start-up. The interface has its own toolbar with the expected GIS related functions for navigation and editing and also features its own status bar displaying the current coordinate system, scale, topographic reference and coordinate.
  - *Graphing* – This tab houses a charting component that is used to display data in chart format where required. The component makes provision for

the usual navigation like pan and zoom. It also features an export function where the user can save the current chart to manipulate it outside of the software for reporting purposes.

  - *Data* – The data tab provides access to the loaded user database and support editing of the data. Once the user database (Excel) is loaded it is converted to a MS Access database which is what is used as the data source and also edited in the data tab.
  - *Log* – The log provide access to the yield model output after the model has been executed. The log also provide the ability to clear, save and open the generated output and a primary and secondary log exits to compare output side by side.
- *Object Tree* – The object tree allows a user to build a scenario making use of selected objects. By default the root object is the *Study Area* which is then further defined making use of available objects. The object popup menu contains functionality to create a scenario or well field, delineation of integrated units of analysis, recharge and baseflow calculation tools and protection zones.
- *Object Inspector* – The object inspector allows access to the properties of any object in the object tree.
- *Main Form Status Bar* – Providing project and database name and a progress bar for lengthy operations.

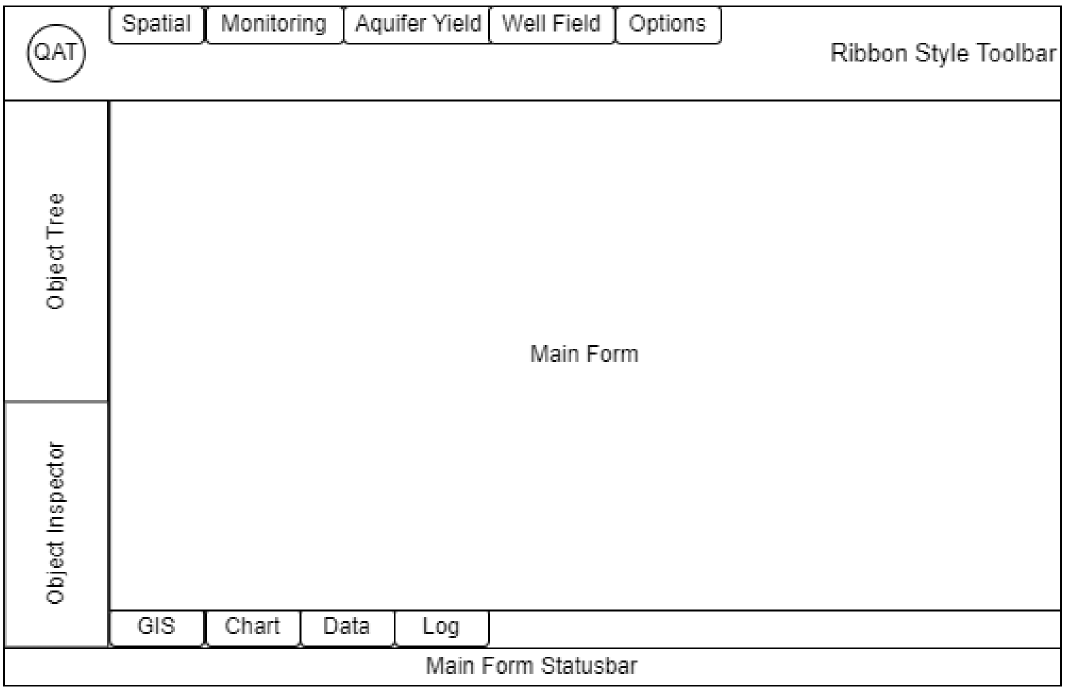

Figure 4: G2 layout of the Main Form in design

2.2.2 Navigating the GUI

Navigation of the GUI takes place through the following components:

- Quick Access Toolbar (see 2.2.1) for accessing file operations, 3rd party utilities and the help system.
- Ribbon Toolbar (see 2.2.1) for selecting the following software categories: *Spatial*, *Monitoring*, *Aquifer Yield*, *Well Field* and *Options*.
- Tab Sheets (see 2.2.1) for switching between data views, each with its own toolbar for navigation. The *Spatial* view has an additional popup menu related to the layer legend of the GIS interface for managing layers and each layer can be double clicked to access thematic rendering and other formatting options.
- Object Tree popup menu that allows the building of the object tree.

2.2.3 High Level Component Interaction

The high level component interaction is depicted in Figure 5. The purpose of this diagram is not to present the flow of information, but merely show the interaction between the major GUI components. At the bottom of the diagram all the databases are listed and will be discussed in a later section.

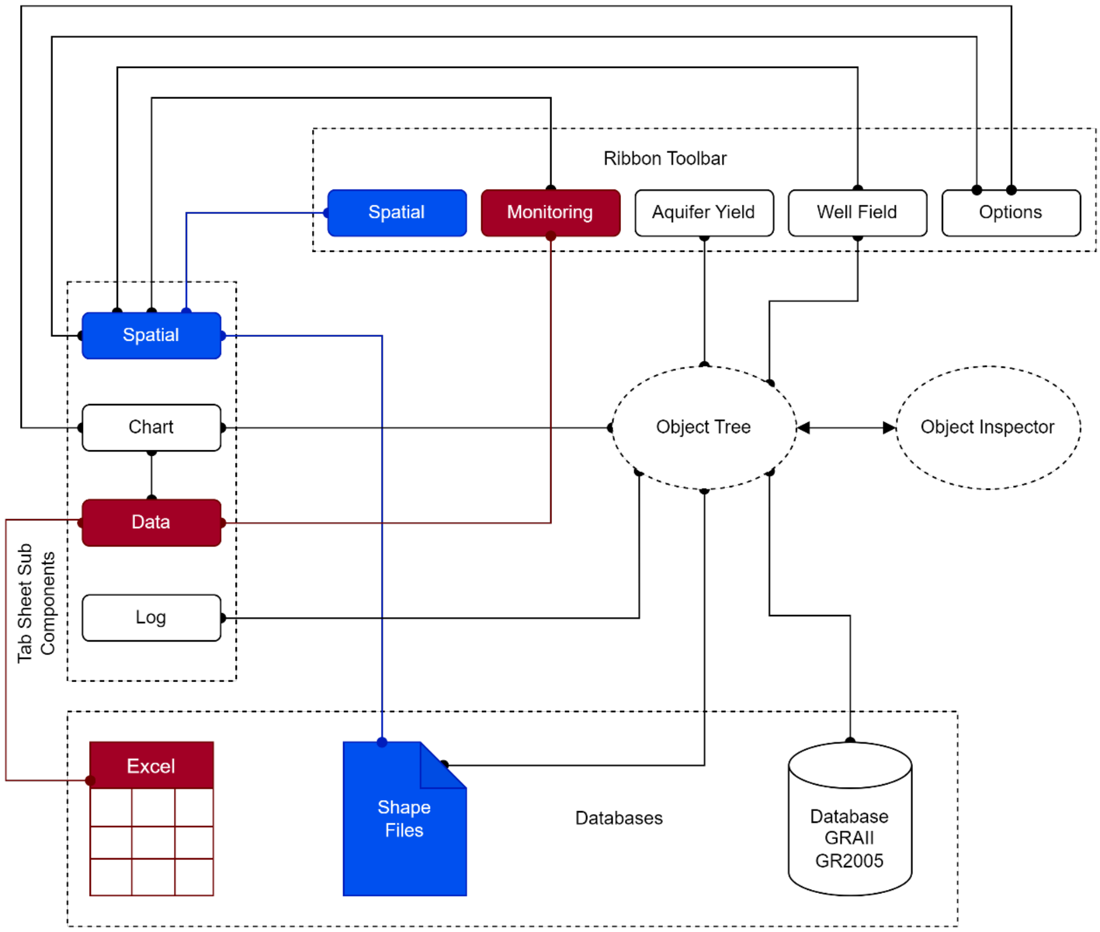

Figure 5: G2 high level component interaction

The majority of the components interact with the object tree (Figure 5), but there are some sub-systems that interact in isolation from the object tree e.g. the monitoring, since monitoring does not explicitly form part of the GRDM methodology and merely serves as an additional source of information when considering the classification component of the GRDM process.

2.3 Development Environment

The development environment used is the Delphi personality of Embarcadero RAD Studio. The reason for the choice in development language was that DWAF at the time standardised on Delphi as the official development language for hydrological and geohydrological software. Since most of these system required a GIS interface a Delphi wrapper was developed around the *ESRI MapObjects Lite* and was known internally as the *GISViewer* component within DWAF. The initial version of G2 was developed using the *GISViewer* component, but later versions made use of a commercial GIS component called *TatukGIS* (www.tatukgis.com) which is written in native Delphi code and had more power than the *ESRI MapObjects Lite* counterpart.

Some off-the-shelf components are used in G2 and Table 5 lists these components and prices quoted are those at the time of this report. Please note that some components are commercial and require a developer licenses, the finished product may be distributed free of any license requirements.

Table 5: G2 off-the-shelf components

Component	**Purpose**	**Price ($)**
TatukGIS Developer Kernel	Provides the GIS interface for G2. A custom wrapper was written around the basic GIS methods, to standardise the interface along the lines of the previous GISViewer component.	$3500*
Steema TeeChartPro	Charting component allowing saving and editing of charts. Delphi ships with the standard version, but the pro version is used since it allows for chart configuration both in runtime and on saved charts.	$600
JAM Software Virtual Tree View	A visual tree view component that represents the object tree. It can handle very large trees and the size of the tree does not have to be known upfront, thus making use of dynamic memory allocation. The tree view is streamed to a file which saves all objects and associated properties which constitutes the GRDM project file.	Free
Bergsoft NextInspector	A visual component that can display all the properties of an object in the object tree. This component serve as the editor or input dialog for all the objects comprising the object tree.	$110
DevExpress Toolbars	A component set that provides a ribbon style toolbar that can be styled, that provide a modern look and feels similar to the new Microsoft Office style toolbars.	$1500*

* Note, initial purchase cost is indicated and annual renewals are substantially lower once purchased

The Main Form layout of the finished product, making us of the specified components, is presented in Figure 6.

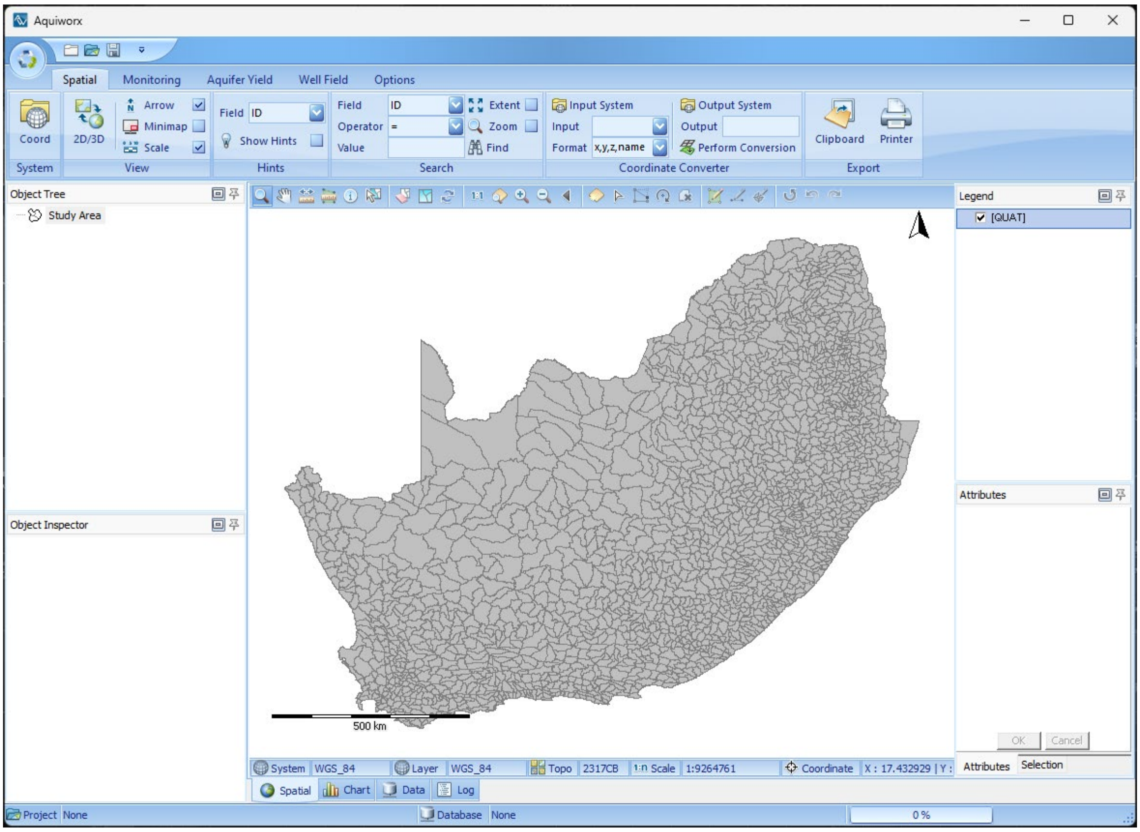

Figure 6: G2 Layout of the Main Form in the actual application

2.4 Database Design

In Figure 5 the three databases are shown that can interact with the system and they will be discussed in this section.

2.4.1 Local Database

The local database is defined as the MS Access relational database containing the WR2005 time series rainfall and naturalised flow data together with the SANS 241:2015 water quality standard.

The time series rainfall was determined for each quaternary catchment through the WR2005 project by using available rain gauges and statistically determining a historic representative rainfall for each quaternary catchment. The naturalized flow for each quaternary is also determined through the WR2005 project by performing rainfall runoff modelling for each quaternary catchment which is calibrated against observed flow gauging. After calibration all anthropogenic features e.g. dams are removed from the model and the model is re-run to obtain the runoff response of the natural catchment i.e. naturalized flow.

The database consist of the tables listed in Table 6 and the table definitions are given in Table 7 to Table 9.

Table 6: G2 local database tables

Table Name	Description
Standard	This table contains the drinking water guidelines based on the SANS 241:2015 standard used to evaluate the monitoring data contained in the user database.
WR_Flow	This table contains the monthly naturalized flow for each quaternary from 1920 to 2005. This data is required for baseflow separation on quaternary catchment level.
WR_Rain	This table contains the monthly rainfall percentages as it relates to the MAP of each quaternary catchment. The MAP is found using the Rain Zone parameter which is present in the spatial database.

Table 7: G2 Standard table

Field Name	Type	Description
Parameter	Text	Parameter official chemical symbol
LongName	Text	Descriptive name of chemical constituent
ShortName	Text	Short name of chemical constituent
Unit	Text	Official unit of measurement
RecLow	Float	Recommended lower standard
RecHigh	Float	Recommended upper standard
AbsHigh	Float	Absolute upper standard
AbsLow	Float	Absolute lower standard

Table 8: G2 Rainfall table

Field Name	Type	Description
YEAR	Integer	Historic year
ZONE	Text	Rain Zone
PER_OCT	Float	Percentage monthly rainfall of MAP for October
PER_NOV	Float	Percentage monthly rainfall of MAP for November

PER_DEC	Float	Percentage monthly rainfall of MAP for December
PER_JAN	Float	Percentage monthly rainfall of MAP for January
PER_FEB	Float	Percentage monthly rainfall of MAP for February
PER_MAR	Float	Percentage monthly rainfall of MAP for March
PER_APR	Float	Percentage monthly rainfall of MAP for April
PER_MAY	Float	Percentage monthly rainfall of MAP for May
PER_JUN	Float	Percentage monthly rainfall of MAP for June
PER_JUL	Float	Percentage monthly rainfall of MAP for July
PER_AUG	Float	Percentage monthly rainfall of MAP for August
PER_SEP	Float	Percentage monthly rainfall of MAP for September

Table 9: G2 Flow table

Field Name	**Type**	**Description**
YEAR	Integer	Historic year
NAME	Text	Name of quaternary catchment
VAL_OCT	Float	Mm^3/month flow for October
VAL_NOV	Float	Mm^3/month flow for November
VAL_DEC	Float	Mm^3/month flow for December
VAL_JAN	Float	Mm^3/month flow for January
VAL_FEB	Float	Mm^3/month flow for February
VAL_MAR	Float	Mm^3/month flow for March
VAL_APR	Float	Mm^3/month flow for April
VAL_MAY	Float	Mm^3/month flow for May
VAL_JUN	Float	Mm^3/month flow for June
VAL_JUL	Float	Mm^3/month flow for July
VAL_AUG	Float	Mm^3/month flow for August
VAL_SEP	Float	Mm^3/month flow for September

2.4.2 Spatial Database

The spatial database refers to the base layer shape file that is loaded when the software starts up and the shapefile name is [QUAT] (see Figure 2). All layer names encapsulated in square brackets are deemed to be system managed layers and a user cannot remove it from the GUI. The [QUAT] layer also falls in this category as it is required to provide default values for various objects in the object tree. The main data sources used to populate the spatial database is the GRAII, WR2005 and AFYM , but other data sources are also used. The attributes associated with each quaternary is presented in Table 10 with a description of each attribute.

Table 10: G2 spatial database ([QUAT] shapefile)

Field Name	Type	Description	Data Source
NAME	Text	Quaternary catchment name	DWS
WMA	Text	Water Management Area	DWS
ZONE	Text	Rain Zone	WR2005
AREA_KM2	Float	Quaternary area (km^2)	DWS
LEVEL_MBGL	Float	Average groundwater level (mbgl)	NGA
DSL_M	Float	Dead Storage Level (m)	AFYM
S_YIELD	Float	Specific yield	GRAII
USE_LPS	Float	Existing ground water use (L/s)	WARMS
RE_LIM_MM	Float	Recharge limit (mm)	AFYM
RE_DEF_PER	Float	Default recharge percentage	GRAII
RE_GRA_PER	Float	GRAII recharge percentage	GRAII
MAP_MM	Float	Mean Annual Precipitation	WR2005
MAR_MM	Float	Mean Annual Runoff	WR2005
MAE_MM	Float	Mean Annual Evaporation	WR2005
BF_DEFAULT	Float	Default baseflow value (Pitman) (Mm^3/a)	WR2005
BF_HUGHES	Float	Hughes modelled baseflow value (Mm^3/a)	WR2005
BF_PITMAN	Float	Pitman modelled baseflow value (Mm^3/a)	WR2005
BF_SCHULTZ	Float	Schultz modelled baseflow value (Mm^3/a)	WR2005
BF_VTONDER	Float	Van Tonder estimated baseflow (Mm^3/a)	-

NOFLOW_PER	Float	Percentage no-flow of river	WR95
ET_EXT_M	Float	Evapotranspiration (ET) extinction depth	AFYM
ET_RIP_PER	Float	Percentage of riparian zone for ET	AFYM
ET_JAN_MM	Float	ET (mm/month) for January	AFYM
ET_FEB_MM	Float	ET (mm/month) for February	AFYM
ET_MAR_MM	Float	ET (mm/month) for March	AFYM
ET_APR_MM	Float	ET (mm/month) for April	AFYM
ET_MAY_MM	Float	ET (mm/month) for May	AFYM
ET_JUN_MM	Float	ET (mm/month) for June	AFYM
ET_JUL_MM	Float	ET (mm/month) for July	AFYM
ET_AUG_MM	Float	ET (mm/month) for August	AFYM
ET_SEP_MM	Float	ET (mm/month) for September	AFYM
ET_OCT_MM	Float	ET (mm/month) for October	AFYM
ET_NOV_MM	Float	ET (mm/month) for November	AFYM
ET_DEC_MM	Float	ET (mm/month) for December	AFYM
RD_POP	Float	Population figure	Census 2001
RD_BHN_LPD	Float	Basic Human Need (L/p/d)	NWA
RD_DEP_PER	Float	Percentage groundwater dependency	-
RD_PSC	Char	Present Status Category	G1

2.4.3 User Database

The user database comprise of an Excel spreadsheet with a predefined structure. This structure is narrowly aligned with that of the WISH system, but are not 100% identical. Due to the similarity in file formats it will not take a user long to convert from one format to another. The provided *Demo.xls* (Figure 2) file is typically used as a template for users to capture their own data.

The user database contains the tables listed in Table 11 and in the Excel spreadsheet each of these tables are represented by a sheet and the table name is the sheet name. All sheet names starting with *Site* indicates site specific data and all sheet names starting with *Time* indicates that it is timeseries data that is recorded in the table. It is important that sheet names and column headings comply 100% with the format specified to ensure error free operation. A user may omit a sheet if not used.

Table 11: G2 user database tables

Sheet Name	Description
Site Info	Contains the site related information e.g. position and type.
Site Standard	User can define a custom standard for a parameter. If a custom parameter is detected, the standard for the parameter in the local database will be ignored and the custom standard applied in evaluation.
BH Info	Contains borehole (aquifer) related parameters required for the well field model to operate.
Time Waterlevel	Contains the time series water level associated with a site.
Time Rainfall	Contains the time series rainfall associated with a site.
Time Flow	Contains the time series flow associated with a site.
Time Discharge	Contains the time series discharge associated with a site.
Time Chemistry	Contains the time series chemistry associated with a site.

The table field definitions for all site related tables is presented in Table 12 and Table 13. The *Site Info* table is used to visualize the spatial distribution of the sites within the GIS system and the *Site Standard* table is used to specify any custom standard associated with a specified site.

Table 12: G2 *Site Info* table

Field Name	Type	Description
SiteName	Text	Unique sitename (may not have spaces in name)
AltName	Text	Alternative name (not in use)
Xcoord	Float	X-coordinate or Longitude of the site
Ycoord	Float	Y-coordinate or Latitude of the site
Zcoord	Float	Z-coordinate or Elevation (mamsl) of the site
SiteType	Char	(B)orehole; (S)urface Site; (R)ain Gauge; (F)low Gauge
Standard	Text	Name of standard specified in *Site Standard* sheet
Comment	Text	Any comment the user want to add – field not used anywhere

Table 13: G2 *Site Standard* table

Field Name	**Type**	**Description**
Standard	Text	Standard name
Parameter	Text	Parameter to which standard belong e.g. SO4 mg/L
AbsLow	Float	Absolute lower standard
RecLow	Float	Recommended lower standard
RecHigh	Float	Recommended upper standard
AbsHigh	Float	Absolute upper standard

All the time series data sheets with the exception of *Time Chemistry* are presented in Table 14 to Table 17 where each of the sheets only differ in the parameter measured.

Table 14: G2 *Time Waterlevel* table

Field Name	**Type**	**Description**
SiteName	Text	Unique sitename related to *Site Info* sheet
DateTimeMeas	DateTime	Date and time measurement was taken
WaterLevel mbgl	Float	Measured waterlevel (mbgl)
Flag	Char	Field not in use
Comment	Text	Comment the user want to add

Table 15: G2 *Time Rainfall* table

Field Name	**Type**	**Description**
SiteName	Text	Unique sitename related to *Site Info* sheet
DateTimeMeas	DateTime	Date and time measurement was taken
Rainfall mm	Float	Measured monthly rainfall (mm)
Flag	Char	Field not in use
Comment	Text	Comment the user want to add

Table 16: G2 *Time Flow* table

Field Name	**Type**	**Description**
SiteName	Text	Unique sitename related to *Site Info* sheet
DateTimeMeas	DateTime	Date and time measurement was taken
Flow m3	Float	Measured monthly flow (m^3)
Flag	Char	Field not in use
Comment	Text	Comment the user want to add

Table 17: G2 *Time Discharge* table

Field Name	**Type**	**Description**
SiteName	Text	Unique sitename related to *Site Info* sheet
DateTimeMeas	DateTime	Date and time measurement was taken
Discharge m3	Float	Measured monthly discharge flow (m^3)
Flag	Char	Field not in use
Comment	Text	Comment the user want to add

The *Time Chemistry* sheet field definitions specified in Table 18 is the only sheet that allows some flexibility in the fields specified as not all chemical parameters would be analysed for each study conducted. Sites contained within the same study could also differ in parameters analysed which leads to fields where no data would exist. In such a case a value of -1 is entered into the field so that the software recognise no data is available for that specific parameter at that point in time.

Users can add and remove fields as required but the *SiteName*, *DateTimeMeas* and at least one parameter must be present. Since the Piper plot requires certain parameters to be present, Table 18 is used to show the minimum parameter set required for the generation of the Piper diagram and the fieldname order is not important.

Table 18: G2 Time Chemistry table

Field Name	**Type**	**Description**
SiteName	Text	Unique sitename related to *Site Info* sheet
DateTimeMeas	DateTime	Date and time measurement was taken
MAlk mg/L	Float	Methyl Orange Alkalinity (mg/L)
PAlk mg/l	Float	Phenolphthalein (mg/L)
Ca mg/L	Float	Calcium (mg/L)
Cl mg/L	Float	Chloride (mg/L)
Mg mg/L	Float	Magnesium (mg/L)
NO3 mg/L	Float	Nitrate (mg/L)
K mg/L	Float	Potassium (mg/L)
Na mg/L	Float	Sodium (mg/L)
SO4 mg/L	Float	Sulphate (mg/L)

The field definitions for the BH Info sheet is presented Table 19.

Table 19: G2 *BH info* table

Field Name	**Type**	**Description**
SiteName	Text	Unique sitename related to *Site Info* sheet
Collar m	Float	Collar height of the borehole (m) (not in use)
S	Float	Storativity of the aquifer
T m2/d	Float	Transmissivity of the aquifer (m^2/d)
Abstraction L/s	Float	Abstraction associated with the borehole (L/s)
Time days	Float	Time of pumping in days
Comment	Text	

2.5 System Functionality

The system functionality is described in this section on a high level only, highlighting key functionality of the G2 system design. This is accomplished making use of Unified Modelling Language (UML) which include Use Case, Class and Sequence diagrams which will be discussed in more detail in the sections that follow. A quick reference to the UML is available in Appendix A.

