Utilisation of the Analytical Element Method in a groundwater Reserve determination

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ABSTRACT

The most important factors of South African water resources are the quantity and quality thereof. Therefore, as prescribed in the Water Services Act (108 of 1997) the Reserve needs to be protected, used, developed, conserved, managed and controlled through various guidance principles. To achieve these goals, the principles of sustainability, equity and efficiency should be used according to the National Water Act (NWA) (36 of 1998).

Regional datasets are mostly available on quaternary catchment scale, as this is the boundary that the Department of Water and Sanitation (DWS) uses for reporting purposes. This has led to the quaternary catchments being used as the basis for GRDM calculations, even though the surface water boundaries and groundwater aquifers are rarely the same. On a regional scale assessment, some of the problem areas are lost to the process of averaging and therefore local scale or well field scale analysis is important. Recent studies in the Vaal and Crocodile catchments has brought the issue of scale to light where Resource Quality Objectives (RQOs) for groundwater systems were set on well field scale for effective protection of the water resource.

This dissertation sets out to improve the current groundwater Reserve methodology by addressing identified limitations of the current water balance approach through the implementation of an Analytic Element Method (AEM) model. Rather than a predefined mesh, which allows for a highly scalable solution, the AEM model domain is described by various analytical elements. The AEM supports elements that represent different recharge zones and aquifer parameters to model an inhomogeneous aquifer system.

This study demonstrates that Visual AEM can be applied to study regional groundwater flow and provide solutions for the existing scale issues by adopting model calibration parameters to obtain a satisfactory representation of the groundwater system. Thus, the overall conclusion is that the model is proficient in representing catchment scale processes that South Africa generally experience.

Key words: AEM, Analytic Element Method, Groundwater, Reserve, Scale, Visual AEM

ACRONYMS AND ABBREVIATIONS

ACRU	Agricultural Catchments Research Unit
AEM	Analytic Element Method
AFYM	Aquifer Firm Yield Model
AnAqSim	Analytic Aquifer Simulator
BHN	Basic Human Needs
CMB	Chloride Mass Balance
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EPA	Environmental Protection Act
ET	Evapotranspiration
EWR	Ecological Water Requirements
FY	Firm Yield
FYM	Firm Yield Model
GFLOW	Groundwater Flow
GGP	Gross Geographical Product
GIS	Geographic Information System
GRAll	Groundwater Resource Assessment Phase ll
GRDM	Groundwater Reserve Determination
GRIP	Groundwater Resource Information Project
GRP	Groundwater resource Potential
IWRM	Integrated Water Resource Management
K	Hydraulic Conductivity
MAE	Mean Annual Evaporation
mamsl	Meters above mean sea level
MAP	Mean Annual Precipitation
MAR	Mean Annual Run-off
mbgl	Meters below ground level
MLAEM	Multi-layer Analytical Element
NAGROM	Dutch National Groundwater Model
NGA	National Groundwater Archive
NGDB	National Groundwater Database
QDGC	Quarter Degree Grid Cell
RDM	Resource Directed Measures
S	Storativity
SLAEM	Single Layer Analytic Element Model
T	Transmissivity
TWODAN	Two – dimensional Analytic Model
UA’s	Units of Analysis
WhAEM	Wellhead Analytic Element Method
WMA	Water Management Area
WR	Water Resources

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1 INTRODUCTION

The most important factors of South African water resources are the quantity and quality thereof. Therefore, as prescribed in the Water Services Act (108 of 1997) the Reserve needs to be protected, used, developed, conserved, managed and controlled through various guidance principles. To achieve these goals, the principles of sustainability, equity and efficiency should be used according to the National Water Act (NWA) (36 of 1998). Quantifying the yield of a catchment is a fundamental matter in when assessing water resources. The impacts of population growth and poor management of water resources on the catchment water balance are considered a fundamental problem (Bugan *et al*., 2012).

It has become essential to optimise water yields and the management thereof within South Africa's quaternary catchments. To manage the catchments, geohydrological modelling has been acknowledged to be an important and effective tool for a range of groundwater quantification problems (Bugan *et al*., 2012). For optimal management of groundwater resources utilised, it is highly advantageous to carry out water balance approaches (Conrad *et al*., 2004).

Van Tonder and Wentzel developed the first Groundwater Resource Directed Measures (GRDM) methodology which was never fully documented, with the authentic GRDM manual written by Parsons and Wentzel in 2007. The Water Research Commission (WRC) (2007) reviewed the initial methodology in an attempt to address some of the limitations such as the issue of scale and the uncertainty in the estimation of surface-groundwater interaction.

Regional datasets are mostly available on quaternary catchment scale, as this is the boundary that the Department of Water and Sanitation (DWS) uses for reporting purposes. This has led to the quaternary catchments being used as the basis for GRDM calculations, even though the surface water boundaries and groundwater aquifers are rarely the same. On a regional scale assessment, some of the problem areas are lost to the process of averaging and therefore local scale or well field scale analysis is important (Dennis *et al.*, 2011).

Recent studies in the Vaal and Crocodile catchments has brought the issue of scale to light where Resource Quality Objectives (RQOs) for groundwater systems were set on well field scale for effective protection of the water resource (DWA, 2010; DWA, 2012; DWAF, 2004; Hobbs *et al*., 2013).

A water balance refers to the principle of conservation of mass, or the continuity equation. It states that, for any arbitrary amount/volume of water body during any period of time, the change in water storage in any volume and the difference between the total input and outputs will be balanced. Consequently, the water balance technique involves quantities of storage and fluxes (rates of flow) of a water body (UNESCO, 1974).

This dissertation sets out to improve the current groundwater Reserve methodology by addressing identified limitations of the current water balance approach through the implementation of an Analytic Element Method (AEM) model. Rather than a predefined mesh, which allows for a highly scalable solution, the AEM model domain is described by various analytical elements. The AEM supports elements that represent different recharge zones as well as areas with different hydraulic conductivities to model an inhomogeneous aquifer system (Strack, 2003).

The resultant models are represented by two case studies where groundwater Reserve studies have previously been completed.

1.1 HYPOTHESIS

By applying the AEM in a groundwater Reserve determination, a better estimation is achieved through the modelling of non-uniform recharge and aquifer parameters.

1.2 AIMS AND OBJECTIVES

1.2.1 Aims

The aim of this research study was to apply the AEM to a groundwater Reserve determination process, to address limitations in the existing methodology as far as possible. It is necessary to determine the Reserve in order to determine the amount of water that can still be sustainably allocated within an area.

1.2.2 Objectives

- Implement the “firm yield” concept through the use of an AEM model,
- Consider non-uniform recharge and aquifer parameters,
- Compare AEM model results with existing and previous methodology using two case studies.

1.3 METHODS OF INVESTIGATION

The limitations of the existing groundwater Reserve methodology will be identified and addressed as far as possible through the implementation of a representative AEM model. Existing groundwater Reserve studies will be compared to the results obtained through the AEM model applied to the same area.

1.4 PROVISIONAL CHAPTER DIVISION

The layout of this dissertation are as follows:

1. Introduction: Background about the analysis to be carried out. Brief reviews of previous research and relevant facts from scientific literature.
2. Literature Review: Review the existing and previous GRDM methodologies focusing on the Reserve to identify the shortcomings and the assumptions these methodologies are based on.
3. Analytical Element Method: Overview of the AEM and the working thereof.
4. Methodology: Discuss the application of the AEM method to the problem of groundwater Reserve determinations as it relates to the regional water balance.
5. Case Study 1: Describe the study area and discuss the existing groundwater Reserve determination for the area. Implement the proposed AEM model for the area and compare results.
6. Case Study 2: Describe the study area and discuss the existing groundwater Reserve determination for the area. Implement the proposed AEM model for the area and compare results.
7. Comparing results: Compare the Parsons & Wentzel (2007) and Dennis *et al*., (2011) method, the Firm yield model and the AEM model results.
8. Conclusions and Recommendations.

2 LITERATURE REVIEW

2.1 INTRODUCTION

The literature reviewed for this research study includes a range of topics. The focus lies in summarising, evaluating and discussing different methods to calculate Reserve. The content of this literature will form part of the overall objective of the dissertation by addressing limitations in the literature. It will connect the conclusions to other applications of the various methods and assist in evaluating the advantages and disadvantages of the methods regarding a Reserve determination study (in South Africa). Further research includes the firm yield model. The focus of this Chapter will be on the Reserve with only a short overview of the different GRDM methods being provided. The full GRDM methodology is discussed in Appendix A.

2.2 FOUNDATIONS OF WATER MANAGEMENT

As early as the 1970s it was a concern that South Africa would most probably have water supply problems by the year 2000. Numerous inter-basin transfer schemes (e.g. the Lesotho Highlands Water Project) helped alleviate some of the predicted water shortages. To address this required innovative planning, strategies and legislation. The NWA (36 of 1998) is one of, if not the main outcome of the process. The NWA (36 of 1998) replaced the Water Act (54 of 1956) which did not focus on environmental issues, equity issues and downstream water requirements. Groundwater was also documented as belonging to the owners of the property (i.e. private use).

With a new government in 1994 it was the ideal time to address the shortcomings of the Water Act (54 of 1956). The NWA (36 of 1998) endorses and encourages the integrated management of all water resources, thereby ensuring the sustainable management of South Africa’s water resources. This is necessary to ensure water resources are protected, developed, conserved, and controlled taking into account interested and affected parties, the environment, society and the economy.

2.3 GROUNDWATER RESOURCE DIRECTED MEASURES

2.3.1 Background

“*Chapter 3 of the NWA (36 of 1998) focuses on protecting the health of South Africa’s water resources. Protection involves the sustaining of a certain quantity and quality of water to maintain the overall ecological functioning of rivers, wetlands, groundwater and estuaries. This Chapter therefore introduces series of measures which together are intended to protect all water resources. These measures are referred to as Resource Directed Measures (RDM), and in the case of where it is related to groundwater, as the GRDM. These measures include Classification, Quantification of the Reserve and RQOs.*

Classification of the resource is basically the describing its current state. Water resources must be classified into one of the following classes (Dennis et al., 2011):

- *Class I water resource: water resources (and associated aquatic ecosystems) are minimally altered from its pre-development condition.*
- *Class II water resource: water resources (and associated aquatic ecosystems) are moderately altered from its pre-development condition.*
- *Class III water resource: water resources (and associated aquatic ecosystems) that is significantly altered from its pre-development condition.*

The Reserve is defined as the quantity and quality of water needed to satisfy basic human needs (BHNs) and to protect aquatic ecosystems in order to secure ecologically sustainable development and use of water resources (NWA, 36 of 1998).

RQOs are numerical or descriptive limits set to reflect a balance between the need to develop and use a water resource while also protecting the water resource in a sustainable matter. They are measurable goals for a resource that define its utility (Colvin et al., 2004).”

2.3.2 GRDM methodology

A generic overview of the GRDM process can be summarised as (Parsons and Wentzel, 2007):

- Preparatory phase

During this phase the DWS decides on the level (e.g. desktop, intermediate or comprehensive) detail required for the GRDM study. The project team is also identified.

- Description of the area

  The appointed project team gathers all data necessary to describe the study area in terms of its physical and geohydrological characteristics in detail appropriate to the level of GRDM assessment.

- Delineation of units

  The delineation process can be based on aquifer boundaries, integrated surface water (aquatic ecosystems) and groundwater boundaries or quaternary catchments.

- Classification of the delineated units

  Here the present state of the delineated units is described and defined. The output of this process will be used as part of the process to set the desired management classes.

- Quantification of the Reserve

  To determine the amount of groundwater needed for BHNs and ecological water requirements (EWRs). The calculation is then made to determine the amount of water that can be abstracted from a groundwater resource without impacting on the Reserve.

- Determination of RQOs

RQOs are there to manage and monitor the groundwater resources. RQOs can be numeric or descriptive but must make sure that the quantity and the quality of a groundwater resource is maintained at a certain level/standard.

2.4 THE RESERVE

2.4.1 Gazetted Reserve methodology

"*The NWA (36 of 2008) defines the Reserve as follows:*

Reserve means the quantity and quality of water required –

a) *to satisfy basic human needs by securing a basic water supply, as prescribed under the Water Services Act, 1997 (Act No 108 of 1997), for people who are now or who will, in the reasonably near future, be –*

   relying upon;

   taking water from; or

   being supplied from,

   the relevant water resource; and

b) *to protect aquatic ecosystems in order to secure ecologically sustainable development and use the relevant water resource.*

In 2010 the then Department of Water Affairs (DWA) gazetted the procedure for determining the Reserve. For each water resource class, must comprise of the following eight steps:

- *Assess ecological water and BHNs requirements.*
- *Delineate resource units*
- *Determine the reference conditions, present ecological status and the ecological importance and sensitivity of each of the selected study sites.*
- *Determine the basic human needs and ecological water requirements for each of the selected study sites*
- *Determine operational scenarios and its socio-economic and ecological consequences.*
- *Evaluate the scenarios with stakeholders and align water resource classification procedure.*
- *Design an appropriate monitoring programme.*
- *Gazette and implement the Reserve."*

2.4.2 Quantifying the Reserve

The ecological component of the groundwater Reserve is often associated with the groundwater contribution to baseflow or the natural baseflow due to the appropriate scale or the lack of data. There is extensive variability in baseflow values (Dennis *et al*, 2011). Additionally, natural baseflow is significantly higher than ecological Reserve requirements relating to its low flow requirements. The groundwater component of the Reserve is expressed in Equation 1:

$$\text{Reserve (\%)} = (EWR_{gw} + BHN_{gw})/Re \times 100 \qquad (1)$$

Where:
Re = Recharge
BHN_{gw} = basic human needs derived from groundwater
EWR_{gw} = groundwater contribution to EWR
Reserve (%) = percentage of the Reserve

Several problems exist when using low flow requirements as guidance, since the Reserve is expressed as a percentage of recharge, which can be a highly variable and an uncertain parameter. In addition, both recharge and the EWR for groundwater are usually derived at catchment scale and is not aquifer specific (Riemann, 2012).

Once the Reserve has been determined, the amount of water that can still be allocated for use can be calculated according to Equation 2:

$$GW_{allocable} = Re - GW_{use} - GW_{Reserve} \qquad (2)$$

Where:
Re = Recharge
GW_{use} = Current groundwater use
$GW_{Reserve}$ = Groundwater contribution to the Reserve
$GW_{allocable}$ = Allocable groundwater

2.4.3 The interaction between groundwater and surface water

The effective management of the quantity and quality of groundwater systems presents many challenges throughout South Africa. Well documented research justifies the range of interactive systems connecting groundwater to topographical, geological and climatic settings. Smaller scale assessments regarding surface and groundwater interactions are mostly done due to a lack of funding and data in South Africa (Tanner, 2013).

Groundwater and surface water bodies are linked in many landscapes. It is thus essential to understand the associations to successfully manage these resources. Management schemes need to include aspects such as quantifying the flow between groundwater and surface water units. When surface water and/or groundwater are used, it can alter the rate, location and direction of flow between them (Levy, 2011).

Levy (2011) describes the most common approach South Africa uses in the following sentence; "*the estimation of average annual fluxes at the scale of fourth-order* *catchments (~500 km²) with base flow separation techniques and then subtracting the groundwater discharge rate from the recharge rate*''. This approach, however, has errors, for example the widespread occurrence of fractured rock in South Africa. Fractured rock aquifers are difficult to conceptualise due to spatial variabilities of groundwater contribution to surface water bodies.

The association between groundwater and surface water bodies are still being extensively researched. This has led to the separation of groundwater and surface water hydrology even though these two entities are part of a single hydrologic cycle (Levy, 2011). Table 1 represents a summary of methods used when investigating groundwater/surface-water interaction in South Africa.

Table 1: Methods used to investigate groundwater/surface-water interaction (adapted from Levy, 2011).

Method	**Scale of application**	**Appropriate for estimates in discrete locations and/or fractured bedrock settings**	**Allows quantification of exchange?**
Seepage meters and miniiezometers	In-stream point measurements	yes	yes
Heat-flow modelling	In-stream point measurements and short river reaches	yes	yes
Upstream/downstream flow measurements	Individual river reaches with no other unknown inputs/outputs	yes	yes
Hydrometry/Darcy's law/water balance	Entire basin or single lake or wetland	no	yes
Geochemistry and temperature	Sub basin and individual river reaches	yes	yes
Stable isotopes ^{2}H and ^{18}O	Sub basin and individual river reaches	yes	yes
Baseflow separation	Entire basin, quaternary catchments or section of basin upstream from point of stream monitoring	no	yes
Conceptual modelling	Entire basin or section of a basin	possibly	no
Numerical modelling	Various, up to entire basin	yes	yes
Vegetation mapping	Various, up to entire basin	yes	no

The groundwater contribution to surface water bodies is an important parameter to determine during a Reserve determination process. This parameter refers to the amount of water that flows from the regional aquifer into surface water bodies such as rivers, contributing to the baseflow and/or low flow. For the optimum ecological function of a river or surface water body, a minimum flow rate must be maintained (Riemann & Blake, 2010).

Hughes *et al*., (2003) incorporated a groundwater component into a rainfall runoff model that can provide a tool for quantifying the groundwater contribution to baseflow. In Parsons and Wentzel (2007), an approach to use for quantifying the groundwater contribution to baseflow is explained.

2.4.4 Quantification of recharge

"*Recharge is the volume of water reaching the saturated zone of an aquifer. The portion of rainfall that infiltrates the soil horizon that contributes to the total volume of the underlying aquifer is of great importance. Recharge is expressed as a percentage of the rainfall figure and varies considerably from year to year, depending on the average annual rainfall"* (Department of Water Affairs and Forestry (DWAF, 2006b & c).

Recharge depends on several factors, including geomorphology, aquifer characteristics (geology, topography etc.), rainfall distribution and rainfall intensity. Dolomite aquifers usually have a wide range of recharge values due to their high permeability, compared to the rest of the aquifer types (DWAF, 2006b & c).

Sustainable withdrawal from groundwater resources depends on the balance between the recharge and the amount of water discharged from the system, including natural outflow of wetlands and the withdrawal from boreholes. Water levels will begin to decline if the amount of withdrawal exceeds the recharge, which can lead to unwanted consequences. Recharge is therefore an important factor to understand and quantify groundwater resources (DWAF, 2006b & c).

The methods used to calculate recharge in this dissertation are discussed and utilised in case study 1 and 2 (Chapter 5). These methods include the saturated volume fluctuation (SVF) method, Chloride method, the distance to sea method, a groundwater recharge map (Vegter, 1995), a Harvest Potential Map (Van Tonder &

Xu, 2000), qualified guesses and recharge values obtained from reliable literature. The DWA, (2009) recommends that the chloride method is useful only as a first estimate of recharge ranges, but the SVF method has higher accuracy ratios. A combination of recharge estimates and methods are preferable to accurately describe the range of recharge for an area of interest.

2.4.5 Quantification of inflows and outflows

A comprehensive understanding of the geohydrological system and the relationships that exist between inflows and outflows in a system are essential when dealing with a Reserve. This includes groundwater linkages, aquifer characteristics, travel times, pathways etc.

Common inflows to a groundwater system include infiltration which becomes recharge from precipitation, injection at boreholes for managed aquifer storage and recovery programs or wastewater treatment and groundwater flow from areas next to the area of interest such as areas up gradient, above or below. Common outflows from groundwater systems include evaporation, transpiration, abstraction from boreholes, natural groundwater flow, discharge at springs and groundwater that seeps to surface water bodies.

The functioning of groundwater and surface water systems play a fundamental role in geohydrology. It is key to understand and measure exchange processes within aquifer systems. Thus, several well-known methods exist for parameter estimation. Kalbus *et al., (*2006) provides an overview of several methods currently used to estimate fluxes in groundwater inflows and outflows. Table 2 summarizes different parameters and their method of measurement:

Table 2: Different methods to measure the interaction between groundwater and surface water (Kalbus *et al*., 2006).

Parameter	Method
Seepage flux	Seepage meters
Temperature gradient	Temperature profiles
Hydraulic head	Piezometers
Hydraulic conductivity	Grain size analysis Permeameter tests Slug tests Pumping tests
Porosity	Sediment sample analysis

Parameter	Method
Groundwater velocity	Tracer tests
Groundwater component	Incremental streamflow Hydrograph separation Environmental tracers Heat tracers
Contaminant concentration	Monitoring wells Grab sampling Passive samplers Integral pumping tests Seepage meters

2.4.6 Quantification of BHNs

The BHNs component of the Reserve determination is based on the population numbers within the confines of a resource unit. The minimum requirement as per the Water Services Act (108 of 1997) of 25 litres/person/day needs to be calculated (Riemann & Blake, 2010).

The BHNs is the highest priority of any water use groups that exist. This is why the BHNs component must be accounted for in water balance models for a groundwater unit. Thus, the location of borehole abstractions must be optimal as it is difficult to regulate and police the groundwater used for BHNs (Wright & Xu, 2000).

2.4.7 Tools to assist with the quantification of groundwater resources

Groundwater quantification in South Africa is not as widely researched as surface water quantification. The Groundwater Resource Assessment Phase II (GRAII) was introduced in South Africa to quantify groundwater resources. The main objectives of this quantification of South Africa's groundwater resources was aquifer storativity, recharge, and yield, which was based on GIS algorithms. Steady state Groundwater Resource Potential datasets (GRP) provides estimates of the maximum amount of groundwater that can be abstracted on a sustainable basis, considering only aquifer storage and recharge from rainfall (Woodford *et al*., 2005).

The basic principle for the water balance is based on the conservation of mass. This means that the groundwater entering and exiting a resource unit over a period of time in steady state conditions is based on Equation 3 (Wright & Xu, 2000):

$$\text{Recharge} - \text{Discharge} = 0 \qquad (3)$$

Quantifying a resource using the mass balance of the water balance approach for a catchment is possible where groundwater is exploited. The following relationship exists where the water balance equation above is modified in Equation 4 (Braune & Dziembowski, 1997):

Adjusted recharge - reduced outflow - pumpage + storage loss = 0 (4)

Although the relationship is understandable, most of the components cannot be accurately or adequately measured directly. Spatial and temporal variances also need to be considered. It is also difficult to quantify adjusted recharge and reduced outflow (discharge, evapotranspiration and evaporation) to a high degree of certainty. For example, the calculated evapotranspiration losses and vegetation interception frequently exceeds total groundwater recharge (Parsons, 1999).

There are several methodologies to estimate long-term average annual recharge; it ranges from simple empirical solutions to detailed numerical models. The methodologies generally depend on available data and hydrogeological knowledge of an area (Parsons, 1994).

2.5 OVERVIEW OF THE GRDM METHODOLOGY BY PARSONS & WENTZEL, (2007)

2.5.1 Quantification of the Reserve

To quantify the groundwater section of the Reserve, Equation 5 is used:

$$GW_{allocate} = (Re + GW_{in} – GW_{out}) – BHN – GW_{Bf} \qquad (5)$$

Where:

$GW_{allocate}$ = groundwater allocation

Re = recharge

GW_{in} = groundwater inflow

GW_{out} = groundwater outflow

BHN = basic human needs

GW_{Bf} = groundwater contribution to baseflow

Thus, groundwater contribution to baseflow and BHNs that are met from the groundwater is the volume of water that is required to sustain the Reserve.

2.5.1.1 Recharge

Recharge is considered the most important parameter when assessing sustainable groundwater abstraction from an aquifer. Parsons & Wentzel (2007) suggest the following resources/methods to determine recharge:

- National scale maps for example Vegter (1995)
- Expert opinions
- Chloride mass balance method
- Spring flow technique
- Hydrograph or baseflow separation techniques
- Saturated volume fluctuation method
- Water table function method
- Cumulative rainfall departure method
- Isotope-based methods
- EARTH model
- Numerical groundwater flow models

2.5.1.2 Groundwater inflows and outflows

Groundwater inflows and outflows must be calculated in addition to recharge from precipitation. Parsons & Wentzel, (2007) recommend the Darcy's Law to determine groundwater inflows into and outflows from groundwater units as shown in Equation 6:

$$Q = T\, i\, w \qquad (6)$$

where:

Q = discharge (m^3/d)
T = transmissivity (m^2/d)
i = groundwater gradient
w = width of groundwater unit perpendicular to flow (m)

2.5.1.3 BHNs calculation

The BHN's component of the Reserve determination is determined as discussed in Section 2.4.6.

2.5.1.4 Groundwater contribution to baseflow

Parsons & Wentzel (2007) recommended the following tools/techniques to calculate the groundwater contribution to baseflow:

- Baseflow separation techniques (e.g. Herold, 1980)
- National scale map showing the relative probability of groundwater contributing to baseflow (source unknown)

They also strongly recommended that the geohydrologist consult an experienced hydrologist during this process.

2.5.2 Limitations GRDM methodology by Parsons & Wentzel, (2007)

The following limitations when considering the Reserve were identified by the by the authors of the 2007 GRDM methodology:

- The groundwater component in the hydrologic field is considered data-poor.
- It is nearly impossible to quantify every parameter in a Reserve assessment with a significant degree of confidence.
- The Reserve was developed for a surface water perspective, not considering groundwater implications.
- GRDM-driven monitoring guidelines in South Africa are lacking.
- New tools and approaches regarding recharge, groundwater use and groundwater contribution to baseflow need to be researched and developed to improve practitioners' abilities in this regard.
- The allocation of water is still of concern in terms of tools and methodologies.

2.6 REVIEWED GRDM METHODOLOGY AS SET OUT BY DENNIS *ET AL*., (2011)

2.6.1 Quantification of the Reserve

The quantification of the Reserve remained the same as that of Parson and Wentzel (2007). However, the groundwater units delineate are replaced with integrated units of analysis which takes into account all aspects of the Reserve within the specific area. In addition, Dennis *et al.,* (2011) addresses scale issues and how to deal with data uncertainty for recharge, groundwater inflows and out flows and groundwater contribution to baseflow.

2.6.1.1 Recharge

The same methods were used as in Parsons and Wentzel (2007).

2.6.1.2 Groundwater inflows and out flows

The groundwater inflows and out flows are determined in the same way as that of Parsons and Wentzel (2007). However, the groundwater units delineate are replaced with integrated units of analysis which takes into account all aspects of the Reserve within the specific area.

2.6.1.3 BHNs calculation

The BHN's component of the Reserve determination is determined as discussed in Section 2.4.6.

2.6.1.4 Groundwater contribution to baseflow

Groundwater contribution to baseflow is where the 2 manuals differ quite significantly. Dennis *et al.,* (2011) discusses groundwater contribution to baseflow in detail for wetlands and rivers. Additional regression curve fitting methods were introduced. Calculations based on the type of river bed material, geology and river stretch were included. These calculations range from simple analytical models to detailed numerical models.

2.6.2 Limitations

Dennis *et al.,* (2011) addressed many of the limitations identified in the document written by Parson and Wentzel (2007), however there will still always be limitations that need to be addressed at a governmental level. Some the limitations and the possible solutions will be discussed below:

- The groundwater component in the hydrologic field is considered data-poor. Groundwater and associated data necessary to quantify the Reserve are sometimes limited, and the data confidence is not always the same. Dennis *et al.,* (2011) provided solutions for addressing data uncertainty.
- The Reserve was developed for a surface water perspective, however by delineating integrated units of analysis and calculating the Reserve for them, all aspects of the Reserve are taken into account.
- GRDM-driven monitoring guidelines in South Africa are lacking.

- New tools regarding groundwater contribution to baseflow have been introduced, however new methods/tools to calculate recharge and groundwater use are still necessary.

2.7 ASSURED YIELD

2.7.1 Introduction

Most methods used to determine the safe yield of an aquifer disregard the element of risk of shortage of supply related to rainfall variability. By not specifying the reliability of the estimated aquifer yield, implies that it is guaranteed. In addition, an aquifer may have a very large storage capacity, but only a small proportion of this may be utilized without causing ‘undesirable’ effects. It can also be that not all of the stored groundwater can be abstracted as a portion of this water is required by for EWRs (Murray *et al.,* 2012).

