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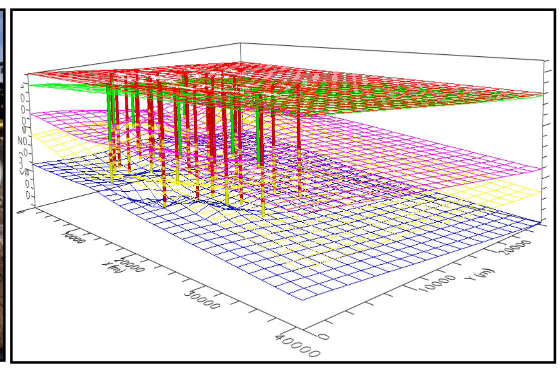
Department of Civil Engineering

Impact of Pumping on Groundwater Resources- An Assessment through steady state modelling: Orapa Wellfield 7, Central Botswana



Keneilwe Mogami

MSc. in IWRM

December 2013

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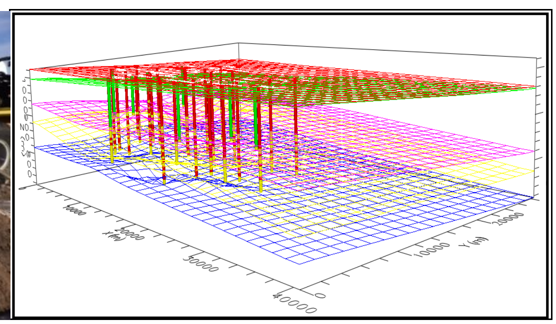

By

Keneilwe Mogami
R128735N

Supervisors: Dr. Richard Owen
Professor B.F. Alemaw

A thesis submitted in partial fulfillment of the requirements for the degree of Masters of Science in Integrated Water Resources Management of the University of Zimbabwe

December 2013

I declare that this research report is my own work and references have been made where ideas have been borrowed from other sources. It is being submitted for the degree of Master of Science in IWRM at the University of Zimbabwe and it has never been submitted for any award, in any university before.

Keneilwe Mogami

Signature:é é é ....

Date:..

This thesis is dedicated to my mother Priscilla E. Mogami. Thank you for always being there for me.

I can do all things through Him who gives me strength: thanks be to God for seeing me through completion of this thesis.

I would like to thank my sponsor, Waternet, and the University of Zimbabwe, Department of Civil Engineering, for making it possible for me to pursue this masters program.

Special thanks goes to Debswana; for allowing me to do work in their wellfield, and Water Surveys Botswana (WSB); for granting me leave of absence to pursue my studies and availing all the facilities and resources that I required for the thesis.

My sincere gratitude goes to my supervisors, Dr Richard Owen and Professor Alemaw, for their academic advices. Your guidance and support is highly appreciated. I especially thank Dr Owen for hand walking me throughout the model build up; your guidance and knowledge remain invaluable to me.

I also want to appreciate all my classmates. Thank you for all the support you gave me during this time, you made all the late nights bearable.

Last and definitely not least, I owe a special gratitude to my family, my mum, my brother, my sister and my daughter, for always being there for me. You guys are the best.

To all those I have not mentioned by name, this does not diminish your help in anyway. Your support and help is highly appreciated.

Debswana Diamond Company, Orapa Letlhakane Damtshaa Mines (OLDM), undertook development works for a new wellfield, Wellfield 7 in 2012/2013. The primary objective was to establish the new wellfield to supply an additional $3Mm^3$/annum of water for the minesô operations, for a 20 year period starting 2014. Abstraction from the wellfield has the potential to have significant impacts on the already existing groundwater resources around the area and thus it is important and necessary that the potential impacts are thoroughly evaluated and addressed. This research used a numerical groundwater model to simulate and predict the potential impact the large scale abstraction from Wellfield 7 will have on the aquifer and estimated the aquifer drawdown expected over the entire abstraction period.

Primary and secondary data on geology, hydrogeology and geophysics were integrated to develop a conceptual model of the area. Visual MODFLOW Pro 4.3 was then used to model the aquifer system under steady state conditions. The parameters assigned to the model were derived from previous studies and pumping tests and they were then adjusted during model calibration. The model was calibrated under non-pumping scenario to static water levels.