2.5.1 Use Case Diagrams

Two Use Case diagrams are presented to reduce complexity and make the diagrams readable. The diagrams of the G2 system are presented in Figure 7 and Figure 8 respectively where Figure 7 describes the overall system, but does not explicitly address the Spatial and Monitoring functionality. Figure 8 is dedicated to only the Spatial and Monitoring functionality. The combination of the aforementioned Use Case diagrams describe the G2 system in its totality.

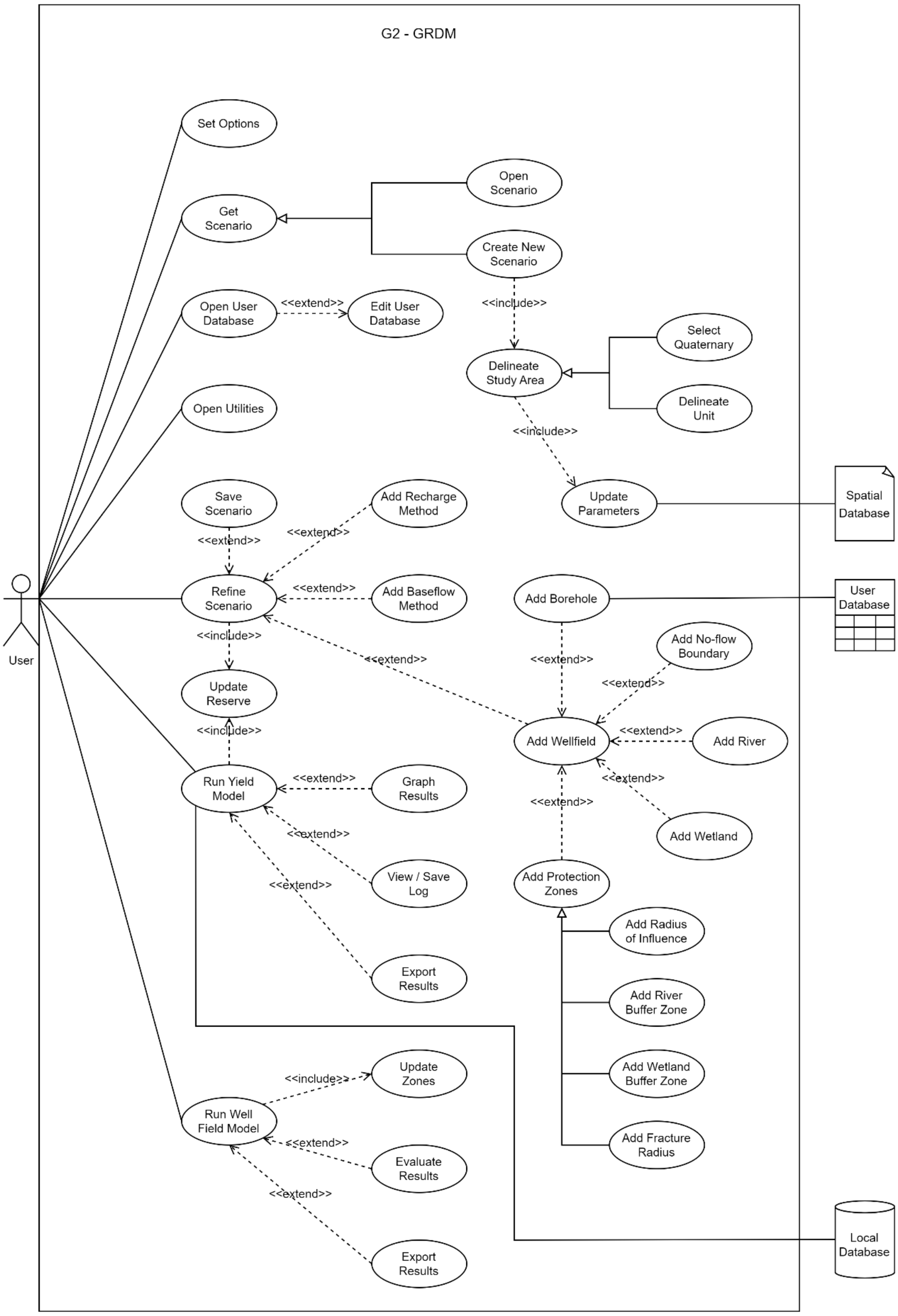

Figure 7: G2 Use Case Diagram (excluding Spatial and Monitoring functionality)

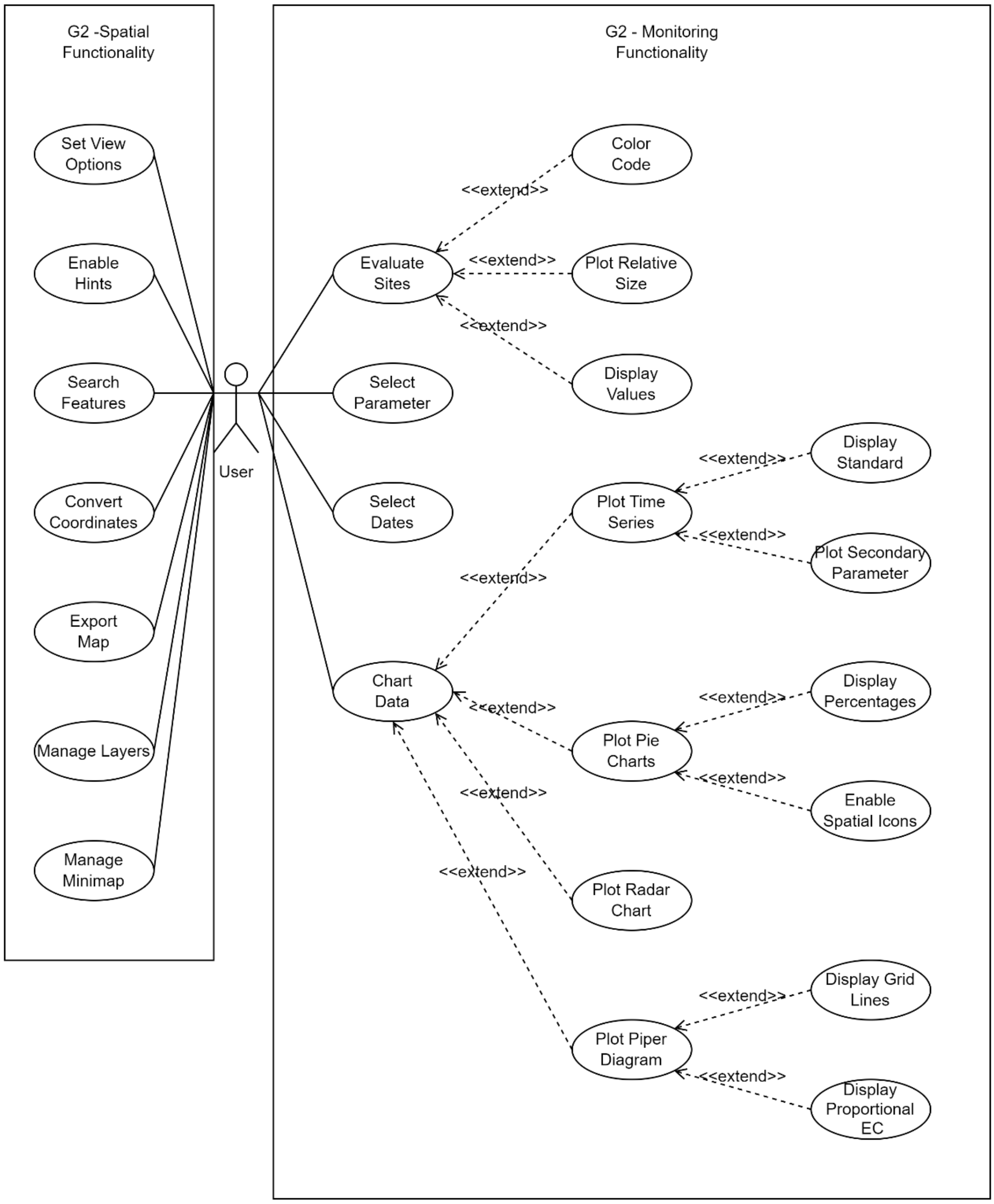

Figure 8: G2 Use Case Diagram for Spatial and Monitoring functionality

2.5.2 Class Diagrams

The class diagram showing the abstraction for each object from the base object is presented in Figure 9. The purpose of the base object is to provide the properties and methods required for exitance in the object tree. Since all objects, with exclusion of some as indicated in Figure 9, inherit from the base object, these are explicitly accounted for in the object tree. The hierarchical layout of Figure 9 represent the level and immeadiate parent object for each object as it exixts in the object tree. This hierarchical structure is enforced in the software through a rule set and menu system that only allows the user to add certain objects to certain parent objects.

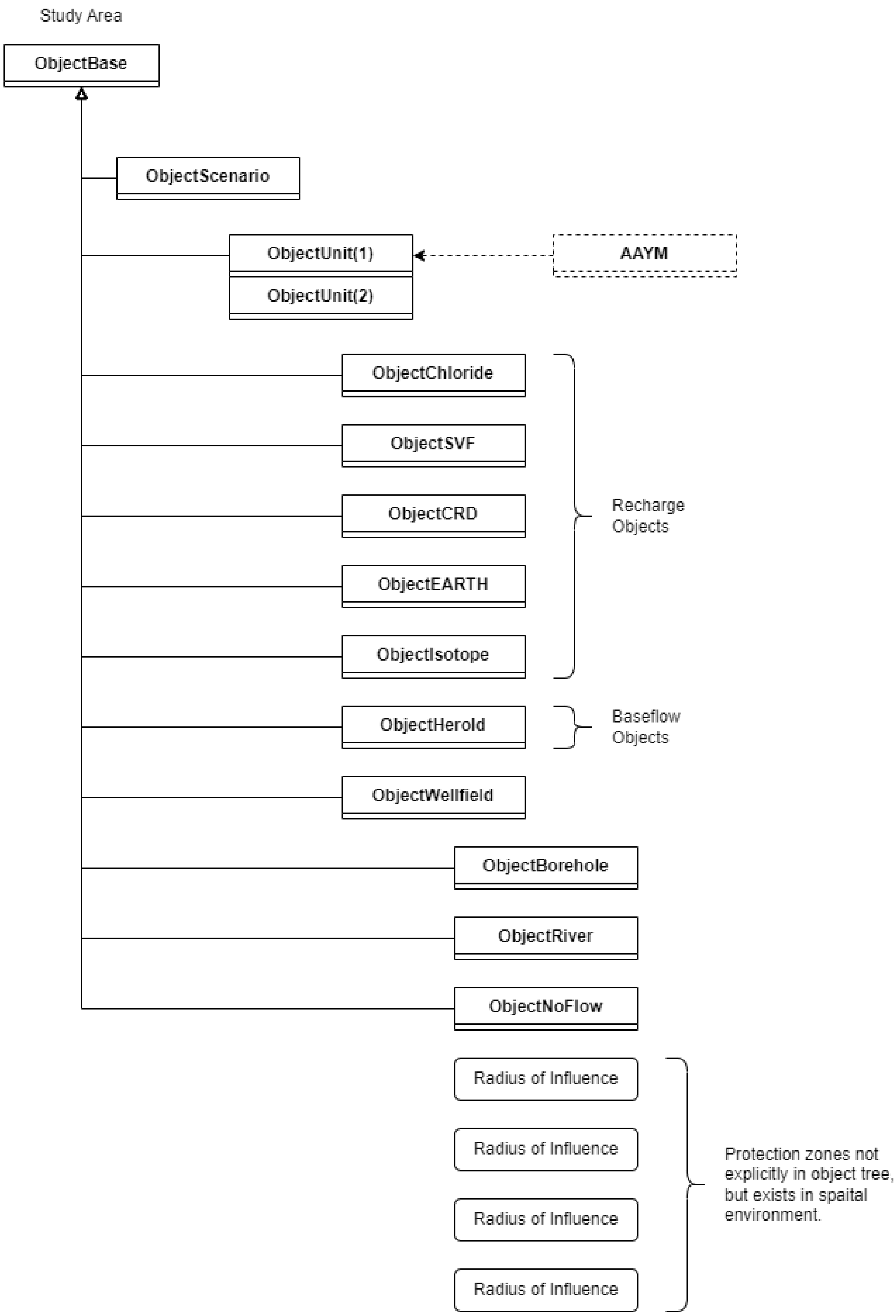

Figure 9: G2 Class Diagram for Spatial and Monitoring functionality

The purpose of ObjectUnit1 and ObjectUnit2 is to represent delineations based on quaternaries and custom delineations respectively. It should be noted that each of the aforementioned objects also contain the underling aquifer yield model as shown in Figure 9 and that the AAYM is not represented by a physical node in the object tree.

2.5.3 Sequence Diagrams

The sequence diagram presented in Figure 10 is used only to explain the various database access through the execution of the application.

The spatial database in the form of a shape file is loaded on start-up of the application and will reside in memory for the duration while the application is executed. This spatial database contains default information required by the *Quaternary* and *Integrated Unit of Analysis* objects. If this database cannot be loaded the application will terminate.

The local database comprise of a MS Access database and a connection to this database is established during start-up. Once again if the connection fail the application will terminate. The success of this connection depends both on the existence of the actual database file as well as the existence of the supporting driver. The database is only queried if time series rainfall or flow is required for a quaternary or when chemical evaluation is done against a standard. If the query fail an error message is displayed indicating the source of the problem.

Finally a user database is loaded only when this functionality is executed by the user. The user database comprise of monitoring data captured by the user in an Excel file. Once the Excel file is successfully read, it is converted into a MS Access database and a connection is established to the newly created database, which is then also considered a local database. The same rules then apply for a local database. Failure to read the Excel file will result in an error message.

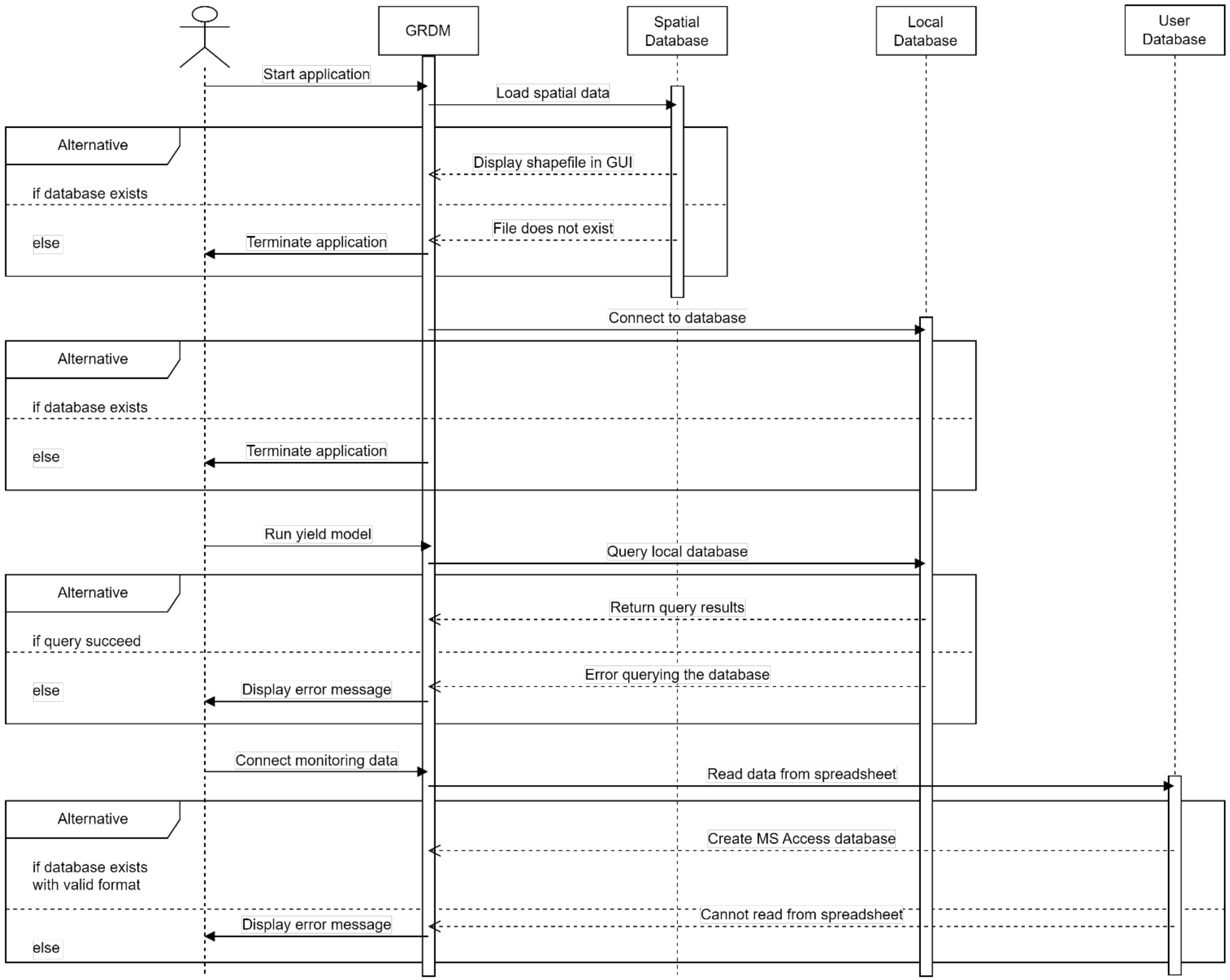

Figure 10: G2 Sequence Diagram for Spatial and Monitoring functionality

Chapter 3 Gap Analysis

3.1 Introduction

A gap analysis, whether it pertains to software applications or departmental objectives is about taking a realistic snapshot of where something is at the current moment and comparing it against where it should be. The difference, or gap, that resides in the middle helps you to understand what needs to happen in order to move from one point to the next. Various workshops where existing users of the GRDM system were engaged were held for the purpose of the gap analysis. The feedback from users were used to compile a list of issues they experience with the existing software generation and this was used to create an action list for targeting specific functionality that needs to be addressed. These are discussed in the next section.

3.2 Analysis of Identified Issues

After consultation with the existing and future users through workshop platforms, the identified issues and requests were categorised into four classes as shown in Table 20.

Table 20: Classification of identified issues

Category	Description
1. Software Enhancement	Enhancement of existing functionality or bug fix required in G2.
2. New Functionality	New functionality required i.e. new methods or change in existing methodology required.
3. Out of Scope	These requests are considered out of scope of this project, but will added to recommendations.
4. Existing Functionality	This is functionality that already exists in G2 and users might not have been aware of it – relates to training of software. Alternatively the issue is already addressed in one of the other categories.

Table 21 to Table 24 provides a summary of the identified list together with the comments from the software development team. All category 4 items were illustrated to the project team that they do in fact exist in the G2.

Table 21: Software functionality to enhance

No	Software Issue Identified	Comments
1	In the current software version, the database requires Microsoft Access Drivers that cannot coexist with newer Office versions such as 365. Thus, the need to migrate to a new database.	Migrating to SqlLite.
2	In the updated version, the interface needs to change to "green" to distinguish it from the Aquiworx blue personality. This is ensuring that users see the change get used to the new change.	Green personality will be assigned to G3.
3	Sometimes the software does not display all the boreholes on the map when imported with the spreadsheet e.g., if you import 8 boreholes only 6 are displayed.	Would be helpful to get dataset that does this. A borehole name are not allowed to have a space in it, maybe it might be such an issue? Testing will be done with provided data.
4	The software should allow for export of the final map.	Image format already supported, will look into PDF format.
5	The software must be stable before release; the PSP shall therefore provide 12 months GRDM software maintenance and technical support services, after the completion of the GRDM software enhancements aspects of the project.	Beta testing will be conducted making use of provided case study. The same case study will form the basis for training workshops and help material.
6	Update GRDM GUI making use of FNC Components.	Proposed by the developer as G2 made use of DevExpresss components and no existing license exists. The developer has a FNC license and these components are web ready as well.
7	The WR2005 data should be replaced by the WR2012 data as this is the most recent dataset.	This requires 450 rainfall text files to be processed and 1946 flow files. Might be worth while writing a program or script to do the processing as it will take quite a bit of time doing it by hand.
8	Update census data.	Research team to provide dataset per quaternary for database update.
9	Update of existing use data (WARMS).	Research team to provide dataset per quaternary for database update.
10	The total Reserve calculation must be re-visited. The calculation should be BHN + GW_{bf} or BHN + EWR_{gw}. Currently the equation appears to add BHN + Baseflow.	The GW_{bf} can be obtained from Herold's method. The EWR_{gw} are not readily available for each quat, but it can be included so that the user specify this.

Table 22: New functionality required

No	Software Issue Identified	Comments
11	Quaternary catchment delineation which is more related to surface water than groundwater which behaves differently. It is recommended to consider aquifer delineation or rather groundwater resource units.	Since the G2 already account for custom delineation of groundwater units, maybe the underlying water balance model requires a new approach. Research team to document new methodology for implementation. The existing Assured Aquifer Yield in the G2 version of the GRDM is presented in Appendix B.
12	The need new methods for groundwater contribution to baseflow.	Currently software supports Herold's method and a mass-balance approach. Research team to document new methodology for implementation.
13	The inclusion of help files or frequently asked questions or prompts during the process that give users tips and pointers or advice regarding tabs they have selected.	Video help tutorials will be created and a FAQ Blog/User Group will be established.
14	The need to provide a comprehensive analysis of water quality.	Research team to document new methodology for implementation.
15	Revisit the formats of various outputs of the software in order to align them with the formats used by the DWS team to report on groundwater Reserve, e.g., Reserve template Tables, maps and their Legends to follow the DWS specifications.	Research team to document new methodology for implementation.
16	Default Chem values using Vegter Maps	Research team to provide dataset per quaternary for implementation.

Table 23: Out of scope requests

No	Software Issue Identified	Comments
17	The need to add an overlaying quaternary map on the map of aquifer types.	The system GIS already makes provision for this and the user can import the groundwater occurrence map. No aquifer map exists for South Africa and it does not fall within the scope of this project to create such a map.
18	Explore the possibility of linking GRDM to the existing and relevant DWS databases as this will ensure use of up-to-date data as it is updated in a given database.	Various databases exist that provide valuable information to the GRDM, these include, WR2012, GRAII, NGA, GRIP, WARMS, DWS Hydrological Services and DWS Resource Quality Services. None of them provide a public interface through which programmatic queries could be directed to obtain the data. An interim solution to have programmatic queries be executed on some of these databases is web scraping, but it should be noted that if any format change takes place on the targeted platform, the web scarping will fail and will have to be adapted. The optimal solution is that each database provide an API to access the required data via the internet.
19	The software should be continuously updateable as new data and information become available. For instance, as new Recharge values become available with various research studies, so these must be editable to replace the old ones from e.g., GRA II.	This only requires the database to be updated. As the current database is local users will only see the updated values if they download an update of the software. An online database is a possibility, but falls outside the scope of this project.
20	Quality characterisation plots must be expanded and not only limited to Piper and Radar charts.	This is not considered as part of the scope of the project unless it is explicitly required by the updated methodology.

Table 24: Functionality already existing

No	Software Issue Identified	Comments
21	The Quaternary shape file containing the base data needs to be updated as it mainly contains the Groundwater Resource Assessment II (GRAII) data.	The GRAII data has not been updated since the release of the project, so there is no new data in GRAII. If a newer dataset can be provided, the shapefile can be updated.
22	Quaternary catchment delineation which is more related to surface water than groundwater which behaves differently. It is recommended to consider aquifer delineation or rather groundwater resource units.	Already supported in G2.
23	The need to capture recharge values per aquifer delineation.	Already supported in G2.
24	The need for specifics about the river where the baseflow comes from.	Current values are representative of quat and obtained from WR2012.
25	Automation of the addition of shapefiles.	Import function does exist and can be automated. The GRDM cannot distribute DWS product without permission. Users must contact data owners and get permission for use.
26	The need to simplify the current 15 steps process for desktop study for delineation.	Current delineation process is not 15 steps. All GRDM steps work in the context of the object tree and therefore steps cannot be reduced.
27	Estimation of groundwater contribution to baseflow. Currently, it seems only the baseflow is considered.	See point 12.
28	The software does not indicate the river from which the baseflow was estimated and its geographical location. It further does not show the name and location of the flow station.	See point 7.
29	The software needs to enable the user to add a hydrological station and upload its data such that this can be included in baseflow separation.	Already supported in G2.
30	Recharge values need to be presented as volumes instead of percentages.	Already supported in G2.
31	It is not readily clear how the issue of groundwater-surface water interaction is handled in the software. This needs to be elucidated.	See point 12.

32	Groundwater quality component methodology needs to be re-conceptualised. This involves coming up with the appropriate way of assessing and presenting quality considering the difficulty of presenting it at a catchment scale. For instance, if there are two boreholes in one catchment, and one has good quality water whilst the other has bad quality water, the Reserve class for the catchment would follow that of bad quality, which might not be applicable to the user who is located in the vicinity of a good quality water borehole.	Please provide methodology to implement. See Point 14.
33	There is a scaling up of the groundwater quality Reserve by 10% provided it is not more than the basic human needs quality Reserve but there is no scientific basis or a definition for such allowance. Additionally, there is setting of the 5th and 95th percentiles that are used for the groundwater quality, however, it is not defined as to when these percentiles are applicable.	See point 14.
34	Layers are not readily available or are hidden, and shapefiles have to be uploaded manually.	See point 25.
35	The software uses WR90 for estimation of baseflow using the Herold method. It is recommended that it uses WR2012, possibly where resource data and information has been enhanced.	See point 7.
36	A toolbox approach should be followed where a software user is able to interrogate the output parameters for a given area, and not use a rigid algorithm.	The toolbox approach is already supported in G2, not sure what is meant with the comment on “a rigid algorithm” as all calculations are indeed based on rigid algorithms.
37	If the output result does not make sense, the user should be able to work through it and come up with a scientifically acceptable result.	Is this a software or user issue? This comment is disregarded.
38	The software must be user-friendly, and it must be able to give a model report in a pre-determined template format.	Please specify which parts are not user-friendly and how this can be improved. See Point 15.