Civil engineers specify the reliability of the yield from a surface water reservoir to be able to sustainable manage the reservoir. This is often referred to as the ‘assured’ or ‘firm yield’ of the reservoir. The assured yield of the system is estimated by statistical analysis of long-term time-series data of inflow versus reservoir storage and can vary according to various design-demand criteria. The risk, in this context, is defined as the percentage of years when the assured yield may not be supplied in full, e.g. a 90% assurance of supply implies a risk that there may be shortages on average in 10 out of every 100 years (Murray *et al.,* 2012).

The key component to both a reservoir and an aquifer is rainfall, which varies considerably. The reservoir and aquifer storage volume are important when determining assured yield of these systems. A reservoir overflows when full, whilst the aquifer discharges water as baseflow dependent on variable levels of storage. Abstraction of water from either causes variance in total available storage and losses from the system (Murray *et al.,* 2012).

The Aquifer Assured Yield Model is a single-cell, lumped parameter model which uses a critical management water level below which aquifer storage levels cannot be drawn down to provide estimates of aquifer firm and assured yields. This level defines the volume of water held in aquifer storage that is available for abstraction and would take into account various physical, legal, societal or environmental constraints.

The assured yield for South African aquifers varies over short distances due to the heterogeneity of the fractured aquifers. Detailed site-specific assessments are therefore required for good estimates of assured yields. Other complicating factors include saline intrusion in coastal aquifers and sinkhole formation in the dolomite aquifers. Enforcement of adaptive management practices is required to address the shortcomings that exist in the assured yield concept (DWA, 2009)

2.8 FIRM YIELD

Firm yield is defined as the uniform rate at which water can be drawn from the reservoir (or groundwater resource) throughout a period of specified severity without depleting the contents so much that withdrawal at the same rate is no longer feasible (Gaillard & Mawdsley, 1982).

The water balance approach assumes that the change in storage within a system is equal to all inflows less all the outflows from the system. Groundwater systems are in its natural state over long periods; thus, natural inputs are in balance with natural outputs, therefore, the storage will be zero. Groundwater resources are then considered to be in steady state, but if abstraction or disturbance takes place, the groundwater component will not be in balance anymore, a new steady state will then be established if the recharge is more than the abstraction. If abstraction is more than the recharge of a system, it implies that the system will not be in an unsteady state (Woodford *et al*., 2005).

Murray *et al*., (2012) present yields through the perception utilised in surface water resource assessments as well as dam reservoir design which have been modified and applied to groundwater such as other approaches like The Harvest Potential (HP) (Baron *et al*., 1998). Moreover, Groundwater Resource Assessment Phase II (GRAII) (DWAF, 2005a) are questionable due to their static nature (cannot change yields and parameters). Consequently, the Aquifer Firm Yield Model is introduced.

The model represented by Murray *et al.* (2012) needs to be modified according to the DWA, (2009) to consider shallow, porous, unconfined aquifers and considerable time lag between discharge and recharge in aquifers. The DWA (2009) also states that it is important to understand recharge-rainfall relationships as it is often non-linear and auto-correlated. The sum of the assured yield for all boreholes in an aquifer must be lesser than the sustainable assured yield of the specific study unit.

Murray *et al*. (2012) aims to identify groundwater potential areas for bulk municipal water supplies, quantifying them with different methods and packaging the information assessable for planning purposes. The study provides us with tools for identifying and quantifying groundwater areas as follows:

2.8.1 The Aquifer firm yield model (AFYM)

Using average inputs and outputs (e.g. mean annual runoff (MAR) and evapotranspiration), single term invariant, average sustainable and/or safe yields can be estimated. The AFYM uses recharge data for specific areas, default values that are provided and if necessary, the user can use site-specific data when available. This is one of the main differences (specifying variables) between the new AFYM and the HP and GRAII methods (Murray *et al*., 2012).

Murray *et al.* (2012) provides two aquifer yield models, namely:

1. The Aquifer Assured Yield Model (AAYM) (regularly perform risk analysis),
   This method is similar to assurance levels in surface water reservoir design. Assured yield is estimated by the statistical analysis of inflow versus reservoir/aquifer storage of long-term time-series data that is variable in terms of design-demand criteria.
2. The AFYM
   This is a modified version of the AAYM providing historical firm yields, not assurance of supply. Firm yield is the maximum amount of water that can be abstracted from a reservoir or aquifer during dry periods; sometimes it is based on the lowest flow/recharge sequence flow in a natural stream on record.

These models are considered as single cell lumped-parameter models that uses critical management water levels (volume of water available for abstraction in aquifer storage) to determine the firm yield or assured yield of an aquifer. This level has various constraints in terms of physical, legal and environmental aspects.

According to Murray *et al.* (2012), the operation of the box model is based on the fact that effective recharge is based on the outflows (evaporation, baseflow and pumping). This effective recharge (Qre) can be less than the recharge (%MAP) and this difference translates to a potential recharge (Qr) volume. The Qre can never be more than the recharge because the recharge serves as the source for the Qre (Figure 1).

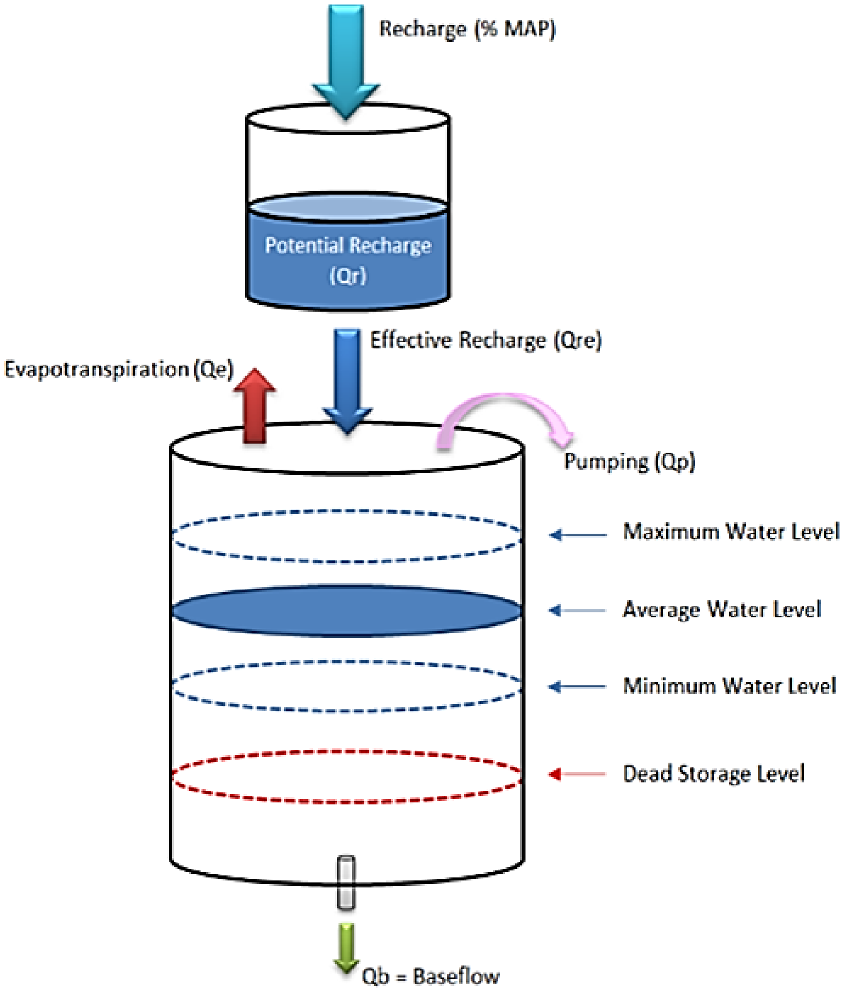

Figure 1: Yield model concepts (Murray *et al.*, 2012).

The AFYM was compared to other recharge assessments of aquifers where yield was estimated. The De Aar aquifer study was conducted by Kirchner *et al*. (1991), using the SVF method. Woodford (SRK, 2007) also investigated the potential of estimating recharge from rainfall using the Maxey-Eakin technique (Murray *et al.,* 2012).

The results of SRK (2007) stated that similar yields were obtained using lower recharge values obtained by Kirchner *et al*. (1991) and assumed realistic wellfield yields. It showed that AFYM produces good results when conservative values are applied to the model, and when using the default values, reasonable results were obtained.

3 THE ANALYTICAL ELEMENT METHOD

3.1 OVERVIEW AND BACKGROUND

By introducing the AEM in this chapter, there are several aspects to be taken into account, the AEM as a whole will be explained as well as its applications in other scientific reports. This chapter describes all of the relevant information using the AEM. By discussing its advantages and disadvantages, various limitations come to attention using the AEM. Previous research overviews and reviews of the AEM are primarily focussed on mathematical theory. Thus, real world problems on the application of this method will be discussed in this literature review, as well as its relevance to this dissertation, conducting a Reserve determination.

The computational skills of in the 1970s could not attain the large numbers of grid nodes needed for the numerical solution necessary for forecasting the effects of regional drawdowns from a 40-mile cut in the streams and canals near the Tenesse-Tombigee waterway. Stack from the University of Minnesota then proposed the model of superposition of analytic functions or analytic elements. This was the start of the AEM (Hunt, 2006).

Stack introduced new or special mathematical formulations; which is the analytic representation of regional groundwater flow problems that includes heterogeneous aquifers and complex (realistic) boundary conditions. It resulted in the development of a dual aquifer flow model with piecewise constant hydraulic conductivity fields with no perimeter boundaries (unbounded flow domain), large model domains, streamline calculations and complex geometries – all without a grid. This facilitated a one-to-one relationship between analytic elements and hydrologic at any location in the model domain. Heads and flow rates can also be defined (Hunt, 2006).

According to Hemholz's decomposition theorem, "*each vector field may be represented by a combination of an irrotational field with nonzero divergence, a divergence-free rotational field and a vector field that is both rotational and divergence-free*". A combination of these three fields meets the boundary conditions and constitutes the solution to the problem (Strack, 2003).

3.2 BASIC THEORY

Strack, (2003:1) states that he AEM combines the elegance and accuracy of analytic solutions via digital computers to accommodate the best of both worlds. It can be applied to represent two-dimensional vector fields and it is applicable to finite and infinite domains. The two-dimensional governing equation for groundwater flow in a mass balance where head values do not vary in vertical direction. The two-dimensional governing equation for groundwater flow is documented in Equation 7:

$$\boldsymbol{\frac{\partial}{\partial x}\left(k_x b \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_x b \frac{\partial h}{\partial y}\right) = -N + S\frac{\partial h}{\partial t}} \qquad (7)$$

Where:
K = hydraulic conductivity regarding the geology
h = piezometric head
b = saturated thickness of the aquifer (given as h − B, where B is the base elevation, if the aquifer is unconfined)
N = recharge or abstraction (vertical influx into the domain)

All elements have mathematical equations that are superimposed to provide a comprehensive groundwater flow potential in an aquifer. That potential can be evaluated at any point to provide a flow rate and head using the above Equation 7.

The Depuit-Forcheimer approximation is used to solve Equation 7. The solutions are notably accurate in terms of discharge, but approximate in terms of piezometric heads where vertical flow components are relatively large, for example where there is a partially penetrating borehole. It is therefore recommended that

- Two dimensional AEM models are used.
- The head may be presented by its average value in the vertical direction; vertical gradients in heads are negligible ($dh/dx \approx 0$).
- Resistance to flow in the vertical direction is negligible (e.g., $k_z \sim\approx \infty$).
- It is appropriate for systems with much larger horizontal extent than vertical extents.

The AEM obtains a solution using the following steps (Steward *et al*., 2005):

- Within a set of analytic elements with prescribed geometry, boundaries of features should be discretised.

- For each analytic element with two properties, formulate closed form solutions;
  a) They satisfy the partial differential equation.
  b) They produce a withdrawal/velocity along the element.
- To satisfy boundary conditions, unknown strength coefficients must be solved.
- To obtain the potentials and vector fields, evaluation of the mathematical expression for all analytic expressions.

3.3 APPLICATIONS OF THE AEM

A variety of AEM based computer programs are available. Commercial programs such as GFLOW, the Single – Layer Analytic Element Model (SLAEM), the Two-dimensional Analytic Model (TWODAN) and the Multi-Layer Analytic Element Model (MLAEM) are also available.

The most comprehensive application of the AEM to this day is the Dutch National Groundwater Model (NAGROM). Due to the AEM's ability to superimpose analytic expressions; it is possible to model large-scale groundwater systems. NAGROM is based on MLAEM, and in this case, a plot of fluxes and heads are generated for the study (de Lange, 1996).

Abbasi *et al*., (2013) states that the AEM proves to be very important to estimate depths to water input parameters when borehole data is severely limited. The DRASTIC method of vulnerability assessment has been done using the AEM to determine the "depth to water input" through the Kriging method. This AEM was generated by GIS databases.

Mclane (2011) introduces the model AnAqSim AEM model for a new theoretical approach based on various model domains that incorporates powerful AEM features. He also states that if data (such as field data) is limited, the AEM can be used and is rapidly becoming the method of choice.

3.4 ADVANTAGES AND DISADVANTAGES OF THE AEM

Majumder & Eldho (2015) and Csoma (2000) listed the following advantages regarding AEM:

- The elements in the model are discrete hydrologic entities (e.g. lakes), rather than a grid cell.

- The main use for the AEM is to estimate source/sink strength in a complex system.
- The AEM is a good tool to view a flow net of a system.
- The AEM is best suited for solving 2-D steady-state problems quickly.
- A useful analytic element model which is easy to obtain by superimposing solutions for rainfall infiltration, uniform flow, line-sinks and wells.
- The versatility of numerical algorithms and digital computers' ability to compute has been replaced by the ingenuity and elegance of analytic solutions to groundwater flow.
- The AEM provides a continuous groundwater surface; the surface is determined by natural or artificial influences within the examined area.
- The discharge potential of the AEM can handle confined and unconfined aquifers, only the transformation to piezometric head is different, it is useful because the aquifer is not known in advance or it is subjected to changes in the case of different situations.
- The AEM follows sharp changes in the groundwater table because of its mathematically accurate harmonic solutions.

The main disadvantage is the three-dimensional modelling of a phreatic surface and further research is necessary. Transient capabilities are also limited.

3.5 COMPARING AEM TO OTHER METHODS OF MODELLING

Rózsa, (2000) compared one of the oldest, most reliable modelling approaches namely, the Finite Difference Method (FDM) to the AEM. A summary is presented in Tables 3 & 4:

Table 3: Comparison of data required for the FDM and AEM models respectively.

Feature	FDM (traditional)	AEM
Boundaries of the area of interest	Provided, fixed outer boundaries.	No fixed outer boundaries.
Subdivision of the area of interest	Geometrical (grid).	Based on hydraulic considerations.
Layout of grid points or elements	Everywhere over the full area.	Only where it is necessary.
Number of grid points of elements	Relatively high.	Usually smaller.
Data requirements	At grid points.	At elements.
Boundary condition requirements	At each outer boundary.	At elements.

Feature	FDM (traditional)	AEM
Local co-ordinate system	May be useful.	Unconcerned.

Table 4: Program development of the FDM and AEM models respectively.

Feature	FDM (traditional)	AEM
Data processing	Simple, general.	May be different for each element.
Set of linear equations	Bend matrix.	Full matrix.
Computer storage capacity requirements	Usually bigger.	Depends on the number of elements, usually smaller.
Computation time requirement	Usually bigger.	Depends on the number of elements, usually smaller.
Presentation of results	Interpolation.	Continuous functions.

3.6 CONJUNCTIVE SURFACE WATER AND GROUNDWATER FLOW

The AEM for regional models is suitable to interpret interactions between groundwater and surface water. Area sinks are used to model infiltration (the entry of water through the phreatic surface in this context), while streams are represented by line elements, thus, it can be constructed to follow the natural streambeds.

When constructing regional groundwater flow models, most streams and lakes are included; these surface water bodies are described as the boundaries of the groundwater flow domain. Surface water either withdraws water from or supplies water to the aquifer. Particularly in small tributaries, or the heads of water in streams, the surface water either is in direct contact with the aquifer or separated by a leaky bottom. Losing streams in the groundwater flow model can supply more water than it has available for streamflow.

Mitchell-Bruker and Haitjema (1996) proposed a conjunctive surface water and groundwater approach to prevent over infiltration of streams and lakes. The streams and lakes that are represented by line-sinks are organised into networks to calculate the baseflow by the accumulation of all groundwater inflows and outflows. Under steady state conditions, a complete streamflow rate can be determined anywhere in the network if an overland inflow rate is specified.

If the model is calibrated, the heads alone can observe the rate of aquifer recharge to hydraulic conductivity. These two parameters can be determined by a second equation, if an additional calibration is to be conducted, is provided. Stream networks, using the analytic element models, are simple and intuitive in the making of a routine groundwater flow model through this practical tool (Haitjema & Strack, 1985).

3.7 RECHARGE AND THE AEM

Dripps *et al*., (2006) defined recharge as water that crosses the water table and is influenced by a majority of factors such as soil type, precipitation, geology, topography, and climate. It is the most uncertain and complex parameter to quantify in the field of hydrology. In groundwater modelling, it is of great importance to understand the spatial and temporal distribution of recharge.

Groundwater modellers usually assume a constant single recharge value, although recharge is a variable parameter. That assumption makes small scale detailed time dependant flow path delineation predictions inappropriate (Jyrkama *et al*., 2002), although it is adequate for long term simulation of groundwater flow modelling. This variability has important implications to address such as water budget calculations, contaminant transport and flow path calculations.

Other authors such as Hunt *et al*. (2000) linked Analytic Element codes and parameter estimations as well as calibrating flow models to the estimation of regional recharge rates (Martin & Frind, 1998). Dripps *et al*., (2006) describe an approach where assumptions are made such as, the only outlet for the flow in a system is the stream with no loss of water from the groundwater system (via evapotranspiration), thus, the recharge is equal to the quantity of water exiting the system through baseflow in the stream. Consequently, the flow system is in steady state. Field measurements determine the baseflow thus, if the contributing area to the stream is known, recharge can be estimated through measurements of the baseflow (Dripps *et al*., 2006).

3.8 SUMMARIZING THE AEM

The AEM superimposes analytic elements to model features in a vector field such as a discharge vector field in an aquifer. For every property of a vector field, an element is chosen and developed to simulate it. The freedom of choosing different elements in the AEM is perhaps the most important characteristic. The AEM offers more advantages over numerical methods; it allows scale independence, high degree of accuracy, and flexibility. The AEM can deal with very large problems at unprecedented efficiency. Efficient elements can create large groundwater flow models to function as a starting point for a variety of investigations and it serves as an intelligent database.

Further development of the AEM is of great importance to realise the potential of the method in practice for example, efficient modelling of abstraction in multi aquifer systems, and the efficient modelling of transient flow.

In respect to this method, numerical methods such as the finite difference and finite element method lags behind the popular implementation of the AEM.

4 METHODOLOGY

4.1 INTRODUCTION

In this chapter, the AEM is mimicking the firm yield model as the firm yield model has certain assumptions and restrictions; therefore, the AEM would provide more detailed results for a reserve determination when refining the model. The main observation in this text is that even though the AEM would provide more detailed results for a reserve determination, the same basic “flaw” exists compared to the conventional RDM. This is the conceptualization of the site conditions (e.g. how many layers are present, aquifer systems and their boundaries etc.), as well as the overall boundary conditions for the site unit of analysis.

The AEM would add value in terms of the surface-groundwater interaction component at the site (which can be simulated using river boundaries) and the impact of abstraction in heterogeneous aquifers (i.e. drawdown cones with boundary conditions). The modelling of any groundwater system needs to include a conceptual model which is critical for the model results (Garbage In, Garbage Out (GIGO) principle). The same can be said for an RDM, in that if the system interactions between groundwater, rainfall, topography, surface water and anthropogenic elements are not clearly quantified and incorporated into the determination then the value/confidence in the reserve determination is lowered.

A detailed description of the conceptual model development is great value to visually understand the concept of the firm yield versus the AEM model, which will be used in the conventional and AEM RDM processes. This will also help in comparing, because both methods of analysis will start with a common base. For the AEM, it is quite important to set up a time frame, by the means of how long the model will be run for until the results would be applicable for the reserve. This timeframe is quite important, because a conventional RDM is more a snapshot of time and considers steady state conditions almost.

The implementation of the standard methodology for classification and Reserve determination to groundwater resources often results in undesirable outcomes and is one of the inhibiting factors for sustainable groundwater development, as some of the aspects and current methods are not applicable to groundwater and not appropriate for implementation.

In order to apply the AEM to the firm yield model, real world situations, environments and setups must be represented in a logical way. It makes sense to model real world environments, as all environments are different. This is where the non-uniform aquifer parameters such as recharge and hydraulic conductivities are used to represent a more accurate firm yield for the catchments in this case.

The Visual AEM program is a graphical interface to model saturated groundwater flow and transport using one calibration engine, namely Ostrich. The basic flow model creation process consists of the information (chapters and steps to follow) to follow throughout this chapter.

When using *Visual AEM*, variables in the model must be modified to simulate reality that is, of course, the purpose of a good hydrogeological model, these variables such as recharge and hydraulic conductivity must be an accurate representation of the real flow phenomena in terms of heads and fluxes.

A series of boreholes are imported into Visual AEM, digitizing the basemaps such as the catchment boundaries, similar geologies, rivers and the different recharge zones according to the geology. Parameters are then estimated using literature and relevant calculated methods to give the different areas their hydraulic conductivities, porosities, aquifers thickness and recharge. This forms the basis of which the model stands on for calibration purposes.

Visual AEM then calibrates the observed hydraulic head data and input parameters to ultimately obtain the best of fit values for the observed versus simulated hydraulic head data. The non-uniform recharge for the catchment is one of the key objectives for this study to ultimately go into detail when dealing with catchment scale approaches. This approach ultimately leads to a more accurate representation of the actual flow phenomena when measuring the firm yield for the catchment.

To calculate the firm yield, a leakage zone around the catchment represents the water flowing out of the catchment. This leakage component is gradually increased to measure the water levels across the entire catchment. The entire catchment is represented by a grid with evenly spaced boreholes to simulate using Visual AEM.

Simulations are run by gradually increasing the leakage zone to measure the loss in head of the boreholes. The first borehole water level to reach a drop of five meters is then used to represent the firm yield.

The main objective for model calibrations is to change the value of input parameters to match the specific field conditions of the study site according to suitable criteria, thus, field conditions at the study site must be properly characterized. The model must represent the actual field conditions of the study site otherwise the model results in a calibrated set of conditions where actual field conditions are not described. Steady-state conditions are typically simulated throughout the calibration procedure. These simulations are required to narrow the range of variability for the reason that there are numerous ranges of input data values. The model calibration consists of comparisons between the field conditions and model-simulated conditions such as the following:

- Observed versus Simulated hydraulic head data,
- Groundwater flow direction,
- Hydraulic-head gradient,
- Water mass balance, etc.

Comparisons are shown by means of graphs, tables or maps. For example, in a calibrated graph of simulated versus observed heads, the closer the heads fall on the “goodness of fit” line, a better evaluation of calibration results can be achieved through professional judgement. The modeller should be able to attempt to minimalize differences between simulated models and measured field conditions. Standard criteria states that the simulated and actual field conditions should not vary more than 10 percent with the field data across the domain.

4.2 DATA COLLECTION

The purpose of data collection for the Reserve is to support in the quantification of a resource. An extensive variety of data and information can be utilised to characterise the hydrology and geohydrology of an area. Possible sources of data are listed in Table 5.

Table 5: Possible sources of data used during GRDM assessments (adapted from Dennis *et al.*, (2011)).

Data	Data and information	Source
Study area	Quaternary catchment boundaries	WR2005
Population data	Population statistics	Central Statistical Services Regional and local municipalities
Water sources	Flow-gauging stations	DWA
Physiography	Topographical maps	Dir. Surveys and Land Information
Climatic data	Rainfall data Evaporation data	WR2005 Local communities, mines and industry DWA Department of Agriculture, Forestry and Fisheries
Geology	Geological maps	Council for Geoscience DWA Consultants Mines
Drainage	Flow data Wetland inventory Springs	DWA WR2005 Working for Wetlands DWA
Surface water information	Cross sections of river beds Dam releases and seepages	DWA Consultants River Health Program
Geohydrology	Geohydrological maps – national groundwater maps – harvest potential map	WRC DWA
Geohydrological data	Geohydrological data – national groundwater database – geohydrological reports – field assessments	DWA: NGDB/NGA DWA Regional Offices Water Research Commission Local authorities Consultants GRIP (where applicable)
Groundwater use (for vegetation, mining, agriculture, forestry, domestic supply, etc.)	WARMS database Regional databases Geohydrological reports	DWA Regional Offices Water Research Commission Local authorities Consultants GRIP (where applicable)

Building a groundwater model also requires hydraulic parameters such as recharge, hydraulic conductivity, transmissivity, aquifer thickness, porosity and storativity. These parameters were either calculated or obtained from previous reports. In this dissertation, the groundwater model is a predictive model since one of the main objectives is to see the change in groundwater head values to ultimately calculate the firm yield.

4.3 GEOHYDROLOGICAL CHARACTERISATION

A groundwater flow model calculates the rate and direction of movement of groundwater in the subsurface (aquifers). The term used to represent these calculations are simulations. A thorough understanding of the hydrogeological characteristics for a specific study area is required for the simulation of any groundwater resource unit. All hydrogeological investigations must include the following (Mandle, 2002):

- A hydrogeological framework (thickness of the aquifers and the subsurface extent).
- Boundary conditions, controlling the rate and direction of groundwater flow.
- Hydraulic properties of the aquifer and its confining units.
- A description of the distribution of hydraulic head within a modelled study site for steady state conditions (equilibrium).
- Groundwater recharge distributions and magnitudes, abstraction to or from surface-water bodies, etc.

4.4 CALCULATING THE GROUNDWATER RESERVE

Once all the data has been collected, the groundwater Reserve is calculated using the following methods:

1. The calculation as documented in Parsons & Wentzel (2007) and Dennis *et al.,* (2011).
2. The firm yield models
3. The AEM model

The generation of the AEM is by far the most time consuming and more information is needed when considering the other two approaches. The steps involved in developing the AEM model include:

Step 1: Create a model domain using model elements such as hydrologic features (rivers, lakes, boreholes, inhomogeneities in conductivity) that correspond with geometric shapes. These polygons and/or polylines with their actual geometries are digitised to modify their properties obtained from the user’s knowledge or research. The data needed for the AEM model includes:

- Number of layers: The aquifer will be a single layer model.
- Topmost Base Elevation: Refers to the elevation of impermeable rock underneath the groundwater (mamsl.). The elevation must be consistent with the topography and specified head values in a single layer model. This elevation is derived from information of subsurface geology from soil borings

and/or speculation. This parameter choice affects the volume of water flowing through the domain if it is of unconfined nature.

- Layer thickness: For an unconfined system, this thickness should be set very high, especially when interacting directly to surface water features. It estimates the amount of water flowing through an aquifer.
- Layer Conductivity: The mean horizontal conductivity of the domain or the conductivity of most of the domain. The hydraulic conductivity of the domain is derived from pumping tests, slug tests, etc. (note: for a rule of thumb use an average or most common conductivity value). This parameter controls the velocity of water movement and estimates the interaction between inhomogeneity in conductivities.
- Layer Porosity: The percentage of soil particles not occupied by soil particles. Porosities of most subsurface geology range between 0.25 and 0.4. This parameter only affects travel times of particles in the model.
- Recharge zones: These zones represent the influence of infiltration of water over an area specified in the model domain. Recharge can be geographically variable by specifying different recharge zones in different areas according to geology or various rainfall gauges.
- Leakage zones: These zones signify areas where water is lost from the bottom of the aquifer at a valued amount. Leakage can also be geographically variable but for this study, a uniform leakage component is required to estimate the firm yield.