Overall, model results compared with the observed data, with the model being able to simulate observed field values to a 66% correlation coefficient and heads departing from the mean by 12m. The model results show that a daily abstraction of $8040m^3$ from the wellfield will result in a drawdown of up to 30m at the end of the 20 year pumping period. This is about 50% of the total available drawdown.

Although the model is accurate and reasonable, the limitations of the model should be taken into consideration before it is applied as a management tool. This is because of, among other things, uncertainties arising from the assumptions made to simplify the complex aquifer system.

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AAC	Anglo American Corporation
CRT	Constant Rate Test
CSO	Central Statistics Office
DGS	Department of Geological Survey
DWA	Department of Water Affairs
EIA	Environmental Impact Assessment
EPM	Equivalent Porous Medium
GAA	Golder Associates Africa
GHB	General Head Boundary
GPS	Geographical Positioning System
MAE	Mean Absolute Error
mamsl	meters above mean sea level
mbgl	meters below ground level
ME	Mean Error
OLDM	Orapa, Letlhakane and Damtshaa Mines
RMSE	Root Mean Square Error
RWL	Rest Water Level
SRK	Steffen Robertson and Kirsten

USGS	United States Geological Surveys
WF7	Wellfield 7
WSB	Water Surveys Botswana
SWS	Schlumberger Water Service

1.1. Research Background

Groundwater is a term used to define water that occurs beneath the earthôs surface, between the soils and geologic formations that are fully saturated (Freeze and Cherry, 1979). It is a vital natural resource, especially in arid and semi arid areas where surface waters are scarce and seasonal. Many people in these areas depend mainly on groundwater for water supplies to meet the rapidly expanding urban, industrial and agricultural water requirements (Morris et al., 2003). To match this requirement in the demand of water, existing water resources have to be constantly developed and new water sources have to be found, all available water resources must be mobilized, especially groundwater. Also, because of the uneven distribution of surface water resources, both spatial and temporal, there has been an increased need in the development of groundwater resources. Groundwater studies are undertaken to assess the resource quantity and/or quality.

As is in many semi-arid regions, groundwater resources play an important role in economic and social development of Botswana as water supply is largely from groundwater (Nicol, 2002). The country relies mainly on groundwater because of the poor and unreliable rainfall, and lack of surface water sources. Of the total amount of water consumed in Botswana, 66% is from groundwater with mining using 60% of all abstractions (Noble et al., 2002, CSO, 2009). This dependency in groundwater has led to an overdraft as abstraction is viewed to be greater than recharge (Kgathi, 1999).

Planning and management of the groundwater resources requires a tool to predict the response of the aquifer to the planned activities (Bear and Verruijt, 1987). Groundwater models are some of the tools widely used by hydrogeologists, hydrologists, engineers and water resources specialists for analyzing groundwater resources impacts. Numerical groundwater models have been deemed the best tool for groundwater management particularly in predictive modelling (Scanlon et al., 2003). Some groundwater models, with the water quality aspect, try to predict the fate and movement of chemicals in the aquifer for els, simulation models, attempt to predict the effects of ndwater abstraction, on the behaviour of the aquifer (Brassington, 1998).

The groundwater models make use of some mathematical equations (Brassington, 1998) and the utilization of a model depends on how closely the mathematical equations approximate the physical system being modelled, essentially describing the groundwater flow system as well as the water balance of the aquifer (Kumar, 2013). One, therefore, needs to have a thorough understanding of the physical system and the assumptions applied when deriving the mathematical equations. These assumptions generally involve; direction of groundwater flow, geometry of the aquifer, heterogeneity or anisotropy of the sediments or bedrock within the aquifer and contaminant transport mechanisms and chemical reactions.