3.3 Implementation of Identified Issues

All new functionality requires the relevant documentation of the approach from the research team and these are presented in the Appendix C and Appendix D respectively. The documentation of the exiting objects available in the G2 version of the GRDM comprising the object tree is presented in Appendix D.

Some of the software enhancements require changes to the software or database structures and these are accounted for in the next chapter where the updated system is discussed.

Chapter 4 Updated System Design

This chapter will highlight only the changes that were made to the G2 version. If not explicitly addressed in this chapter, the design remained unchanged and details are available in Chapter 2.

4.1 Software Deployment

Software deployment takes place through an installer to ensure that all files are deployed correctly and that an application icon is created for the user in the Windows menu system. Administrator rights are required to install the software to the target PC and the relevant Microsoft Office drivers are required since the user database is in a Microsoft Excel format.

The software is released in two flavours; 32bit for older operating systems and a 64bit version for newer operating systems. The installer automatically selects the correct executable to deploy based on the target operating system.

The user, however, must ensure that the correct Microsoft Office drivers are deployed if not already exiting on the target operating system. The installer cannot be used to automatically deploy the Microsoft Office drivers based on the target operating system, since a 32bit Microsoft Office version can be run on a 64bit operating system and by automatically deploying the 64bit Microsoft Office drivers will cause a conflict.

On successful installation, the directory structure and associated files are presented in Figure 13. When comparing the directory to that of the G2 structure (Figure 2), it is evident that the Utilities have fallen away since these are redundant in the G3 version.

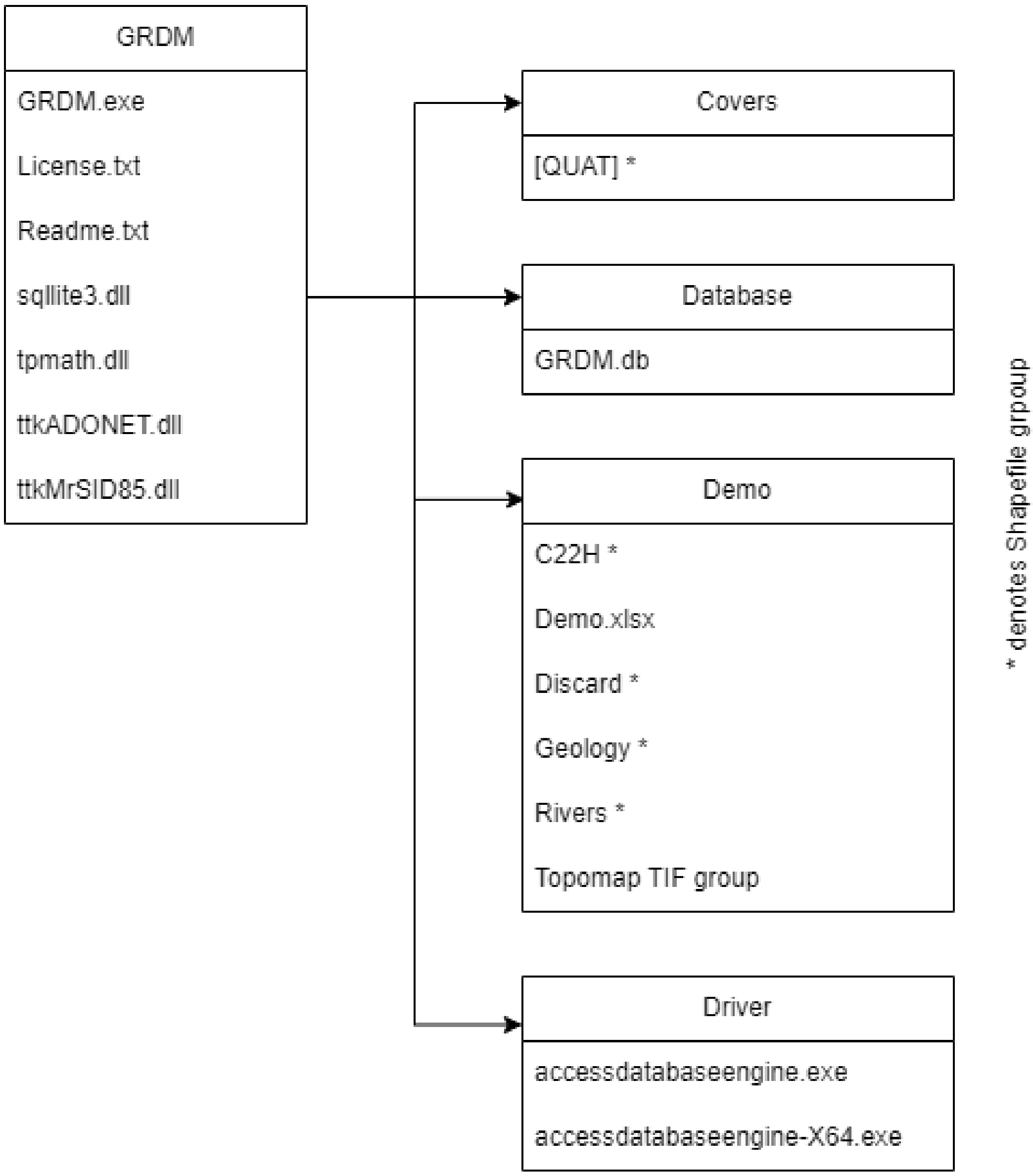

Figure 11: G2 deployment directory structure

4.2 Software GUI

The updated GUI of the GRDM G3 is presented in Figure 12 and the strong resemblance with the G2 version is evident when compared to the general layout of the main form as was presented in Figure 4. The GUI is styled in green to make a clear distinction between the G3 version and the G2 version that was styled inn blue (Figure 6). Due to the similarity between the G2 and G3 version, the navigation of the GUI remains the same as described in section 2.2.2 .

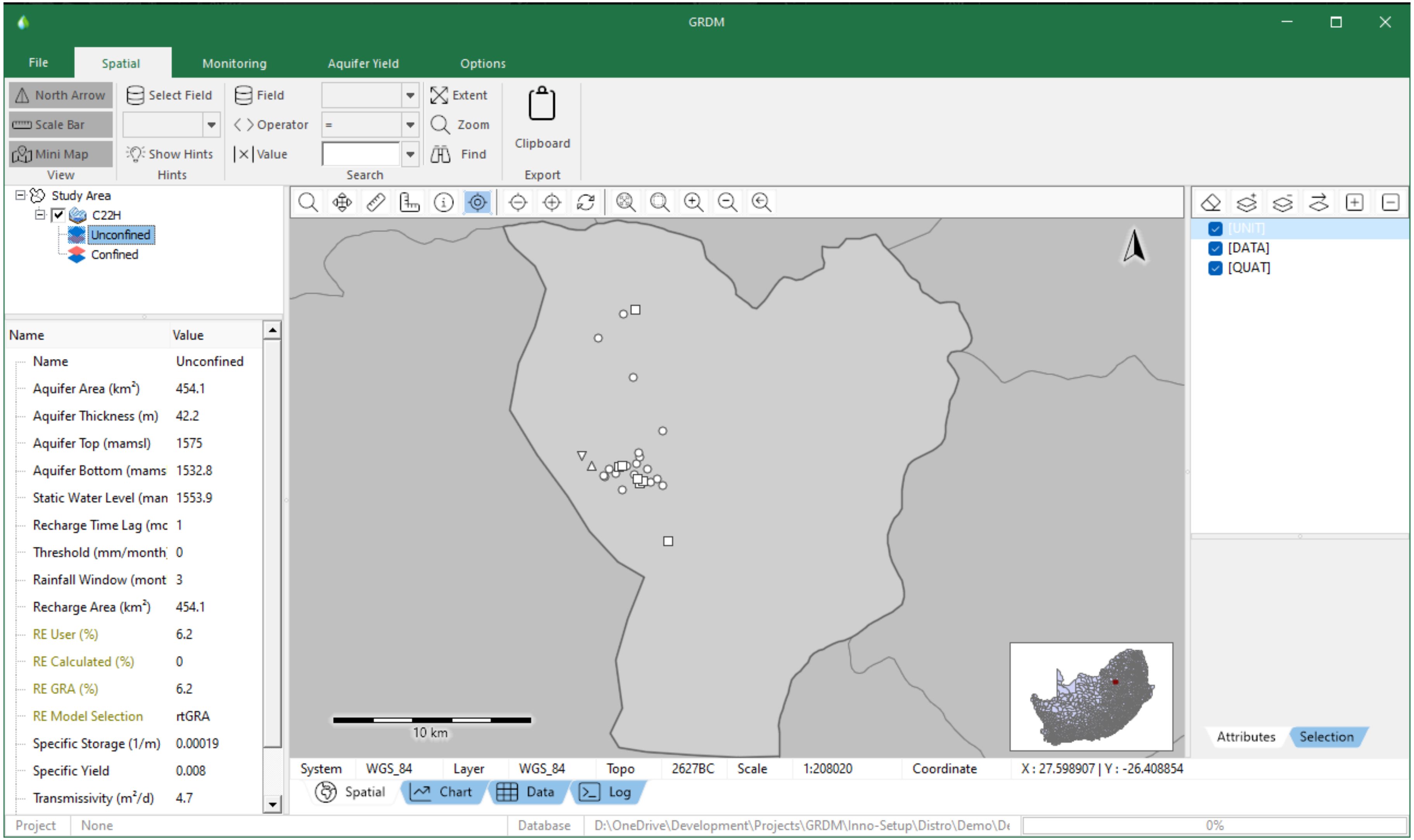

Figure 12: Updated GUI of G3

4.3 Database Design

The overall database design remained generally unchanged. The major differences between the G2 and G3 versions are basically where the data are stored. The following sections provide more detail of the G3 database structure.

4.3.1 Local Database

The local database has been migrated from the G2 Microsoft Access database to the G3 SqlLite database. Table 25 list the table names and provides a description of the contents of each table in the SqlLite database.

Table 25: G3 local database tables

Table Name	Description
flow	This table contains the monthly naturalized flow for each quaternary from 1920 to 2012. This data is required for baseflow separation on quaternary catchment level.
rain	This table contains the monthly rainfall percentages as it relates to the MAP of each quaternary catchment. The MAP is found using the Rain Zone parameter which is present in the spatial database.
quat	This table store quaternary related parameters, previously stored in the spatial database of the G2 version.
standard	This table contains the drinking water guidelines based on the SANS 241:2015 standard used to evaluate the monitoring data contained in the user database.
meta	This table contains meta data of the data stored within the local database for reference purposes.

4.3.2 Spatial Database

The data contained in the spatial database of the G3 version is presented in Table 26. The fields contained in this database have dramatically been reduced and the remaining fields with the exception of the quaternary name is only for reference and information purposes. The parameter values used in calculations are now stored in the local database as discussed in the previous section.

Table 26: G3 spatial database ([QUAT] shapefile)

Field Name	Type	Description
NAME	Text	Quaternary catchment name
MAP	Float	Mean Annual Precipitation
HUGHES	Float	Hughes modelled baseflow value (Mm^3/a)
PITMAN	Float	Pitman modelled baseflow value (Mm^3/a)
SCHULTZ	Float	Schultz modelled baseflow value (Mm^3/a)

4.3.3 User Database

The only change to the user database is the naming of the coordinates in the Site Info table as presented in Table 27. The application expect that all coordinates are presented in geographic coordinates (latitude and longitude) against the WGS84 datum.

Table 27: G3 *Site Info* table

Field Name	Type	Description
SiteName	Text	Unique sitename (may not have spaces in name)
AltName	Text	Alternative name (not in use)
Longitude	Float	Longitude of the site
Latitude	Float	Latitude of the site
Elevation	Float	Elevation (mamsl) of the site
SiteType	Char	(B)orehole; (S)urface Site; (R)ain Gauge; (F)low Gauge
Standard	Text	Name of standard specified in *Site Standard* sheet
Comment	Text	Any comment the user want to add – field not used anywhere

4.4 Database Update

The following database updates were performed as identified in the gap analysis discussed in the previous chapter:

- Census data was updated from the 2001 to the 2022 data. The population count was provided per municipality and this information was spatially processed to yield a composite population count per quaternary catchment.

- The rain zones and naturalised flow data contained in the local database was updated from WR2005 to the latest data available from the WR2012 database.

4.5 System Functionality

4.5.1 Use Case Diagrams

The updated system design has not changed the Use Case diagrams so Figure 7 and Figure 8 also represents the sequence diagram for the updated G3 version of the GRDM.

4.5.2 Class Diagrams

It should be noted that the G2 version supported multiple scenarios in a single project file whereas the G3 counterpart only support a single scenario in each project file. The reason for this is to reduce steps in the process flow when multiple scenarios are not required. Multiple scenarios are now supported through individual project files each associated with a scenario, therefore no functionality lost with this design change.

The changes in the Class diagram is highlighted in green and is presented in Figure 13. A summary of the changes is as follows:

- A dual layer aquifer model was developed to replace the AAYM used in the G2 version (Appendix B).
- The formulation of the aquifer object (Appendix C) is introduced and is of type confined and unconfined and together represent the dual layer model associated with ObjectUnit which act as the parent in the object tree. The dual layer model is built into the ObjectUnit as was the case with the AAYM in the G2 version, but the newly introduced ObjectAquifer source the layer information to the dual layer aquifer model.
- A baseflow calculation method (Appendix E) is introduced based on a water balance approach and is termed ObjectBalance for the purpose of this document.
- A water quality assessment object (Appendix E) for the RQO is introduced and is termed ObjectRQO for the purpose of this document.
- The existing wellfield model is up graded making use of the Theis equation (Appendix E) rather than the Cooper-Jacob equation. This allows for better drawdown estimations at lower pumping times.

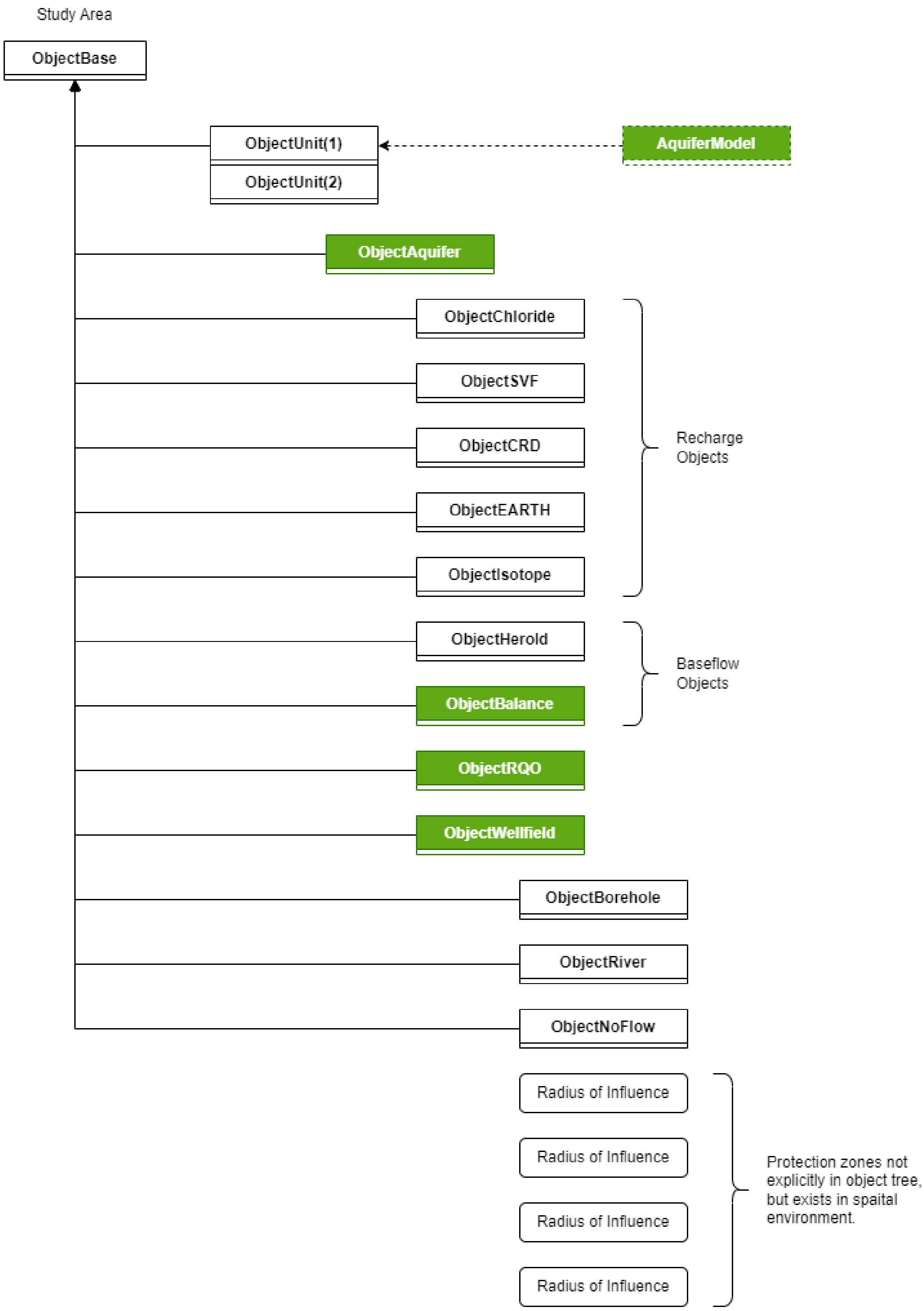

Figure 13: G3 Class Diagram for Spatial and Monitoring functionality

4.5.3 Sequence Diagram

The updated system design has not changed the Sequence diagram therefore Figure 10 also represents the sequence diagram for the updated G3 version of the GRDM.

Chapter 5 Results and Discussion

It is evident from the gap analysis that users were not aware that the majority of issues raised was actually already addressed in G2. This points to the fact that a lack of training on the G2 existed and as mentioned in the introduction of this report only one official training session was scheduled for DWS.

Valid issues with the G2 were identified through the gap analysis and a recurring theme in all previous versions of the software is the issue of using surface water boundaries as groundwater delineation units and there is no consideration given to deeper lying aquifers. This remains a challenge in the software as the solution to the problem is to have a system that first allows for the conceptualisation of the study area based on existing data and then transfer the conceptual model into an appropriate numerical model. By implication the GRDM GUI would need to become a numerical groundwater model, which would require groundwater modelling specialists as users. This will defeat the purpose of the GRDM and this issue was also discussed in the relevant workshops.

The G3 version succeeds in supporting a dual layer aquifer system making it possible to delineate the shallow aquifer system based on a surface water catchment (assuming the topographical highs act as no-flow boundaries) and also delineating an underlying aquifer system which represents a deeper regional aquifer system. The G3 version provides the functionality to run the system as a single layer model or dual layer model to allow the user to choose a model as close to the conceptual model of the area as possible.

The dual layer model also addresses the issue where historical generations of the GRDM could have shown stressed conditions since only the shallow aquifer was considered. The dual layer model explicitly provides for a recharge zone for the deeper confined aquifer to account for abstractions taking place in the underlying aquifer system.

This report only discusses the design considerations of the newly implemented methodology and the benefits and improvements of the G3 version will have to be tested and quantified through future case studies.

Chapter 6 Recommendations

As datasets are updated the local database of the GRDM will not be synchronised and users would have to download the latest version of the software to get the benefit of the update. This could create the situation where an external user submits a RDM study to DWS and that the Desktop level assessments differ due to the fact that the underlying databases also differ. It is recommended that, in future, a cloud based database be used to overcome this problem, although it will still require a database administrator to physically update the database.

Various databases exist that provide valuable information to the GRDM, these include, WR2012, GRAII, NGA, GRIP, WARMS, DWS Hydrological Services and DWS Resource Quality Services. These databases is either online where a request is sent for data or simply exists as a collection of files that can be downloaded or requested. None of them provide an Application Program Interface (API) through which programmatic queries could be directed to obtain the data. An interim solution to have programmatic queries be executed on some of these databases is web scraping, but it should be noted that if any format change takes place on the targeted platform, the web scarping will fail and will have to be adapted to ensure future function. The optimal solution is that each database provide an API to access the required data via the internet.

Considering the previous two recommendations related to online data sets it is further recommended that the next generation of the GRDM (G4) be considered as a web application. This guarantees that all users always use the latest version of the software and no installation issues exist on computers that are subject to a corporate image which only allows administrators to authorise the deployment of software on the user's computer which is the case for DWS. During the update from G2 to G3, various Delphi components were introduced that already allow for running in a web environment and the underlying TatukGIS component does have a web server version, so the possibility is there to migrate the system to a web application in totality. It should be noted that cloud solutions come at a cost and subscription fees will apply.

The remainder of the out-of-scope requests not yet addressed in the previous recommendations relate to "nice-to-have" functionality e.g. the implementation of a full suite of water quality plots. Implementation of these will certainly offer more functionality to the user, but will not have a significant impact on the outcome compared to making use of the existing set of tools provided the G3 version.

Chapter 7 References

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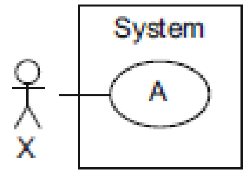
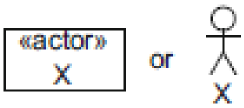
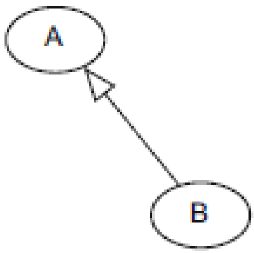
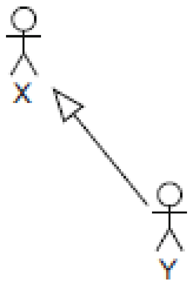
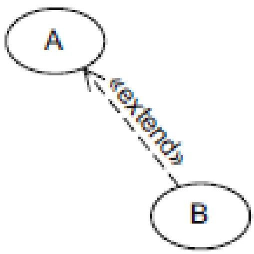
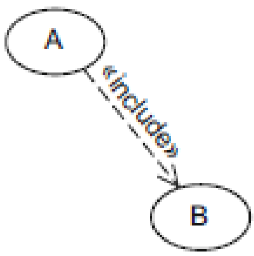
Appendix A Unified Modelling Language (UML)

This section presents the definitions of the Unified Modelling Language (UML) symbols used in this document (Seidl, et al., 2012).

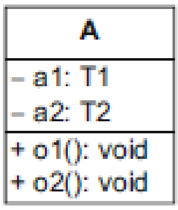
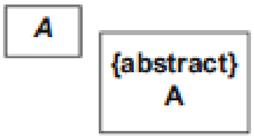
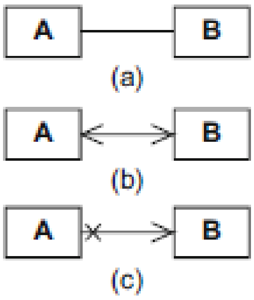
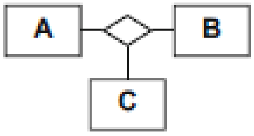
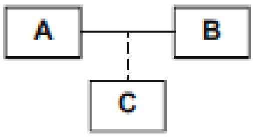
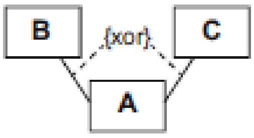
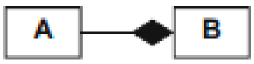
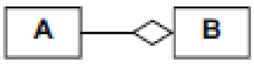
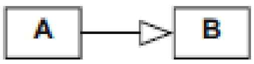
Use Case Diagrams

The use case diagram describes the behaviour of a system from the view of the user. This means that this diagram presents the functionalities that the system offers but does not address the internal implementation details. The boundaries of the system—what can the system do and what can it not do?—are clearly defined. The users (actors) are always outside the system and use the functionalities of the system, which are depicted in the form of use cases. The relationship between a use case and an actor is referred to as an association. To keep use case diagrams as compact as possible, generalization is supported for both actors and use cases, which allows the extraction of common properties. Use cases can also access the functionality provided by other use cases by means of «include» and «extend» relationships. The most important notation elements are summarised in the table below.

Name	*Notation*	*Description*
System		Boundaries between the system and the users of the system
Use case		Unit of functionality of the system
Actor		Role of the users of the system
Association		X participates in the execution of A
Generalization (use case)		B inherits all properties and the entire behavior of A
Generalization (actor)		Y inherits from X; Y participates in all use cases in which X participates
Extend relationship		B extends A: optional incorporation of use case B into use case A
Include relationship		A includes B: required incorporation of use case B into use case A

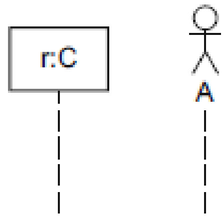
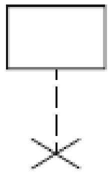
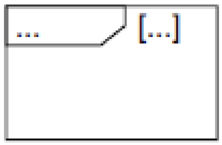
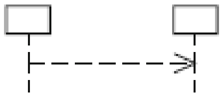
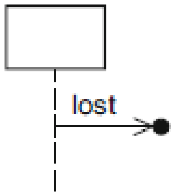
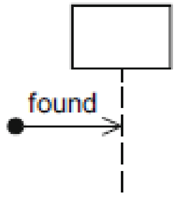
Class Diagram

We use the class diagram to model the static structure of a system, thus Class diagram describing the elements of the system and the relationships between them. These elements and the relationships between them do not change over time. For example, students have a name and a matriculation number and attend various courses. This sentence covers a small part of the university structure and does not lose any validity even over years. It is only the specific students and courses that change. The class diagram is without doubt the most widely used UML diagram. It is applied in various phases of the software development process. The level of detail or abstraction of the class diagram is different in each phase. The most important notation elements are summarised in the table below.