Step 2: Edit the model domain by selecting hydrologic features such as river nodes, modifying conductivities or increasing pumping rates.

Step 3: Visual AEM has an extensive model-checking program to check the validity of the model where the user will be warned when a parameter was overlooked or any problems exist in the conceptual or mathematical model.

Step 4: When the user is finished creating the model domain, the system must be solved with a desired engine to converge the model.

Step 5: Manual and numerical calibration tools are available to solve the system and view the results and errors, this step is to change the model until one is satisfied with the results, increasing the complexity of the model until the domain is well characterised.

Hydraulic heads and groundwater flow rates are described as the output of these groundwater simulations that are in equilibrium with specific hydrogeological conditions. The model calibration process uses different hydrogeological condition values to improve the accuracy of the model and to reduce disparity between field data and model simulations.

4.5 COMPARING RESULTS

Different types of models exist to describe the fate of groundwater flow. Some models describe exact solutions to equations that describe very simple groundwater flow models (analytical model) and others may be approximations of equations that describe very complex conditions (numerical models). Both models may also simulate one or more processes that govern groundwater flow rather than all of the flow processes. Whether it is a complex numerical model or a simple analytical model, both have the applicability and usefulness in hydrogeological investigations.

Analytical models are exact solutions of a specific, often greatly simplified groundwater flow equations. These equations are a simplification of more complex three-dimensional groundwater flow equations. Prior to the development of computers, a need for the simplification of equations due to complex three-dimensional equations. Specifically, these simplifications led to reducing groundwater flow to one dimension. This resulted in changes in model equations that include one-dimensional uniform groundwater flow, uniform hydraulic properties and simple flow boundaries. Analytical models are typically steady-state and one-dimensional whereas the AEM are two-dimensional. These simplifications do not account for field conditions that change over time and space. This is why the AEM includes variations in groundwater flow rates, variations in hydraulic properties and complex hydrogeological flow conditions.

Analytical models are best used for initial site assessments where a high degree of accuracy is not needed, designing data collection plans prior to beginning field activities, an independent check of numerical model simulation results or where field conditions support the simplifying assumptions embedded in the analytical models.

On the other hand, numerical models can solve more complex equations that describe groundwater flow. Numerical models use approximations to solve differential equations describing groundwater flow. These approximations require the model domain and time be discretized. Numerical and analytical models may be used to simulate very simple equations. However, numerical models are generally used to simulate problems which cannot be accurately described using analytical models.

Once all the calculations are completed for the two case studies. The results of the three different methods will be compared for both case studies. Based on the comparisons, conclusions will be made.

5 CASE STUDY 1: CATCHMENT C22C

5.1 LOCATION

The catchment is located in the Gauteng province near Boksburg, Springs and Alberton in the East Rand (see Figure 2). There is a significant dolomite outcrop east of Alberton and north-west of Heidelberg, known as the Natalspruit compartment lying within the Mesic Highveld Grassland region. More specifically, the case study area falls in Quarter Degree Grid Cell (QDGC) 2628AC with coordinates: 26°26’22.07” - 28°05’50.79” south and 26°26’27.55 - 28°05’49.63” east. The area is downstream of the Vaal Dam located in the Upper Vaal Water Management Area at the confluence between the Rietspruit and Kliprivier with the Natalspruit branching between those rivers. These perennial rivers drain the site in different directions (Envirolution Consulting, 2014).

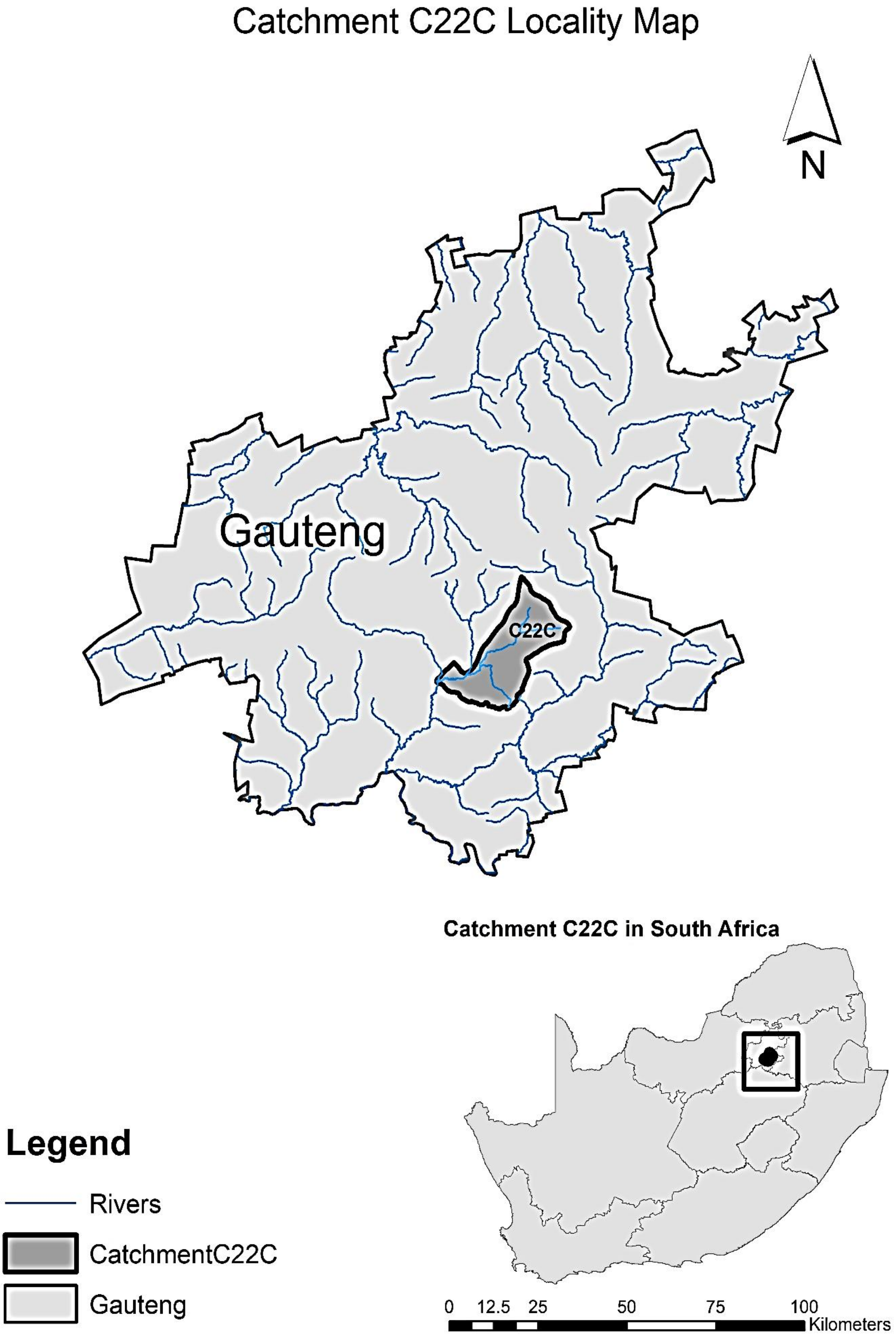

Figure 2: Locality map of catchment C22C.

5.2 CLIMATE

The MAE ranges from 1600 mm to 2200 mm in this area. The catchment is characterised by periodic rainfall with higher rainfall figures experienced during the summer months (December and January). The catchment receives a MAP of 684 mm with a MAR of 31 mm. The average monthly rainfall is shown in Figure 3.

Average annual temperatures range from 12 °C to 20 °C with an average daily maximum temperature ranging from 20 °C to 32 °C in February and the daily minimum temperature in July ranges from -2 °C to 4 °C (DWAF, 2004a).

Rainfall is considered an indirect parameter that consist of the basis of a more complex parameter namely recharge, this parameter requires statistical analysis to obtain rainfall volumes/amounts measured in millimetres (mm):

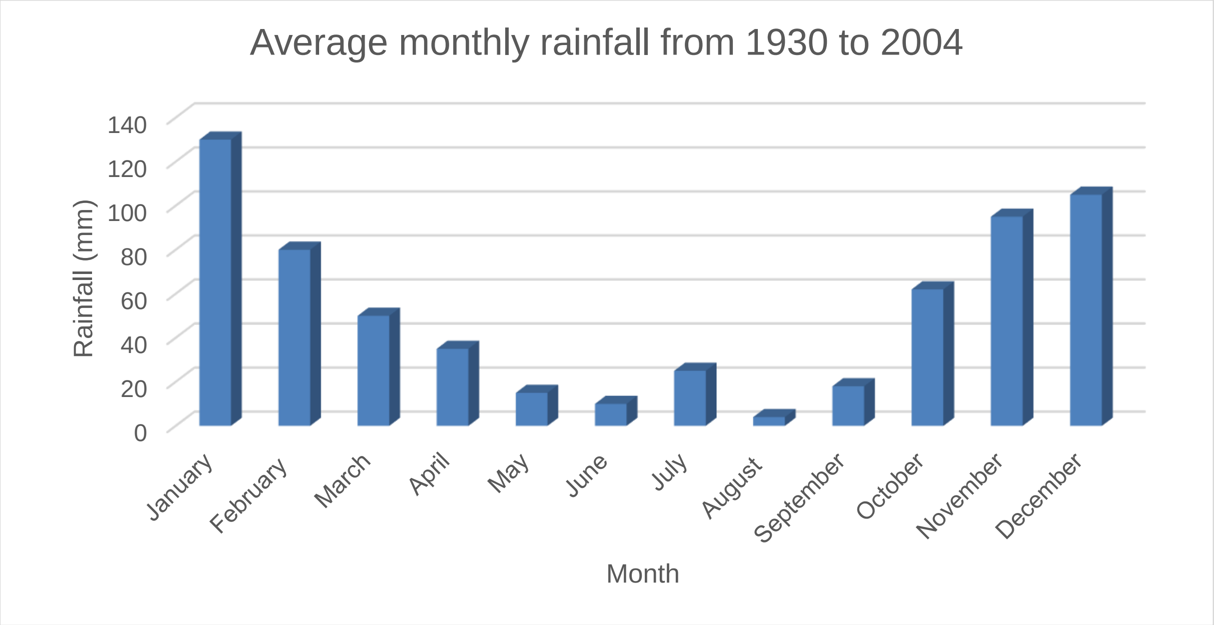

Figure 3: Average monthly rainfall for catchment C22C.

5.3 TOPOGRAPHY AND DRAINAGE

The topography of the area consists of a higher-lying area on the southern side of the catchment area with the highest point at 1915 mamsl, further north the altitude drops to 1471 mamsl. The Rietspruit drains the central and western parts of the study area. Within this area the stream is made up of numerous, small ephemeral tributaries.

The numerous coal and gold mines in the northern part of the catchment contribute to the pollution of both groundwater and surface water resources. (Dennis *et al*., 2015).

5.4 GEOLOGY

As seen on Figure 9, a geology illustration is included in the model representation for a better understanding of the study area. The recent rocks consist of sand, gravel and soils that were probably set aside by the transport of water and wind.

The East Rand is partly covered by the Ventersdorp, Transvaal and the Karoo Supergroups. There is a decrease in the thickness towards the south-eastern edge of the aquifer from the Central Rand (7315m), to Heidelberg (4267m). In general, all subdivisions of the Witwatersrand are thinner and more clayey There are prominent markers in the eastern Witwatersrand, not developed in the West Rand. This is the Bird-gemstone, which is well-developed east and southeast of Boksburg, and the Blue gravel stone in the series Government Ridge south of Heidelberg. Other markers and reefs seem to be quite persistent. The Jeppestown lava, the magnetic slate and the reef of the series Governance Ridge are represented from the far West Rand to the East Rand (Jones, 2003:178).

The Ventersdorp Supergroup is about 1524m thick near Heidelberg and covers the Witwatersrand Supergroup. Since the lithological composition is fairly unchanged, it is only divided into two groups. In the lower volcanic group, there is predominantly lava with locally developed tuff, especially in the basal part. Pyroclastic sediment, tuff, clayey sandstone, granite and conglomerates make up the upper sandy group 2003:179).

In the Transvaal Supergroup, the Swartrif and Dolomite series cover a strip, partly covered by the Karoo System, from Delmas to Vereeniging. The Pretoria series is North of Delmas and some isolated spots are spread across the northern boundary of the country. According to borehole data, the Transvaal System forms a wide strip under the Karoo from Delmas to Bethal. The Dolomite series and the Swartrif series are featured in this system. The Dolomite series consists mainly of dolomite, dolomite limestone, marble, layered quartzite and sporadic chert. The Swartrif series consists of rocks such as quartzite, shale, gravel, and conglomerate (Jones, 2003:179).

Dolomite is composed of carbonate minerals, specifically calcium and magnesium carbonate, such as calcium, aragonite, siderite and other carbonate species, including inorganic carbonate species such as chalk, and remnants of microorganisms. Caves naturally form in these dolomite rocks due to carbonate rock that dissolve, especially when exposed to acidic water, as seen in the Rietspruit River. Dolomite neutralises the acidic water associated with the surrounding mines. Dolomite aquifers are important aquifers since they can store large amounts of water. The prevalence of dolomite in South Africa is abundant, especially in the Gauteng province (Craincross, 2004).

Chert is a very fine-grained silicate rock that is typically dark grey in colour; it can be formed inorganically by infiltration of silicates of existing geological formations. If there are large amounts of iron in the chert, the chert can become very hard and form banded iron formations (Craincross, 2004).

Shale is composed primarily of clay minerals that are associated with high conductivity, about 20 % quartz and chert (both SiO_2), with a lesser amount of feldspar and even less carbonates, iron oxides and other minerals (Yaalon, 1961).

The Karoo Supergroup consists of the Ecca and Dwyka series. The Ecca series consists mainly of shale, sandstone, clay, conglomerate, limestone, marble and coal layers, while the Dwyka series consists of two rocks, namely, tillite (glacier deposits) and shale.

The Dwyka rocks that fill cavities in the pre-Karoo floor vary in thickness and are spread irregularly. Some conglomerates at the base of the Ecca series are "processed" tillite. The Étage Lower-Ecca is rarely present, but a thickness of 9 to 12m is found in boreholes near Standerton. The Étage Middle-Ecca is widely spread and up to 275m thick. The Étage Upper-Ecca is found in a few boreholes at Standerton that is 43m thick. The contact between the Ecca series and dolerite plates could not be determined accurately because of the scarcity of outcrops (Jones, 2003:179).

The Post – Karoo system includes the intrusive igneous rock dolerite. Dolerite is mostly post-Ventersdorp to post-Transvaal in age and partly related to the Bushveld Igneous Complex. Most dolerite rocks are fine grained, but in larger intrusions, it may consist of larger crystals, and can be found in intrusive plates or dykes. Dolerite is harder than the surrounding sedimentary rocks, so outcrops can frequently be seen since it has a greater resistance to weathering.

5.5 GEOHYDROLOGY

The geology of the catchment area consists mainly of carbonate rocks, fine-grained felsic rocks, mafic and ultramafic volcanic rocks and silicate rocks. With this in mind, it can be assumed that the area consists of dolomitic/karst type aquifer, weathered rock aquifer and a fractured aquifer. The upper aquifer is formed due to vertical infiltration of water from precipitation (rainfall), which is reflected by the weathered material and is constrained by the lower permeable underlying rock material. The groundwater then collects above the weathered material and moves downwards according to the slope to lower-lying areas. In some areas, the groundwater flows through the surface, which contributes to the Rietspruit and Klip River as baseflow.

Figure 4 shows a good correlation (94.72 %) between the borehole water levels and the topography of the catchment. Therefore, a groundwater flow map is conducted through the Bayesian interpolation method to generate a groundwater flow direction map as shown in Figure 5.

The water levels in Figure 5 range from 1.4 m to 120 m. The water levels and the flow direction clearly follow the topography of the study area. The map clearly shows where the lower laying areas are, this is where the rivers occur, namely the Rietspruit (Main River) and the Natalspruit River. The velocity of the water changes as the topography of the study area changes, the steeper the slopes, the faster the water flows. This can be seen in the different colours on the map (Figure 5). The perennial Rietspruit River clearly shows that it drains the catchment area. The flow directions of the groundwater and surface waters flow in an eastern and western direction towards the rivers, but the bulk volumes of groundwater flow southwards, similar to the river.

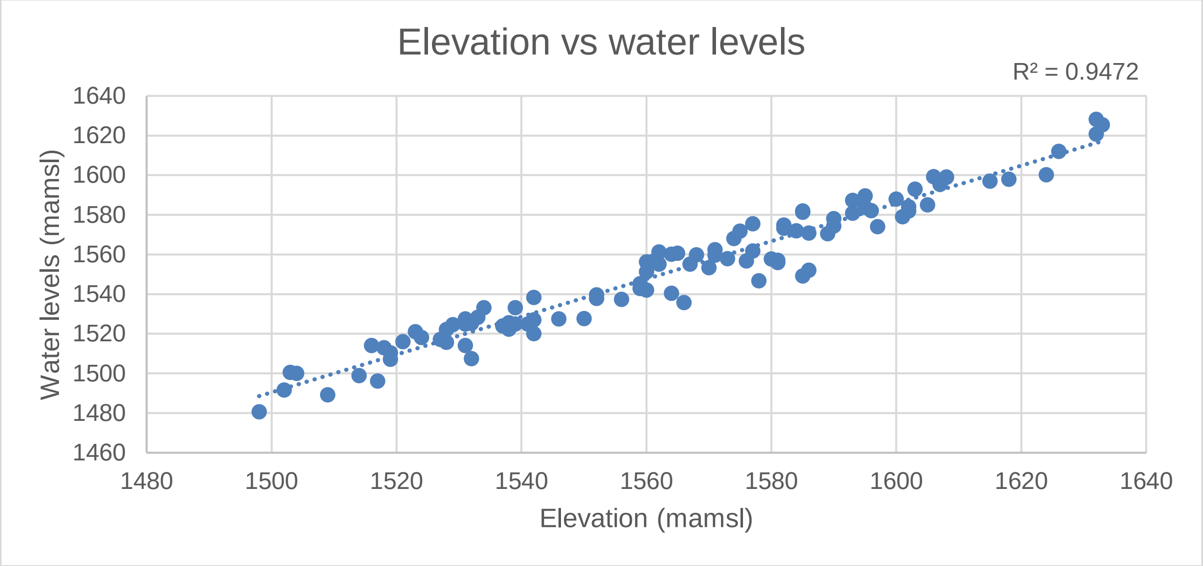

Figure 4: Elevation vs water levels.

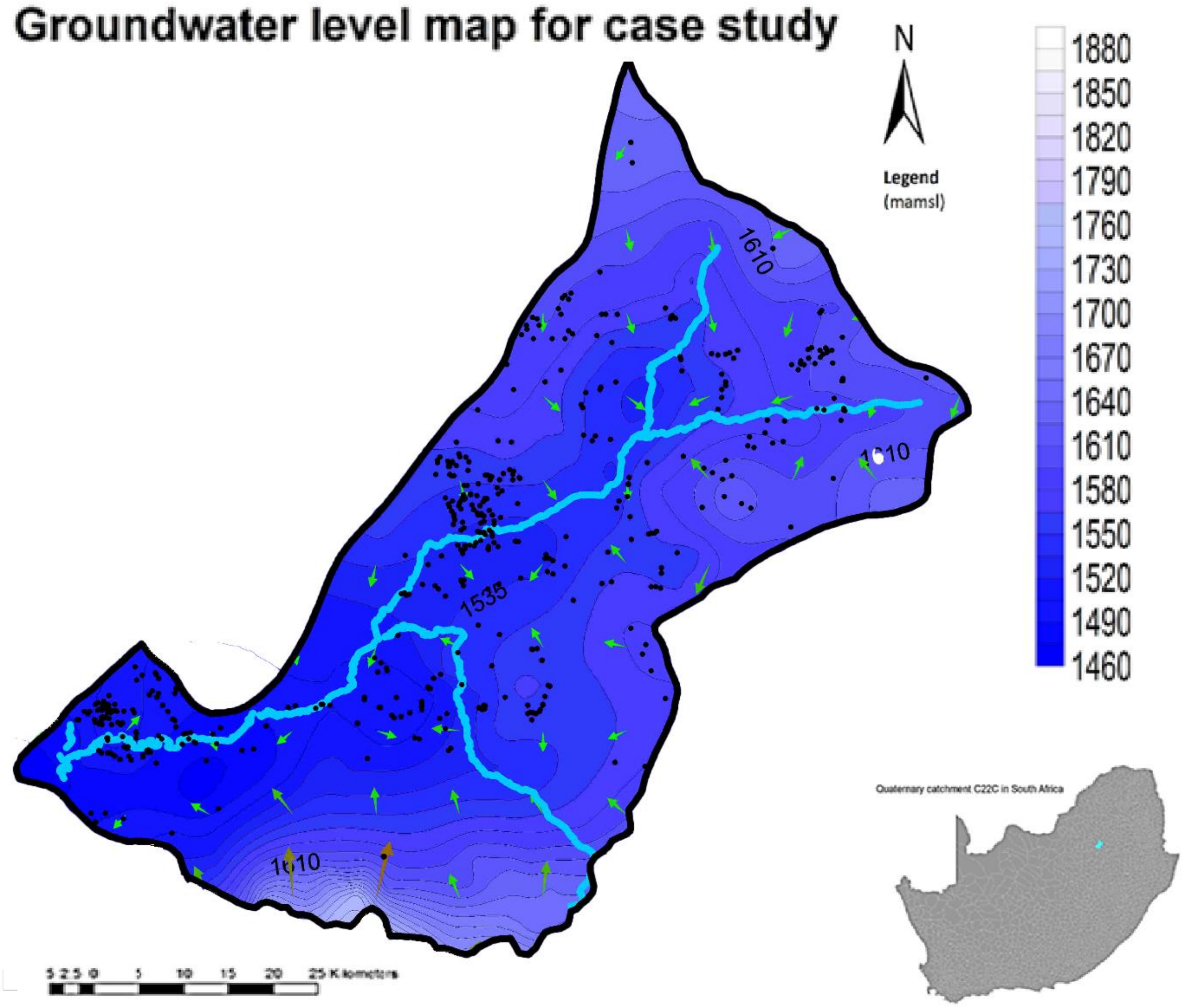

Figure 5: Groundwater level map with flow directions for catchment C22C.

5.6 DETERMINATION OF THE RESERVE AND ASSOCIATED ALLOCABLE WATER

5.6.1 Data requirements

5.6.1.1 Transmissivity/Hydraulic conductivity

Murray (1996) (as cited by Driscoll, 1986) presented a possible explanation that the maximum recommended drawdown in primary aquifers is 68 % of the saturated thickness when calculating the transmissivity (Driscoll, 1986). This method calculates effective transmissivity for the catchment due to the large area that consists of dolomite (~62 %) and conclusively takes the whole area of different aquifer yields into account. Thus, the equation incorporates different aquifer yields according to each area's geology. Driscoll (1986) used the following equation:

$$\mathbf{Q = 0.068Ts} \tag{8}$$

Where

Q = Aquifer yield (l/s)

T = transmissivity (m^2/day)

s = available drawdown (m)

Table 6 summarizes the specific areas for each calculation with their corresponding aquifer yields obtained from Figure 6. These calculations consider three different areas in the catchment due to three different aquifer yields. For each zone, the highest specific yield for each area is used due to the highly transmissive nature of the geology (mostly dolomites).

Table 6: Parameters for the transmissivity method of Driscoll (1986).

Area	Enclosed Area (km^2)	Yield (l/s)	Calculated T (m^2/d)
A_1	227.36	0.1 - 0.5 (intergranular and fractured)	6.3
A_2	169.8	>5 (Karst)	63.5
A_3	66.71	0.5 – 2 (intergranular and fractured)	25.4

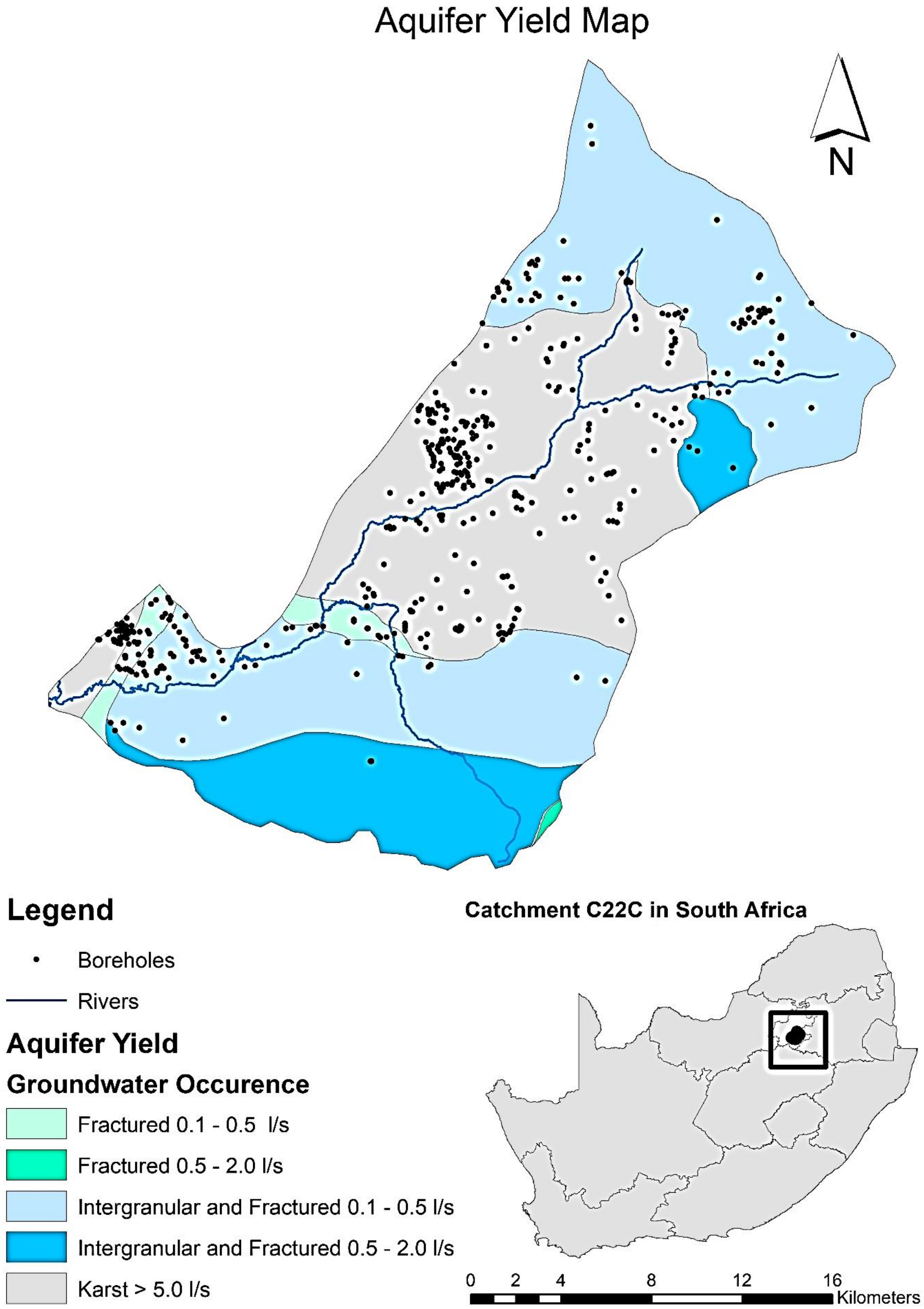

Figure 6: Aquifer yield map of catchment C22C for effective transmissivity calculation

The effective transmissivity is then calculated taking into account each area of different transmissivity values proportional to the size of the whole catchment. The resultant transmissivity is 29.98 m^2/d. The following equation states:

$$\mathrm{T} = \mathrm{Kb} \tag{9}$$

Where:
T = Transmissivity (m^2/d)
K = Hydraulic Conductivity (m/d)
b = Aquifer thickness (m)

By assuming the aquifer thickness is 100m, then K is equal to 0.3 m/d

Utilising the South African yield map for the groundwater occurrence is transformed into transmissivity ranges as documented in Table 7 (DWAF, 2010).