To evaluate the applicability or utilization of a model, there are 4 major factors that determine selection of an appropriate model;

1. Objective(s) of the investigation
2. Available resources (time, budget, skilled manpower, computers and codes)
3. Available field data
4. Legal and regulatory framework applying to the situation

1.2. Problem Statement

Orapa, Letlhakane and Damtshaa Mines (OLDM) began operation in 1969. The mines relied on both groundwater from the wellfields and surface water from Mopipi dam until 1984 when the dam dried up, after which the only source of water was groundwater. This led to development of more wellfields in the Orapa area in search for more water to supply to the mines. Over the years a total of 9 wellfields have been developed, the latest being Wellfield 7 (WF7).

gan in 2012. The primary objective was to establish the al $3Mm^3$/annum of water for OLDM operations. This additional water supply requirement was caused by decommissioning of old boreholes in other wellfields and commissioning of new slimes dams, which led to decrease in recycled water. Work initially commenced in 2008, but was suspended due to economic downturn in 2008/2009 (WSB, 2013a). About 40 boreholes were drilled in total, 11 drilled in 2007 and 29 drilled in 2012/2013. This wellfield is planned to start production in 2014 and run for a period of 20 years.

Abstraction from the wellfield has the potential to have significant impacts on the already existing groundwater resources around the area and thus it is important and necessary that the potential impacts are thoroughly evaluated and addressed. Potential impacts, among others, include: alteration of groundwater flow thereby affecting regional water supply; increase in salinity of the groundwater due to salt water intrusion; and decline in water table which may lead to drying of surface water sources. This research proposes to use a numerical groundwater model to simulate and predict the potential impact the large scale abstraction from WF7 will have on the aquifer and estimate the aquifer drawdown expected over the entire abstraction period.

1.3. Objectives

1.3.1 General Objective

The main objective is to construct a predictive numerical groundwater model to simulate the impact pumping from WF7 will have on the aquifer drawdown.

1.3.2 Specific Objectives

The specific objectives are:

del of the aquifer system based on ground observations ysis.

2. To set up and calibrate a numerical groundwater flow model of the aquifer system.
3. To develop a scenario illustrating the effect of pumping from WF7 on the aquifer drawdown.

1.4. Research Questions

The questions expected to be answered from this study are as follows:

1. What are the aquifer characteristics?
2. Can the model accurately simulate the aquifer and its response to the groundwater abstraction
3. How much drawdown is expected in the aquifer at the end of the abstraction period?

1.5 Scope of Work

Previous groundwater modelling studies carried out in this area were at a regional scale. This study narrowed it down, covering only WF7 area and thus using only the borehole data from WF7. The study entailed gathering and compiling hydrogeological data to develop a conceptual model for WF7 groundwater flow system, and then developing and calibrating a 3-D steady state numerical model of the area based on the conceptual model.

1.6 Structure of the Thesis

The thesis is organized into nine (9) chapters: **Chapter 1** is on the introduction of the research; stating the problem and why the research is important. The research objectives, the questions that the study is attempting to answer, as well as the scope of the study are outlined in this chapter. **Chapter 2** is on review of literature on previous studies done in the area. The principles of groundwater modelling are also discussed in this chapter, with particular focus

MODFLOW, as they are used in the study. In **Chapter** udy area is given; in relation to the location, climate, geology, hydrogeology and structures of the area. Materials and methods employed to undertake the study are discussed in **Chapter 4**. **Chapter 5** is on data processing and analysis where the field data is synthesized and prepared into model input. **Chapter 6** is on the development of conceptual model of the area, by defining and characterizing the aquifer. The numerical model is in **Chapter 7**. Code selection, model design, calibration and sensitivity analysis are all discussed in this chapter. **Chapter 8** is on presentation and discussion of the modelling results. Limitations of the model are also discussed here. Conclusions on the study, on the basis of analysis of the result, are stated in **Chapter 9**. Issues that cannot be addressed are outlined and recommendations are indicated in this chapter.

2.1 Previous work

There have been numerous hydrogeological and groundwater modelling studies conducted in the Orapa area in the past with purpose to quantify the groundwater resource and determine its sustainability.

Most of the modelling studies were done at a regional scale. The first regional modelling exercise was a 2 dimensional finite difference model constructed in 1984 by Dames and More Consulting Engineers. This model could not produce results that compared with the field observations so it was rejected. Since then up to about 2001, several regional groundwater models with satisfactory results were constructed. After Mopipi Dam dried up in 1985 and surface water was no longer available, more boreholes were drilled at Wellfield 5. SRK Constructed a short term model in 1986, to ascertain the wellfield performance incorporating data from the new boreholes. In 1988 and 1989, SRK also constructed simplistic short term models to predict and verify location of wells in Wellfield 6 (AAC, 1990).