Name	*Notation*	*Description*
Class		Description of the structure and behavior of a set of objects
Abstract class		Class that cannot be instantiated
Association		Relationship between classes: navigability unspecified (a), navigable in both directions (b), not navigable in one direction (c)
N-ary association		Relationship between *N* (in this case 3) classes
Association class		More detailed description of an association
xor relationship		An object of A is in a relationship with an object of B or with an object of C but not with both
Strong aggregation = composition		Existence-dependent parts-whole relationship (A is part of B; if B is deleted, related instances of A are also deleted)
Shared aggregation		Parts-whole relationship (A is part of B; if B is deleted, related instances of A need not be deleted)
Generalization		Inheritance relationship (A inherits from B)
Object		Instance of a class
Link		Relationship between objects

Sequence Diagram

The sequence diagram is one of four interaction diagrams in UML. Interaction diagrams model the communication between different interaction partners, whereby each of the four diagrams focuses on a different aspect. In practice, the sequence diagram is the most frequently used of the interaction diagrams. The presentation of communication protocols and design patterns are particularly prominent applications of sequence diagrams as they enable a compact and clear specification. In addition to the interaction partners, which are depicted in the form of lifelines, the sequence diagram contains different types of messages (synchronous, asynchronous, response message, create message). The chronological order of the messages is generally assumed to be from top to bottom along the vertical line. Twelve types of combined fragments provide you with different control structures that enable you to control the interaction. The most important elements of the sequence diagram are summarized in the table below.

Name	*Notation*	*Description*
Lifeline		Interaction partners involved in the communication
Destruction event		Time at which an interaction partner ceases to exist
Combined fragment		Control constructs
Synchronous message		Sender waits for a response message
Response message		Response to a synchronous message
Asynchronous message		Sender continues its own work after sending the asynchronous message
Lost message		Message to an unknown receiver
Found message		Message from an unknown sender

Appendix B – Assured Aquifer Yield Model (AAYM)

The following text is an extract from the following report:

A Groundwater Planning Toolkit for the Main Karoo Basin:

Identifying and quantifying groundwater development options incorporating the concept of wellfield yields and aquifer firm yields

R Murray, K Baker, P Ravenscroft, C Musekiwa and R Dennis

WRC Report No: 1763/1/11

ISBN: 978-1-4312-0215-7

February 2012

WATER RESEARCH COMMISSION

LUMPED BOX MODEL

The fact that a water balance model can be applied on quaternary catchment scale, subject to certain assumptions e.g. natural groundwater divide boundaries, allows for the translation of the natural system into a lumped box model as shown in Figure 14.

The operation of the box model is based on the fact that effective recharge is based on the demand of the evapotranspiration, baseflow and pumping. This effective recharge can be less than the potential recharge and this difference translates to a reserve volume. The effective recharge can never be more than the potential recharge as the potential recharge serves as the source for the effective recharge.

The implication of this reserve volume is that each time step of the model has a different reserve volume associated with it. External demands will not influence the water level in the box as long as the reserve volume exceeds the external demand. Due to this fact the average reserve volume can theoretically serve as a conservative estimate of the aquifer assured yield.

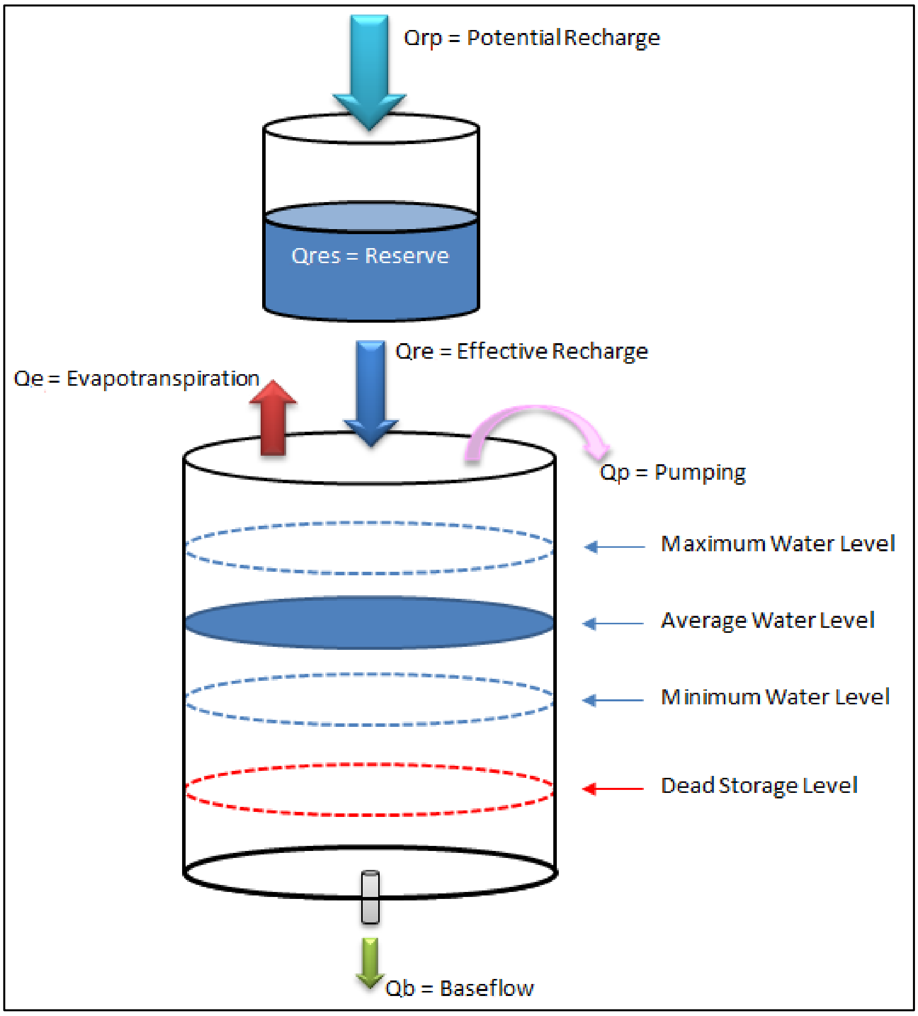


Figure 14: Lumped box model

The water balance equation describing the lumped box model is given as follows:

$$Q_{re} = Q_e + Q_b + Q_p \quad (1)$$

$$Q_{re} = Q_{rp} - Q_{res} \quad (2)$$

where

Q_{rp}	=	Potential recharge
Q_{re}	=	Effective recharge
Q_{res}	=	Reserve
Q_e	=	Evapotranspiration
Q_b	=	Baseflow
Q_p	=	Pumping

In Equation 1 and Equation 2, estimates for Q_{rp}, Q_e and Q_b are obtained through the use of the WR2005 and GRAII data sets. The pumping rate Q_p is known due to the fact that it is controlled by the model.

It is clear from Figure 14 that if the potential recharge is used instead of the effective recharge and the potential recharge is greater than the effective recharge there will be a continuous rise in the regional water level until the physical system is totally flooded.

Three scenarios exist for the discharge to a stream as shown in Figure 15 (Alley, et al., 1999):

A. Under natural conditions recharge at the water table is equal to groundwater discharge to the stream: $Q_{re} = Q_b$. If evapotranspiration is also accommodated in this scenario the water balance equation becomes: $Q_{re} = Q_e + Q_b$
B. Assume a borehole is installed and is pumped continuously at a rate Q_p. After a new state of dynamic equilibrium is achieved, inflow to the groundwater system from recharge will equal outflow to the stream plus the withdrawal from the well. A new balance equation can now be written: $Q_{re} = Q_e + Q_b + Q_p$. For the system to stay in equilibrium and not affect the evapotranspiration and baseflow, Q_p needs to be sourced by the reserve Q_{res}.
C. If Q_p exceeds Q_{res} then the balance is made up from the baseflow and evapotranspiration as water levels drop and evapotranspiration stops. When the baseflow component is totally consumed the system tries to reach a balance again by sourcing water from the stream. If the stream contribution is insufficient water levels will keep dropping until the resource is depleted and failure occurs.

Note: for the purpose of the AAYM no water will be allowed to be sourced from the stream.

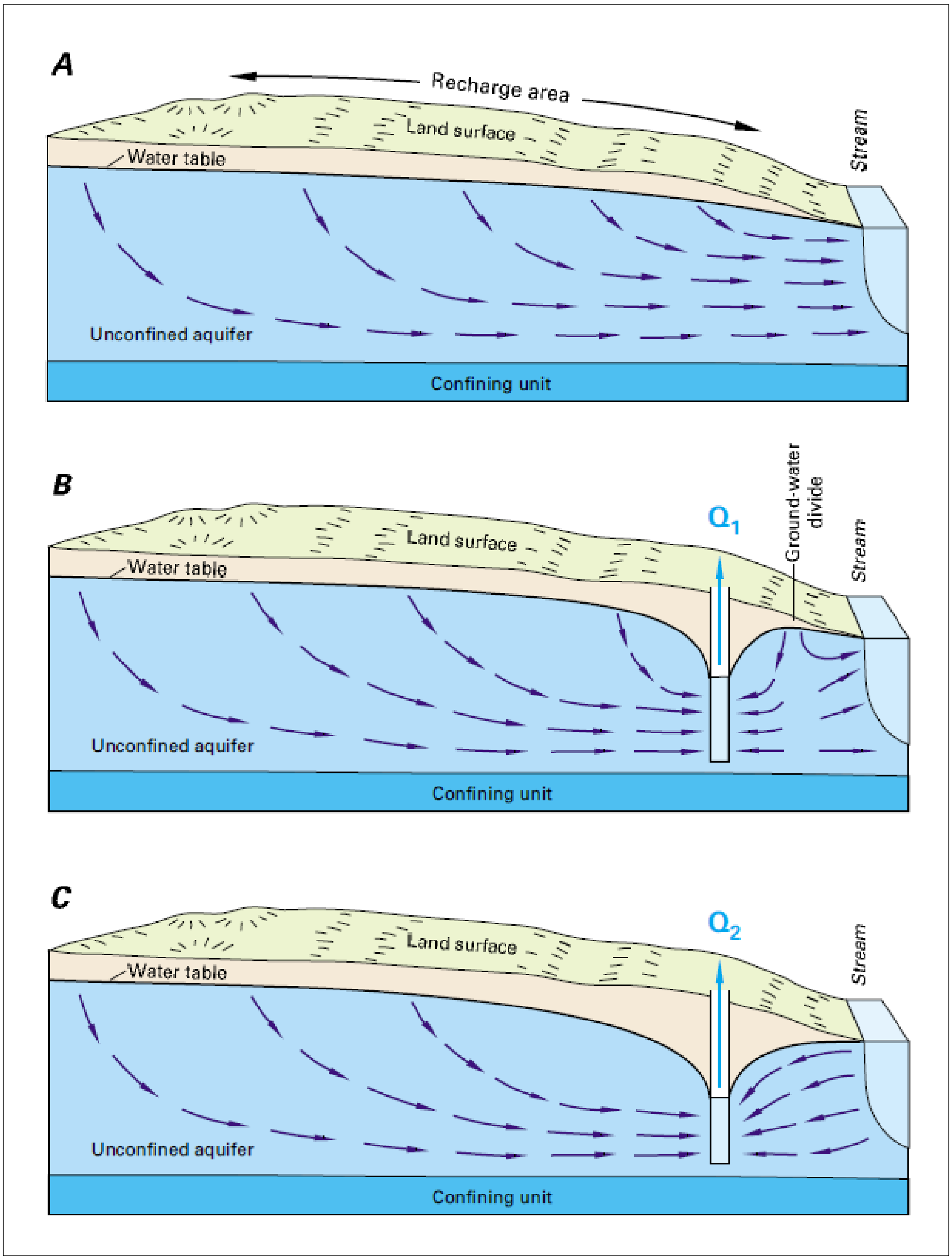


Figure 15: Effects of pumping that effects discharge to the stream

MODEL COMPONENTS

This section describes the individual model components.

Recharge Estimation (Q_{rp})

Time series monthly rain fall data is available in the WR2005 data set for each quaternary catchment from 1920. These rainfall records are obtained through the use of patching and combining data from individual precipitation stations for various rainfall zones across South Africa. Each quaternary catchment is assigned to a rainfall zone; hence more than one quaternary may have the same rain zone. For more detail refer to the User's Guide on Water Resources of South Africa, 2005 Study.

Similarly as the available data dictates the scale of assessment, it also dictates the time step used in the model; hence monthly time steps are used in the simulations.

Recharge percentages for all the quaternaries exist through the GRAII dataset. Two recharge models are available in the AAYM:

- Threshold model
- Cavé Model (Cavé, et al., 2003)

Both models provide a mechanism to control recharge for low precipitation events.

Threshold Model

This model makes use of the recharge percentage and a recharge threshold that is specified in mm. It is a known fact that recharge only takes place for precipitation events of a certain magnitude and the threshold is specifying this lower limit for each quaternary catchment.

$$R_i = (P_i - P_T) \times R_E \tag{3}$$

where

R_i	=	Recharge in month *i* (mm)
P_i	=	Precipitation in month *i* (mm)
P_T	=	Precipitation threshold (mm)
R_E	=	Recharge (%)

Cavé Model

The Cavé model (Cavé, et al., 2003) is based on work done where recharge values for various boreholes were plotted against the average annual rainfall as shown in Figure 16. A general fit was obtained from the data that models a similar recharge threshold value based on precipitation events.

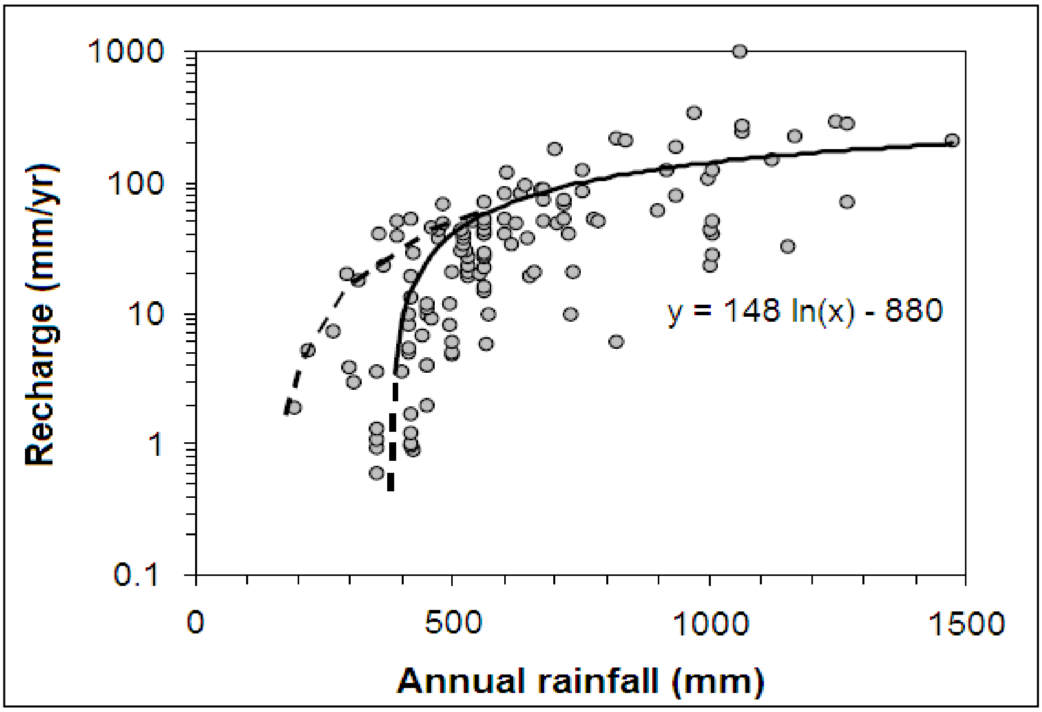


Figure 16: Recharge rates in South Africa (Cavé, et al., 2003)

The model implementation is as follows:

$$if\ P_i < 35\ then\ R_i = 0 \tag{4}$$

$else$

$$R_i = \frac{148\ln(12P_i) - 880}{12} \tag{5}$$

where

R_i = *Recharge in month i (mm)*

P_i = *Precipitation in month i (mm)*

Groundwater Contribution to Baseflow Estimation (Q_b)

Groundwater contribution to baseflow still remains a hot topic in surface-groundwater interaction research and is either subject to baseflow separation or recession curve estimations. Various models exist that estimate this component on quaternary catchment scale.

For the purpose of the AAYM existing baseflow values for the quaternary catchments as determined by various individuals are presented to the user to make an appropriate selection. The selected baseflow value will then be used in the AAYM to perform an automatic baseflow separation through the use of the Herold method (3.2.2.1) on the monthly flow data obtained from WR2005. A list of the available baseflow determinations are shown in Table 28.

Table 28: List of baseflow estimations

Existing Baseflow Estimations
Pitman
Shultz
Hughes
Van Tonder

In transient state the model will make use of the allocated baseflow as stress conditions are reached, but will not reverse baseflow to provide water to the system. If a baseflow value other than zero is assigned to the quaternary and baseflow is depleted during the transient state, it is recommended that a higher recharge value is assigned to sustain the baseflow or the maximum drawdown condition be relaxed.

Herold Method of Baseflow Separation

Vegter and Pitman (Vegter, 1995) explains the Herold method as follows:

$$Q_i = QG_i + QS_i \tag{6}$$

where

Q_i = Total flow during month i

QG_i = Groundwater contribution

QS_i = Surface water contribution

The assumption is made that all flow below a certain value (called *GGMAX*) is groundwater flow, hence:

$$QS_i = Q_i - GGMAX \ (for \ Q_i > QGMAX) \tag{7}$$

$$QS_i = 0 \ (for \ Q_i \leq QGMAX) \tag{8}$$

$$QG_i = Q_i - QS_i \tag{9}$$

The value of *GGMAX* is adjusted each month according to the surface runoff during the preceding month and is assumed to decay with time, hence

$$GGMAX_i = (DECAY \times GGMAX_{i-1}) + (PG \times QS_{i-1}) \tag{10}$$

where subscripts *i* and *i-1* refer to the current and preceding month

DECAY	=	Groundwater decay factor (0 < DECAY < 1)
PG	=	Groundwater growth factor (0 < PG > 1)

An added constraint is that *GGMAX* may not fall below a specified value, *QGMAX*. Calibration of this model is achieved by selecting an appropriate value of *DECAY*, *PG* and *QGMAX* so that a realistic division between surface runoff and groundwater is obtained.

Evapotranspiration Model (Q_e)

The AAYM simulates monthly groundwater evapotranspiration losses from aquifer storage in the riparian zone. Evapotranspiration only takes place from the aquifer underlying the riparian zone when the regional water level lies within a zone extending from the ground surface down to a user specified depth below surface, termed the *Evapotranspiration Extinction Depth* as shown in Figure 17. The AAYM provides the user with a default value for the area of the riparian as a percentage of the areal extent of the aquifer system. The user has the option to adjust this value. The following equation is used to estimate monthly groundwater evapotranspiration from the riparian zone:

$$ET_i = EP_i \times \left[\frac{D_E - WL_{i-1}}{D_E}\right]^{P_f} \tag{11}$$

where

ET_i	=	Calculated evapotranspiration in month i (mm)
EP_i	=	Mean Penman-Monteith potential ET in month i (mm)
D_E	=	Evapotranspiration extinction depth (m)
WL_{i-1}	=	Riparian water level in month i-1
P_f	=	Evapotranspiration rate behaviour (0=constant, 1=linear, 2.5=exponential)

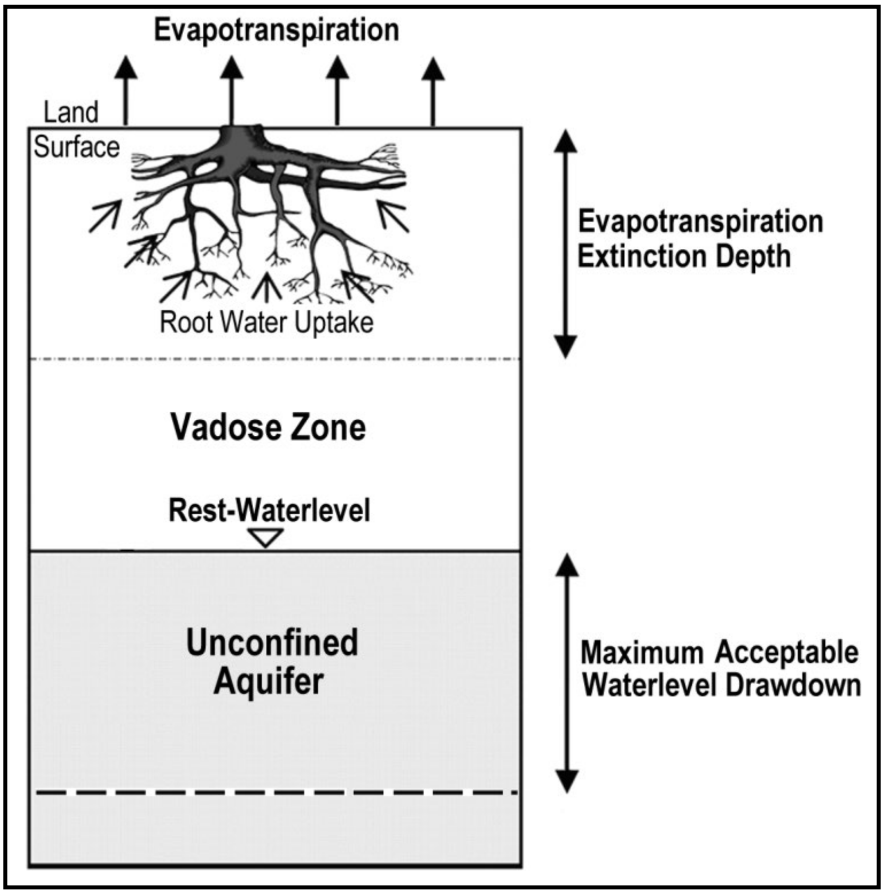


Figure 17: Evapotranspiration model depths

Saturated Flow Volume Fluctuation

The Saturated Flow Volume Fluctuation method describes the water level fluctuation in terms of the various inflows and outflows into the system (Van Tonder & Xu, 2001). The following equation expresses the water level in mbgl.

$$h_i = h_{i-1} - \frac{R_i}{S_y} + \frac{E_i A_r}{S_y A_t} + \frac{(Q_b + Q_{res} + Q_p)}{S_y A_t} \tag{12}$$

$$Q_{rp} = R_i A_t \qquad Q_e = E_i A_r$$

$$h_i = h_{i-1} -+ \frac{(Q_{rp} + Q_e + Q_b + Q_{res} + Q_p)}{S_y A_t} \tag{13}$$

where

h_i	=	Head at month *i* (m)
h_{i-1}	=	Head at previous month
R_i	=	Recharge in month *i* (m)
E_i	=	Evapotranspiration in month *i* (m)
Q_{rp}	=	Recharge rate in month *i* (m^3/month)
Q_e	=	Evapotranspiration rate in month *i* (m^3/month)
Q_b	=	Baseflow rate in month *i* (m^3/month))
Q_{res}	=	Reserve in month *i* (m^3/month))
Q_p	=	Abstraction rate in month *i* (m^3/month)
A_t	=	Area of aquifer (m^2)
A_r	=	Area of riparian zone (m^2)
S_y	=	Specific yield

It is evident from the above equation that when the outflows (Q_e, Q_b, Q_p, Q_{res}) exceed the inflow (Q_{rp}) the drawdown (mbgl) will increase as water is depleted from storage and vice-versa.

MODEL OPERATION

The first step in the model is to choose an appropriate recharge model with appropriate parameters. This will establish the potential recharge for the model based on the WR2005 rainfall data.

The second step is to choose the percentage of the total area representing the riparian area. A typical extinction depth should also be provided.

The AAYM consists of three states: *AMBIENT*, *STEADY* and *TRANSIENT* which is discussed in the following sections.

Ambient State

The ambient state keeps the regional water level fixed according to the input provided and applies the following water balance (Alley et al., 1999):

$$Recharge(water\ entering) = Discharge(water\ leaving) \tag{14}$$

The pseudo code for the ambient state is presented in Table 29. The main objective is to calculate the average Q_{res} required in the steady state. When baseflow is modified the model will issue a warning to allow the user to change the initial conditions to minimise baseflow modification.

The fact the water levels are kept constant allows the model to calculate the average Q_{res} that is available for external demand, without affecting the average trend for steady state water levels. In steady state there should not be a significant increasing or decreasing trend in water levels as the water level should reflect a sustainable level.

Table 29: Pseudo code for ambient state

Pseudo Code	Comments
For each monthly time step:	
Qrp = Area * Recharge	Potential recharge is area * monthly recharge
Qb = Herold	Baseflow is calculated through Herold
Qp = 0	No pumping takes place in ambient state
Hi = Hi-1	Water level is equal to previous water level
Qe = ET Model	ET is calculated with the ET model
Qres = Qrp – Qe – Qb - Qp	Calculate the reserve
if Qres < 0 then	Reserve must be greater or equal to zero
begin	
Qres = 0	If reserve is negative make it zero
Qe = Qrp – Qb - Qp	Adjust ET to compensate for the Qres change
if Qe < 0 then	
begin	
Qe = 0	If ET is negative set it to zero
Qb = Qrp - Qp	Adjust baseflow to compensate for ET change
end	
end	
Hi = Hi-((Qrp-Qe-Qb-Qres-Qp)/(Sy*At))	Calculate water level according to SVF method
After all time steps:	
Qavg = Average(Qres)	Calculate the average reserve for steady state

Steady State

In the steady state, the model allows for a varying aquifer water level based on the SVF equation presented in Equation 13. Time series rainfall is translated into time series water level information through the use of Equation 13. The pseudo code for the steady state is presented in Table 30.