Table 7: Aquifer parameters using the South African yield map.

Yield (l/s)	**Transmissivity (m^2/d)**
0.0 – 0.1	0.25
0.1 – 0.5	0.25 – 1.50
0.5 – 2.0	1.50 – 6.25
2.0 – 5.0	6.25 – 17.5
> 5.0	17.5 – 25.0

5.6.2 Porosity

The selected porosity is 0.3, as most porosities range from 0.25 to 0.4 for subsurface media (Freeze & Cherry, 1979).

5.6.3 Storativity

As with hydraulic conductivity and transmissivity, storage is also considered highly variable due to the heterogeneity of dolomites. According to GRAII (DWAF, 2005a), the storativity value for the catchment is 0.01. In South Africa, an estimated storativity of typical karst aquifers is 0.05. Table 8 documents typical storativity values for different aquifer types:

Table 8: Storativity ranges for different aquifer types (DWAF, 2010).

Aquifer Type	Storativity
Fractured	0.001
Fractured and Intergranular	0.005
Karst	0.01
Intergranular	0.1

5.6.4 Recharge calculation for the model domain

Numerous methods were used to determine the recharge value for the aquifer. These methods are discussed in detail in Appendix B. Additional recharge values were obtained from literature. A summary of the results is documented in Table 9.

Table 9: Summary of recharge values obtained.

Method/reference	Recharge (%)
GRAII (DWAF, 2005a)	6.3
Chloride Method	10
Groundwater recharge map (Vegter, 1995)	13.8
(DWAF, 2006)	6.3
Hobbs, *et al*. (2013)	4.5
(CMB) Distance to sea method (Aquiworx (2017))	3.45
SVF - method	6.24
Vivier & Wiethof, (2006)	7-15
Harvest Potential map	3.65
Average	7.25

5.6.5 Parsons & Wentzel (2007) and Dennis *et al.,* (2011) method

According to Hobbs *et al.* (2013) the total population in the study area is 295024. The total population dependent on groundwater is not known, therefore it is assumed that the total population is dependent on the resource. If every person uses 25 l/d, then the BHNs for the area is total groundwater use in the catchment as 2.7 Mm^3/a.

Herold's baseflow separation (Figure 7) is used to determine the groundwater contribution to baseflow according to Dennis *et al*., (2012:51) and this is assumed to be equivalent to the low flow necessary to sustain the EWRs and it is determined as 6.17 Mm^3/a. The total groundwater Reserve is therefore 8.87 Mm^3/a.

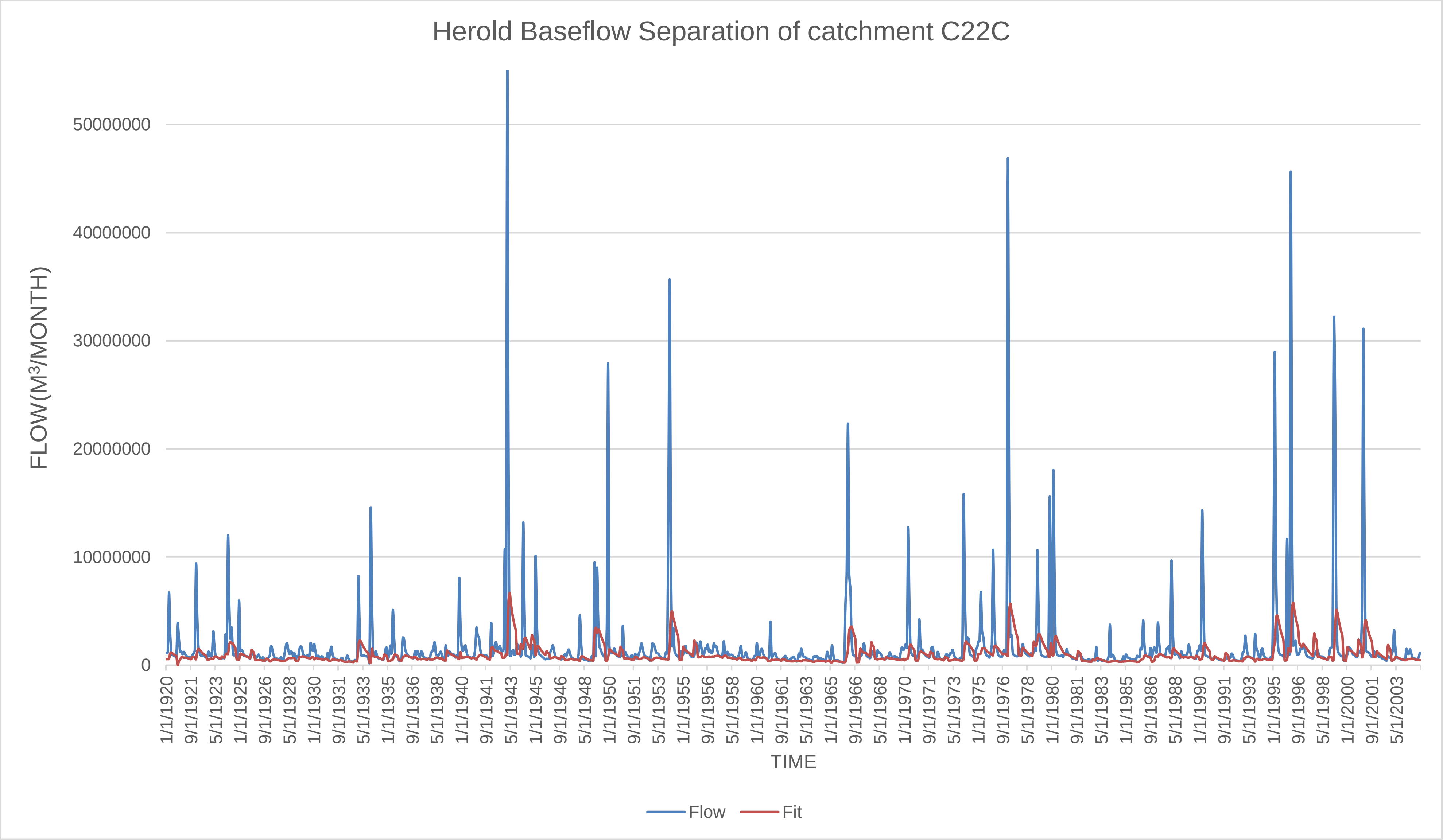

Figure 7: Baseflow separation of C22C (Aquiworx, 2017).

The allocable volume of groundwater can now be determined. Hobbs *et al.* (2013) has identified livestock farming as the only other groundwater users. This value amounts to 0.0299 Mm^3/a. According to Table 9, the average recharge is 7.25% for the area of the catchment that is 465 km^2. Therefore, the total recharge is 23.1 Mm^3/a. The allocable groundwater (according to Equation 2) is 14.2 Mm^3/a.

5.6.6 Firm yield model

A firm yield model was developed in Aquiworx (2017), using parameters specified for the catchment. It calculates the firm yield for the specific aquifer as 9.13 Mm^3/a as seen in Figure 8. That is, if the pumping rate of the aquifer is held below 9.13 Mm^3/a, sustainable utilisation of the aquifer will take place therefore no depletion of water takes place. If more than 9.13 Mm^3/a is withdrawn, it can be problematic for the environment and the surrounding biota, resulting in sinkholes, wetland losses and so forth.

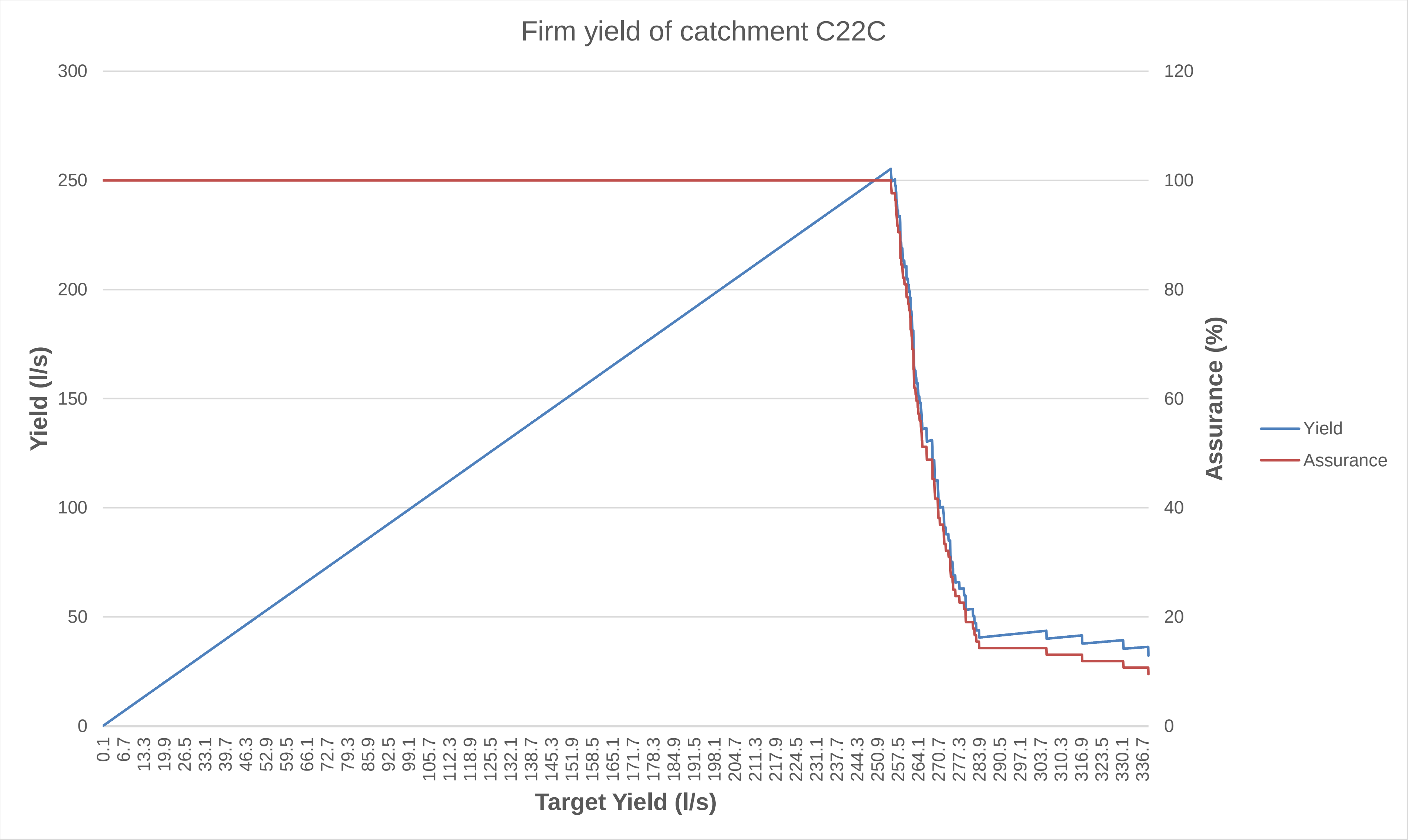

Figure 8: Firm yield of C22C (Aquiworx, 2017)

5.6.7 AEM model

The AEM model is shown in Figure 9. There are three different recharge zones digitised according to the underlying geology of the area.

To calculate the firm yield, a leakage (abstraction) zone around the catchment represents the water flowing out of the catchment. This leakage component is gradually increased to measure the water levels across the entire catchment. The entire catchment is represented by a grid with 43 evenly spaced points (as seen in Figure 10). Aquifer parameters as discussed in Section 5.6.1 and groundwater levels were included in the model.

By inserting a grid to calculate the leakage component, it resembles a uniform abstraction rate over the whole catchment/area of interest. As mentioned above, the leakage component is gradually increased until a 5 m drop in water level is achieved to ultimately measure the firm yield of the area of interest, this 5 m drop is set to sustainably withdraw water from an aquifer, a drop of more than 5 m is unsustainable which can have severe consequences for an aquifer. However, inserting a grid does have its own shortcomings since there are no abstractions taking place in certain parts of the area of interest. Thus, digitizing different recharge zones does help to address the problem as it resembles a more defined catchment area.

Furthermore, each point on the grid represents an evenly spaced borehole with a certain elevation so each borehole is represented separately. When gradually abstracting water from the aquifer, some boreholes may experience a faster decrease in water level than other boreholes. This is mainly due to the various aquifer and rock types as well as the different recharge zones. The borehole with the fastest decrease in water level when achieving a 5 m drop is used to represent the firm yield of the catchment although some boreholes may decrease in water level over longer periods of time.

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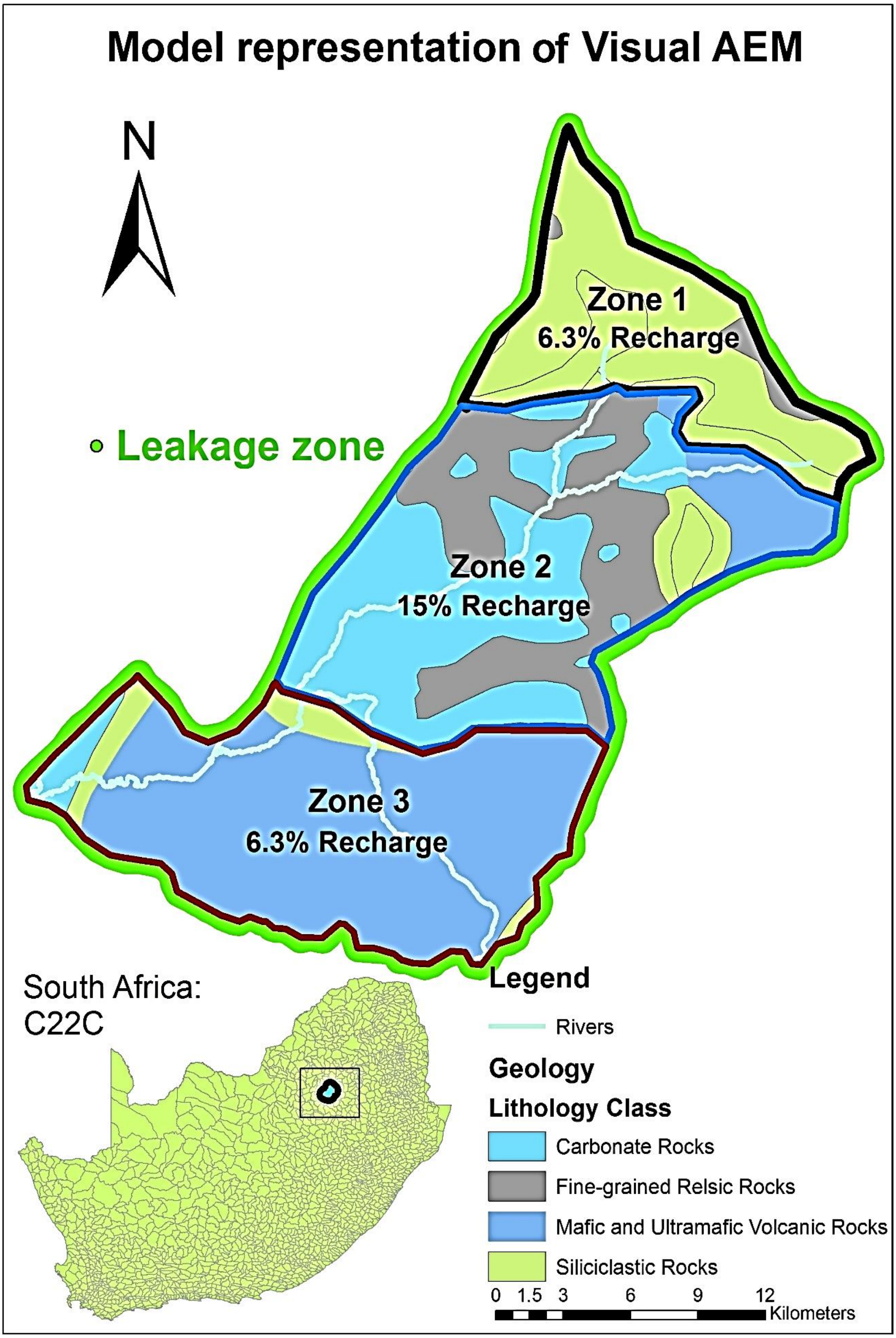

Figure 9: Model in Visual AEM.

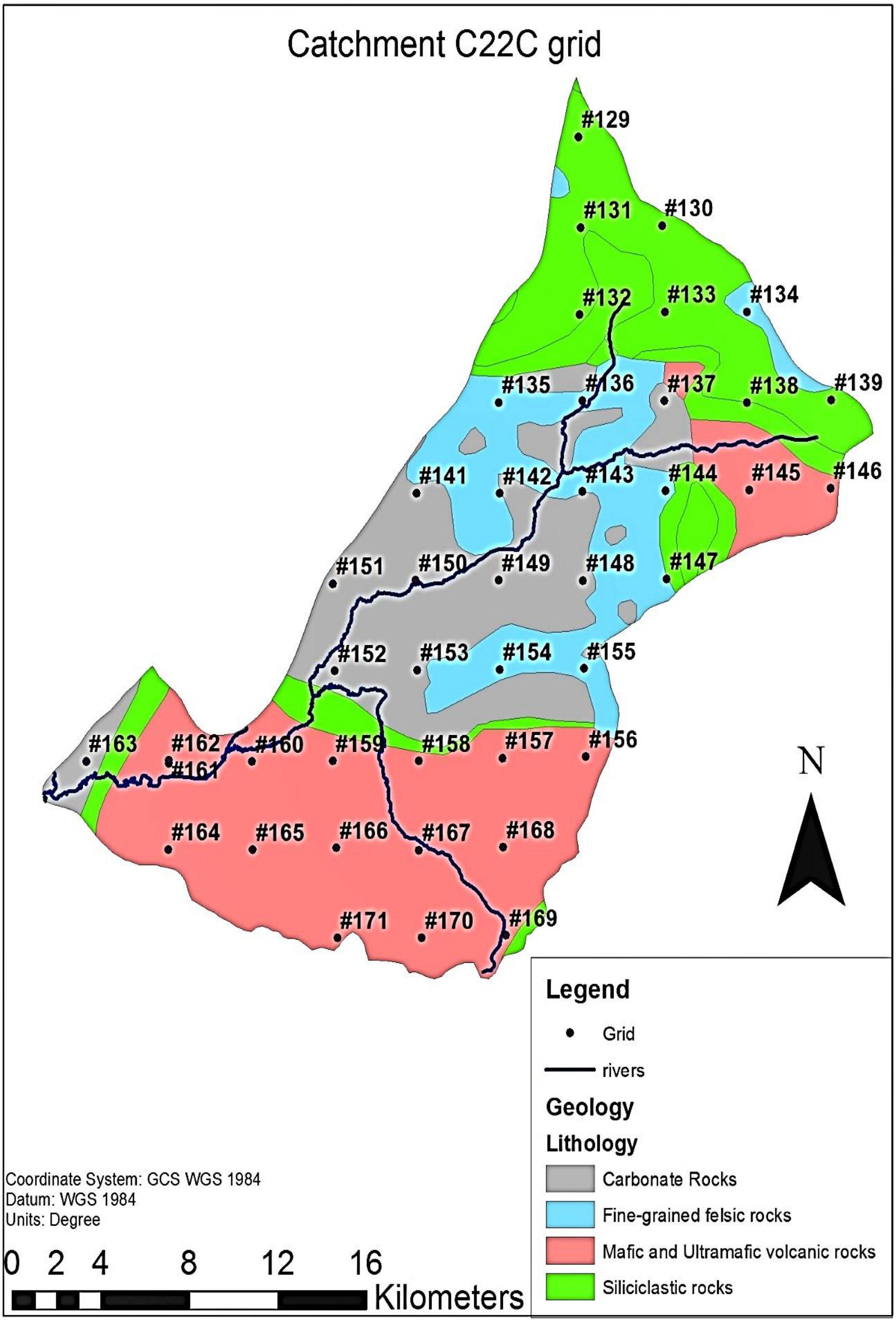

Figure 10: Catchment C22C grid

The calibration process is done manually in order to understand the significance and relevance of the recharge, hydraulic conductivity and aquifer thickness of the system. Calibration is also done to gain access to modelling functions and obtain results through “Ostrich” (software to find the best fit in recharge/hydraulic conductivity combinations for the provided heads).

Numerous boreholes (Figure 11) throughout the study area were used for the steady state model calibration. The given water level data for the representative boreholes shown in Figure 13 were used for the steady state model calibration. Figure 13 displays all borehole head values (mamsl.) for the catchment and the representative boreholes (calibrated heads).

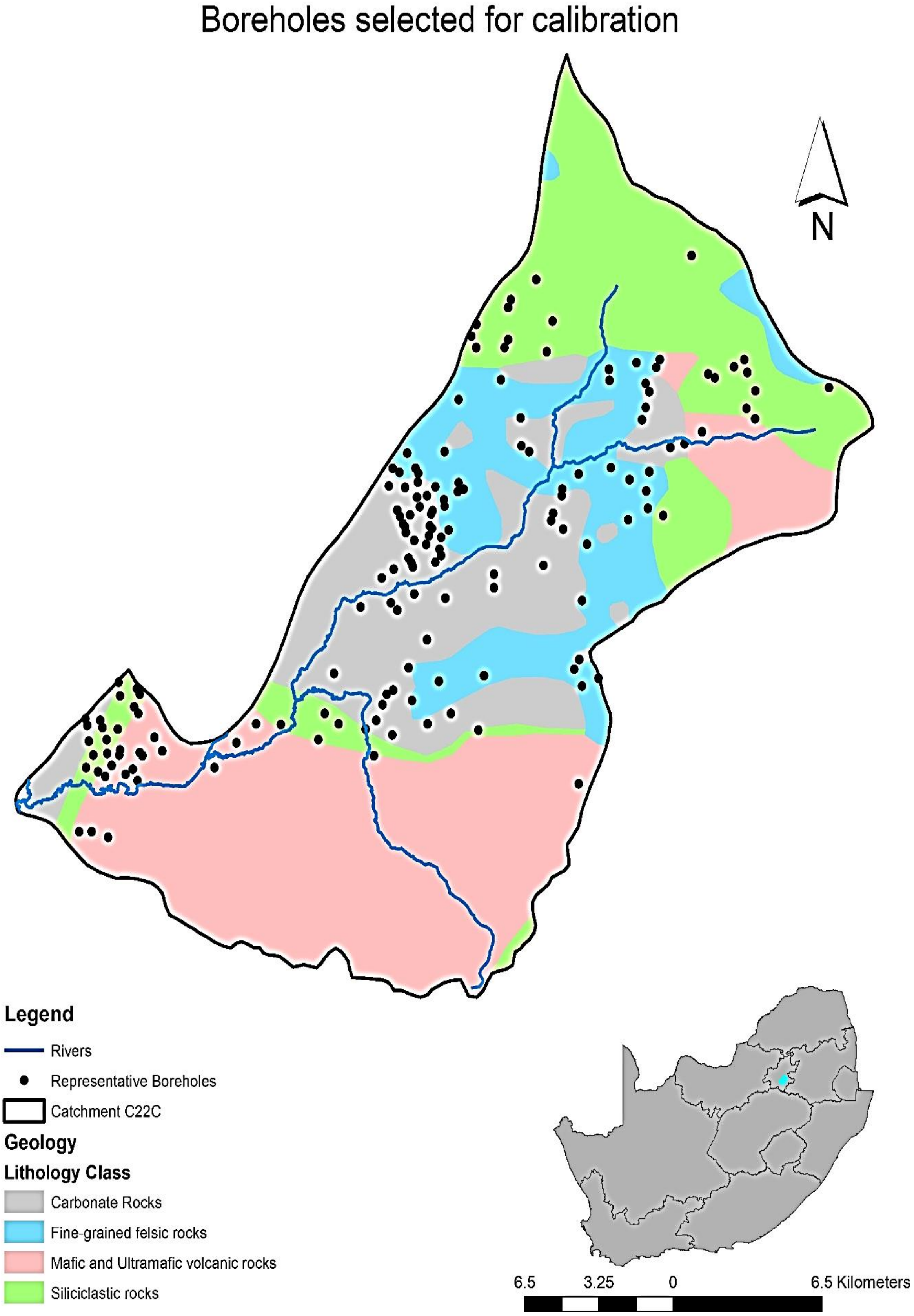

Figure 11: Boreholes used for calibration in catchment C22C.

For the model to calculate the head distribution for the steady state flow system, it relies on the rainfall for recharge, hydraulic conductivity, aquifer thickness and other hydraulic parameters as well as the boundary conditions. A simulated head distribution is created and compared with the measured head distribution with effective recharge and hydraulic conductivity values that can be adjusted for an accurate and acceptable correspondence between the simulated and measured heads.

Figure 12 illustrates the relationship between the observed and simulated heads for catchment C22C.

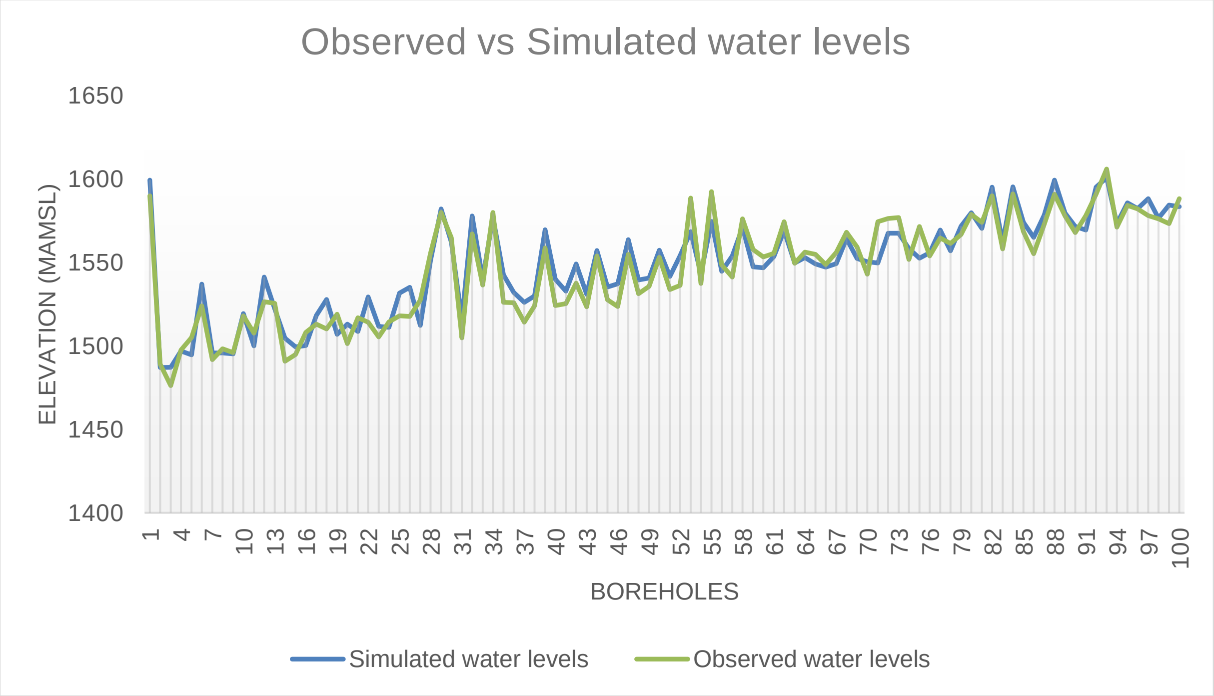

Figure 12: Illustrates the relationship between the observed and simulated heads for catchment C22C.