The first long term model was constructed in 1990. This single layer system, modelled in MODFLOW, assessed the water supply outlook for the following 20 years. It reviewed borehole yields and recommended sustainable yields for the existing boreholes and proposed 57 new ones (AAC, 1991). The 1990 model was upgraded in 1991 with 2 layers model, and the results compared with the previous model, ascertaining that there is enough water in the aquifer to supply Orapa for the next 20 years. Although the results compared, this model recommended 6 additional boreholes instead (AAC, 1991).

Another model, a 2-D finite element model was constructed in 1995 using AQUA package. The aquifer was modelled to establish optimal abstraction rates for a 20 year period while meeting demand. Risk analysis was performed to verify the current systems ability to achieve required wellfield abstraction quantities and dewatering requirements. An updated model was done in 2000 to assess the hydrogeological regime around the mine area. This model

the mines provided wellfield abstraction and dewatering
rehole were recommended (AAC, 2002).

After 2001, a number of important changes occurred around the area including among others: dewatering at OLDM, development of AK6 mine, expansion of Wellfield 6 & Letlhakane village wellfields and development of Boteti villages Wellfield. In 2004/2005, a revision of the 2001 regional model was undertaken to incorporate some of these features as they became available. It became apparent then that the new data led to an overly complex finite element structure and divergence between the original model and new data (WSB, 2008).

(WSB, 2006) carried out development works at WF7 area with the objective to drill and test exploration boreholes in the designated WF7 area as well as provide a higher confidence level in the aquifers hydraulic parameters for inclusion in to the simulated Greater Orapa groundwater model. Although, the borehole development works were suspended until 2012, a decision was made, in 2007, to reconstruct the regional model using the most recent data so as to minimise the divergences between the model and the physical world.

In 2008, WSB conducted the Greater Orapa regional groundwater modelling assessment, where the regional model was reconstructed using the best available data to 2007. Hypothetical boreholes at WF7 and AK6 were included in the updated model and various future wellfield development scenarios were run to aid future management of the groundwater resources in the area (WSB, 2008).

The most important finding about the regional models in general is that despite the early models and the current rebuild being different in construction and parameters, they give broadly the same results. Figure 2.1 shows area covered by the regional models.