Table 30: Pseudo code for steady state

Pseudo Code	Comments
For each monthly time step:	
Qrp = Qrp(Ambient)	Potential recharge is equal to ambient state recharge
Qres = Qres(Ambient)	Reserve is equal to the ambient state reserve
Qb = Qb(Ambient)	Baseflow is equal to the ambient state baseflow
Qp = 0	No pumping takes place in steady state
Hi = Hi-1	
Qe = ET Model	Water level is equal to previous water level
	ET is calculated with the ET model
Hi = Hi-((Qres-Qavg)/(Sy*At))	
	Calculate the steady state water level based on
Qres = Qrp - Qe - Qb - Qp	the average Qres calculated in the ambient state
if Qres < 0 then	
begin	Reserve must be greater or equal to zero
Qres = 0	
Qe = Qrp - Qb - Qp	If reserve is negative make it zero
if Qe < 0 then	Adjust ET to compensate for the Qres change
begin	
Qe = 0	
Qb = Qrp - Qp	If ET is negative set it to zero
end	Adjust baseflow to compensate for ET change
end	

Transient State

The transient state is a duplication of the steady state scenario, with the difference that an increasing Q_P is applied to the model until the water level exceeds the maximum drawdown level. The pseudo code for the transient state is shown in Table 31.

Table 31: Pseudo code for transient state

Pseudo Code	Comments
For each monthly time step:	
Qrp = Qrp(Steady)	Potential recharge is equal to ambient state
Qres = Qres(Steady)	Reserve is equal to the ambient state reserve
Qb = Qb(Steady)	
Qp = Incremented by model	Baseflow is equal to the ambient state baseflow
Hi = Hi-1	Pumping is automatically increased by model
Qe = ET Model	
	Water level is equal to previous water level
Qres = Qrp - Qe - Qb - Qp	ET is calculated with the ET model
if Qres < 0 then	Calculate the reserve
begin	
Qres = 0	Reserve must be greater or equal to zero
Qe = Qrp - Qb - Qp	
if Qe < 0 then	If reserve is negative make it zero
begin	Adjust ET to compensate for the Qres change
Qe = 0	
Qb = Qrp - Qp	
end	If ET is negative set it to zero
end	Adjust baseflow to compensate for ET change
Hi = Hi-((Qrp-Qe-Qb-Qres-Qp)/(Sy*At))	Calculate water level according to SVF method

Firm Yield Calculation

The typical surface water trajectory is shown in Figure 18. Of specific interest in this diagram are the full supply volume (FSV) and the dead storage volume (DSV). In analogy to the FSV an average long term sustainable water level is calculated for the aquifer. This water level corresponds to the steady state water levels and does vary with time but there is no resultant trend in an upward or downward direction. The DSV is related to the maximum allowable drawdown specified by the user.

The firm yield calculation is shown in Figure 19. A certain target draft or target yield is applied to the system and if no failure (DSV constraint) takes place the system can deliver the required target. This results in a 45 degree line as long as the target can be achieved. For each month the system cannot deliver the target, the resultant yield becomes less, resulting in a decaying curve. The last yield point to meet the required target is the firm yield point.

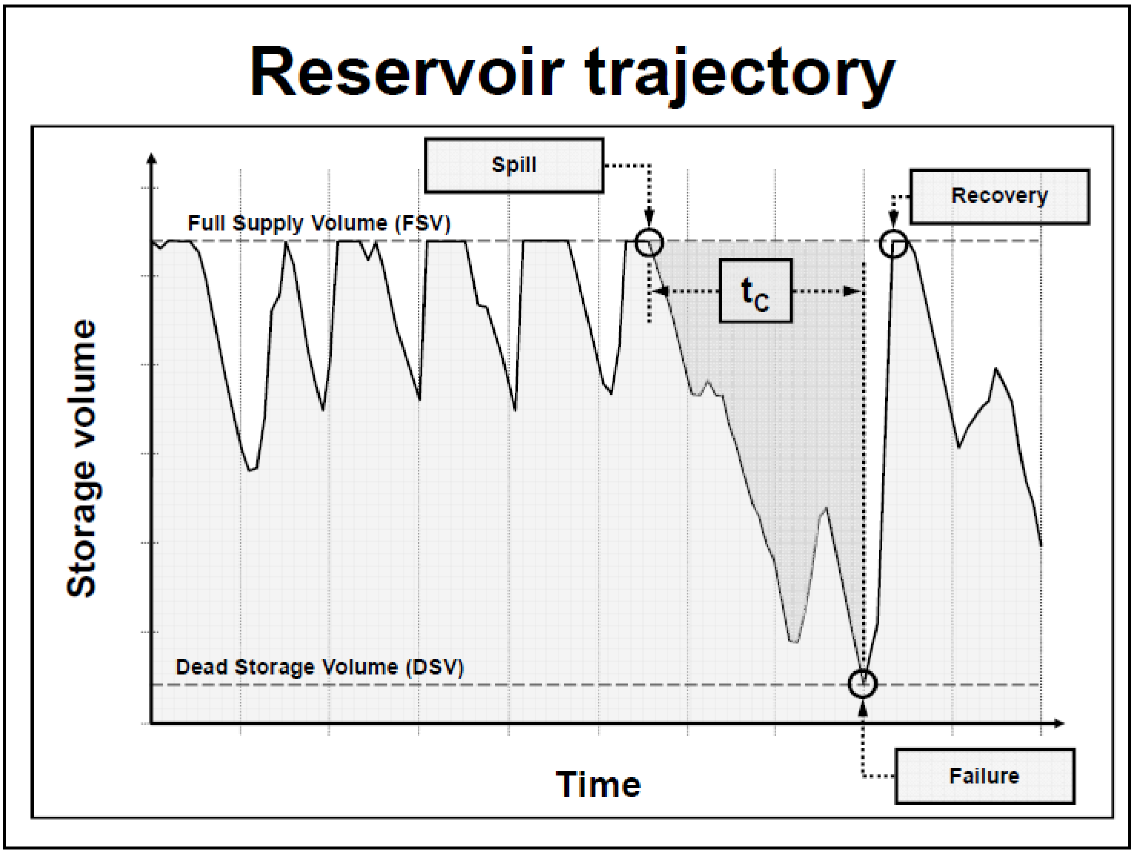


Figure 18: Reservoir trajectory

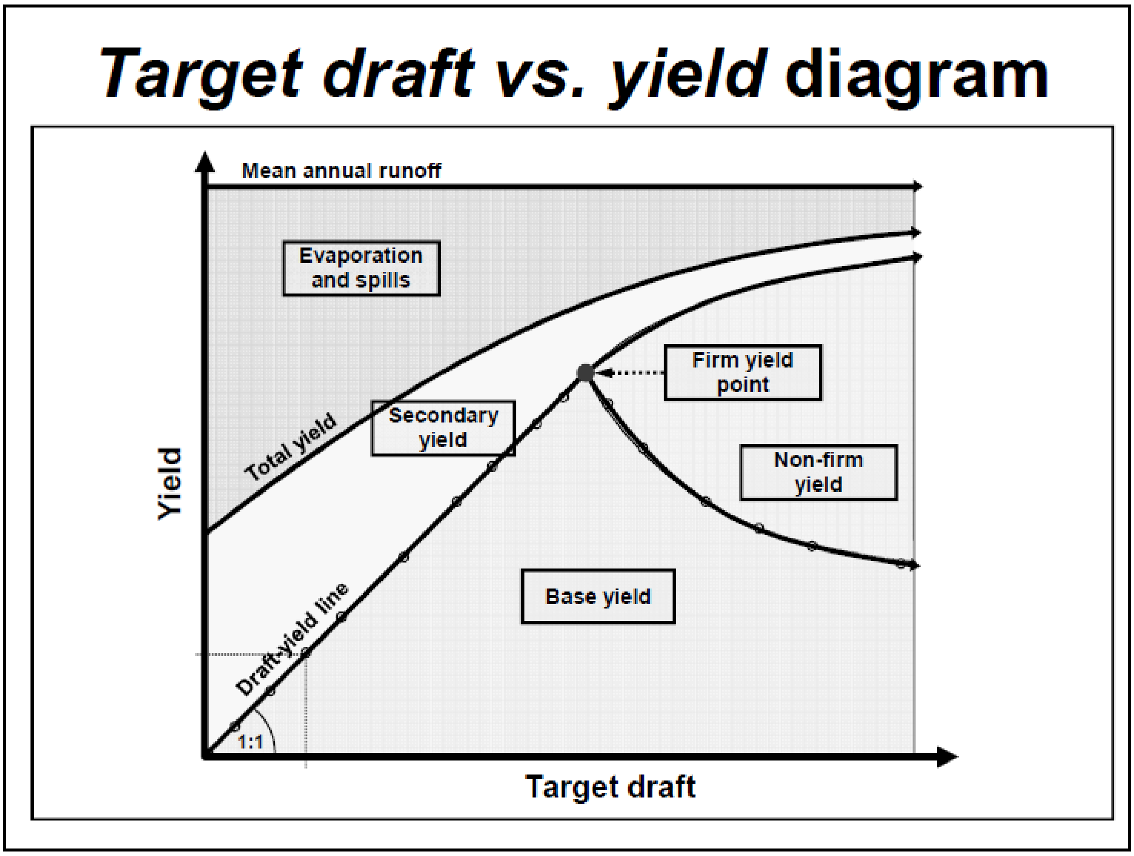


Figure 19: Target draft vs. yield diagram

Appendix C – Dual Layer Model (DLM)

INTRODUCTION

The National Water Act (NWA) (Act No. 36 of 1998) (RSA, 1998) aims to ensure access to a limited resource on an equitable basis in an integrated, managed and sustainable manner. The Act moves away from riparian and property rights, but recognizes basic human needs and water needs to sustain the environment. The promulgation of the Act has resulted in significant changes in the way in which we use and manage water. Because of the shift from private to public water, this is particularly true of the groundwater component of the hydrological system (Parsons & Wentzel, 2007).

The initial GRDM methodology (Parsons & Wentzel, 2007) and the later updated methodology (Dennis, et al., 2012) serves as a framework to give effect to the groundwater reserve component as described in the NWA (RSA, 1998). The water balance model used is a lumped box model and not a distributed model due to the requirement that the GRDM studies undertaken must be verified by the Department of Water and Sanitation (DWS) personnel who are not groundwater modelers. If uncertainty exists around a particular reserve determination, the DWS will then issue an instruction to perform detailed modelling and this will be done by an expert in groundwater modelling.

A general criticism of the existing GRDM methodology is the fact that the groundwater reserve studies are undertaken on quaternary catchment scale which is representative of surface water boundaries which does not necessarily align with the aquifer boundaries under consideration. The quaternary delineation originates from the fact that the surface water models within the Department of Water and Sanitation (DWS) rely on input on quaternary scale. The Groundwater Resources Assessment Phase II (GRA2) (Department of Water and Sanitation, 2005) project reports geohydrological parameters on a 1km x 1km grid and also on quaternary catchment scale for the whole of South Africa. Similarly the Water Resources of South Africa, 2012 Study (WR2012) (WRC, 2012) reports hydrological data also on quaternary catchment scale. The aforementioned data projects is used to provide default geohydrological and hydrology parameter values respectively for the GRDM water balance model.

In an attempt to improve the exiting modelling methodology, the lumped box model was extended to a double layer model which explicitly accounts for both the shallow unconfined system as well as the deeper confined system. The development of the model is discussed in this paper.

MODEL DEVELOPMENT

Conceptual Model

A conceptual drawing of the system to be modelled is presented in Figure 20. The shallow unconfined system report to the stream and the unconfined system receives recharge though direct infiltration. The confined system underlies the unconfined system and receives recharge from an area which could lie outside the surface catchment boundary as illustrated. The groundwater of the unconfined system near the catchment boundaries are assumed to behave like natural groundwater divides.

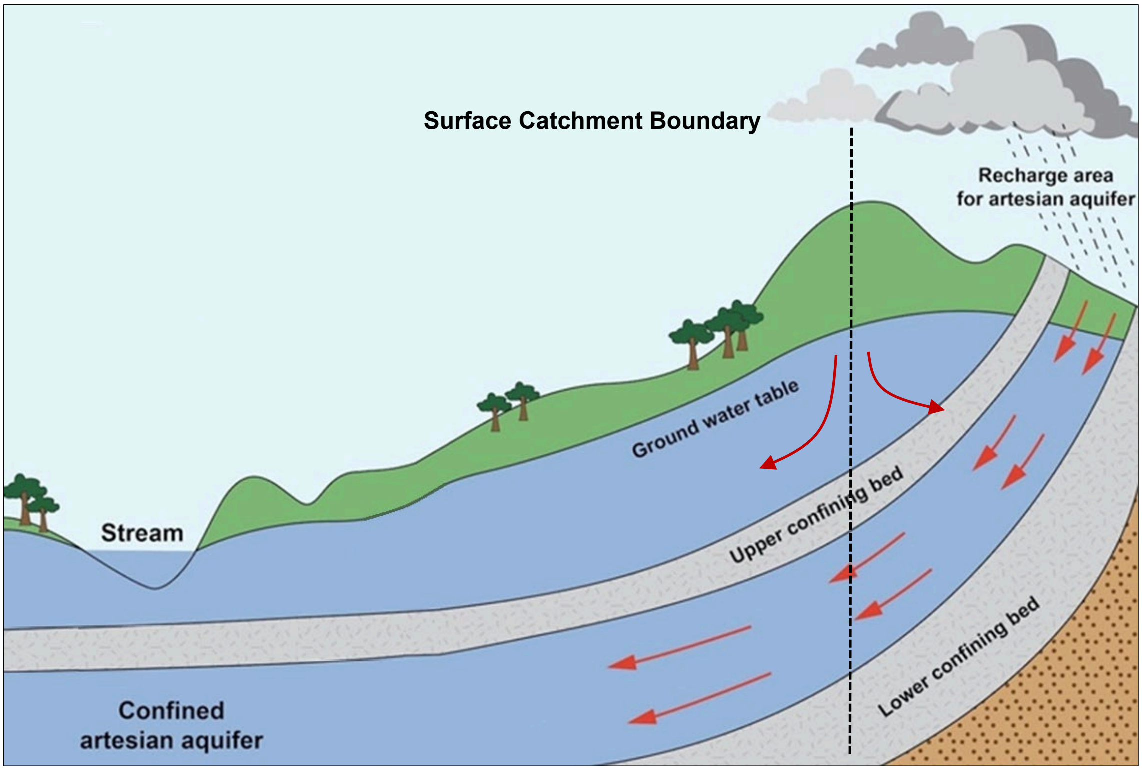


Figure 20: Conceptual model of aquifer systems

Model Simplification

The simplification of the conceptual model presented in Figure 20 is shown in Figure 21. The two layers are represented by lumped box models, the unconfined layer parameters are denoted by *u* and the confined layer parameters are denoted by *c*. One of the short comings with these types of models are the fact that parameters are lumped and no spatial discretisation exists e.g. uniform recharge is assumed across the model area, which is not the case in reality and the whole aquifer response is presented with a single water level across the model domain.

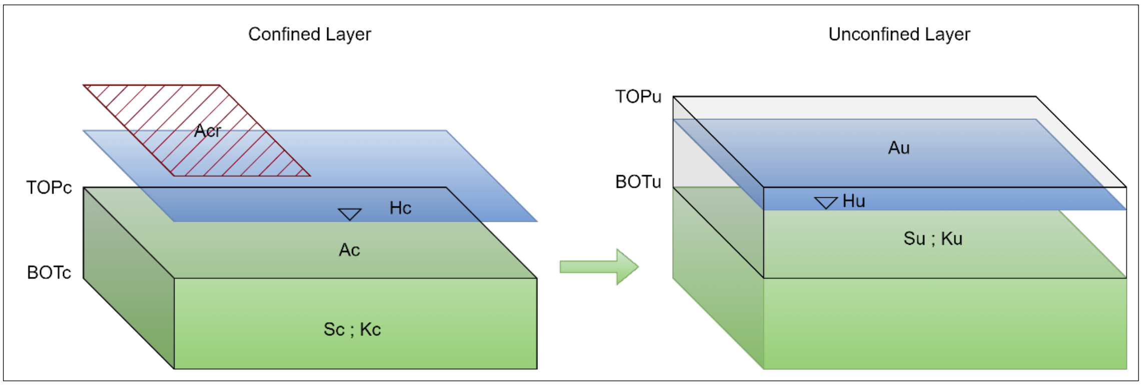


Figure 21: Lumped model definition

In Figure 21 the confined layer is displayed to the left of the double layer setup for the purpose of visualizing the different parameters associated with it as described in Table 32, but it should be noted that physically the unconfined system underlies the unconfined system. It is evident from Figure 21 that the head associated with the confined system is higher than the top of the confined layer. It is important to note that the confined layer will transition from confined to unconfined conditions when the head value drops below the top of the layer.

Table 32: Model parameters

Parameter	Description
A_u , A_c	Area of layer *u* and *c* respectively [L^2]
A_{cr}	Recharge area associated with the confined system [L^2]
H_u , H_c	Head value of layer *u* and *c* respectively [L]
S_u , S_c	Storativity of layer *u* and *c* respectively
K_u , K_c	Hydraulic Conductivity of layer *u* and *c* respectively [L/T]
TOP_u , TOP_c	Top of layer *u* and *c* respectively [L]
BOT_u , BOT_c	Bottom of layer *u* and *c* respectively [L]

The storage capacity of an aquifer is referred to as the storativity or storage coefficient. The storativity for an unconfined aquifer is dominated by the specific yield (S_y) (Woessner & Poeter, 2020). The difference between the storativity in an unconfined aquifer and a confined aquifer is that in the confined aquifer the entire aquifer remains saturated when a unit change in head occurs and all released water is derived from the specific storage term (S_s) times the saturated thickness (*b)* of the aquifer (Equation 1) (Woessner & Poeter, 2020).

$$S_{unconfined} = S_y + S_s b$$
$$S_{confined} = S_s b \qquad \text{Equation 1}$$

where,

S	=	*Storativity*
S_y	=	*Specific Yield*
S_s	=	*Specific Storage [1/L]*
b	=	*Average aquifer thickness [L]*

It has been stated in the introduction that a general criticism of the existing GRDM methodology is the fact that the groundwater reserve studies are undertaken on quaternary catchment scale which is representative of surface water boundaries which does not necessarily align with the aquifer boundaries under consideration. The existing GRDM methodology does make provision for the delineation of custom boundaries that do not have to conform to quaternary boundaries where new parameters will be calculated based on the proportional contribution of the underlying quaternaries.

The double layer model assumes groundwater of the unconfined system near the catchment boundaries behave like natural groundwater divides, therefore the unconfined system should align with a quaternary or a combination of quaternary boundaries associated with the local flow component shown in Figure 22. The confined system is then representative of the intermediate or regional flow regime which underlies the unconfined system. From Figure 22 it is evident that the extent of intermediate and regional flow is much larger than that of the local flow and for this reason the extent of the confined system in the double layer model does not have to match the extent of the unconfined system and therefore the following general condition holds true: $A_u \leq A_c$.

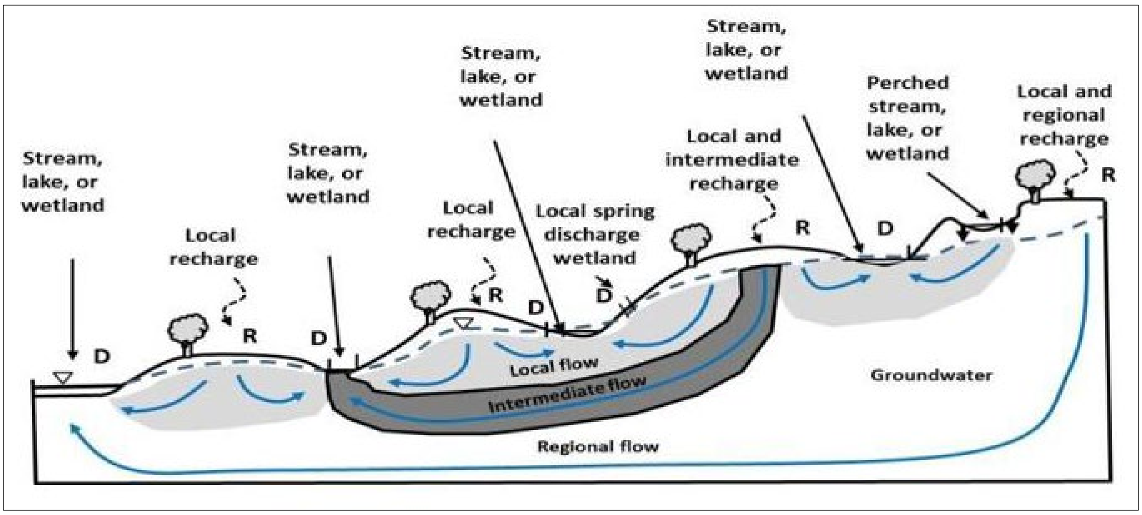


Figure 22: Schematic cross section indicating local, intermediate and regional flow (Woessner, 2020)

Recharge and Discharge Mechanisms

The various recharge and discharge mechanisms of the conceptual model is depicted in Figure 23 and each component is discussed in the sections that follow.

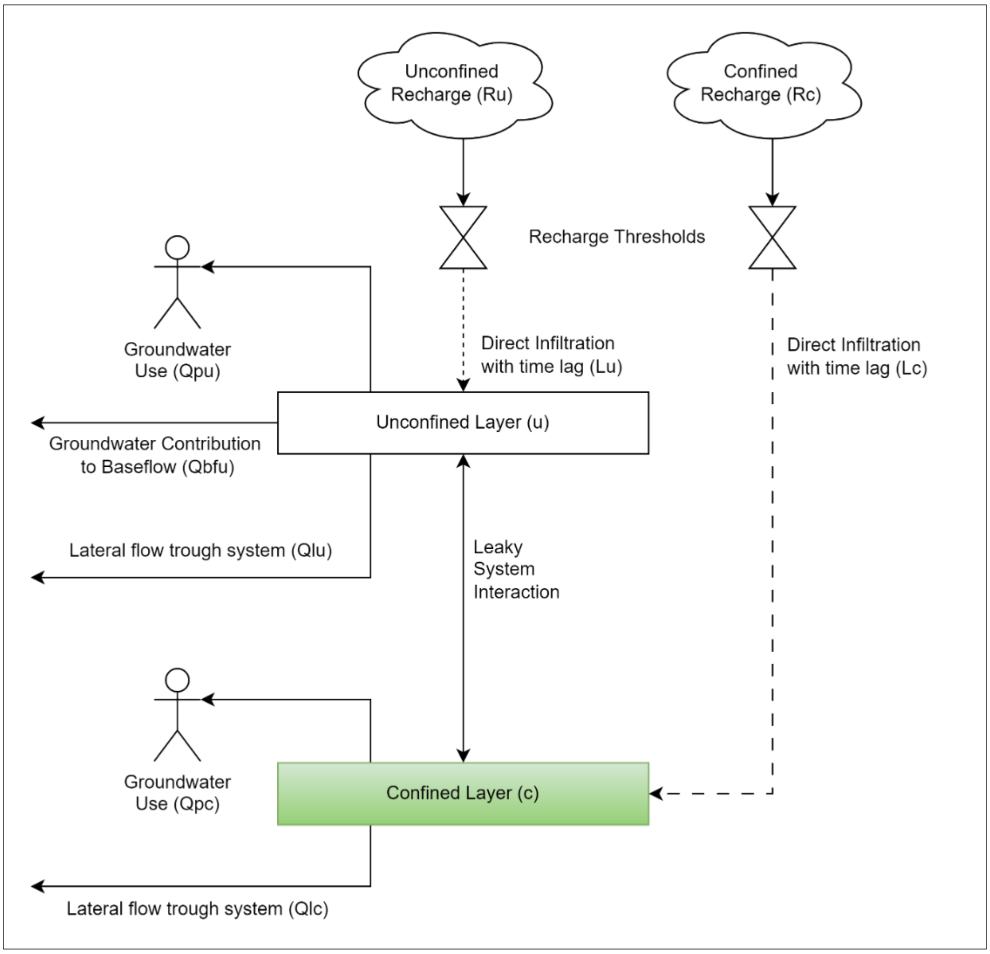


Figure 23: Recharge and discharge components

Recharge

Two recharge sources are present (Figure 23), one for the unconfined system (R_u) and the other for the confined system (R_c). Each of the aforementioned sources are subject to a recharge threshold that must be exceeded before a recharge event takes place, however a zero threshold could be specified to bypass this functionality. The recharge components are also subject to a lagged response (L_u and L_c) with respect to the modelled groundwater level. The observed lag is typically governed by the geological setting and therefore observation data is required to determine the associated lag. Since the confined system are associated with intermediate and regional groundwater flow regimes (Figure 22), the following general relationship will hold true for most cases: $L_u \leq L_c$.

The recharge component indicated Figure 23 in refers to the part of the infiltrated rainfall that breaks through the zone where evaporation occurs and percolates to the saturated zone. Therefore the recharge is considered direct infiltration and the primary source of recharge. For leaky systems a secondary source of recharge will exist for one of the layers dictated by the hydraulic gradient between these layers and the associated conductance.