A hundred boreholes were used in the calibration process. Water levels were simulated using the Visual AEM program. The R-squared value (R^2) from the calibration results shows a 91.43 % correlation between the observed and the simulated water levels as seen in the following Figure 13:

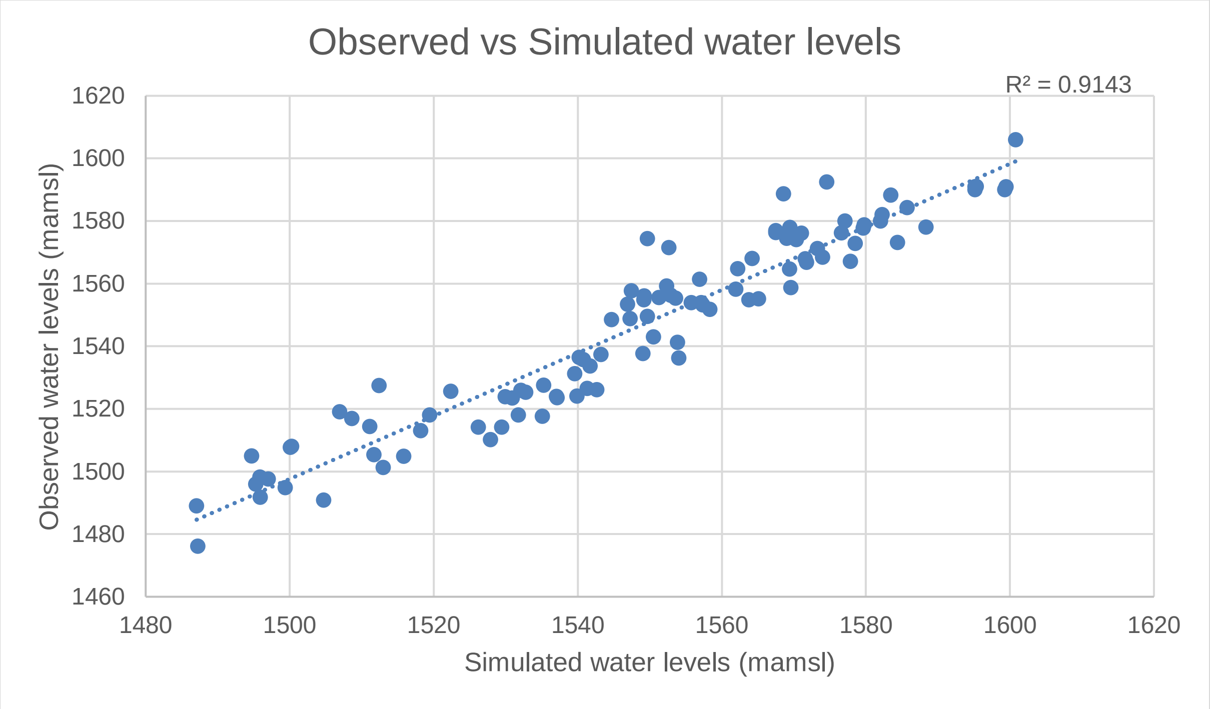

Figure 13: Observed vs simulated water levels for catchment C22C

On the completion of the calibration, a simulation is run where the water levels are dropped by abstracting a gradual amount of water until a 5 m drawdown is achieved to ultimately measure the firm yield of the aquifer. This gradual abstraction is achieved by changing the leakage (abstraction) component of the model to simulate the change in water level. The water level must not exceed the 5 m drop as it is evident that it can damage the aquifer as a whole when abstracting more than the calculated amount.

Three representative boreholes are used to represent the firm yield. The top borehole in Figure 14 reaches the 5 m point first and is therefore regarded as the firm yield. The overall firm yield for the catchment is 380 l/s (12 Mm^3/a). Thus, by keeping the pumping rate below 380 l/s, sustainable abstraction of water is accomplished.

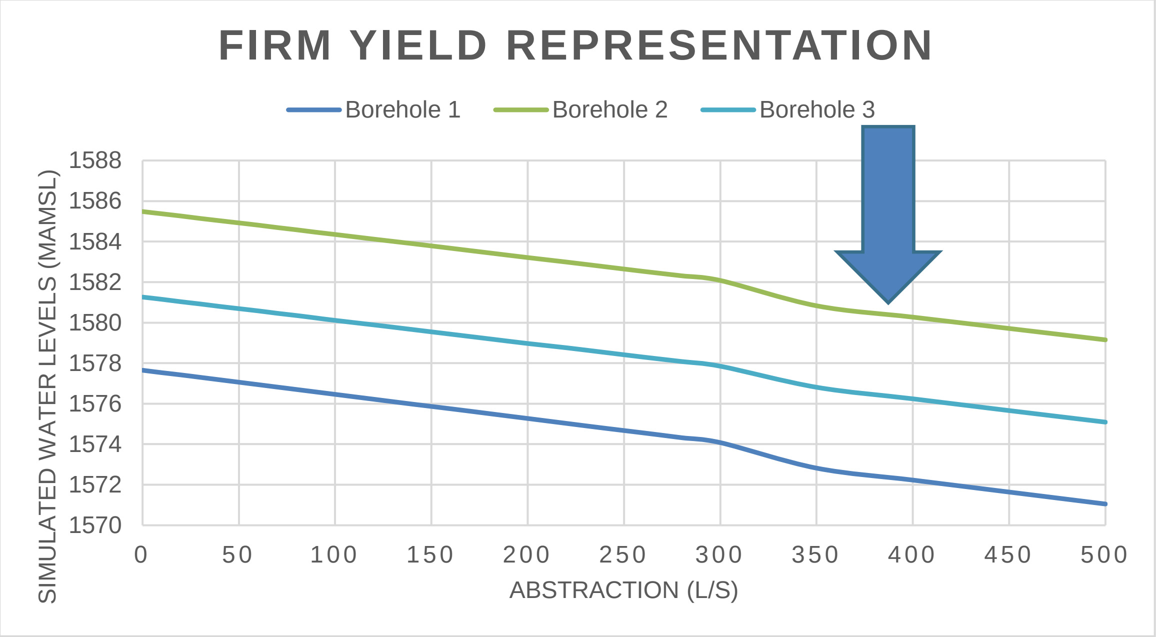

Figure 14: Firm yield representation for catchment C22C

If an AEM model is satisfactorily calibrated, AEM utilisation for borehole protection zones can be specified. AEM does not include a radius of influence however; one can see how much water can be extracted from a borehole before the baseflow of a river is impacted. This can also aid in wetland, estuaries and springs protection zones. Figure 15 illustrates the baseflow component for the AEM model which represents the main river in the case study followed by representations of the response to each of the stream sections.

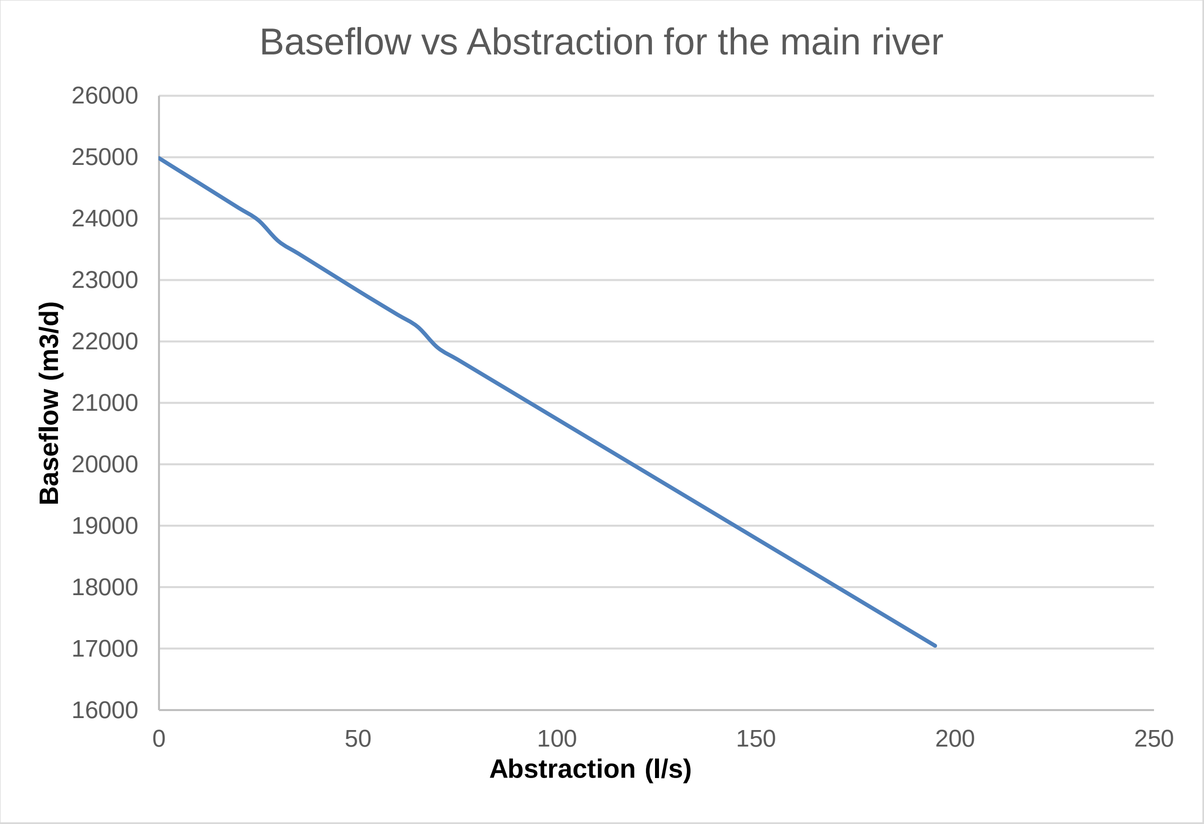

Figure 15: Total flux contributed or removed from wells, recharge and surface water within the zone budget polygon for the main river

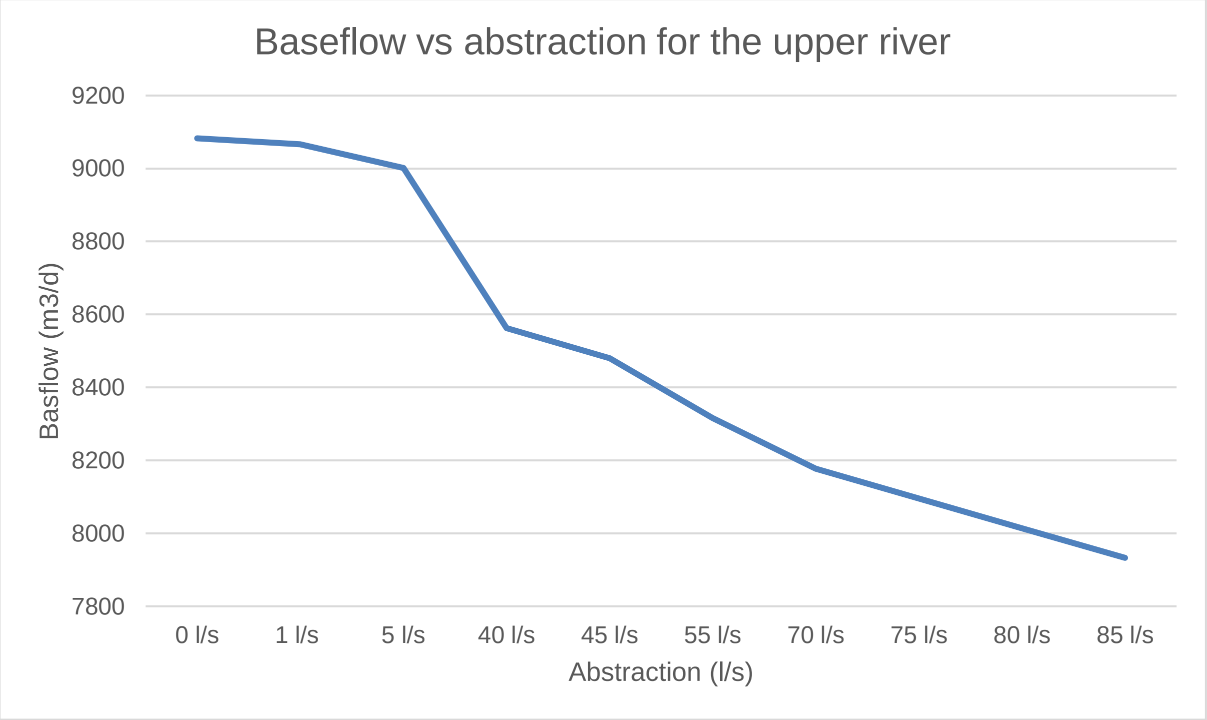

Figure 16: Total flux contributed or removed from wells, recharge and surface water within the zone budget polygon for the upper river

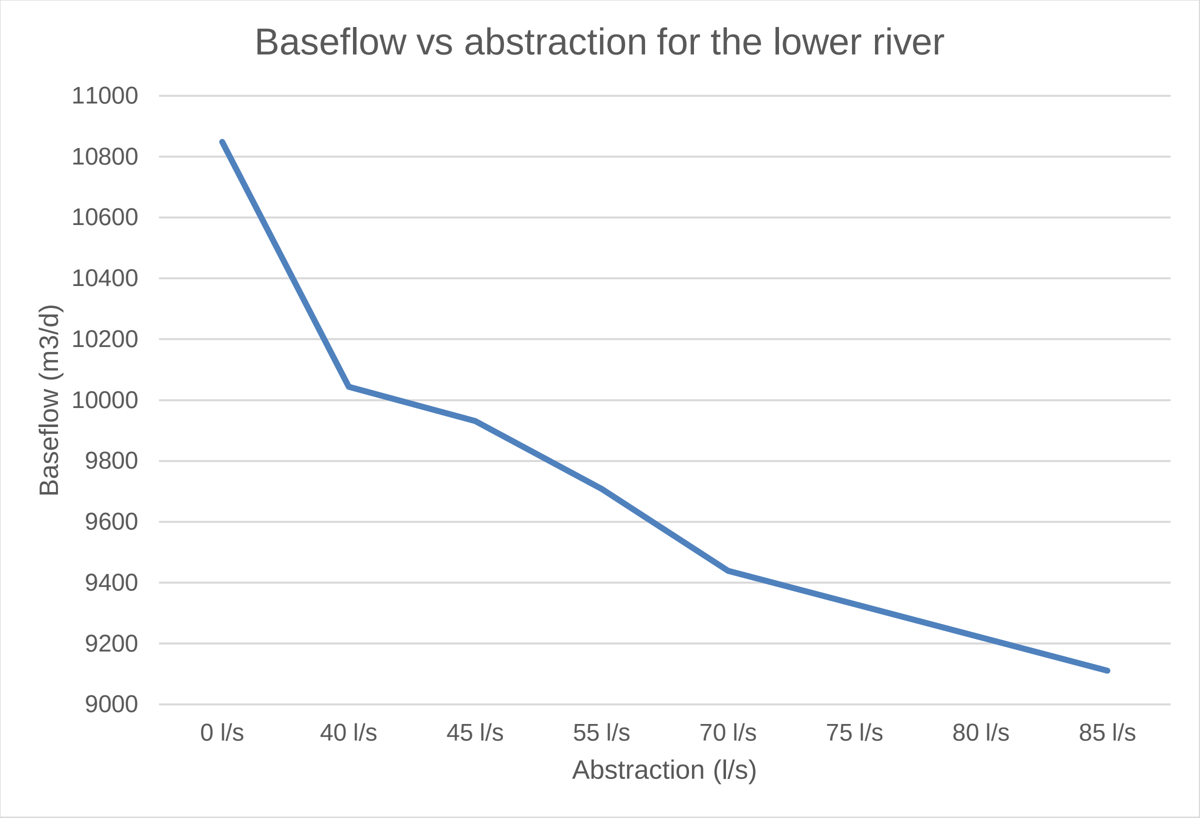

Figure 17: Total flux contributed or removed from wells, recharge and surface water within the zone budget polygon for the lower river

Figure 15 illustrates the baseflow of the main river declining as the abstraction component increases. It is estimated that the baseflow necessary to sustain the Reserve is 6.17 Mm^3/a. If this is maintained then the firm yield drops to 5.7 Mm^3/a. Figure 16 and Figure 17 illustrates the response to each of the stream sections whereas it is expected to see the tapering of the baseflow as the abstraction increases. Table 10 is a summary of the results.

Table 10: Summary of results for Determination of the Reserve

Method/reference	**Firm yield/allocable volume (Mm^3/a)**
Parsons & Wentzel (2007) and Dennis *et al.*, (2011) method	14.5
Firm yield model	9.13
AEM model	5.7

Parsons & Wentzel (2007) and Dennis et al., (2011) is a lumped analytical equation, that calculates a single value for the whole study area. Similarly, the Firm yield is also a box model that calculates a single value for the whole study area but has a limit of 5 m on the drawdown in the system.

The AEM model proves to be a good estimate of the firm yield since it falls in the range of the Parsons & Wentzel (2007) and Dennis *et al.*, (2011) method and firm yield model. Satisfactory model calibration was achieved through Visual AEM. The application of the calibrated model for the Determination of the Reserve illustrated through this case study can be utilised to represent the real-world situation.

6 CASE STUDY 2: CATCHMENT W70A – ZULULAND COASTAL PLAIN

6.1 Description of study Area

Catchment W70A forms part of the Zululand Coastal Plain (ZCP), located on the north-eastern coastline of KwaZulu-Natal. The ZCP is the largest primary aquifer in South Africa, inhabiting several major water bodies where groundwater dependent ecosystems thrive (WRC, 2015:1).

Catchment W70A covers an area of 2589 km^2 and comprises of the Cretaceous age arenaceous formations, which developed as a result of multiple sea-level regressions of Cenozoic unconsolidated deposits and the aggression of the warm Indian Ocean. This can be seen by the extensive parallel dune complexes along the ZCP (WRC, 2015:1).

The ZCP comprises of a dual aquifer system with primary porosity and distinct hydrogeological properties. A shallow aquifer of 1-6 mbgl., comprising of fine grain sand of the Kwambonambi Formation occurs in the eastern and southern regions of the ZCP and the deeper aquifer comprises of Karst weathered shelly coquina and calcarenites from Cretaceous deposits. This deeper aquifer is intercepted at depths of 30-40 mbgl., which is irregularly distributed. Since borehole yields are in the order of 15 to 25 l/s, the deeper aquifer is used for production purposes, characteristic of aquifers with high transmissivities and storativity properties (WRC, 2015:1).

6.2 Location

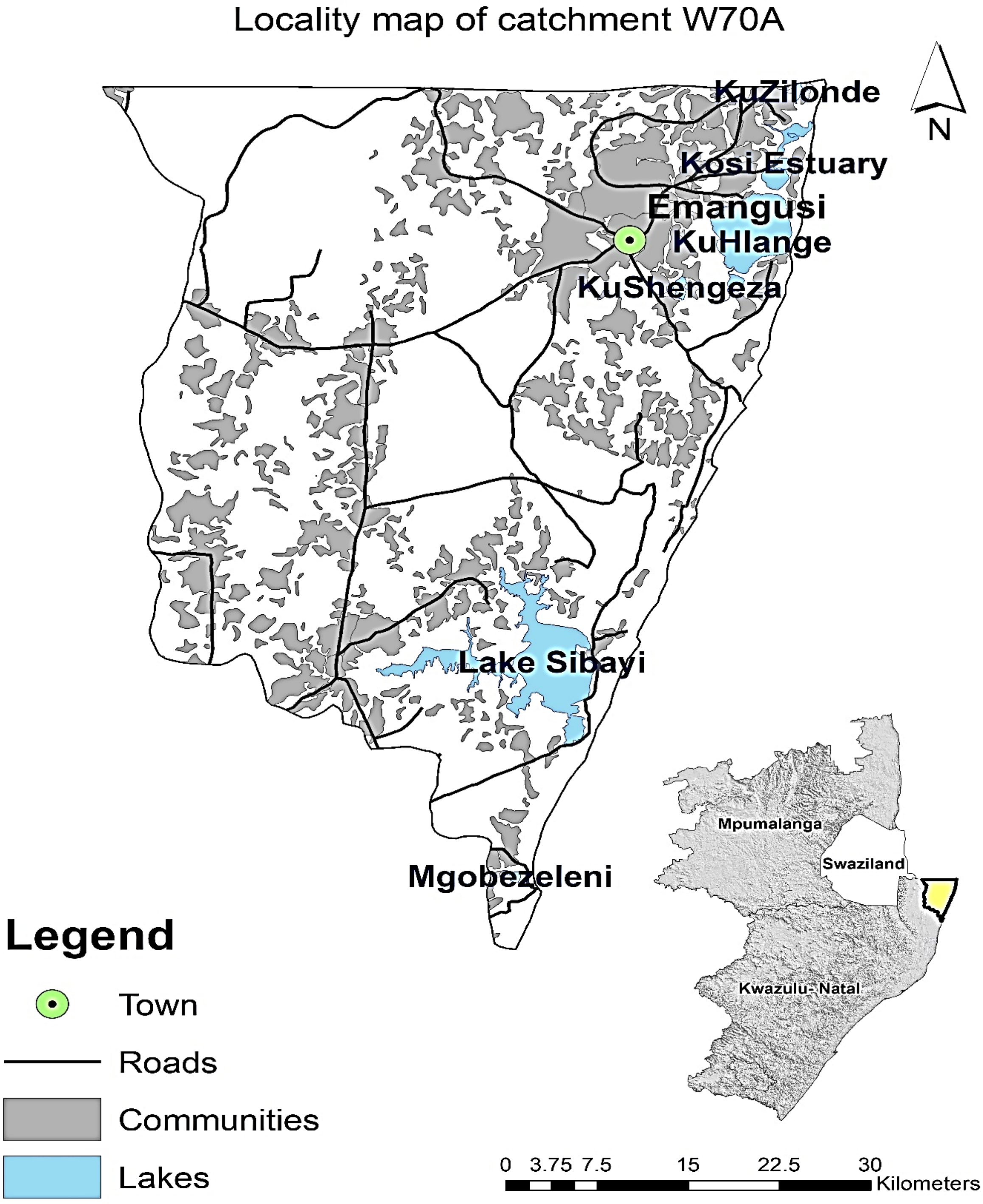

Figure 18: Location map of catchment W70A.

The study area is situated northeast of KwaZulu-Natal with approximate coordinates: 27°1'37" S and 32°6'18" E, extending from Esiphahleni in the south and Kwa-mshudo to the north of the catchment. This catchment forms part of the Usuthuto to Mhlathuze Water Management Area (WMA). From there the coastal plain extends for more than

1000 km further into Mozambique. The ZCP is therefore seen as the largest primary aquifer in South Africa. The map above indicates the exact location of the study area W70A (WRC, 2015:4).

6.3 Climate

The ZCP is accustomed to humid, subtropical climates where temperatures ranged from 18.1 °C to 26.3 °C along the Lebombo foothills and 11.5 °C to 28.7 °C along the coast. The main recharge mechanism for the catchment is the rainfall originating from tropical and mid-latitude cyclones. However, 80 % of the precipitation occurs in the summer months where convective thunderstorms are experienced, this is due to advection of warm moist air from the Indian Ocean and low-level convergence. The MAP for catchment W70A is in the order of 716 mm located in rain zone W3E with high evaporation rates throughout the year, especially during summer months where it can reach up to 189.4 mm and 82.3 mm in June (Barath, 2015: 23).

6.4 Topography

The topography is relatively flat where the elevation ranges from 336 – 455 mamsl in the north-eastern parts of the catchment to -2 -15 mamsl along the coastline of the catchment. Stacked dunes display abrupt changes in relief where these dunes can reach heights of 180 mamsl expanding from 1 to 2 km wide, serving as coastal barriers within the catchment (Barath, 2015:21).

6.5 Geology

The geology consists of the Pre-Cretaceous geology, Lebombo Group, Zululand Group and more specifically, the Maputuland Group which will be discussed in more detail above since it is the foundation of the hydrogeology for catchment W70A:

After deposition of the Zululand Group, uplift in the continental shelf took place subjecting it to erosion for approximately 30 Ma years. This, in turn, led to the Aloa formation of the Maputoland Group. It consists of fluvial, aeolian, lagoonal and shoreline to shallow marine deposits, approximately 250 m thick originating from the Late Miocene to Holocene Age (Barath, 2015: 32). The stratigraphy is shown in Table 24 and Figure 51.

Table 11: Stratigraphic column for the Maputoland Group (modified from Barath, 2015:33)

Era	Sub-Era	Period	Epoch	Group	Formation
Cenzoic	Quaternary	Pleistogene	Holocene	Maputaland	Redistributed sand.
					High dune sand (Berea)
			Pleistocene		Unconsolidated dune sand (Berea)
					Port Dunford Formation (sand, lignite, sandstone and clay rich sandstone)
	Tertiary	Pleistocene to Miocene	Early		Calcarenite (Bluff)
			Late		Pecten Beds and Uloa Formation (calcareous sandstone)
Mesozoic		Cretaceous	Late	Zululand	St. Lucia Formation
			Early		Mzinene Formation
					Makatini Formation
					Bumbeni Complex
					Mpilo and Movene Formation
					Msunduze Formation
		Jurassic	Middle	Lebombo	Jozini Formation

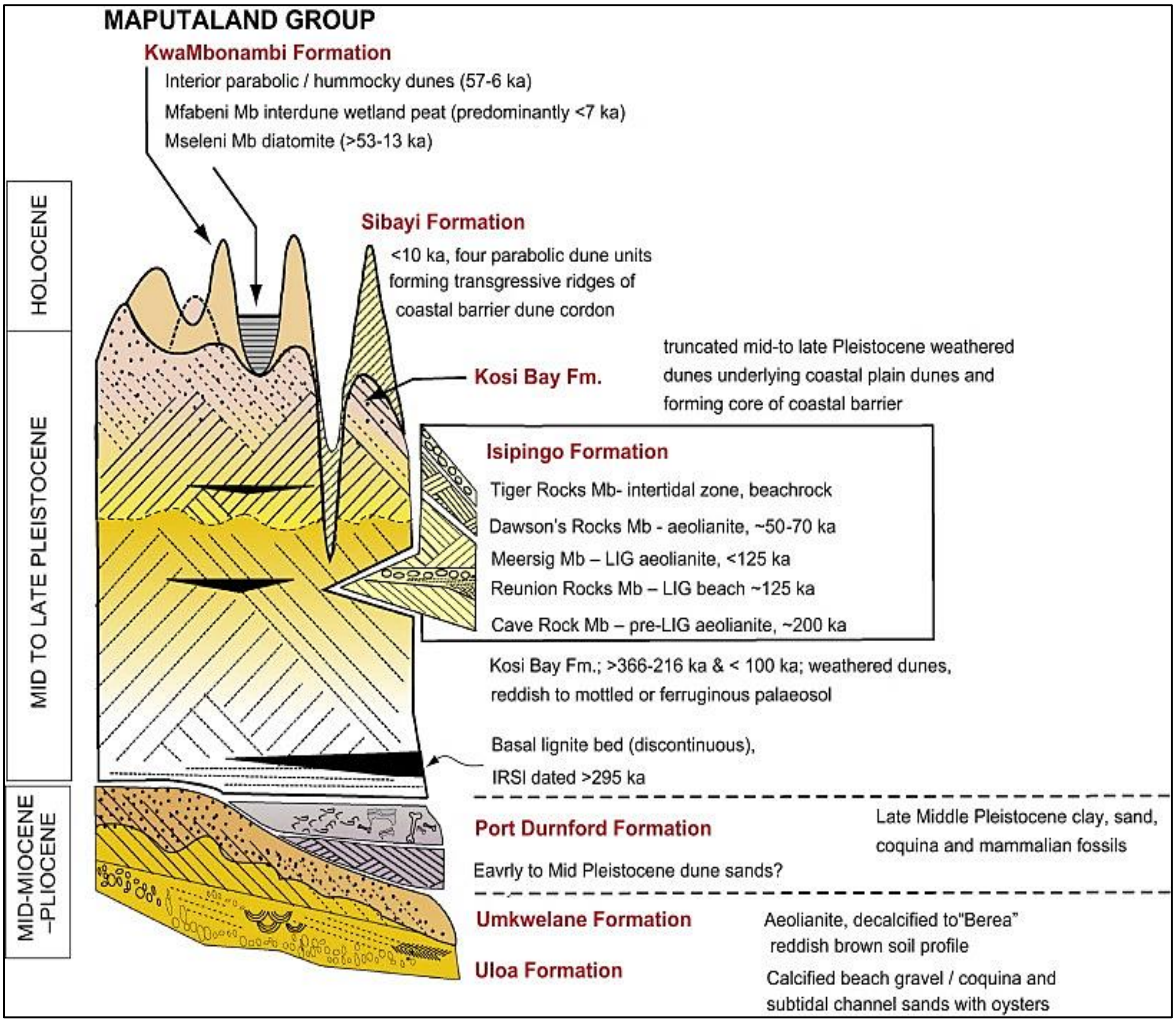

Figure 19: Schematic representation of the Maputuland Group lithostratigraphic unit (Barath, 2015:34).