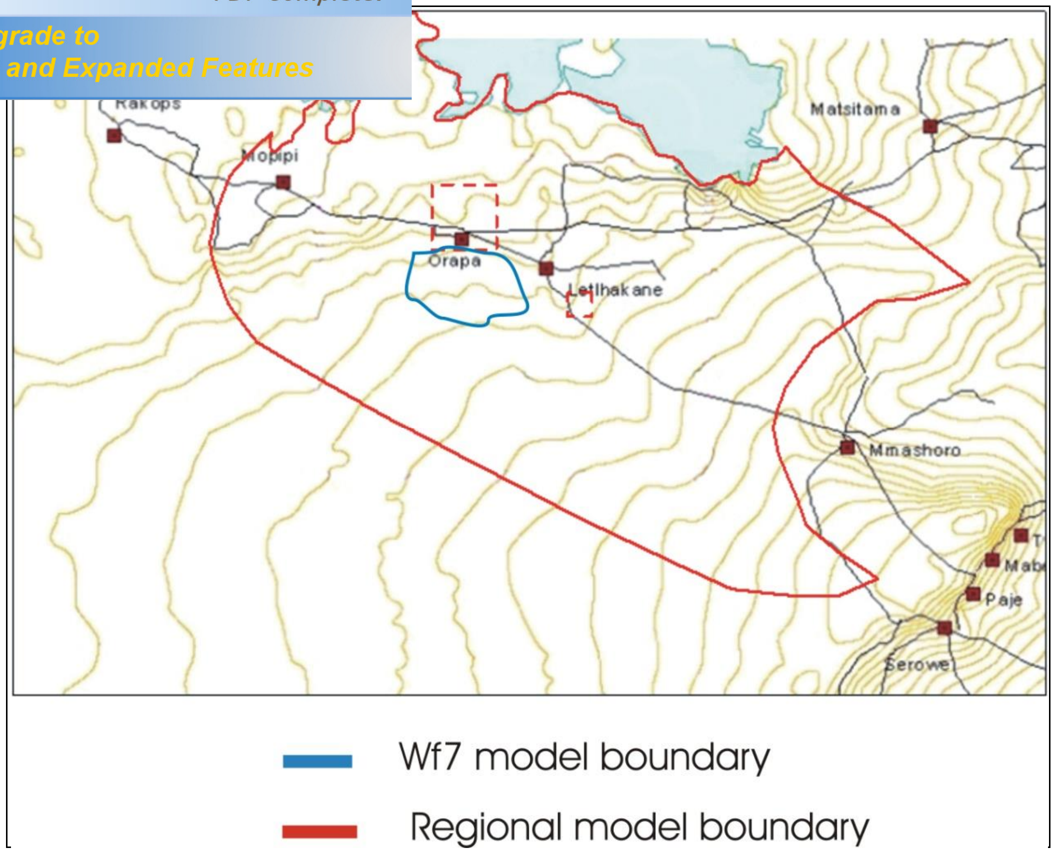

Figure 2.1: Area covered by the regional models (WSB, 2013)

2.2 Groundwater Modelling

Groundwater models are computer models of groundwater flow systems, used to simulate and predict aquifer conditions (Anderson and Wang, 1982), mainly in the fields of groundwater quantity and quality. Quantitative modelling is only focused in flow and movement of the water, based on the equation of motion and continuity of mass equation and combined to give the groundwater flow equation (Anderson and Woessner, 1992). In qualitative analysis there is a component of contaminant transport.

There are various methods used to solve the partial differential equations describing the behaviour of groundwater flow system, with the finite difference, finite element and analytical element method being the most popular ones (Kahsay, 2008). Finite difference method was the first method to be used for the systematic numerical solution of partial

any numerical models of groundwater flow use finite-
erning partial differential flow equation (Kahsay, 2008) (Mehl and Hill, 2002).

According to (Anderson and Woessner, 1992), the basic governing equation used in groundwater modelling studies is as follows:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - W = S_s \frac{\partial h}{\partial t} \qquad (1)$$

For steady state the equation reduces to:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - W = 0 \qquad (2)$$

Where:

h = Potentiometric head (L)
W = Volumetric flux per unit volume and represents sources and/or sinks (T^{-1})
Ss = Specific storage of porous material (L^{-1})
t = Time (T)
kx, ky and kz = hydraulic conductivities along x, y and z coordinates.

The solution to the equation is controlled by boundary conditions which are mathematical statements specifying the dependent variable or the derivative of the dependent variable at the boundaries of the problem domain (Anderson and Wang, 1982, Anderson and Woessner, 1992). There are three types of mathematical boundaries that can be applied and care must be taken when selecting the boundaries conditions in order not to mis-represent the modelled system:

1. Specified head boundary where head is given. When hydraulic heads in the model are higher than the fixed head, the fixed head will discharge water from the model and

model are lower than the fixed head, the fixed head will

2. Specified flow boundary where flux is known across the boundary. By specifying a zero flux, the boundary will simulate no-flow conditions (Anderson and Woessner, 1992).

3. Head-dependent flow boundary (general head boundary) where flux across the boundary is calculated given a boundary head value (Anderson and Woessner, 1992).

Several computer softwares for groundwater modeling are in use; MODFLOW, FEFLOW, GWFLOW, ParFlow, HydroGeoSphere, OpenGeoSys, etc.

2.3 MODFLOW

MODFLOW is a 3-D finite-difference groundwater model published by the US Geological survey. The first public version, MODFLOW-88, was released in 1988, followed by MODFLOW-96. These versions were originally designed to simulate saturated 3-D groundwater flow through porous media. MODFLOW-2000 attempts to incorporate the solution of multiple related equations (McDonald and Harbaugh, 2003). MODFLOW can simulate the effects of wells (pumping or injection), rivers, drains, head dependent boundaries, recharge and evapotranspiration. MODFLOW can compile and run on Microsoft Windows.

Since MODFLOW was first published various codes have been developed for simulating specific features of the hydrologic system. The different modules in MODFLOW can simulate flow in confined and confined aquifers.