Natural Discharge

It is assumed that groundwater contribution to baseflow (Q_{bfu}) is a discharge associated with the unconfined aquifer as shown in Figure 23. If a leaky system is assumed and the piezometric level of the confined aquifer is higher than the water table of the unconfined aquifer, there will be flow from the confined aquifer to the unconfined aquifer. In the aforementioned scenario a certain portion of the groundwater contribution to baseflow also originates from the confined aquifer. A lateral flow associated with each of the layers (Q_{lu} and Q_{lc}) is also accounted for which is governed by the change in hydraulic gradient in the system.

Artificial Discharge

Artificial discharge is represented through two water use components (Q_{pu} and Q_{pc}) as indicated in Figure 23. A sub-component of the water use is the Basic Human Need (BHN) component is protected through the NWA (RSA, 1998). Since boreholes can either intersect the shallow unconfined aquifer, or the deeper confined aquifer or both aquifer systems, each model layer accounts for the associated abstraction. It is a requirement of the double layer model that appropriate apportionment be done between the layers with respect to total abstraction.

Model Formulation

The model formulation is based on two water balance models that is linked through a conductance term. The selection of the water balance models is based on an appropriate solution as well as selecting one with as few input parameters as possible since the lumped water balance model pose a challenge with respect to calibration in extended areas as it is unlikely to obtain a single borehole with observation data that is representative of the whole system being modelled. A general approach is to average the observation data of multiple boreholes in the study area, but if contrasting geologies are present this technique can degrade the synthetic average to such an extent to render it useless.

Cumulative Rainfall Departure

Both layers are modelled through a revised Cumulative Rainfall Departure (CRD) method (Xu & Van Tonder, 2001) with an additional modification discussed later in this section. The method is appropriate for both the saturated and unsaturated zones and also includes a cutoff value that will represent the recharge threshold discussed in the previous section. Furthermore the method is suitable for use with a broad range of parameter values as summarized in Table 33.

Table 33: CRD applicability (Beekman & Xu, 2003)

Zone	Limitations	Flux (mm/year)	Area (km^2)	Time (years)
Saturated - Unsaturated	Deep (multi-layer) aquifer; sensitive to specific yield (S_y)	0.1 - 1000	1 - 1000	1 - 20

The general formulation of the CRD term (Xu & Van Tonder, 2001) is presented in Equation 2 and the water balance equation where a change in storage is expressed as a change in water level is presented in Equation 3.

$$CRD(i) = \sum_{i=1}^{i} P_i - \left(2 - \frac{1}{P_{av} i} \sum_{i=1}^{i} P_i\right) iP_t \qquad \text{Equation 2}$$

where,

i = *1,2,3,…,I*

P_n = *Precipitation amount in the i^{th}-month*

P_{av} = *Average precipitation of all precipitation events*

P_t	=	*Threshold value representing aquifer boundary conditions (0 to P_{av}) with 0 indicating aquifer being closed and P_{av} implying the aquifer is open, perhaps regulated by spring flow*

$$\Delta h_i = \frac{rCRD(i)}{S} - \frac{\left(Q_{p_i} + Q_{out_i}\right)}{AS} \qquad \text{Equation 3}$$

where,

i	=	*1,2,3,…,I*
Δh_i	=	*Change in water level representing a change in storage in the i^{th}-month*
CRD(i)	=	*CRD term in the i^{th}-month (see Equation 2)*
r	=	*Fraction of CRD that contributes to recharge*
S	=	*Storativity*
A	=	*Recharge area [L^2]*
Qp_i	=	*Groundwater abstraction in the i^{th}-month*
$Qout_i$	=	*Natural groundwater outflow in the i^{th}-month*

The CRD concept has hydrologic meaning in the short term and when used as a well calibrated water balance model it has good predictive ability. However, the concept can be misused if extended over lengthy periods (Weber & Stewart, 2004).

<u>Rainfall Infiltration Breakthrough</u>

The Rainfall Infiltration Breakthrough (RIB) process (Xu & Beekman, 2003) also represents a lumped water balance model with a lot of similarity to the revised CRD method (Xu & Van Tonder, 2001) with the difference being that only a sliding window of the precipitation data set is used in the calculation.

The general formulation of the RIB term presented in Equation 4 reduces to the CRD term (Equation 2) if rainfall events from P_m to P_n show no trend and subsequently the cumulative rainfall averages to P_{av} (Xu & Beekman, 2003).

$$RIB(i)_m^n = \sum_{i=m}^{n} P_i - \left(2 - \frac{1}{P_{av}(n-m)} \sum_{i=m}^{n} P_i\right) \sum_{i=m}^{n} P_t \qquad \text{Equation 4}$$

where,

i	=	*1,2,3,…,I*	*M < N < I*
n	=	*i,i-1,i-2,…,N*	

m	=	*i,i-1,i-2,…,M*
P_i	=	*Precipitation amount in the i^{th}-month*
P_{av}	=	*Average precipitation of all precipitation events*
P_t	=	*Threshold value representing aquifer boundary conditions (0 to P_{av}) with 0 indicating aquifer being closed and P_{av} implying the aquifer is open, perhaps regulated by spring flow*

<u>Modified Cumulative Rainfall Departure</u>

Since it is known that the CRD method does not perform well over extended time periods (Weber & Stewart, 2004), this could be solved by only considering a sliding window of the total precipitation record as is the case in the RIB term (Equation 4). The general form of the proposed water balance equation (Equation 5) is then obtained by substituting Equation 4 into Equation 3 to replacing the CRD(i) term. In addition, Equation 5 also explicitly account for the recharge area as the recharge area and model area differ for the confined system (Figure 21).

$$\Delta h_i = \frac{rA_r RIB(i)_m^n}{AS} - \frac{\left(Q_{p_i} + Q_{out_i}\right)}{AS} \qquad \text{Equation 5}$$

where,

i	=	*1,2,3,…,I*
n	=	*i,i-1,i-2,…,N* $\quad M < N < I$
m	=	*i,i-1,i-2,…,M*
Δh_i	=	*Change in water level representing a change in storage in the i^{th}-month*
RIB(i)	=	*RIB term in the i^{th}-month (see Equation 4)*
r	=	*Fraction of CRD that contributes to recharge*
S	=	*Storativity*
A	=	*Model area [L^2]*
A_r	=	*Recharge area [L^2]*
Qp_i	=	*Groundwater abstraction in the i^{th}-month*
$Qout_i$	=	*Natural groundwater outflow in the i^{th}-month*

The *m* and *n* parameters in Equation 4 are determined through the use of an iterative solver (Xu & Beekman, 2003) by minimizing the error between the observed and simulated values. Since GRDM study areas can be quite large and contain multiple aquifer systems, it is unlikely obtain representative observation data to calibrate with. Against this backdrop it is recommended to set $n = i - L_x$ where *L* represents the lag time in time steps associated with recharge and *x* represent the aquifer type (*u* = unconfined or c = confined) as shown in Figure 24. In addition set $m = L_x - w_x$ where w_x is the sliding window length (Figure 24), also in time steps, to be determined making use of available observation data. When $L_x = 0$ recharge takes place relatively quickly which is typical for fractured rock aquifers and when $L_x > 0$ piston flow recharge takes place which is typical for unconsolidated aquifers (Xu & Beekman, 2003).

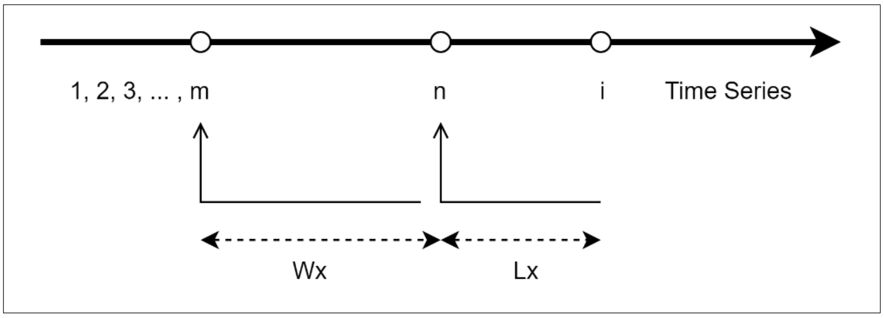


Figure 24: Recharge scenarios (after (Xu & Beekman, 2003))

Combined Model Formulation

The water balance equations representing the unconfined (u) and confined (c) layers are presented in Equation 6 and Equation 7 respectively. The aforementioned equations are based on the model parameters presented in Figure 21 and Figure 23 where the water level of the previous time step is used as the reference for the water level in the current time step.

$$H_{u_i} = H_{u_{i-1}} + \frac{A_{ru}R_{u_i} - Q_{pu_i} - Q_{lu_i} - Q_{bfu_i} - Q_{leak\,i}}{A_u S_u}$$ Equation 6

where,

$$R_{u_i} = r_u RIB_u(i)_{(L_u - w_u)}^{(i-L_u)}$$

$$H_{c_i} = H_{c_{i-1}} + \frac{A_{rc}R_{c_i} - Q_{pc_i} - Q_{lc_i} + Q_{leak\,i}}{A_c S_c}$$ Equation 7

where,

$$R_{c_i} = r_c RIB_c(i)_{(L_c - w_c)}^{(i-L_c)}$$

Two model restrictions apply 1) Q_{bfu} may not be altered by any type of discharge present in the model and 2) discharges may deplete Q_{lu} and Q_{lc} but only to a zero value, not flow reversal is allowed.

The two equations are combined through a common term Q_{leak}. If the two layers operate independently from each other i.e. the vertical hydraulic conductivity is zero then $Q_{leak} = 0$, then Equation 6 and Equation 7 can be solved independently of each other. However, if a leaky system is considered where the vertical hydraulic conductivity is non-zero, then $Q_{leak} \neq 0$ and then Equation 6 and Equation 7 have to be solved simultaneously via an iterative process.

Calculation of vertical conductance is required when cells are connected vertically. The default behavior for is to calculate vertical conductance under the assumption that both layers *u* and *c* are fully saturated. This is the default behavior even if the layers are partially dewatered and it is the same approach followed in MODFLOW 6 (Langevin, et al., 2017). The equation for the vertical conductance is presented in Equation 8 (Langevin, et al., 2017) in terms of the conceptual model parameters assigned in Figure 21 and the Q_{leak} term is presented in Equation 9.

$$\frac{1}{C_v} = \frac{1}{\frac{A_u K_u}{(1/2)(TOP_u - BOT_u)}} + \frac{1}{\frac{A_u K_c}{(1/2)(TOP_c - BOT_c)}} \qquad \text{Equation 8}$$

$$Q_{leak_i} = C_v\left(H_{u_{i-1}} - H_{c_{i-1}}\right) \qquad \text{Equation 9}$$

Groundwater Contribution to Baseflow

To determine the groundwater contribution to baseflow (Q_{bfu}) in Equation 6, Herold's baseflow separation technique (Vegter & Pitman, 2003) is applied to the naturalized flow associated with the study area under consideration. Note that the monthly rainfall records and flow records obtained from the WR2012 dataset (WRC, 2012) correspond with respect to the record size and the index *i* used. The general surface water balance equation is presented in Equation 10 (Vegter & Pitman, 2003).

$$Q_{t_i} = Q_{bfu_i} + Q_{s_i} \qquad \text{Equation 10}$$

where,

i	=	*1,2,3,…,I*
Q_{bfu}	=	*Groundwater contribution to baseflow from unconfined system*
Q_t	=	*Total flow during month*
Q_s	=	*Surface runoff during the month*

An assumption is made by Herold (Vegter & Pitman, 2003) that all flow below the term GG_{MAX} is associated with groundwater flow. The formulation of GG_{MAX} and associated conditions is presented in Equation 11.

$$GG_{MAX_i} = \left(D_G GG_{MAX_{i-1}}\right) + \left(P_G Q_{s_{i-1}}\right) \text{ with } GG_{MAX_i} > Q_{GMAX} \qquad \text{Equation 11}$$

where,

GG_{MAX}	=	*Maximum groundwater contribution*
D_G	=	*Groundwater decay factor (0 < D_G <1)*
P_G	=	*Groundwater growth factor (0% < P_G < 100%)*
Q_{GMAX}	=	*Specified maximum used as fitting parameter*

Applying Equation 11 to Equation 10 results in the Herold method formulation presented in Equation 12.

$$Q_{s_i} = Q_{t_i} - GG_{MAX_i} \;\; \text{for } Q_{t_i} > Q_{GMAX}$$
$$Q_{s_i} = 0 \;\; \text{for } Q_{t_i} \le Q_{GMAX} \qquad \text{Equation 12}$$
$$Q_{bfu_i} = Q_{t_i} - Q_{s_i}$$

Lateral Flow Component

The lateral inflow components are modelled through a conductance term and the difference between the water level and the bottom of the layer. The general formulation of this term is presented in Equation 13.

$$Q_{lx_i} = C_{lx}\left(H_{x_i} - BOT_x\right) \qquad \text{Equation 13}$$

where,

x	=	*Layer u (unconfined) or c (confined)*
Q_{lx}	=	*Lateral flow for layer x*
C_{lx}	=	*Conductance for layer x*
H_x	=	*Head value for layer x*
BOT_x	=	*Bottom of layer x*

Model Calibration

Model calibration remains a challenge for a lumped water balance model over large areas as it is difficult to obtain representative observation data to calibrate against. The

GRDM double layer model provides an automatic calibration function to assist users to calibrate the model, but this functionality is routed in some assumption.

Automatic Calibration Assumptions

In the absence of observation data certain assumptions are required to achieve model calibration and these assumptions are as follows:

- All required input parameters are correct. The GRDM model obtain default parameter values form the available national datasets (discussed later in this paper), but it is still required to validate these default parameter sets by applying appropriate analysis methods.
- During model calibration vertical hydraulic conductivity does not play a major role and can therefore be omitted so that model layer can be calibrated independently of each other.
- The difference between the layer head and bottom elevation is assumed to be the head difference used to estimate the conductance term for the lateral flow associated with each layer.
- The natural long-term water level response of each layer exhibits no increasing or decreasing water level trend.

Automatic Calibration Steps

The calibration steps performed in the background for the automatic calibration is summarized in the following steps:

1. Verify valid input to the model.
2. Set Q_{leak} to zero (layers are independent of each other).
3. Set Q_{pu} and Q_{pc} to zero (assume a natural state where no abstraction takes place).
4. Calculate Q_{bfu} by setting $D_G = 0.1$ and $P_G = 0.1$ and fitting Q_{GMAX} so that the long-term annual average of Q_{bfu} is equal to the specified annual average baseflow figure.
5. Solve for Q_{lu} and Q_{lc} so that the long-term water level response for each layer exhibits no increasing or decreasing water level trend.
6. Solve for C_u and C_c making use of Q_{lu} and Q_{lc} and assuming the head difference causing Q_{lu} and Q_{lc} is the difference between the long-term average water level in each layer and the bottom of the respective layers.
7. Enable Q_{leak} to connect the layers.

Model Limitations

Since the formulated model bear strong resemblance to that of the RIB box model (Xu & Beekman, 2003) the same limitations apply as specified for the RIB model (Xu & Beekman, 2003). The GRDM dual layer model comprise of two lumped water balance models which do not take into account the spatial variability of aquifer parameters and this leads to difficulty in model calibration. A procedure for automatic model calibration is applied, but this is based on the calibration assumptions stated earlier.

NATIONAL DATASETS

In the context of the GRDM water balance model, default values are required for the set of model parameters for South Africa as a whole. As stated in the introduction the GRA2 project (Department of Water and Sanitation, 2005) present selected geohydrological parameters both on a 1km x 1km grid as well as quaternary level for the whole of South Africa and hydrological parameters are presented on quaternary scale also for the whole of South Africa through the WR2012 project (WRC, 2012). It should be noted that even though quaternary catchment delineations exist for Lesotho and Swaziland not all parameters are reported for these regions in by the aforementioned data projects.

In terms of dataset updates the GRA2 (Department of Water and Sanitation, 2005) dataset has not been updated since its final release in 2005 and is considered a static dataset. The Water Resources of South Africa on the other hand had different updates since the first release of the WR90 (1990). After this initial release there were three more updates; WR95, WR2005 and WR2012. The WR2012 (WRC, 2012) dataset is considered a dynamic dataset as it is being updated on a continual basis which reflects the latest results of the surface water modelling of the various study areas. Due the sheer volume of work in performing surface water modeling for the whole country, it is not possible to have the WR2012 reflect annual updates, therefore is many instances the latest update may already be a few years old.

Geohydrological Parameters from GRA2

The following section will discuss the default geohydrological datasets used.

Aquifer Thickness (m)

Since the double layer model distinguishes between a unconfined and a confined aquifer, the average thickness of these model layers are required. The only dataset that provides a thickness parameters originate from the GRA2 dataset (Department of Water and Sanitation, 2005) where a distinction was made between the weathered and fractured zone thicknesses. Although technically not correct, the weathered zone thickness are assumed to be representative of the unconfined aquifer and the fractured zone thickness are assumed to be representative of the confined system. The map representation of the 1km x 1km grid data of the weathered zone thickness and that of the fractured zone thickness are presented in Figure 25 and Figure 26 respectively.

To obtain a better approximation for the required thicknesses of the double layer model, it is suggested to analyse the borehole logs obtained from the National Groundwater Archive (NGA) (Department of Water and Sanitation, 2023). In addition, a geostatistical analysis (Dennis & Dennis, 2020) can be performed based on the Vegter methodology (Vegter, 1995) to inform the layer thicknesses.

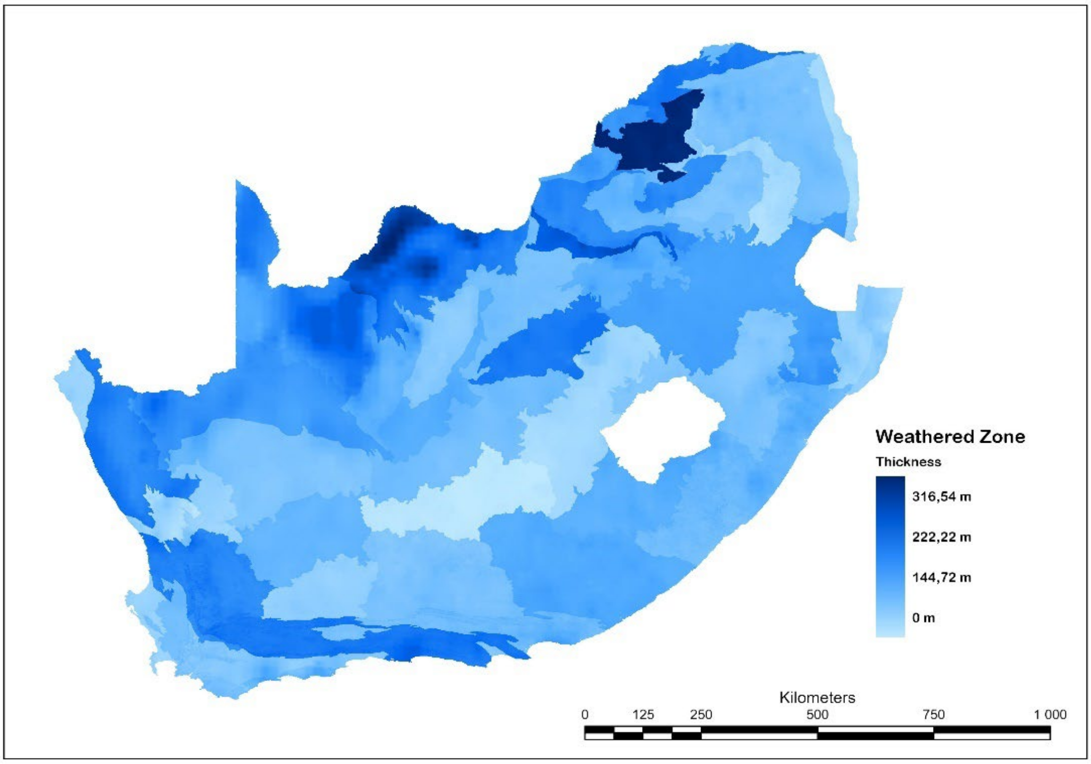


Figure 25: Weathered zone thickness

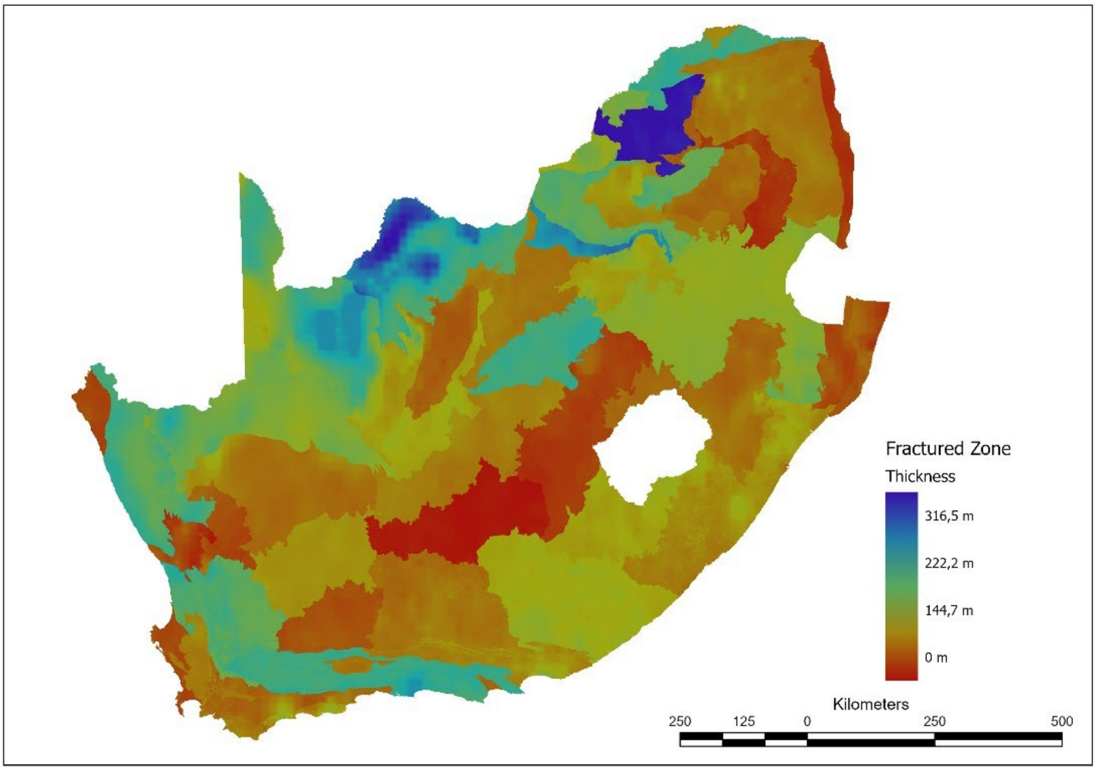


Figure 26: Fractured zone thickness

Transmissivity (m^2/d)

The vector data of transmissivity map available with the WR2012 dataset (WRC, 2012) presented in Figure 27. It is evident that the regions depicted follow that of the geohydrological yield map of South Africa detailing groundwater occurrence. A similar approach was used in the creation of the DART Index (Dennis & Dennis, 2012) where the groundwater occurrence class was related to a transmissivity as shown in Figure 28. The map representation of the 1km x 1km grid data of the transmissivity obtained from the GRA2 dataset (Department of Water and Sanitation, 2005) is presented in Figure 29. From Figure 29 it is clear that the source data was obtained from selected boreholes likely the NGA (Department of Water and Sanitation, 2023).