The Uloa formation contains a lower coquina (glauconite rich and calcrudites) and upper calcarenite layer deposited in the Late Miocene. The base of the formation is a 2.5 m conglomerate layer resting on the St. Lucia formation. The coquina is 4.3 m thick, indicative of shallow marine waters. The calcarenite in the formation is coarse grained and well bedded, typical of shallow marine environments. The upper portions of the Uloa Formation consist of aeolian deposits which display steep cross bedding. The Uloa Formation can reach a thickness of 20 m in some areas; however, the general thickness for the Uloa Formation is 6 m (Barath, 2015: 34-35).

Overlying the Aloa Formation, the Umkwelane Formation consists of a beach or sedimentary course grain rocks of marine succession overlain by cross-bedded calcarenites. This formation is karstified on the upper surface and attains a thickness of 4 m. The Umkwelane Formation is erratically distributed across the ZCP. Erosion, weathering and Karst development together with periods of marine regression are manifested by the deep weathered dune cordons forming the Berea-type red sand (Barath, 2015: 35).

The Port Durnford Formation lies on top of the Uloa Formation. This Formation consists of loose consolidated sands, silts, clays and lignite layers. This formation is 25 – 30 m thick and can be found along the entire coastal belt. Dividing this formation, one finds lower argillaceous blue-grey sands and mudstones underneath a yellow-brown sand and reddish shelly sandstone. The upper arenaceous member from the Port Durnford Formation is the Kosi Bay Formation which has a thickness of 15 m predominated by aeolian facies, mostly fine grained with large scale cross bedding occurring in the formation (Ndlovu, 2015: 13).

Most of the ZCP is assumed to be covered by the Kosi Bay formation consisting of semi-consolidated weathered sand dunes, these sand dunes are intercalated with lenses of clay and lignite which overlies the Port Dunford Formation. The WRC (2015) suggest that the weathered profile be referred to as the Berea-type red sands as the variation in colour is characteristic of the Kosi Bay Formation, these colours vary from yellow to light brown with ferricrete, mottles and concretions in abundance on the upper surface. The Kosi Bay aeolian deposits reach a thickness of 15 m where clay enriched profiles of the Kosi Bay cause perched water tables which creates wetlands as demonstrated by the Kosi Lake in the study area (Barath, 2015: 36).

The Isipingo Formation consists of calcified dunes and beach deposits as a result of sea level fluctuations spread along the eastern coastline. It forms an essential part of the coastal barrier dune cordon (Barath, 2015: 32).

When the last glacial maximum occurred, substantial portions of the continental shelf were exposed due to marine regression. This states that the Kwambonambi Formation overlies the Port Durnford and Kosi Formations in the Richards Bay area. This formation comprises of decalcified dune sediments which derived from older dune sands that were reworked, freshwater diatomite and inter-dune wetland deposits. The Kwambonambi Formation consists of unconsolidated to loosely consolidated sediments and is also known to have heavy mineral deposits, believed to have resulted from the reworking of older dunes. The Kwabonambi Formation has closely spaced north orientated parabolic dunes, hummocky dunes and wind drift parabolic dune limb remnants. The hummocky dunes have a thickness ranging from 10 m to 15 m above the ZCP. There are discreet patterns to be seen due to the drainage systems of the Sibayi, St. Lucia and Kosi-Bay systems which formed inter-dune wetlands and hygrophilous grass (Barath, 2015: 36-37).

During the Holocene marine transgression, coastal valleys and lakes were flooded, as seen through the presence of beach ridges in coastal lakes as well as beach rock along the coast. Thus, as a result of the amalgamation of multiple dune cordons, these remnants of alluvial sedimentation restricted the connection with the Indian Ocean, referring to it as the Sibayi Formation (Barath, 2015: 37).

The Sibayi Formation is calcareous homogenous aeolian deposits, underlain by boulders and pebbles which forms north-south parabolic dune cordons. These dunes can reach heights of between 120 m to 172 mamsl. along the eastern coastal shores which define the morphology of the present coastline (Barath, 2015: 37).

Barath (2015: 37-38) refers to the Sibayi and Kwabonambi Formations as the cover sands of the ZCP, consisting of medium to well-rounded grains where the thickness of these cover sands ranges from 0.5 to 3 m. This results in high permeability and porosity areas which decrease with depth due to compaction.

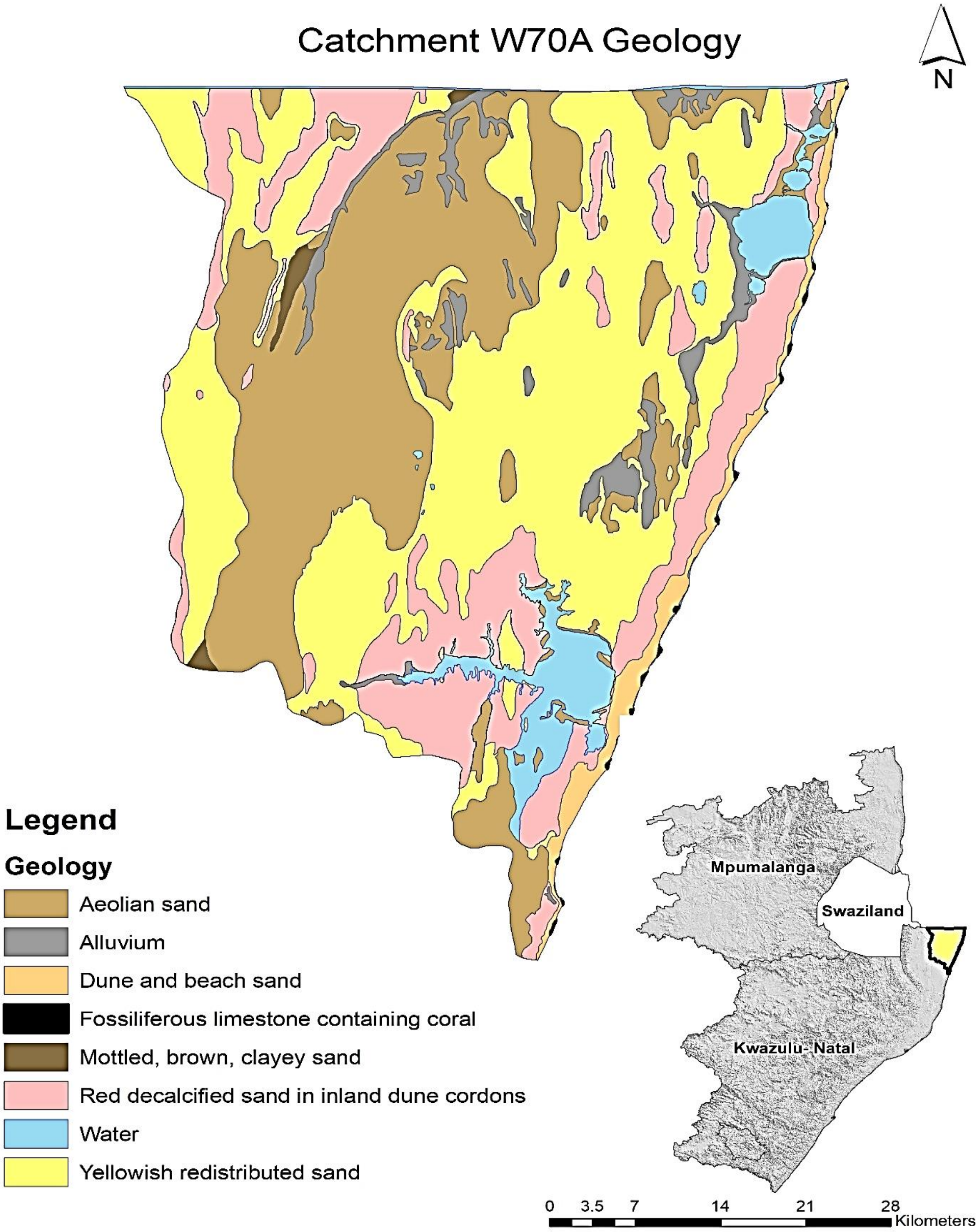

Figure 20: Geology of catchment W70A

The study area is dominated by yellowish, redistributed sand throughout the catchment, especially the eastern half of the catchment known as Arenite, from the Algoa group formations and the Salnova lithostratigraphic unit, also known as the

Sibayi formation. Aeolian sand, Alluvium and Calcarenite sands dominate the western part of the catchment originating from the Kalahari-Algoa group formations. Alluvium and Red decalcified sand in inland dune cordons also occur throughout the catchment. The western portion of the catchment consists of Arenite, originating from the Bluff-Strandveld lithostratigraphic unit, also known as the Berea formation.

Table 12: Geological labels

Lithostratigraphic Unit	Group/Formation/Complex
Alluvium, sand, calcrete	Kalahari - Algoa
Bluff	Bluff Formation
Salnova	Algoa Group

Table 13: Lithologies

Lithostratigraphic Unit	Lithology 1	Lithology 2	Lithology 3
Alluvium, sand, calcrete	Sedimentary	sand	Calcrete
Bluff	Arenite		
Salnova	Arenite		

6.6 Soils

The soils of the ZCP consist of arenosols and alluvial soils, which is very sandy, and low in nutrients. The dunes consist of pure quarts sands with local concentrations of heavy minerals. The recent sands are mostly whitish while the older sands are reddish to brownish with elevated clay content. The older dunes have higher humus content and has a dark greyish-brown colour. Catchment W70A mainly consists of soil group A and soil group B according to the definitions of soil groups as set out in Figure 53 (WRC, 2015: 19-20):

6.7 Geohydrology

The study area is underlain by an intergranular aquifer which consists of water saturated sediments such as gravel and sand. The groundwater is thus stored in the intergranular pores where it can be transmitted to boreholes and springs.

As previously stated, the ZCP is a primary aquifer consisting of relatively young, unconsolidated to semi-consolidated sediments and the cover sands of the upper aquifer consists of medium well-rounded grains which makes it highly permeable. As a result of these high permeable sands, recharge can occur rapidly through the sediments. Furthermore, the topography is relatively flat in the coastal plain making the primary aquifer unconfined in areas of low topography where the water table can fluctuate in undulating form and slope (WRC, 2015:24).

6.7.1 Groundwater Levels

The catchment has a relatively flat topography which increases in surface relief closer to the coast as previously mentioned where the dune cordons act as barriers along the coastline. The mountainous areas along the western side of the catchment have steep slopes which gently flatten in the eastern direction until the coastal barriers occur (WRC, 2015:25-26).

The WRC (2015:26) shows studies where it is evident that the vertical hydraulic conductivity throughout the vertical succession was significantly high. Although this study was undertaken around the Lake Mzingazi and Mhlatuze River, it can be relevant due to the homogenous intergranular ZCP primary aquifer. Certain areas also showed perched water tables where clay and silty sand occurred in the shallow depths.

Surface elevation versus groundwater levels are plotted in the Figure 55, which shows a strong correlation coefficient of 98.76 %. This confirms a strong Bayesian relationship exists since the groundwater levels follow the topography. This also confirms that it can be assumed that the aquifer is of unconfined to semi-unconfined nature. Therefore, Bayesian Interpolation was used to generate groundwater levels and flow directions for the area.

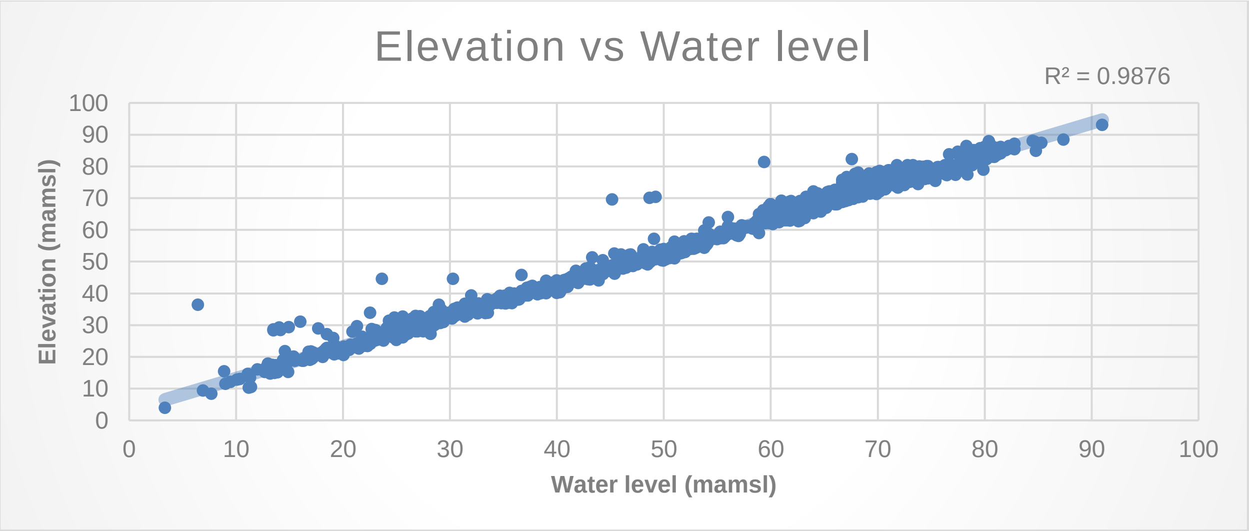

Figure 21: Elevation vs Groundwater levels for catchment W70A.

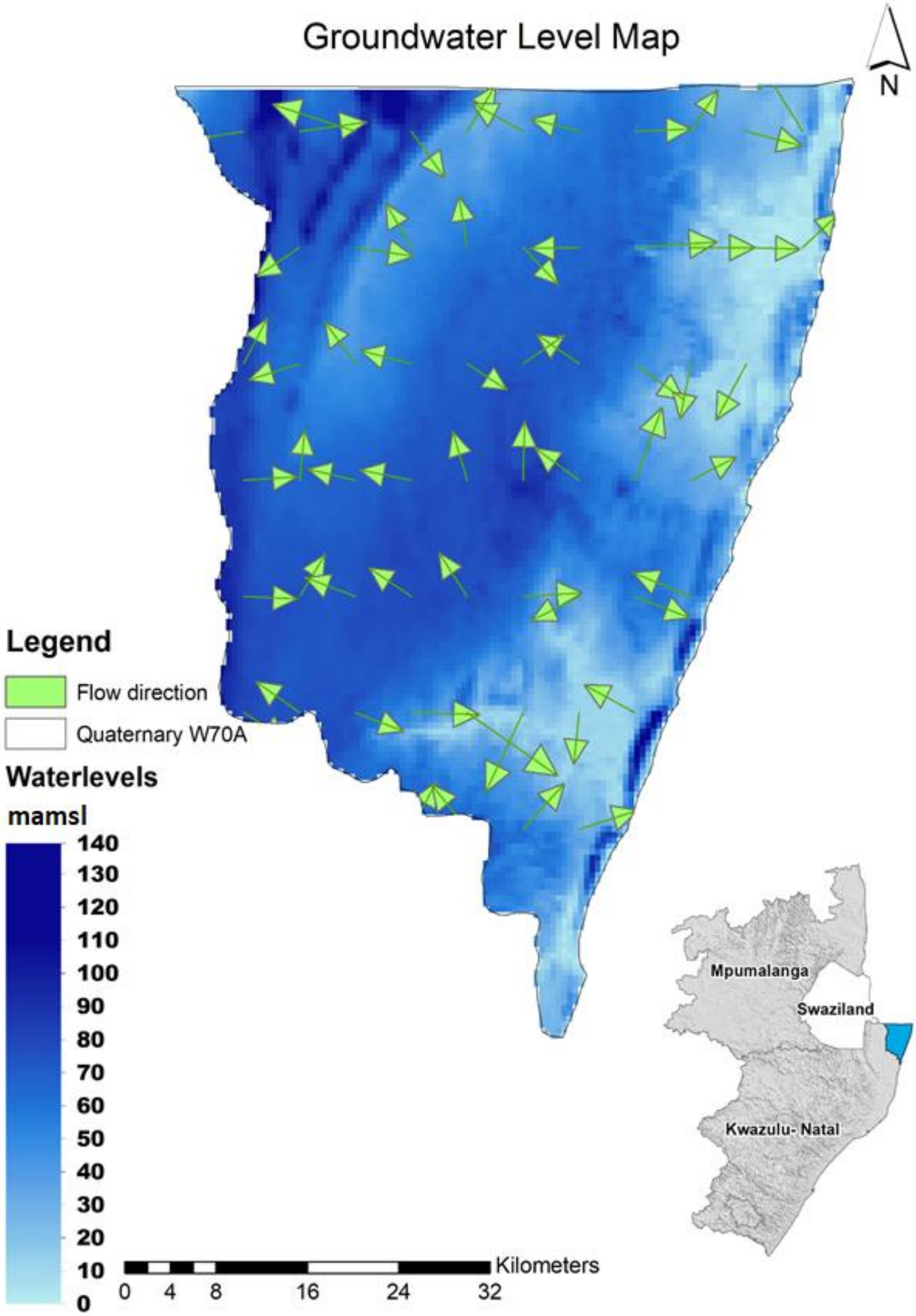

Figure 22: Water level and flow direction map for catchment W70A

The groundwater levels range from 3.22 – 91 mbgl. This means a relatively shallow groundwater level occurs throughout the study area considering the size of the study area. The coastal (eastern) parts of the study area has shallow groundwater levels gradually increasing towards the centre of the study area where deeper groundwater levels are found. Due to unconfined and low topographic areas, the water table fluctuates in undulating form and slope, the highly permeable sands and the rate of recharge moving through the sediments are the main mechanism causing these characteristics in the study area.

6.7.2 Lakes

- The Kosi Bay system – Four interconnected lakes that lead to an estuary opening to the Indian Ocean and consists of vast areas of swamps. This drainage system covers an area of approximately 500 km^2.
- Lake Sibayi – This is the largest freshwater lake in South Africa with a surface area of 65 km^2 and a catchment area of 536 km^2. The average depth is 13 m reaching a maximum of 43 m (WRC, 2015:29).

6.8 DETERMINATION OF THE RESERVE AND ASSOCIATED ALLOCABLE WATER

6.8.1 Data requirements

6.8.1.1 Transmissivity/Hydraulic conductivity

According to research cited by Ndlovu (2015: 54) the Uloa and Umkwelane Formations are considered as main aquifers in the Kosi Bay system. Hydraulic conductivities in these areas range from 0.5 - 23.6 m/d and the sustainable yield is in the order of 5- 20 l/s respectively. Furthermore, the storage coefficient ranges from 2×10^{-4} - 6×10^{-4}.

The Port Durnford Formation is a leaky aquifer made up of consolidated sand which is loosely packed, silt and clay. This formation has a hydraulic conductivity of 4.3 m/d where the Kosi Bay formation has a hydraulic conductivity of 4 – 5 m/d due to the relatively low hydraulic characteristics of the formation (Ndlovu, 2015: 54).

Ndlovu (2015:54) states that the hydraulic conductivity ranges from 0.87 -15.6 m/d and 0.5 – 5 l/s for the Kwambonambi and Sibayi Formations respectively. This shallow aquifer overlies the Kosi Bay Formation mainly known as the extensive Holocene cover sands. Ndlovu (2015: 54) also calculated the transmissivity for this shallow aquifer using the Cooper Jacob's method where an average transmissivity of 305 m^2/day was obtained.

Barath (2015: 7) states that the ZCP comprises of sporadically distributed calcarenite which reaches a thickness of >20 m in certain areas. The hydraulic conductivity and storage coefficients were calculated at 2.5 m/d and 6×10^{-4}, respectively also stating that the transmissivity is highly variable.

Barath, (2015:10-11) revealed that aquifer testing of boreholes recorded transmissivity values ranging from 75 to 500 m^2/d for the Kwabonambi Formation sands, as well as high transmissivity values for the Uloa formation (>1000m^2/d).

Table 14: Aquifer parameters (WRC, 2015:24)

Geology	Horizontal hydraulic conductivity (m/d)	Vertical hydraulic conductivity (m/d)	Specific storage	Specific yield
Alluvium/clay-sand/limestone	5	0.5	1×10^{-4}	0.2
Yellow sand	10	1.0	5×10^{-4}	0.25
Red/dune/beach sand	25	2.5	1×10^{-3}	0.3

Transmissivity (T) Affects groundwater outflow and impact of abstraction on baseflow. This parameter must be set to a regional median value, and not values obtained from test pumping of high yield boreholes. Generally, 2-10 l/s. Increasing this value increases groundwater outflow and results in a more rapid baseflow depletion response to abstraction (Sami, 2015:23).

According to Weitz and Demlie, (2013:5) the hydraulic characteristics for the different aquifer units within the study area are summarized below:

Table 15: Hydraulic characteristics for the different aquifer units.

Aquifer name	Thickness (m)	Hydraulic Conductivity (m/d)	Transmissivity (m^2 /day)	Borehole yields (l/s)
Sibayi and Kwambonambi Formations	20-30	0.87–15.6 (mean: 5)	1490	0.5-5
Kosi Bay Formation	15-20	4–5 (mean: 4.3)	-	2-10
Uloa/Umkwelane Formation	5-20	0.5–25 (mean: 4.5)	116	5-25
St Lucia Formation	900	-	-	<1

Note: The thickness for the Kwambonambi and Kosi Bay formations are based on rough approximations due to their complex relationships.

A transmissivity of 800 m^2/d is used in the model calibration for optimal calibration purposes. Please refer to equation 9 on page 44. By assuming the aquifer thickness is 40 m and a transmissivity value of 800 m^2/d, the K is equal to 20 m/d. Thus, calculations made for this study match calculations of publications such as Barath, (2015), Ndlovu, (2015) and Weitz and Demlie, (2013).

6.8.2 Porosity

The porosity of the domain indicates the percentage of soil volume not occupied by soil particles but will not affect the water levels of the water table; it only affects the velocity of an individual parcel of water.

The selected porosity is 0.3, as most porosities range from 0.25 to 0.4 for subsurface media (Freeze & Cherry, 1979).

6.8.3 Storativity

According to GRAII (DWAF, 2005a), the storativity value for the catchment is 0.0123. In South Africa. Table 16 documents typical storativity values for different aquifer types.

Table 16: Storativity ranges for different aquifer types (DWAF, 2010).

Aquifer Type	Storativity
Fractured	0.001
Fractured and Intergranular	0.005
Karst	0.01
Intergranular	0.1

6.8.4 Aquifer Thickness

The base of a primary aquifer is moderately well defined in the form of solid rock underlying the unconsolidated sediment or soil, e.g. alluvial aquifers (DWAF, 2006a: 10). DWAF (2014: 11) state that the shallow primary aquifer reaches a depth of 30 m under the coastal dune belt and a maximum elevation of 20 mamsl. The thickness of the aquifer is derived from borehole data which falls within the ranges of published data (Ndlovu, 2015:54). Table 19 above from Weitz and Demlie, (2013:5) states an aquifer thickness of 5 – 30 mamsl. For optimal calibration purposes, the aquifer thickness calibrates best at 40 m.

6.8.5 The Topmost Base Elevation

The value for the calibrated model (conceptual model) is 0 mamsl, since the catchment is bordering the coastline. This value must be consistent with topographic maps and specified head values (i.e. river, boreholes).

6.8.6 Recharge calculation for the model domain

As previously acknowledged, recharge is a complex process where gross simplification occurs. The volume of water entering a groundwater system is a function of geology, topography, soil types and the rate and volume of water entering the groundwater system as well. The recharge is presented as the %MAP for comparative and estimative purposes (WRC, 2015:25).

In this study area, rainfall is the main mechanism for catchment W70A, where the high permeability of the sand causes rapid recharge for the intergranular aquifer. The lakes, pans and shallow peat swamps in the study area represent minimum contribution to the recharge of the system (WRC, 2015:25).

Numerous methods were used to determine the recharge value for the aquifer. These methods are discussed in detail in Appendix C. Additional recharge values were obtained from literature. A summary of the results is documented in Table 17:

Table 17: Summary of recharge values.

Method/reference	Recharge (%)
WRC, (2015:25)	5-18
GRAII (DWAF, 2005a)	10.2
DWAF, (2014)	5-18
Weitz and Demlie, (2013: 7)	7
Ndlovu (2015: 55)	13
Barath, (2015: 7)	8-30
Chloride method	9.6
Distance to sea	12.06
Vegter, (1995)	10.2
ACRU Recharge	7.31
Harvest Potential Map	10.2
Groundwater component of river baseflow	7.3 (minimum recharge)
Average	10.74

6.8.7 Parsons & Wentzel (2007) and Dennis *et al.,* (2011) method

The assumption is made that the total population is dependent on groundwater. According to Aquiworx (2017) the total population is 93886. The total population dependent on groundwater is not known, therefore it is assumed that the total population is dependent on the resource. If every person uses 25 l/d, then the BHNs for the area is total groundwater use in the catchment as 0.86 Mm^3/a.

Herold's baseflow separation (Figure 21) is used to determine the groundwater contribution to baseflow according to Dennis *et al*., (2012:51) and this is assumed to be equivalent to the low flow necessary to sustain the EWRs and is determined using the Herold's method which is included in Aquiworx (2017) as 22.4 Mm^3/a. The total groundwater Reserve is therefore 23.26 Mm^3/a.