2.4 Visual Modflow

Visual MODFLOW is used by professionals to model groundwater flow and contaminant transport in 3-D. It was first released in 1994 based on the USGS MODFLOW-88 and MODPATH codes (SWS, 2004). The first Windows based version was released in 1997.

andard modeling Visual MODFLOW package with Win D-Explorer to give a complete and powerful graphical modeling environment (SWS, 2004). Table 2.1 shows the different features of Visual MODFLOW. Applications include wellhead capture zone delineation, pumping well optimization, aquifer storage and recovery, groundwater remediation design, natural attenuation simulation, and saltwater intrusion (SWS, 2004).

Table 2.1: Features found in the Visual MODFLOW package (SWS, 2004)

Module	Version		
	VMOD Standard	VMOD Pro	VMOD Premium
MODFLOW 96/2000/2005	x	x	x
MODPATH	x	x	x
ZoneBudget	x	x	x
MT3DMS	x	x	x
RT3D1.0/2.5	x	x	x
PHT3D		x	x
Stream Routing	x	x	x
Multi-Node Well (MNW)		x	x
MGO		x	x
WinPEST		x	x
VMOD 3D Explorer		x	x
SEAWAT		x	x
MIKE11 Support		x	x
SAMG		x	x
GMG		x	x
EnviroBase Pro		x	x
MT3D99	add-on	add-on	x
MFSURFACT	add-on	add-on	add-on

Visual MODFLOW has easy-to-use graphical tools which allow you to:

- quickly dimension the model domain and select units,
- conveniently assign model properties and boundary conditions,
- run model simulations for flow and contaminant transport,
- calibrate the model using manual or automated techniques,
- optimize pumping and remediation well rates and locations and

D (x-section or plan view) or 3-D graphics at any point
lopment.

The interface has been specifically designed to increase modeling productivity, and decrease the complexities typically associated with building three dimensional groundwater flow and contaminant transport models (SWS, 2004).

There are three main sections in Visual MODFLOW; input section, run section and output section, all accessed from the Main Menu when a Visual MODFLOW project is started, or an existing project is opened. In the Input section model parameters are assigned graphically during model build up and are set up in order for easy build of the model. In the Run section the numeric engines are set up for different run-time options each with its own default settings. The Output section allows for various displays of modeling and calibration results.

2.5 PEST

Parameter estimation provides tools for the efficient use of data to aid in mathematical modeling, and the estimation of the constants used in these models (SWS, 2004). For the purposes of groundwater modeling, the Calibration and Predictive Analysis applications of Parameter Optimization are the most relevant:

ÅCalibration - A model is said to be calibrated when model parameters are adjusted such that the results correspond to the actual measurements taken in the field. If this is achieved, the model is believed to be able to represent the behaviour of the system in response to other disturbances.

Å Predictive Analysis - Once a parameter set has been determined for which the model behaviour matches the observed system behaviour, it is then reasonable to ask whether another parameter set exists which also results in reasonable simulation by the model of the

, an even more pertinent question is whether predictions meter set are different.

Before attempting to run a parameter estimation simulation, the model must meet the following two requirements:

1. The model runs successfully and produces meaningful results

2. The model has one or more (preferably many more) observations against which to compare the calculated results. Observations can be in the form of measured or estimated values of head or concentration at discrete points in the model, or in the form of measured or estimated groundwater fluxes into (or out of) one or more grid cells.

dy Area

3.1. Location

WF7 is located about 20km south of Orapa Lease area and about 10km north-west of Letlhakane village in Boteti sub-district of Central Botswana. It covers an area of about 358km^2. Figure 3.1 shows the location of the study area. WF7 is accessible through gravel road constructed from Letlhakane village.

3.2. Climate

The climate of the study area, as is the rest of the country, is semi-arid. It is characterized by hot wet summers and cold dry winters. The rainfall occurs from October to April, with an average of between 350 to 400 mm per annum. Summers are very hot, with average monthly maximum temperatures of 34^{0}c. Winter times are warm during the day and very cold at night and early mornings. The average minimum temperatures go as low as about 6^{0}c during these times. Potential evapotranspiration rate is high throughout the year, ranging from about 100mm/month when it is lowest in winter to about 200mm/month when it is highest in summer (Obakeng, 2007). Given such high potential rates, the potential for groundwater recharge from rainfall is very limited. Data for temperature and rainfall were taken from the Department of Metereological Services (DMS) recorded from a weather station located in Letlhakane village, about 20km from the study area and Orapa Power Station about 40km from the study area. Figure 3.2 shows annual rainfall for the stations and figure 2.3 shows the mean monthly maximum and minimum temperature as recorded from 1994 to 2010.