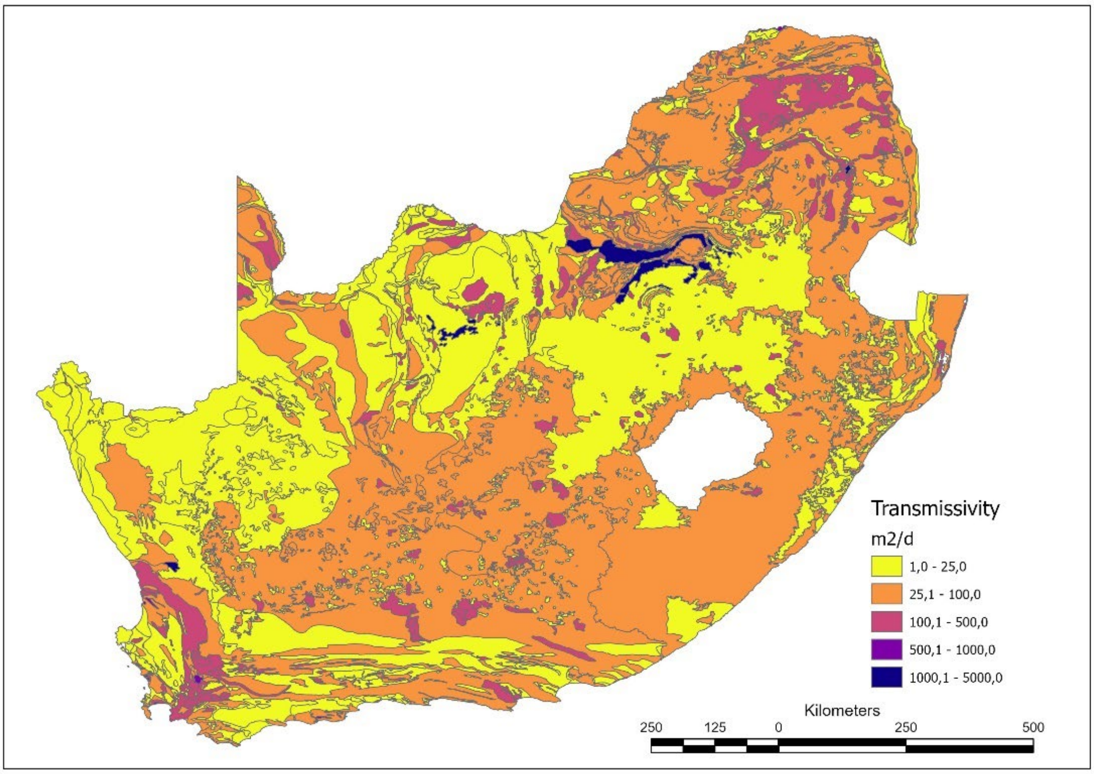


Figure 27: WR2012 transmissivity map

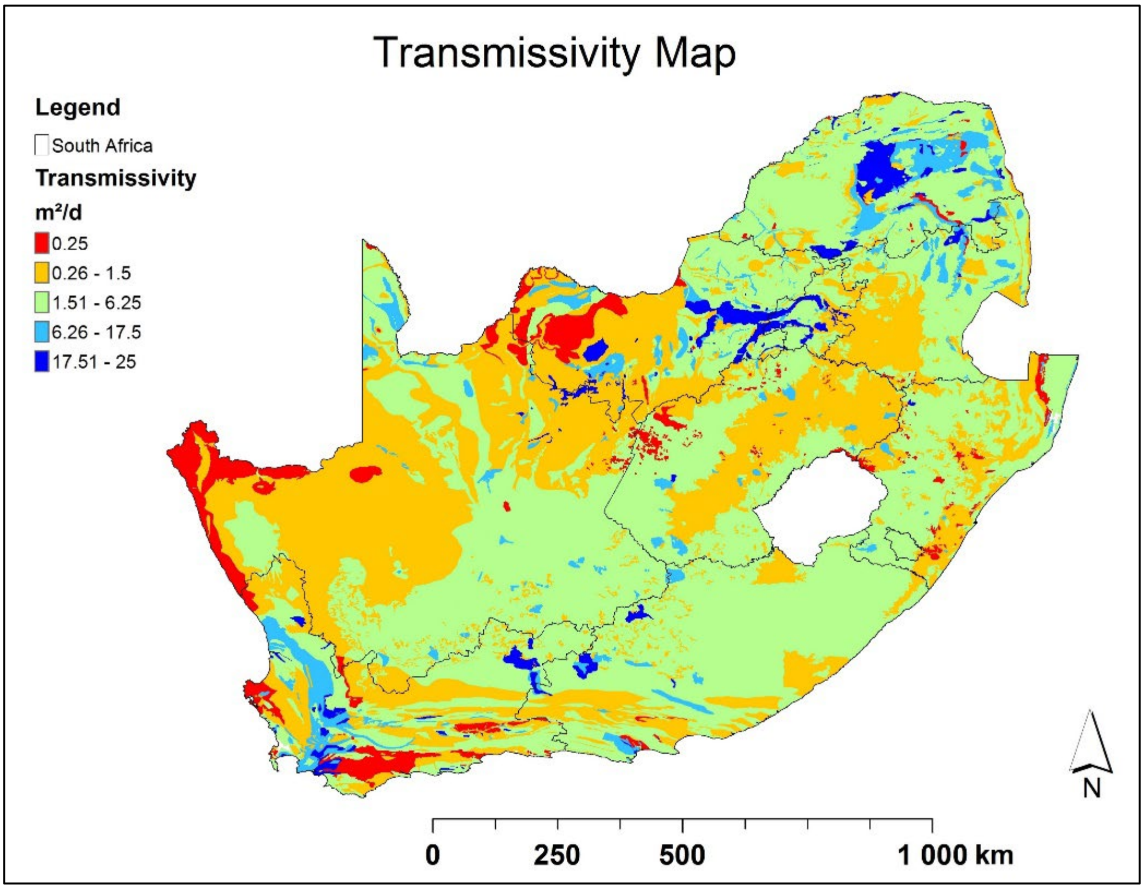


Figure 28: DART transmissivity map (Dennis & Dennis, 2012)

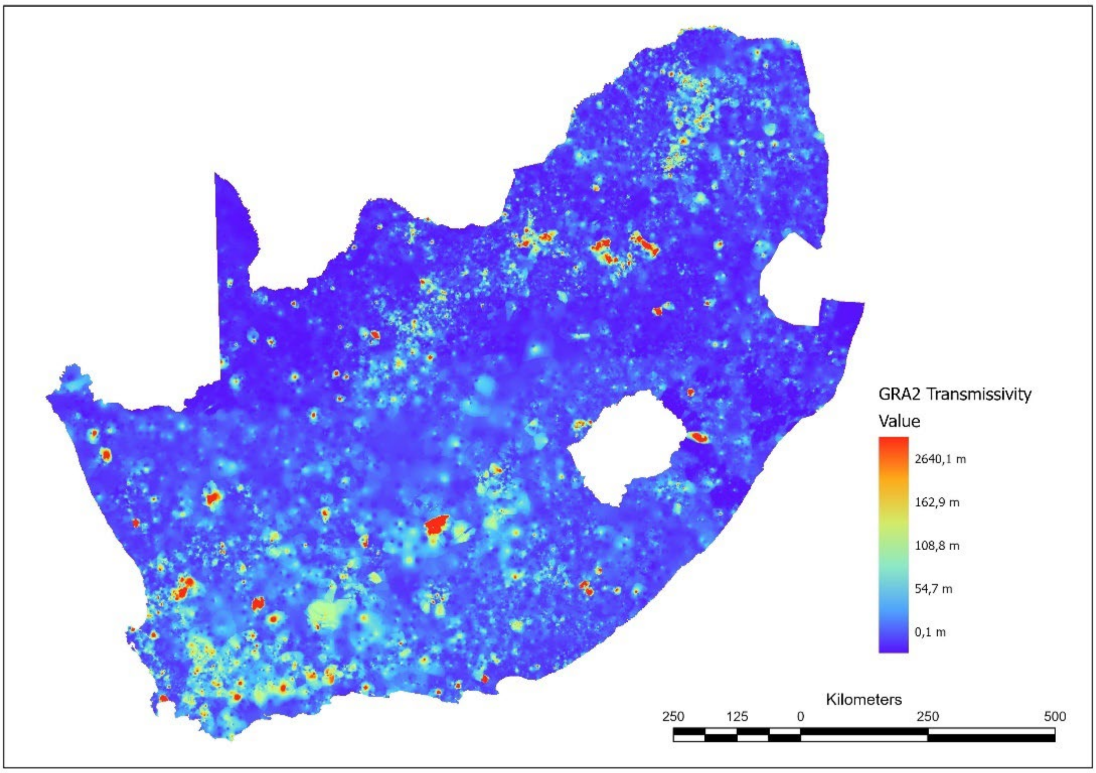


Figure 29: GRA2 transmissivity map

Storativity

In addition to the DART Index (Dennis & Dennis, 2012) transmissivity map a storage coefficient or storativity map was also generated making use of the groundwater occurrence classes and this map is presented in Figure 30. The map representation of the 1km x 1km grid data of the storativity obtained from the GRA2 dataset (Department of Water and Sanitation, 2005) is presented in Figure 31.

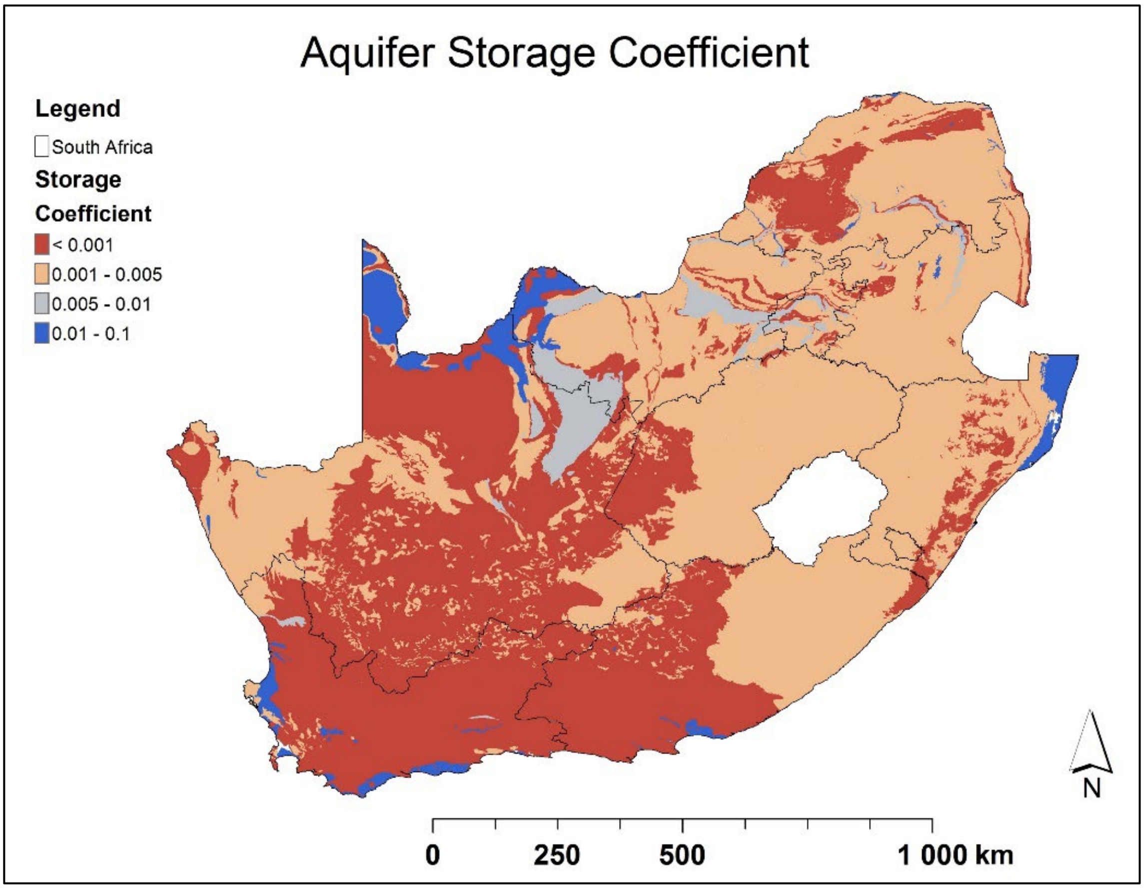


Figure 30: DART storativity map (Dennis & Dennis, 2012)

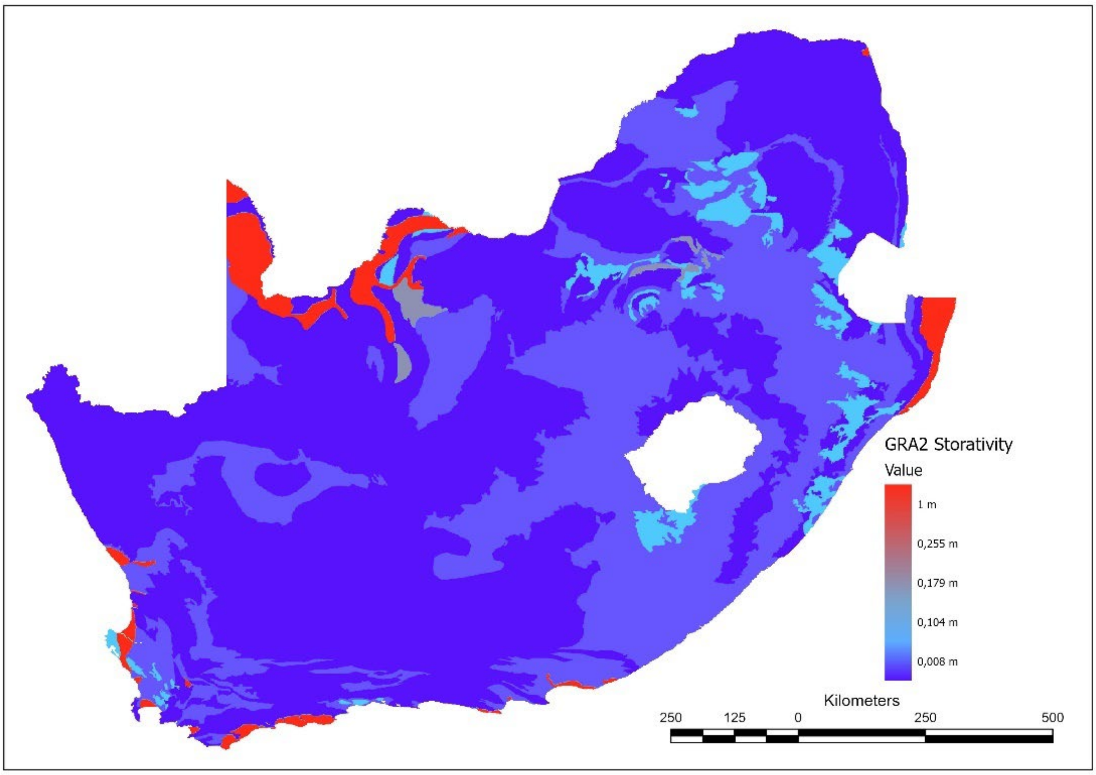


Figure 31: GRA2 storativity map

Recharge (mm/a)

The map representing the1 km x 1km grid of recharge values is presented in Figure 32. The method used to generate recharge values for the whole country is the Chloride Mass Balance (CMB) method (Beekman & Xu, 2003) making use of the concentration of Chloride in the groundwater and rainwater.

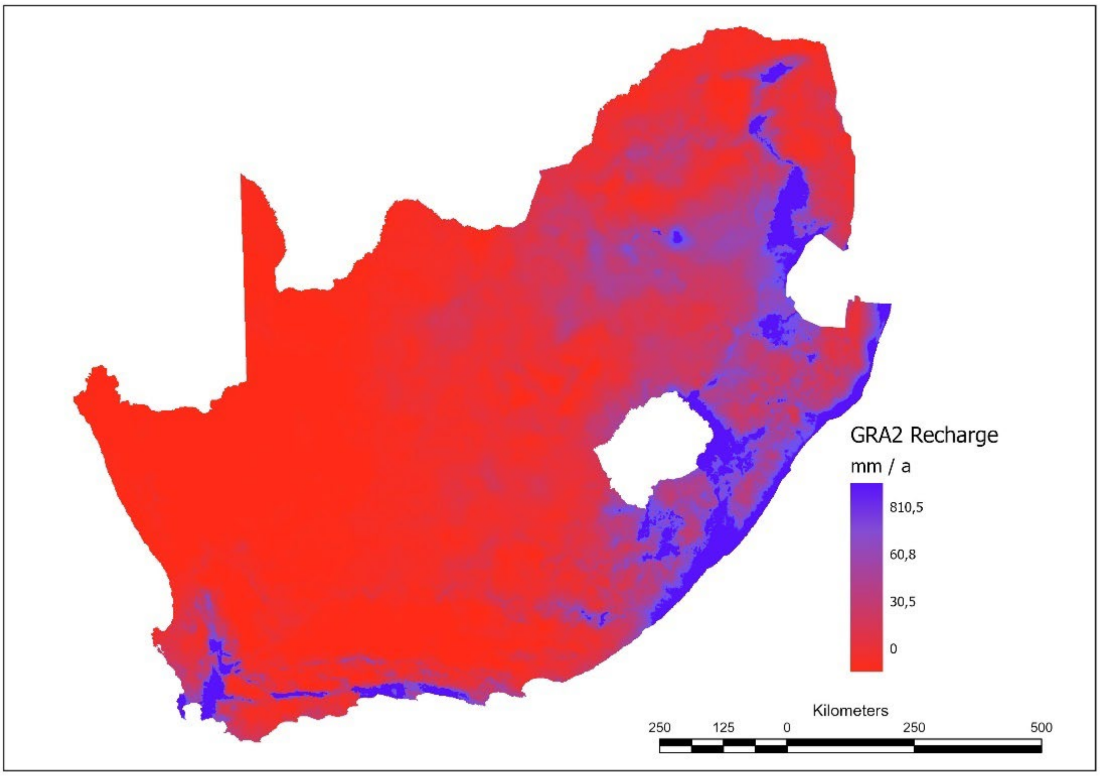


Figure 32: GRA2 recharge map

Groundwater Level (mbgl)

The average groundwater level obtained from the GRA2 dataset (Department of Water and Sanitation, 2005) expressed on the 1km x 1km grid is shown in Figure 33. These groundwater levels were established at the time making use of available borehole information, in particular the NGA dataset (Department of Water and Sanitation, 2023). Note these levels are expressed in depth to groundwater level or meters below ground level.

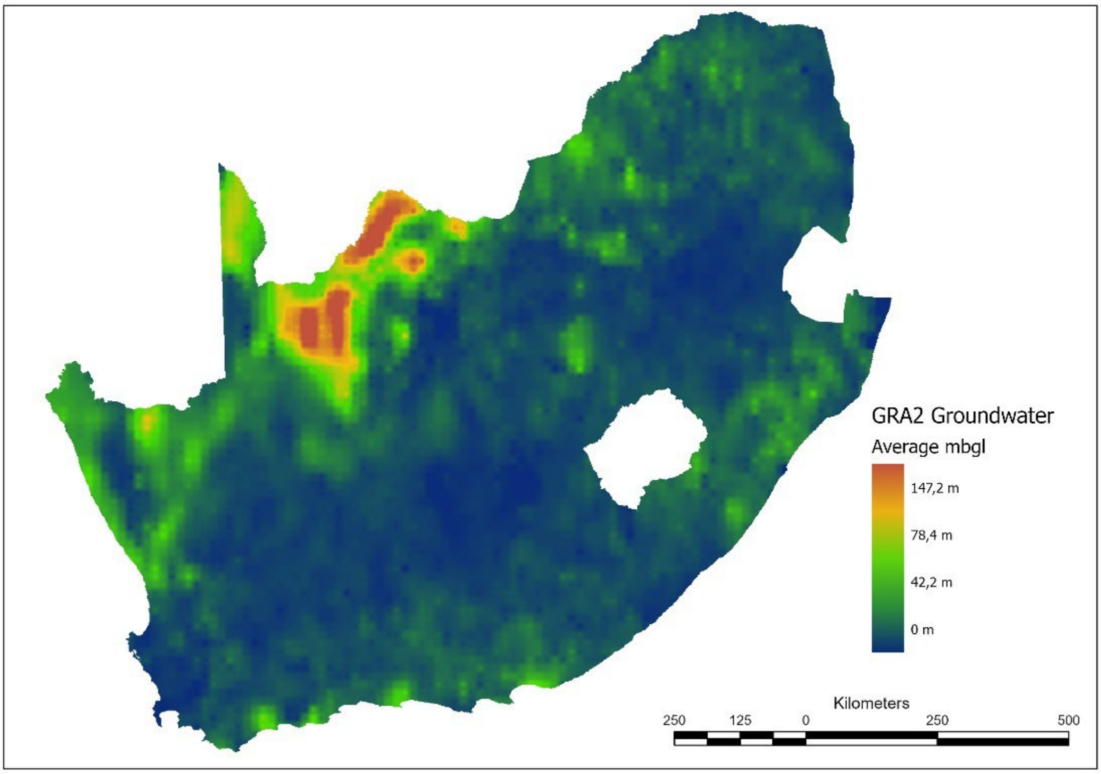


Figure 33: GRA2 average groundwater level map

Hydrological Parameters from WR2012

The following sections discuss the time series data required for the double layer model.

<u>*Long-term Rainfall (mm/month)*</u>

The WR2012 dataset (WRC, 2012) associate each quaternary catchment with a rain zone. The different rain zones express monthly rainfall as percentage of the Mean Annual Precipitation (MAP) associated with each area. Quaternary catchments sharing similar rainfall patterns share the same rain zone, but the individual rainfall volumes are still unique as the MAP will differ across these quaternary catchments. The rain zone responses are established making use of exiting rain gauges across South Africa and patching the measured rainfall where required.

The recharge via rainfall is the driving input to the double layer model and the WR2012 dataset (WRC, 2012) provides monthly rainfall per hydrological year starting in 1920 up to 2012 with the first release of the WR2012 data (WRC, 2012). As the WR2012 is now being updated on a continuous basis, the rainfall window may extend well beyond the 2012 depending on the last update per quaternary catchment.

Naturalized Flow (m^3/month)

As the groundwater contribution to baseflow requires protection by the NWA (RSA, 1998) it is explicitly accounted for in the double later model. To obtain monthly baseflow values, baseflow separation is required and since the double layer model use quaternary catchments as the primary delineation criteria, a runoff response is required for each quaternary catchment. The WR2012 (WRC, 2012) provides a naturalized flow sequence for each quaternary catchment over the same time period as the long-term rainfall.

The process followed by the WR2012 project (WRC, 2012) of obtaining the naturalized flow is to first calibrate the surface runoff models that represents all surface catchments of South Africa to the available flow gauging measurements. Once the models are calibrated all anthropogenic features are removed from the models and the new model runs then represent the naturalised flows for each modelled catchment. This data is then processed and proportioned to the different quaternary catchments.

Appendix D – Formulation of Existing Objects

Please note only objects responsible for calculations are presented here, parent objects that only act as group nodes are not presented here as they only have a type and a name associated with them.

ObjectUnit (Reserve) : Reserve Calculation

The relationship of the groundwater component of the reserve is specified in Equation 14 to express the reserve percentage.

$$Reserve\% = \left(\frac{BHN_{gw} + EWR_{gw}}{R_e}\right) \times 100 \qquad \text{Equation 14}$$

where,

Reserve%	=	*Reserve percentage*
R_e	=	*Recharge*
BHN_{gw}	=	*Basic Human Need derived from groundwater*
EWR_{gw}	=	*Groundwater contribution to EWR*
Q_s	=	*Surface runoff during the month*

Once the resource has been quantified, it is possible to allocate water to the different groundwater users. Most importantly, the volume needed by the BHN and the EWR should be set aside as this equates the reserve. The remainder can then be assigned to other groundwater users. The formula used to determine the amount of water that can be allocated is presented in Equation 15.

$$GW_{alloc} = (R_e + GW_{in} - GW_{out}) - (GW_{use} + BHN_{gw} + EWR_{gw}) \qquad \text{Equation 15}$$

where,

GW_{alloc}	=	*Groundwater that can be allocated (m^3/a)*
R_e	=	*Recharge (m^3/a)*
GW_{in}	=	*Groundwater inflow (m^3/a)*
GW_{out}	=	*Groundwater outflow (m^3/a)*
GW_{use}	=	*Groundwater use (m^3/a)*
BHN_{gw}	=	*Basic Human Need derived from groundwater (m^3/a)*
EWR_{gw}	=	*Groundwater contribution to EWR (m^3/a)*

ObjectHerold (Baseflow) : Herold Method

To determine the groundwater contribution to baseflow (Q_{bf}), Herold's baseflow separation technique (Vegter & Pitman, 2003) is applied to the naturalized flow associated with the study area under consideration. Note that the monthly rainfall records and flow records obtained from the WR2012 dataset (WRC, 2012) correspond with respect to the record size and the index *i* used. The general surface water balance equation is presented in Equation 16 (Vegter & Pitman, 2003).

$$Q_{t_i} = Q_{bf_i} + Q_{s_i} \qquad \text{Equation 16}$$

where,

i	=	*1,2,3,…,I*
Q_{bf}	=	*Groundwater contribution to baseflow*
Q_t	=	*Total flow during month*
Q_s	=	*Surface runoff during the month*

An assumption is made by Herold (Vegter & Pitman, 2003) that all flow below the term GG_{MAX} is associated with groundwater flow. The formulation of GG_{MAX} and associated conditions is presented in Equation 17.

$$GG_{MAX_i} = \left(D_G GG_{MAX_{i-1}}\right) + \left(P_G Q_{s_{i-1}}\right) \text{ with } GG_{MAX_i} > Q_{GMAX} \qquad \text{Equation 17}$$

where,

GG_{MAX}	=	*Maximum groundwater contribution*
D_G	=	*Groundwater decay factor (0 < D_G <1)*
P_G	=	*Groundwater growth factor (0% < P_G < 100%)*
Q_{GMAX}	=	*Specified maximum used as fitting parameter*

Applying Equation 17 to Equation 16 results in the Herold method formulation presented in Equation 18.

$$Q_{s_i} = Q_{t_i} - GG_{MAX_i} \text{ for } Q_{t_i} > Q_{GMAX}$$

$$Q_{s_i} = 0 \text{ for } Q_{t_i} \leq Q_{GMAX} \qquad \text{Equation 18}$$

$$Q_{bf_i} = Q_{t_i} - Q_{s_i}$$

ObjectChloride (Recharge) : Chloride Mass Balance

The formulation of the chloride mass balance method (Beekman & Xu, 2003) is given in Equation 28.

$$R = \frac{PCl_p + D}{Cl_{gw}}$$ Equation 19

where,

R	=	*Recharge (mm/[T])*
P	=	*Precipitation (mm/[T])*
D	=	*Chloride dry deposition (mg/m^2/[T])*
Cl_p	=	*Chloride in precipitation*
Cl_{gw}	=	*Chloride in groundwater*

Since the dry deposition is seldom available it is assumed to be zero and the recharge is expressed a percentage to align with the other recharge methods used so Equation 28 is rewritten as Equation 29.

$$R_e = \frac{Cl_p}{Cl_{gw}}$$ Equation 20

where,

R_e	=	*Recharge (%)*
Cl_p	=	*Chloride concentration in precipitation (mg/L)*
Cl_{gw}	=	*Chloride concentration in groundwater (mg/L)*

Since Equation 29 require the chloride concentration in precipitation which is generally not readily available, sample data of chloride concentration in precipitation across South Africa was used to determine a relationship between the chloride concentration in rainfall versus the distance from sea and this relationship is shown in Figure 34. The mathematical relationship of Figure 34 is presented in Equation 21.