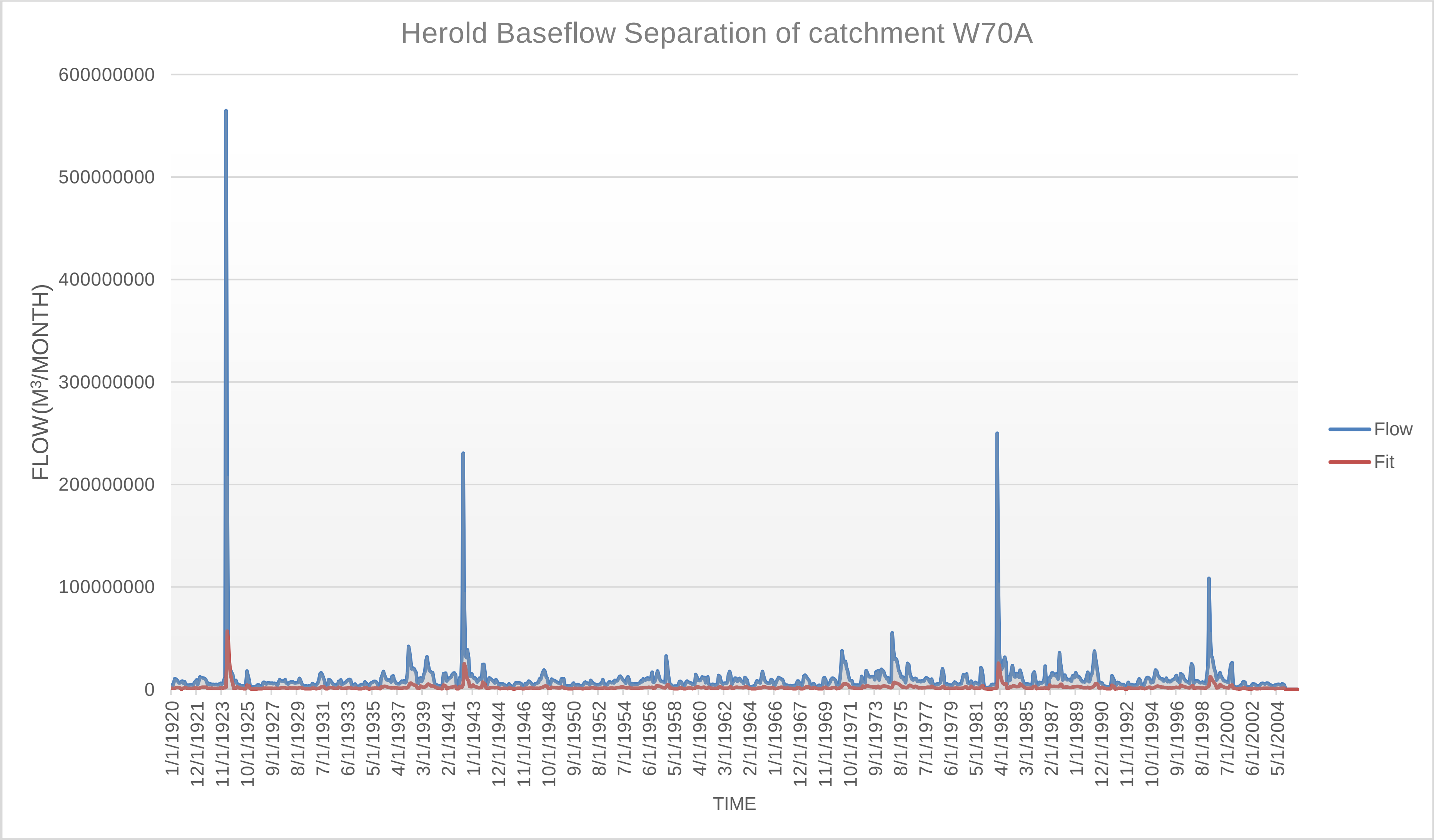

Figure 23: Baseflow separation of W70A (Aquiworx, 2017).

The allocable volume of groundwater can now be determined. The groundwater use according to Dennis and Dennis (2016) amounts to 29.2 Mm^3/a. According to Table 18, the average recharge is 10.74 % for the area of the catchment that is 2589 km^2. Therefore, the total recharge is 137.2 Mm^3/a. The allocable groundwater (according to Equation 2) is 85.6 Mm^3/a.

6.8.8 Firm yield model

Aquiworx (2017) calculates the firm yield for quaternary catchment W70A as 53.2 Mm^3/a. That is, if the pumping rate of the aquifer is held below 53.2 Mm^3/a, sustainable utilisation of the aquifer will take place therefore no depletion of water takes place. If more than 53.2 Mm^3/a is withdrawn, it can be problematic for the environment and the surrounding biota, resulting in sinkholes, wetland losses and salt water intrusion in the case of this coastal aquifer.

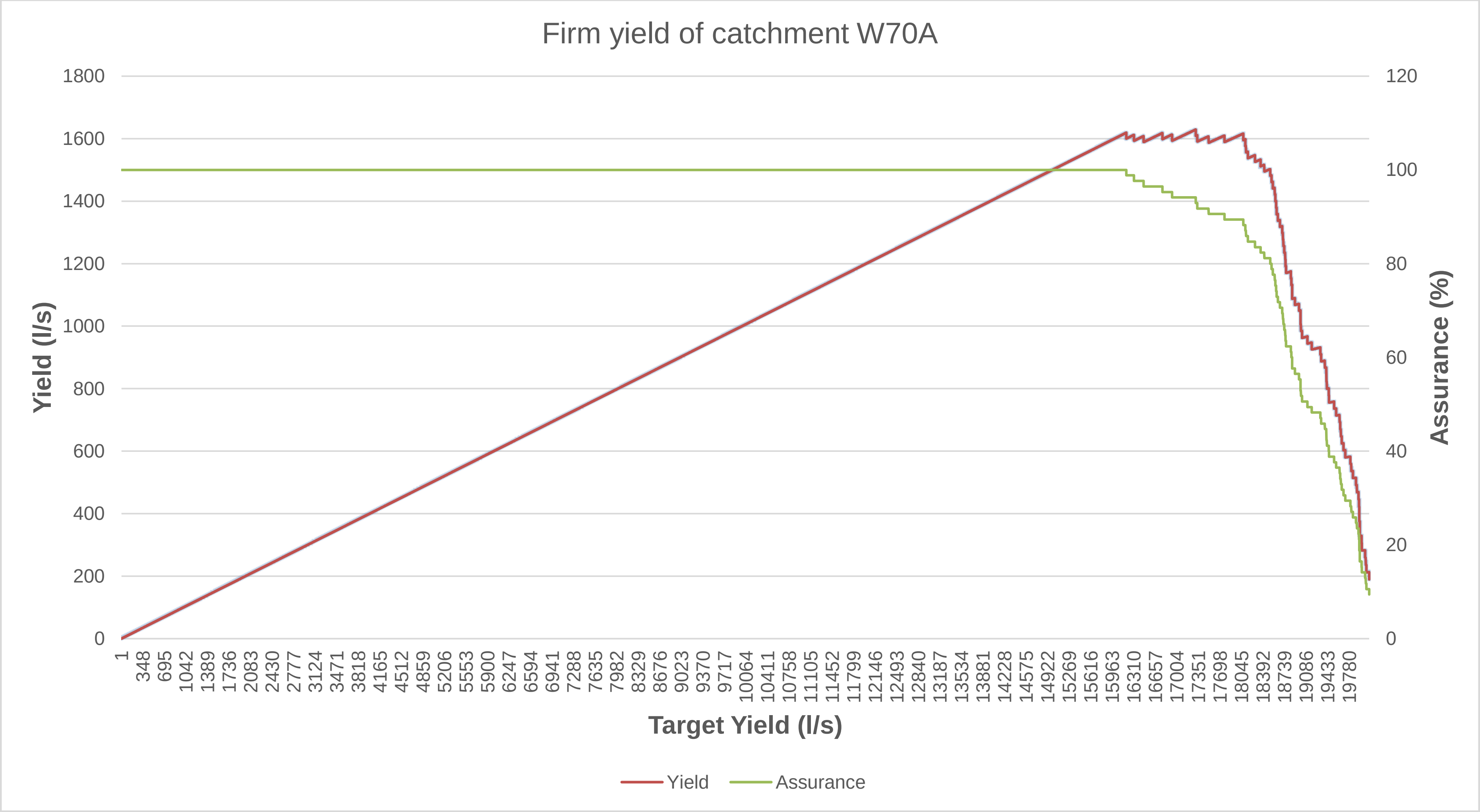

Figure 24: Firm yield of W70A (Aquiworx, 2017)

6.8.9 AEM model

The AEM model is shown in Figure 23. There are two different recharge zones digitised according to the underlying geology of the area.

To calculate the firm yield, a leakage (abstraction) zone around the catchment represents the water flowing out of the catchment. This leakage component is gradually increased to measure the water levels across the entire catchment. The entire catchment is represented by a grid with 243 evenly spaced points (as seen in Figure 23). Aquifer parameters as discussed in Section 6.8.1 and groundwater levels were included in the model.

This Visual AEM model has fixed heads along the western boundary set on initial water levels and as well as fixed heads along the eastern boundary of the catchment. The value along this boundary must be zero to coincide with the coast line.

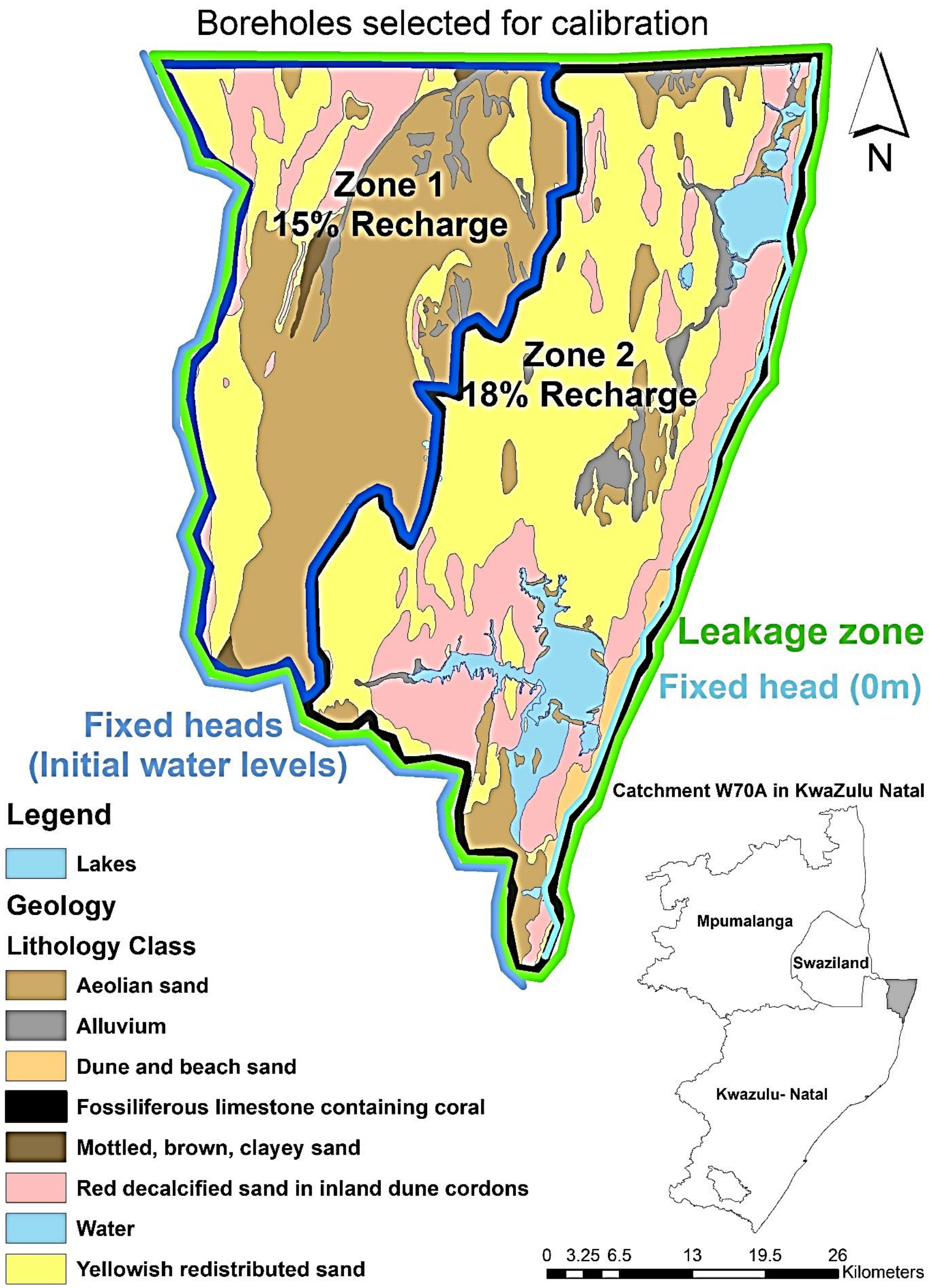

Figure 25: Representation of catchment W70A in Visual AEM.

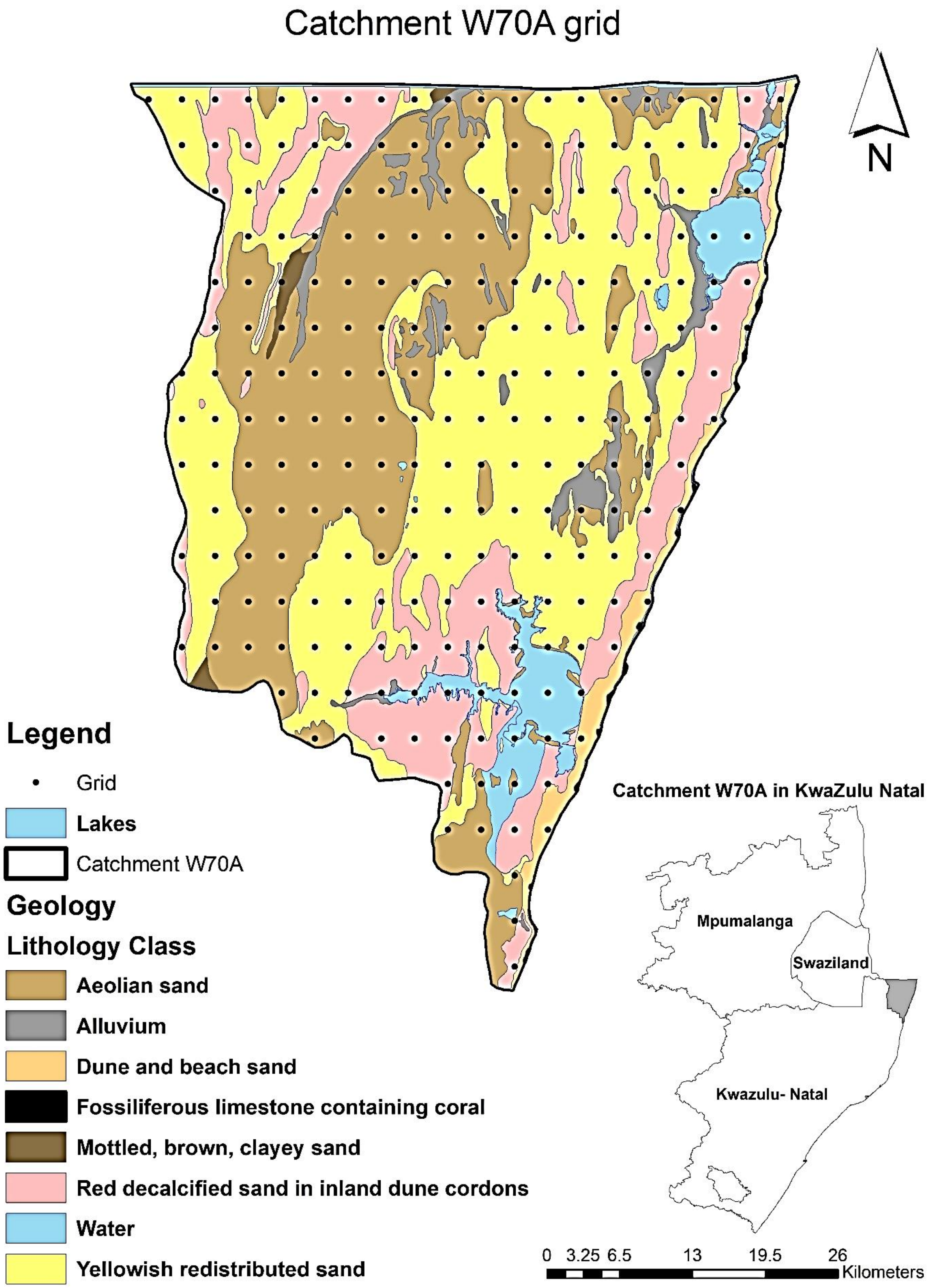

Figure 26: Representation of the catchment W70A grid in Visual AEM.

The calibration process is done manually in order to understand the significance and relevance of the recharge, hydraulic conductivity and aquifer thickness of the system. Calibration is also done to gain access to modelling functions and obtain results through “Ostrich” (software to find the best fit in recharge/hydraulic conductivity combinations for the provided heads).

Numerous boreholes throughout the study area were used for the steady state model calibration. The given water level data for the representative boreholes shown in Figure 25 were used for the steady state model calibration.

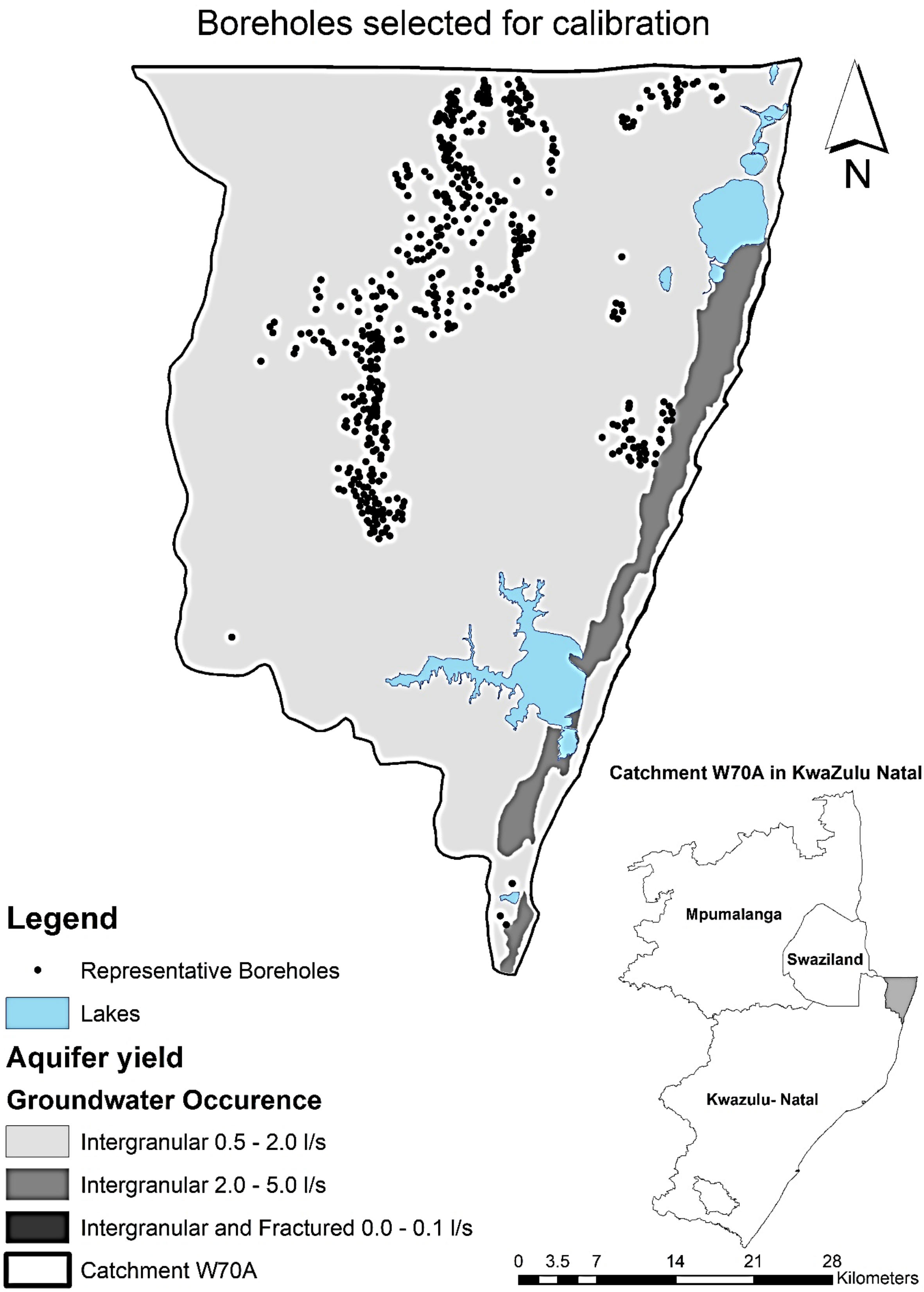

Figure 27: Boreholes used for calibration of catchment W70A

For the model to calculate the head distribution for the steady state flow system, it relies on the rainfall for recharge, hydraulic conductivity, aquifer thickness and other hydraulic parameters as well as the boundary conditions.

A simulated head distribution is created and compared with the measured head distribution with effective recharge and hydraulic conductivity values that can be adjusted for an accurate and acceptable correspondence between the simulated and measured heads.

Figure 26 illustrates the relationship between the observed and simulated heads for catchment W70A.

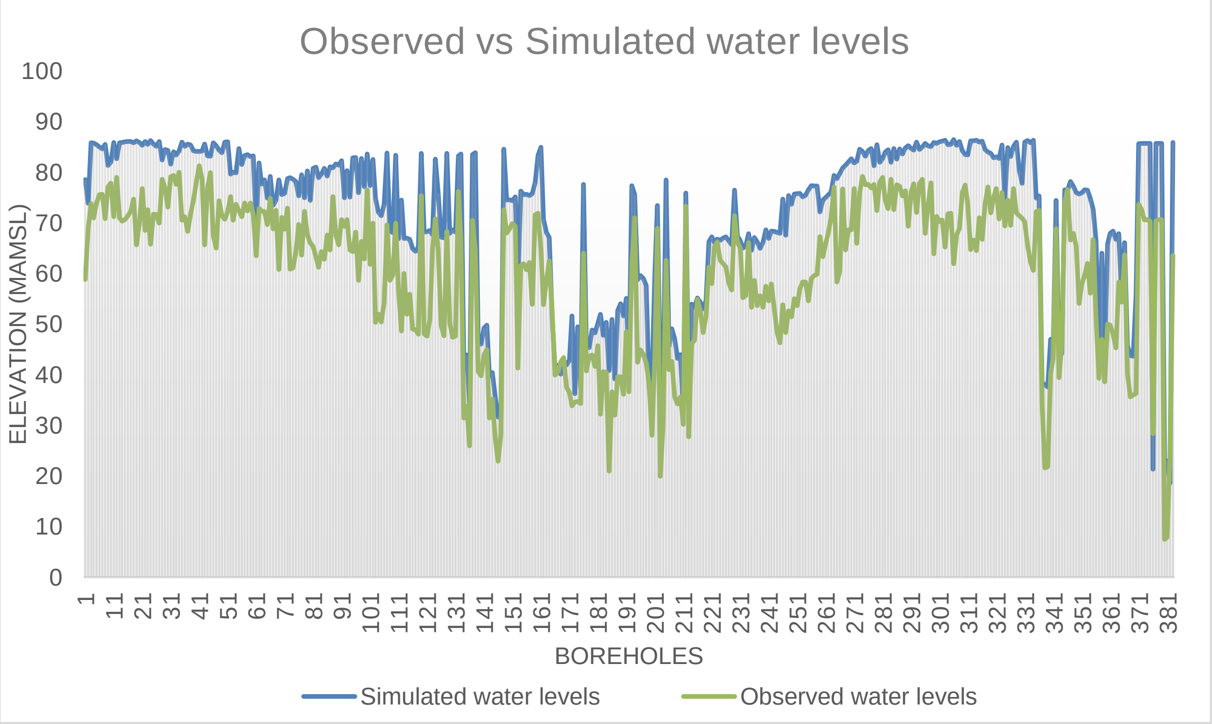

Figure 28: Comparing the Observed vs Simulated water levels for catchment W70A.

Three hundred and eighty-one boreholes were used in the calibration process. Water levels were simulated using the Visual AEM program. The R-squared value (R^2) from the calibration results shows an 84.33. % correlation between the observed and the simulated water levels as seen in the following Figure 27:

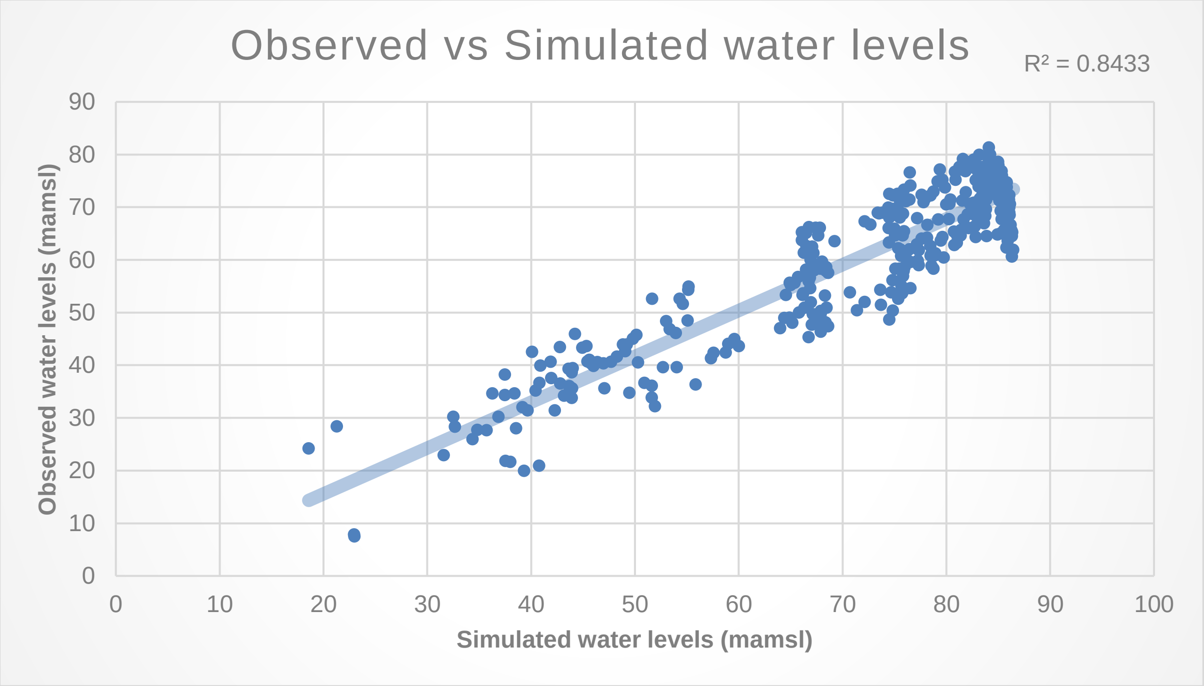

Figure 29: Observed vs Simulated water levels for catchment W70A.

On the completion of the calibration, a simulation is run where the water levels are dropped by abstracting a gradual amount of water until a 5 m drawdown is achieved to ultimately measure the firm yield of the aquifer. This gradual abstraction is achieved by changing the leakage (abstraction) component of the model to simulate the change in water level.

Three representative boreholes are used to represent the firm yield. The top borehole in 29 reaches the 5 m point the first and is therefore regarded as the firm yield. The overall firm yield for the catchment is 28.4 Mm^3/a. Thus, by keeping the pumping rate below 28.4 Mm^3/a, sustainable abstraction of water is accomplished.

There are no rivers in the study area and the baseflow is attributed to the lakes in the area. Table 18 presents a summary of the results.

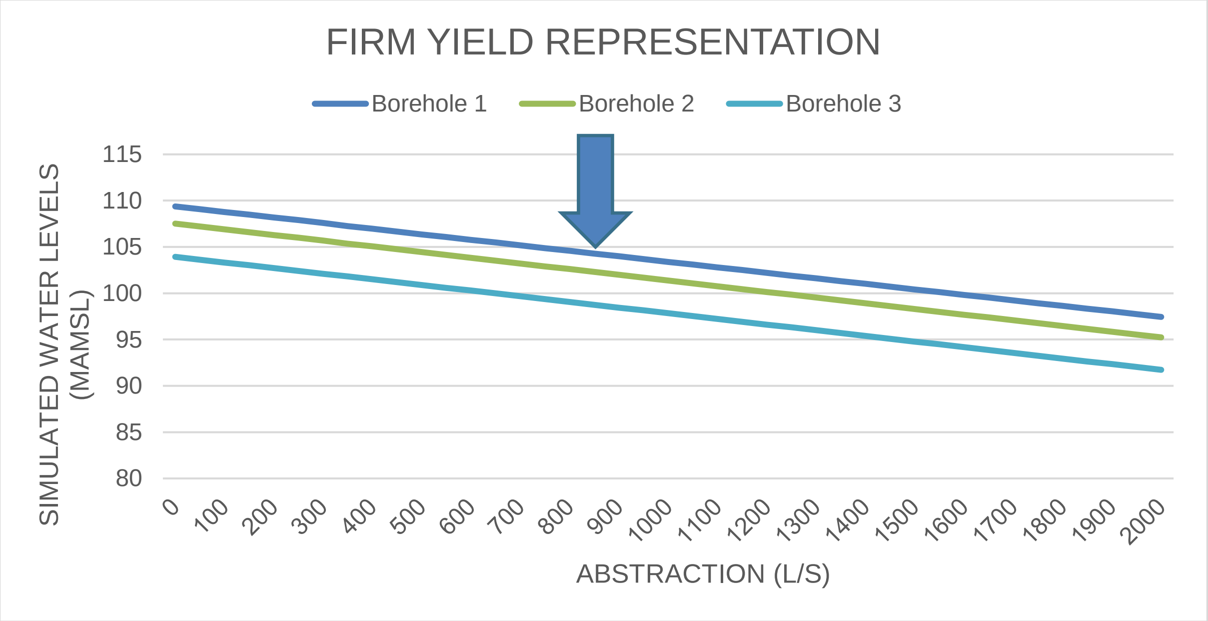

Figure 30: Firm yield representation of catchment W70A

Table 18: Summary of results

Method/reference	**Firm yield/ Allocable water (Mm^3/a)**
Parsons & Wentzel (2007) and Dennis *et al.*, (2011) method	85.6
Firm yield model	53.2
AEM model	28.4

The Parsons & Wentzel (2007) and Dennis *et al.*, (2011) method result for the firm yield show a much higher value as for the firm yield model and the AEM model. One of the reasons for this is the assignment of uniform parameters to the entire catchment area. The AEM method does take spatial variations of parameters into account. It is therefore seen as a more accurate representation of reality.

The boreholes illustrated in Figure 28 are located in the Aeolian sands which has a high hydraulic conductivity. These boreholes are chosen since they represent the 5 m decrease in water levels faster than the rest of the boreholes, these figures obtained from the AEM model can therefore be the worst-case scenario for the firm yield representation for this case study.

7 COMPARING RESULTS

The Parsons & Wentzel (2007) and Dennis et al., (2011) method are considered as a lumped parameter approach. This method relies on parameters which are quantified in terms of one value per parameter for an entire area of interest (i.e. a constant single recharge value), not considering any change in the environment, therefore no detail is needed when utilising this method. This may have implications on the overall water budget. The AEM model utilises a more detailed approach where non-uniform aquifer parameters are utilised since different recharge zones and aquifer parameters consequently involves a more accurate representation of the real-world environment.

The Firm yield model is painstaking restricted since a 5 m drop in water level only involves one water level for an area of interest/quaternary catchment where the AEM model involves several water levels obtained from different boreholes in various locations. The firm yield model uses hydrogeological data which provides a monthly flow output for a complete quaternary catchment, together with other sources of data for individual parameters. This groundwater balance model is simple to use and provides storage dynamics depending on the variable volumes of inflow and outflow. It also provides groundwater yields at 100 % assurance of supply. By applying non-uniform aquifer parameters, a better calibration was archived since a better understanding of the groundwater system is achieved and it represents a more accurate representation of the real-world environment

The AEM model is considered the most accurate model between the three methods since a more detailed model of the environment can be presented. Thus, the AEM model will be the most accurate representation of the firm yield to determine the Reserve. When addressing the shortcomings of a Reserve determination, the older methods only exert simplistic box models until the FY concept originates. Although the FYM incorporates time series data, it is still a box model. This dissertation focusses on taking this concept to the next level by dividing the box model according to different water levels where the FYM only includes one water level over an entire area. This is also aided by different recharge zones for more accurate results in calibration. Another advantage of AEM, at any point in a river where the model is calibrated, the volume of water at that specific point can be noted as Visual AEM calculates the amount of inflows and outflows anywhere in the model domain.

Furthermore, elements in the model is discrete hydrologic entities, the AEM model follows sharp changes in the groundwater table due to mathematically accurate harmonic solutions and when a model is calibrated, the heads alone can observe the aquifer recharge to hydraulic conductivity.

There is much discussion on which is the most appropriate model of investigation, since every modelling approach has its own strengths and limitations. Thus, the most suited model usually depends on the intended use and the data availability. Lumped modelling approaches lack spatial detail but, a better understanding for larger-scale water management issues can be reached.

This study demonstrates that Visual AEM can be applied to study regional groundwater flow and provide solutions for the existing scale issues by adopting model calibration parameters to obtain a satisfactory representation of the groundwater system. Thus, the overall conclusion is that the model is proficient in representing catchment scale processes that South Africa generally experience.

8 CONCLUSIONS AND RECOMMENDATIONS

Satisfactory model calibration was achieved through Visual AEM to model groundwater flow and determine the Ecological Reserve, more specifically the firm yield by using two case studies. With accurate data, this software can be used to represent the real-world environment in determining the Ecological Reserve more accurately, thereby providing better management of groundwater systems and even better model outputs.

The calibration process was done manually in order to understand the meaning and relevance of the recharge and hydraulic conductivity as well as gain control over the water balance. Furthermore, we gain access to inverse modelling functions and results through Ostrich. The model is gradually increased in complexity until the domain is well characterized. Conceptualization of the model results are based on the GIGO principle where if the system interactions between groundwater, rainfall, topography surface water and anthropogenic elements are not clearly quantified and incorporated in the determination, the confidence level is lowered. This dissertation focusses on quantifying the yield for an Ecological Reserve determination.

Rainfall is the primary mechanism of recharge in most aquifer systems. In the occurrence of the east west gradient in case study 2 (chapter 6), the rainfall exhibits a high rainfall pattern (~1200 mm) along the coast and a lower rainfall pattern (~600 mm) further inland. Rainfall is directly related to higher and lower altitudes, tropical vegetated areas and non-vegetated areas etc. (WRC, 2015: 151). Thus, recharge zones for the AEM model was adjusted and proven effective as the calibration results show to make the model domain more aquifer specific and consequently, add detail to the model domain.

Recharge moves rapidly through highly permeable sands causing undulating forms and slopes in terms of the groundwater table. This occurrence come about in case study 2 where unconfined low topographical areas are found. As for case study 1, recharge is highly affected by the dolomites in the area, which has a high permeability compared to the surrounding geology. Thus, recharge is variable in terms of different geological regions.

When addressing the shortcomings of a Reserve determination, the older methods only exert simplistic box models until the FY concept originates. Although the FYM incorporates time series data, it is still a box model. This dissertation focusses on taking this concept to the next level by dividing the box model according to different water levels where the FYM only includes one water level over an entire area. This is also aided by different recharge zones for more accurate results in calibration. Another advantage of AEM, at any point in the model domain if the model is calibrated, the volume of water at that specific point can be noted, as Visual AEM calculates the amount of inflows and outflows along every point. There is no need for given boundary conditions in the AEM if there is no information in terms of the borders of an area. However, the AEM can model regional and local effects where groundwater levels vary.

Scale differences between surface and groundwater bodies need to be considered in Reserve determination processes, especially for classification and developing RQO's. This means that for example, aquifer boundaries do not match surface water boundaries like in the case of fractured aquifers, groundwater discharge occurs at different areas such as springs of river reaches which is not evenly distributed across a catchment or aquifer. Furthermore, groundwater flow is much slower than surface water flow, this impacts groundwater discharge as well as water availability due to seasonal patterns in groundwater flow.

For national management in modelling groundwater, a definition of the scale is required to compare results of nationwide manageable models. Utilisation of the AEM can make groundwater flow modelling extremely flexible which enables different model scales to be combined. Thus, the effects of groundwater behaviour in large domains can be presented in accurate and clear ways to policymakers.

In terms of quantifying the yield in the hydrological field, it remains a fundamental problem, especially on quaternary catchment scale. Nevertheless, the AEM serves as a decent tool and a good background analysis for a water balance at catchment scale when calculating the sustainable yield. Sustainable yields can be determined with analytical models where pumping tests from monitoring boreholes are used. Thus, impact of surface water on nearby single abstraction boreholes can be quantified. Furthermore, more groundwater data is needed for better estimates of the firm yield.

Ultimately, the firm yield relies heavily on adequate infrastructure, borehole sitting, proper funding, drilling, development and construction for the aquifer to be effectively exploited and understood.

If an AEM model is satisfactorily calibrated, AEM utilisation for borehole protection zones can be specified. AEM does not include a radius of influence however; one can see how much water can be extracted from a borehole before the baseflow of a river is impacted. The key to this is to protect the baseflow component (EWRs) by having the borehole to be a certain distance from the river or another borehole. This can also aid in wetland, estuaries and springs protection zones.

The determination of allocable amount water is of utmost importance and the Reserve forms part of this calculation. The most important objective is to ensure enough water are of suitable quality to provide for basic human needs. This is emphasized by the policy that 25 litres per person per day under the urban and rural requirements are maintained. When this quantity increases in the future, the Reserve should be re-determined. Further work on the Reserve is required to improve the determination of the Reserve due to very limited knowledge of the extensive range of habitats and water requirements.

As population growth continues, utilisation of rivers as water sources, agriculture and forestry are consuming a substantial amount of water that in turn, modifies the groundwater and surface water regime. Thus, a certain amount of groundwater is necessary to maintain the status of these environmental systems as in the case of rivers, lakes, estuaries and more importantly wetlands and natural vegetation. This concludes that the firm yield aspect for a Reserve is of utmost importance for groundwater practitioners. The DWS should monitor the quantity of these anthropogenic impacts on groundwater (i.e. quantity and quality).

Monitoring is an important aspect as part of water management within a study area. This is crucial in terms of understanding changes in groundwater flows/levels, identifying, quantifying and capturing measurable and feasible data. The overall point of monitoring is mainly assessing the performance of preventative measures such as catchment objectives and compliance of licence conditions.

The National Water Act recognises the hydrological cycle and the integrated nature of water resources. As such the management of groundwater needs to be integrated with the management of all other water resources. The management of groundwater entails assessing and controlling the degree of fluctuation that can be tolerated in an aquifer. This ensures that water levels remain above a critical level below which further pumping could cause harmful and often irreversible effects. A significant aspect of the management of groundwater resources is the recognition of groundwater's function in maintaining the ecological reserve. The use of water balance models offers a means of integrating the management of groundwater and other water resources in this way addressing the mis-accounting and mis-allocation of water resources

A database of all determination studies should be maintained. The purpose of the database would be to record salient features of studies and provide a mechanism for improving all levels of determination based on past experiences. Rainfall data was sparse and complete time series data sets were a challenge, furthermore, several data sets associated with boreholes were incomplete. It takes years for substantial time series data to be meaningful in a GRDM assessment. Thus, only available information is used for a GRDM assessment, sometimes augmented by field work.

There is much discussion on which is the most appropriate model of investigation, since every modelling approach has its own strengths and limitations. Thus, the most suited model usually depends on the intended use and the data availability. Lumped modelling approaches lack spatial detail but, a better understanding for larger-scale water management issues can be reached. New tools and approaches regarding recharge, groundwater use and groundwater contribution to baseflow still needs to be researched and developed to improve practitioner's abilities in this regard.

The AEM superimposes analytic elements to model features in a vector field such as a discharge vector field in an aquifer. For every property of a vector field, an element is chosen and developed to simulate it. The freedom of choosing different elements in the AEM is perhaps the most important characteristic. The AEM offers more advantages over numerical methods; it allows scale independence, high degree of accuracy, and flexibility.

This study demonstrates that Visual AEM can be applied to study regional groundwater flow and provide solutions for the existing scale issues by adopting model calibration parameters to obtain a satisfactory representation of the groundwater system. Thus, the overall conclusion is that the AEM model is proficient in representing catchment scale processes that South Africa generally experience. By applying the AEM to a groundwater Reserve determination, a better estimation achieved through the modelling of non-uniform recharge and aquifer parameters. Both case studies showed a decline in estimated frim yield from AEM (62% and 52%) when compared to the existing AFYM.

I would recommend that further revisions should include a detailed description of the conceptual model development for the site, which will be used in the conventional and AEM RDM processes. This will also help in comparing, because both methods of analysis will start with a common base. For the AEM, it is quite important to set up a time frame, by the means of how long the model will be run for until the results would be applicable for the reserve. This timeframe is quite important, because a conventional RDM is more a snapshot of time and considers steady state conditions almost.

The implementation of the standard methodology for classification and Reserve determination to groundwater resources often results in undesirable outcomes and is one of the inhibiting factors for sustainable groundwater development, as some of the aspects and current methods are not applicable to groundwater and not appropriate for implementation.

Different types of models exist to describe the fate of groundwater flow. Some models describe exact solutions to equations that describe very simple groundwater flow models (analytical model) and others may be approximations of equations that describe very complex conditions (numerical models). Both models may also simulate one or more processes that govern groundwater flow rather than all of the flow processes. Whether it is a complex numerical model or a simple analytical model, both have the applicability and usefulness in hydrogeological investigations.

Analytical models are best used for initial site assessments where a high degree of accuracy is not needed, designing data collection plans prior to beginning field activities, an independent check of numerical model simulation results or where field conditions support the simplifying assumptions embedded in the analytical models.

In conclusion, there seems to be no clear answer between using the analytical element model and using the numerical model whereas similar data sets are needed for both types of models and the calibration is similar. One of the explanations suggest that analytical methods give exact solutions while numerical methods give approximate solutions. Another explanation suggests that the difference is that an analytical method gives a solution in the form of symbols i.e. closed form solution. A numerical method gives solution at certain points only. Analytical models offer an inexpensive way to evaluate the physical characteristics of a ground-water system. Such models enable investigators to conduct a rapid preliminary analysis of ground-water flow. A number of simplifying assumptions regarding the ground-water system are necessary to obtain an analytical solution. Although these assumptions do not necessarily dictate that analytical models cannot be used in “real-life” situations, they do require sound professional judgment and experience in their application to field situations. Nonetheless, it is also true that in many field situations few data are available; hence, complex numerical models are often of limited use. When sufficient data have been collected, however, numerical models may be used for predictive evaluation and decision assessment. This can be done during the later phase of the study. Analytical models should be viewed as a useful complement to numerical models. The ingenuity and elegance of classical analytic solutions to groundwater flow are largely replaced by the versatility of numerical algorithms and the computational power of the digital computer. However, in a number of case studies, an analytical model is adequate enough and a numerical model only lead to overkill. The advantage of analytical methods is that they can give a quick insight in the sensitivity of the solution for various physical parameters (such as transmissivity, storativity). Moreover, they can serve as verification of solutions of more complex systems obtained by numerical methods. During the early phase of a ground-water study, analytical models offer an inexpensive way to evaluate the physical characteristics of a ground-water system. Such models enable investigators to conduct a rapid preliminary analysis of a ground-water analysis. Nonetheless, it is also true that in many field situations few data are available; hence, complex numerical models are often of limited use. When sufficient data have been collected, however, numerical models may be used for predictive evaluation and decision assessment. This can be done during the later phase of the study.

Finally, models can also be distinguished on the basis of the reason for their application, varying from policy analytical (rough and broad) to scientific research models (detailed and narrow). In fact, it is not always possible to clearly distinguish between these fields. An analytical approach is seldom possible, but is certainly very preferable to any other method when it is possible. Independent variation of factors is simple to carry out but ignores the interaction between factors (co-variance).

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APPENDIX A

Chloride method

The Chloride Mass Balance (CMB) method was established on the assumption of conservation of mass amongst the chloride flux in the subsurface and the input of atmospheric chloride assuming steady state conditions (Xu & Maclear, 2003).

The CMB can be validated with respect to conditions that typically occur in South Africa, where it is discussed based on known and model generated cases. The excel Recharge Estimation Model in Excel includes this method (Van Tonder & Xu, 2000). This method estimates recharge value is the effective recharge. The method is based on the following assumptions:

- The only source of chloride in the soil water is from precipitation.
- The chloride is conservative in the system.
- A steady state condition is maintained with regard to long-term precipitation and its chloride concentration.
- It is a downward vertical flow of soil moisture (i.e. a piston flow regime).

The general equation to calculate the recharge is:

$R = (Cl_p / Cl_{gw}) * P$

Where:
R = Average annual recharge (mm/a)
P = 684 mm = mean annual precipitation (mm/a)
Clp =1.36 mg/l = chloride in rain (mg/l) obtained from (Bredenkamp *et al*., 1995)

The harmonic mean for the chloride concentration in groundwater is 14.6 mg/l based on chloride concentrations obtained from NGA, (2015) data.

Therefore: R = (1.36 mg/l x 684 mm)/ 14.6 mg/l

= 63 mm/a average annual recharge

Percentage Recharge = 100 x average annual recharge (mm) / average annual rainfall (mm)

= 100 x 63 mm/684 mm

= 9.3 %

Saturated Volume Fluctuation (SVF) - Method

Van Tonder and Xu, (2000) state that the Saturated Volume Fluctuation (SVF) method integrates a lumped parameter approach. This means that the prominence of the aquifer, which is based on water level fluctuations, is united so that its variation over time can be analysed. Using interpolation, a saturated volume status for the complete aquifer is produced by the piezometric levels of observation boreholes. The SVF-method is based on a classical hydrogeological water balance equation for an aquifer with an impermeable base such as:

$I – O + R – Q = S\Delta V$

Where:
I = Mean lateral inflow to the system
O = Mean lateral outflow to the system
R = Groundwater recharge (unknown)
Q = Net discharge or abstraction
ΔV = Change in saturated volume of the aquifer
S = Specific yield/effective porosity (unknown)

A recharge spreadsheet uses the SVF-method to simulate the above parameters automatically when adjusting the parameters such as storativity and recharge. The rainfall and average time water levels from boreholes are used to find the best-fit model to give rise to an indication of what the recharge and specific storage is. Data from 1987 to 1998 and 2004 to 2015 respectively, is used since corresponding water level and rainfall data is limited. Table C1 summarises the results to justify the recharge and specific yield used in the model calibration:

Table C1: Summary of SVF results.

Boreholes	Year	%Re	S
1	1987	6,1	0,007118
2	1988	6,2	0,007344
3	1989a	5,9	0,014422

4	1989b	6,6	0,011648
5	1990	6,1	0,013491
6	1991	6	0,010176
7	1992	7,2	0,020146
8	1993	6,8	0,028753
9	1994	6,5	0,024076
10	1995	6,1	0,036861
11	1997	6,7	0,03093
12	1998	6	0,013612
13	2004	6	0,01143
14	2005	6,4	0,063692
15	2006a	6	0,021392
16	2006	7	0,014398
17	2007	6	0,063146
18	2009	6	0,032038
19	2010	6	0,031753
20	2011	6	0,028361
21	2013	6,1	0,089476
22	2014	6	0,072007
23	2015	6	0,055184
Average		6,241666667	0,02977

An average recharge, based on the SVF-method, is 6.2 % with a storativity of 0.03. The input values for recharge and storativity during model calibration is 6.3 % and 0.0123 respectively for optimal calibration purposes.

This method can be applied to an area with a number of boreholes as well as a single borehole where time water level data is available. It is: however, regarded as a key issue that water level fluctuation data is regarded as representative for the aquifer as a whole when applying the SVF method (Parsons, 2014).

Distance to sea method- Aquiworx (2017)

The recharge is calculated using the distance to sea method in Aquiworx (2017); this method requires the distance from the catchment to the sea as well as the average chloride concentration in groundwater, as provided by the NGA, (2015). The distance to sea method estimates the concentration of chloride in rainfall. A higher concentration (mg/l) chloride is present closer to the sea and vice versa.

The distance from catchment C22C to the nearest sea water body is calculated as 375.5 km, an average chloride concentration in the groundwater is calculated as 29 mg/l and the standard concentration of chloride in rainfall is 1 mg/l if no chemical data for rainfall is available to substitute into the equation. Aquiworx (2017) calculated the recharge to be 3.45 %.

Harvest Potential (HP)

The HP is derived from an evaluation of the average annual recharge which gives an indication of the maximum volume of groundwater that can be abstracted without exhausting the aquifer. The Harvest Potential for the study area was determined by using the groundwater Harvest Potential Map (DWA, 2011). The quaternary catchment is pined on the map and from there the harvest potential is calculated.

Recharge (mm/a)	**25,00**
% Recharge	**3,65**
HP from Map[m3/km2/a]=	25000

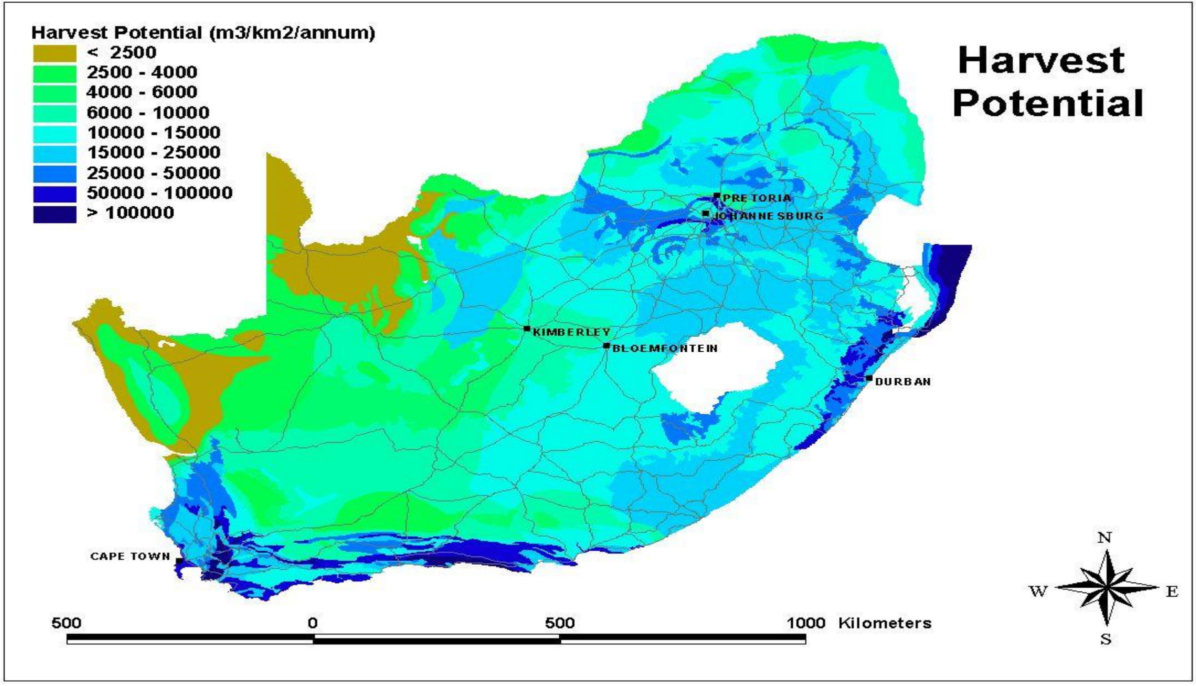

Figure 1: Groundwater Harvest Potential Map (DWA, 2011).

References

Xu, Y. & Maclear, L.G.A. 2003. Recharge Estimation in Fractured Rock Aquifer from Rainfall – Spring Flow Comparisons: The Uitenhage Spring Case. (*In* Xu, Y. &

Beekman, H.E., *ed.* Groundwater recharge estimation in Southern Africa. UNESCO Paris: Cape Town. p. 128.

APPENDIX B

Calculations for the Chloride method

General equation: $R = ((Cl_p \times P + P \times D)/Cl_{gw})$

Where:
R = Average annual recharge (mm/a)
P = *716 mm* = mean annual precipitation (mm/a)
D =0*.8 mg/l* = dry chloride deposition (mg/l)
Clp =*2.42 mg/l* = chloride in rain (mg/l)

The harmonic mean refers to the chloride concentration in groundwater; Eriksson (1985), gives the following equation:

$$Cl_{\mathrm{gw}} = \frac{N}{\sum_{i=1}^{N} \frac{1}{Cigw}}$$

Where:
Cigw = individual chloride concentrations
N = Total number of observations

Thus, the harmonic mean for the chloride concentration in groundwater is 36.14 mg/l based on chloride concentrations obtained from NGA data.

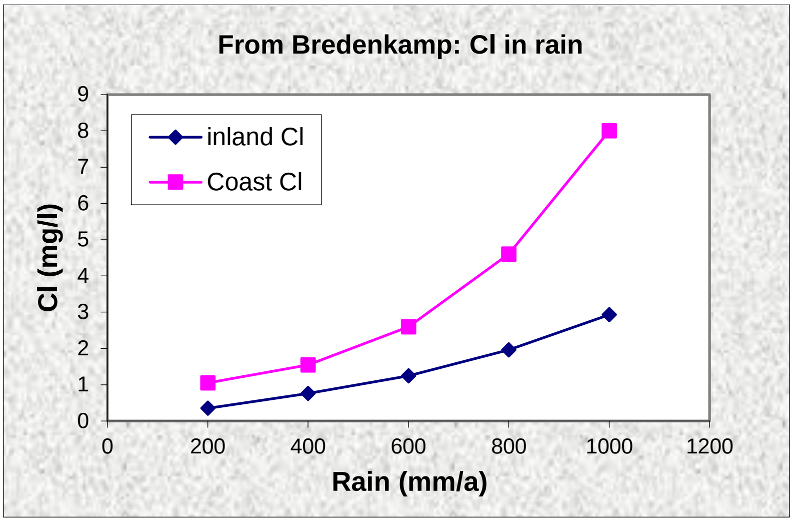

Figure 1: Inland and coastal chloride concentrations according to rainfall (Bredenkamp *et al*., 1995).

Thus; R = (2.42mg/l x 716mm + 716 mm x 0.8)/ 36.14 mg/l

= 63.8 mm/a Average annual recharge

Percentage Recharge = 100 x Average annual recharge (mm) / Average annual rainfall (mm)

= 100 x 63.8 mm/716 mm

= 9.6 %

Distance to sea method

The recharge is calculated using the distance to sea method in Aquiworx (2017); this method requires the distance from the catchment to the sea as well as the average chloride concentration in groundwater, as provided by the NGA, (2015). The distance to sea method estimates the concentration of chloride in rainfall. A higher concentration (mg/l) chloride is present closer to the sea and vice versa.

These estimated rainfall concentrations range from 5.82 mg/l on the coast line (~1 km from the sea) to 2.89 mg/l on the farthest side of the catchment (~50 km from the sea) from the coast line since the catchment borders with the sea line. An average rainfall concentration is then calculated to be 4.36 mg/l that represents the whole catchment.

An average chloride concentration in the groundwater is calculated as 36.14 mg/l and the standard concentration in rainfall is 1 mg/l if no chemical data for rainfall is available to substitute into the equation. Aquiworx (2017) calculated the recharge to be 12.06 %.

Qualified guesses

Using REME, the following groundwater recharge percentages were calculated:

Table 1: Summary of recharge estimations using REME.

Method	**Recharge (%)**
Vegter, (1995)	10.2
ACRU Recharge	7.31
Harvest Potential Map	10.2
Groundwater component of river baseflow	7.3 (minimum recharge)
Average	8.8