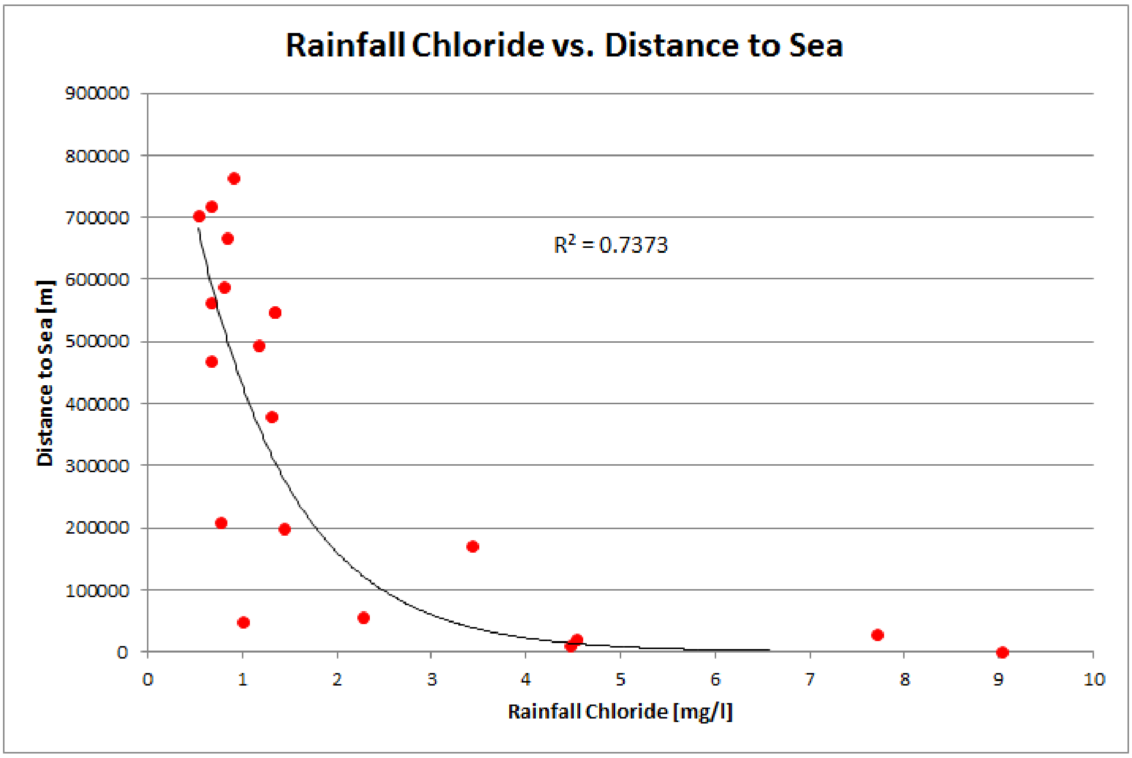


Figure 34: Chloride in rainfall versus distance to sea

$$Cl_p = -0.75 \ln(D_{sea}) + 11 \quad \text{Equation 21}$$

where,

Cl_p	=	*Chloride concentration in precipitation (mg/L)*
D_{sea}	=	*Distance to sea (m)*

ObjectSVF (Recharge) : Saturated Volume Fluctuation (SVF)

The SVF method (Beekman & Xu, 2003) based on a general groundwater balance, where the change in storage is expressed as a change in groundwater level and all inflows and outflows are translated to a change in head through the use of the aquifer area and specific yield as shown in Equation 29.

$$h_t = h_{t-1} + \frac{P_t R_e}{S_y} + \frac{Q_{in} - Q_{out}}{AS_y} \qquad \text{Equation 22}$$

where,

t	=	*Current time step [T]*	S_y	=	*Specific Yield*
h_t	=	*Head in current time step [L]*	*A*	=	*Aquifer surface area [L^2]*
h_{t-1}	=	*Head in previous time step [L]*	Q_{in}	=	*Sum of all groundwater inflows [L^3]*
P_t	=	*Precipitation in current time step [L]*	Q_{out}	=	*Sum of all groundwater outflows [L^3]*
R_e	=	*Recharge (%)*			

ObjectCRD (Recharge) : Cumulative Rainfall Departure (CRD)

The CRD method presented here is actually a modified SVF method and not the true CRD method. The actual CRD method is described in Appendix C. The modified SVF equation used is shown in Equation 30 and requires a minimum precipitation before recharge will take place, much like the CRD method. The reason for this specific implementation stems from the recommendation of Prof Gerrit Van Tonder that was involved in the development of the G1 version of the GRDM based on the observation that the CRD does not perform well over long periods of rainfall (Weber & Stewart, 2004).

$$h_t = h_{t-1} + \frac{(P_t - P_{\min})R_e}{S_y} + \frac{Q_{in} - Q_{out}}{AS_y} \qquad \text{Equation 23}$$

where,

t	=	*Current time step [T]*	S_y	=	*Specific Yield*
h_t	=	*Head in current time step [L]*	*A*	=	*Aquifer surface area [L^2]*
h_{t-1}	=	*Head in previous time step [L]*	Q_{in}	=	*Sum of all groundwater inflows [L^3]*
P_t	=	*Precipitation in current time step [L]*	Q_{out}	=	*Sum of all groundwater outflows [L^3]*
R_e	=	*Recharge (%)*	P_{min}	=	*Minimum rainfall required for recharge*

ObjectEarth (Recharge) : EARTH Method

The EARTH method (Van Tonder & Xu, 2001) is presented in Equation 31 where the water level response is governed by a resistance term and the recharge volume is translated to a water level through the use of specific yield.

$$h_t = h_{t-1} + \frac{h_{t-1}}{R_s} + \frac{P_t R_e}{S_y} \qquad \text{Equation 24}$$

where,

t	=	*Current time step [T]*	S_y	=	*Specific Yield*
h_t	=	*Head in current time step [L]*	R_s	=	*Resistance*
h_{t-1}	=	*Head in previous time step [L]*			
P_t	=	*Precipitation in current time step [L]*			
R_e	=	*Recharge (%)*			

ObjectIsotope (Recharge) : Isotope Method

The formulation of the isotope method (Beekman & Xu, 2003) is presented in Equation 25. It should be noted that the presented method is only allowed for recharge events less than 20 mm/a.

$$R = \left(\frac{20}{\Delta\delta}\right)^2 \qquad \text{Equation 25}$$

where,

R = *Recharge (mm/a)*

Δδ = *Displacement from local meteoric water line*

ObjectRiver (Zone) : River Protection Zone

The protection zone should be large enough that the flow through the system is not altered. The derivation of the protection zone is shown below making use of the recharge volume and Darcy's law. The final expression is given in Equation 28 with a conceptual layout presented in Figure 35.

$$Q = Area \times R = LWR$$

$$Q = TiW$$

$$LWR = TiW$$

$$L = \frac{Ti}{R} \qquad \text{Equation 26}$$

where,

L	=	*Distance from river (m)*
W	=	*Width of the section of river (m)*
Area	=	*Area (m^2)*
T	=	*Transmissivity (m^2/d)*
i	=	*Groundwater gradient towards river*
Q	=	*Volume (m^3/[T])*
R	=	*Recharge (m/[T])*

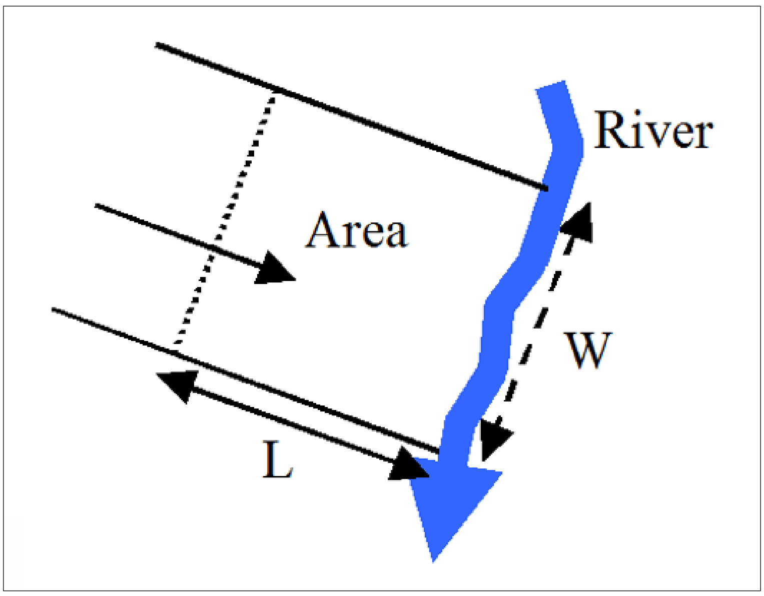


Figure 35: River protection zone conceptual layout

ObjectWetland (Zone) : Wetland Protection Zone

The protection zone should be large enough that the flow through the system is not altered. The derivation of the protection zone is shown below making use of the recharge volume and Darcy's law. The final expression is given in Equation 29 with a conceptual layout presented in Figure 36.

$$A = \frac{Q}{R}$$

$$\textit{Assume wetland radius } r = W/2\pi \textit{ and } Q = TiW$$

$$W = 2\pi r \rightarrow r = \frac{W}{2\pi}$$

$$A = \pi(r+L)^2 - \pi r^2$$

$$\pi(r+L)^2 - \pi r^2 = \frac{Q}{R}$$

$$2\pi rL + \pi L^2 = \frac{Q}{R}$$

$$L = \frac{\frac{\sqrt{\pi^2 r^2 R + \pi Q}}{\sqrt{R}} - \pi r}{\pi} \qquad \text{Equation 27}$$

where,

L	=	*Distance from wetland (m)*
r	=	*Radius of the wetland (m)*
Area	=	*Area (m^2)*
T	=	*Transmissivity (m^2/d)*
i	=	*Groundwater gradient towards river*
Q	=	*Volume (m^3/[T])*
R	=	*Recharge (m/[T])*

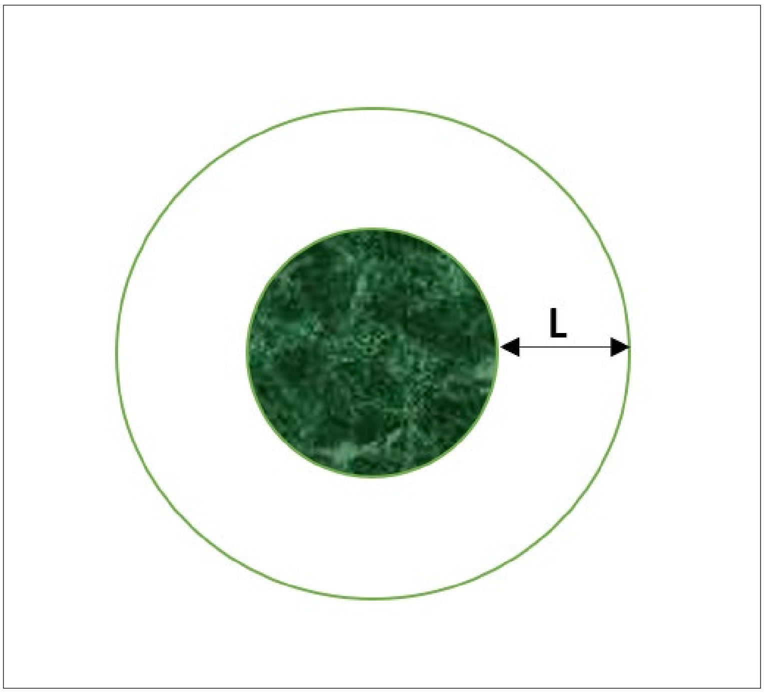


Figure 36: Wetland protection zone conceptual layout

ObjectWellfield (Wellfield) : Cooper-Jacob Model

The wellfield model is based on the Cooper-Jacob equation (Kruseman & De Ridder, 1991) presented in Equation 28 and the conceptual model is shown in Figure 37.

$$s = \frac{2.3Q}{4\pi T} log \frac{2.25Tt}{r^2 S} \qquad \text{Equation 28}$$

where

s	=	Drawdown
Q	=	Abstraction rate of the borehole
T	=	Transmissivity
t	=	Time of abstraction
S	=	Storativity
r	=	Distance from borehole where drawdown is measured.

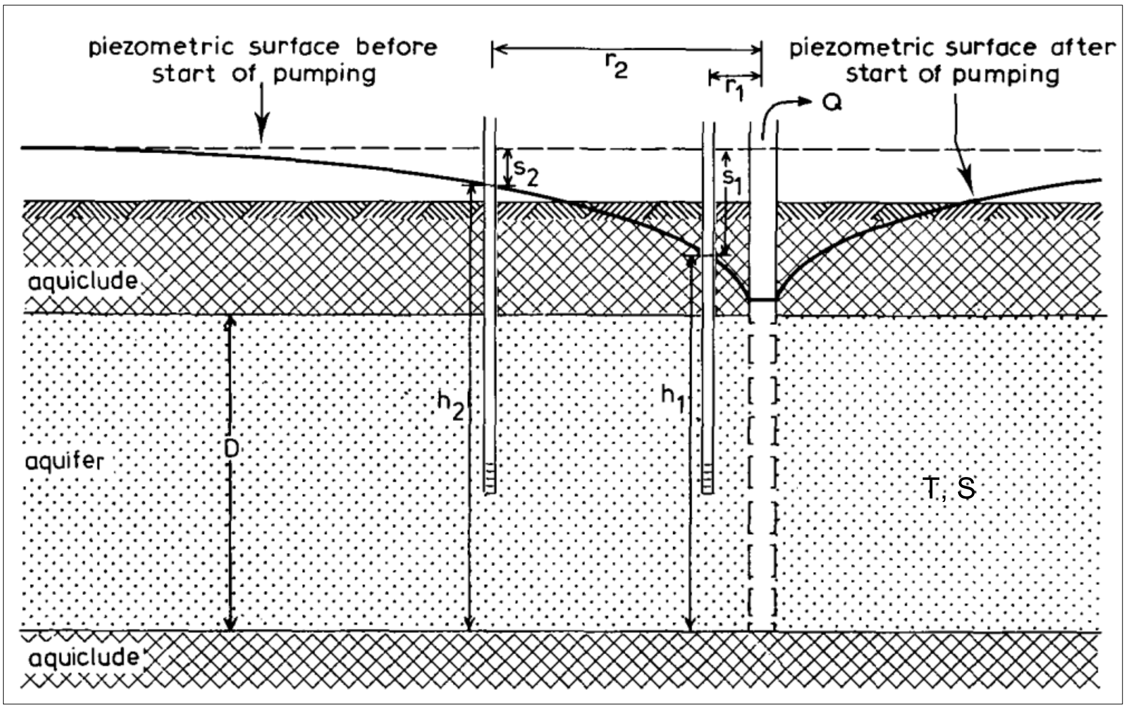


Figure 37: Cooper-Jacob conceptual model (Kruseman & De Ridder, 1991)

The wellfield model makes use of the principal of superposition and calculate the effect of the pumping borehole on neighbouring boreholes, by calculating the resultant drawdown at *r* where *r* represents the distance to the neighbouring borehole. This is shown graphically in Figure 38 where the dotted lines indicate the drawdown cones associated with each of the boreholes and the solid blue line shows the resultant drawdown curve after superposition is applied to the individual drawdown curves.

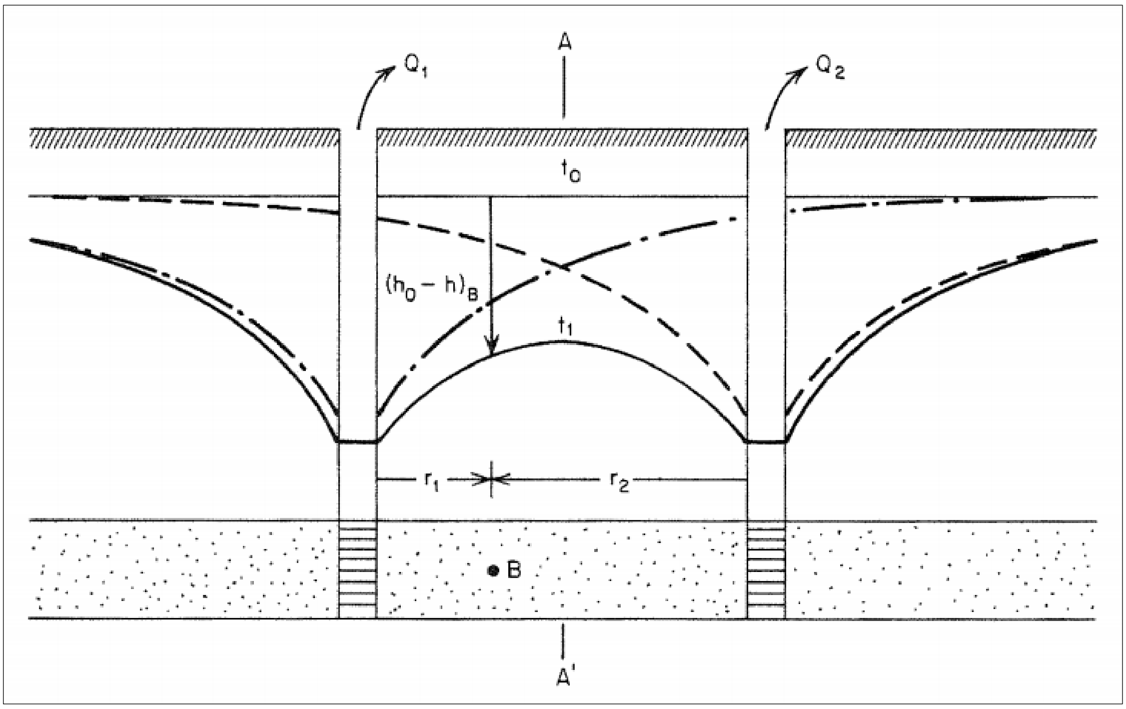


Figure 38: Effect on neighbouring boreholes (Freeze & Cherry, 1979)

To model a no-flow boundary an image well (borehole) with the same parameter set is placed twice the distance of the no-flow boundary from the pumping borehole and modelled as a neighbouring borehole, making use of superposition as depicted in Figure 39.

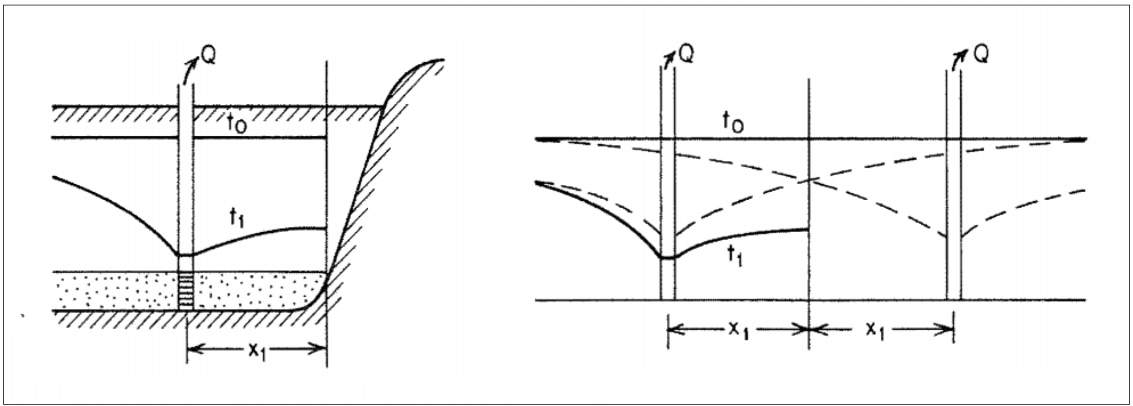


Figure 39: Modelling a no-flow boundary using an image well (Freeze & Cherry, 1979)

To model a constant head boundary an image well (borehole) with the same aquifer parameters, but opposite pumping rate is placed twice the distance of the constant head boundary from the pumping borehole and modelled as a neighbouring borehole, making use of superposition as depicted in Figure 40.

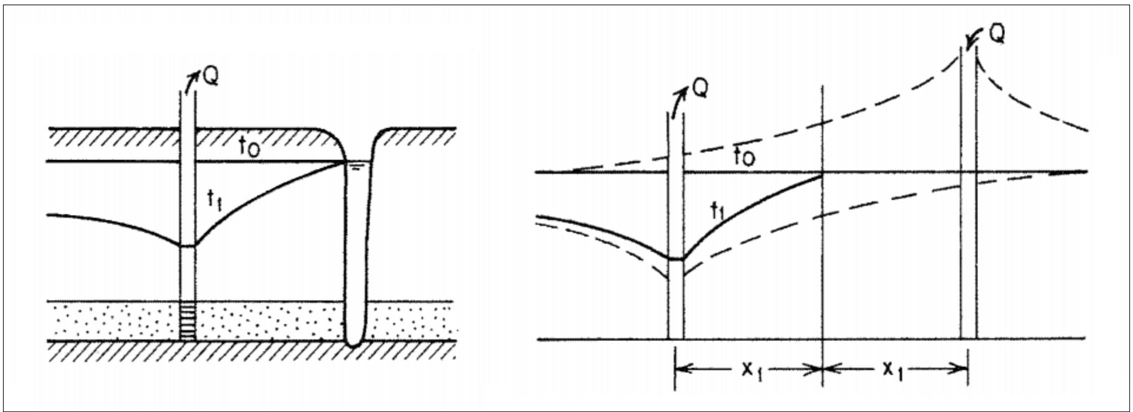


Figure 40: Modelling a constant head boundary using an image well (Freeze & Cherry, 1979)

Appendix E – Formulation of New Objects

ObjectBalance (Baseflow): Groundwater Contribution to Baseflow

The calculation of the groundwater contribution to baseflow is based on the conservation of mass. The method requires the measurement of flow and concentration of a conservative chemical constituent in the water both up-stream and down-stream of the section of the stream/river where groundwater contribution to baseflow is required. Consider the network shown in Figure 41 and associated equations (Equation 29 and Equation 30). The method requires that both equations yield the same result for the assessment to be considered valid.

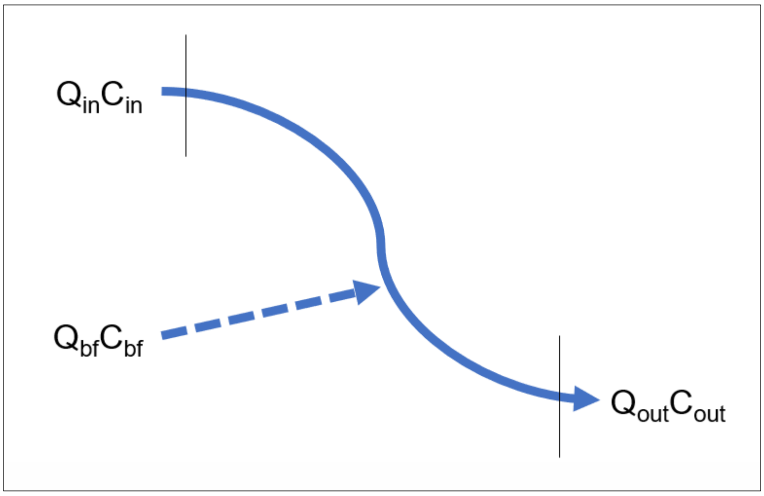


Figure 41: Conceptual flow network

$$Q_{bf} = Q_{out} - Q_{in} \qquad \text{Equation 29}$$

$$Q_{bf} = \frac{Q_{out}C_{out} - Q_{in}C_{in}}{C_{bf}} \qquad \text{Equation 30}$$

where

Q_{bf}	=	Groundwater contribution to baseflow
Q_{in}	=	Flow in
Q_{out}	=	Flow out
C_{in}	=	Concentration of water sample at inflow
C_{out}	=	Concentration of water sample at outflow
C_{bf}	=	Concentration of groundwater near stream/river

ObjectRQO (Quality): Quality Component

The procedure followed for the water quality component is described as follows by the research team on the project:

- To determine the ambient condition for each water quality parameter, take the median value.
- The BHN is the limit according to SANS241.
- To get groundwater quality reserve, add 10% to the median value and that is the limit for the reserve.
- NB: if the ambient condition is above the limit, then take median as the limit and not add the 10%. An example is seen in Table 34 for Chloride.
- In the case of pH, add the 10% for the upper limit and subtract the 10% for the lower limit.

Table 34: Physio-chemical criteria

Parameter	Ambient Ground Water Quality[1)]	Basic Human Needs Reserve[2)]	Ground Water Quality Reserve[3)]
Calcium (mg/L)	88.00	<150	96.80
Magnesium (mg/L)	62.50	<100	68.75
Sodium (mg/L)	132.00	<200	145.20
Chloride (mg/L)	**248.00**	<200	**248.00**
Sulphate (mg/L)	106.00	<400	116.60
Nitrate (mg/L)	2.78	<10	3.05
Fluoride (mg/L)	0.60	<1.0	0.66
EC (mS/m)	171.15	<150	171.15
pH	7.30	5.0 – 9.5	6.57 - 8.03

ObjectWellfield (Wellfield) : Theis Drawdown Model

All aspects of the wellfield object remain the same as described in Appendix D (ObjectWellfield), the only difference is that the Cooper-Jacob equation is replaced by the Theis equation (Kruseman & De Ridder, 1991) as shown in Equation 31 and the series expansion is calculated to 9 terms in Equation 31.

$$s = \frac{Q}{4\pi T}\left(-0.5772 - \ln(u) + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \cdots\right.$$ Equation 31

$$u = \frac{r^2 S}{4Tt}$$ Equation 32

where

s	=	Drawdown
Q	=	Abstraction rate of the borehole
T	=	Transmissivity
t	=	Time of abstraction
S	=	Storativity
r	=	Distance from borehole where drawdown is measured.