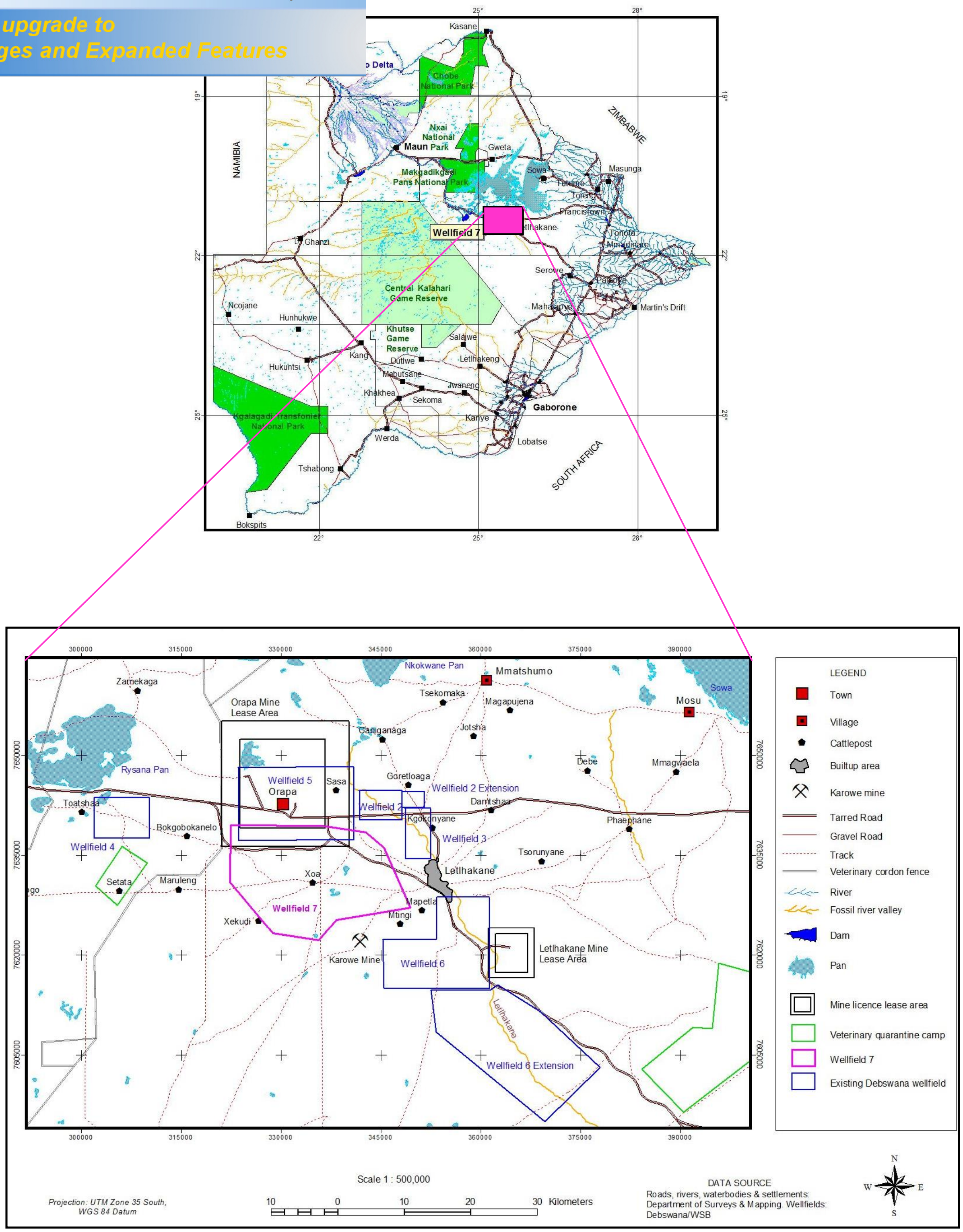

Figure 3.1: Location Map of the study area

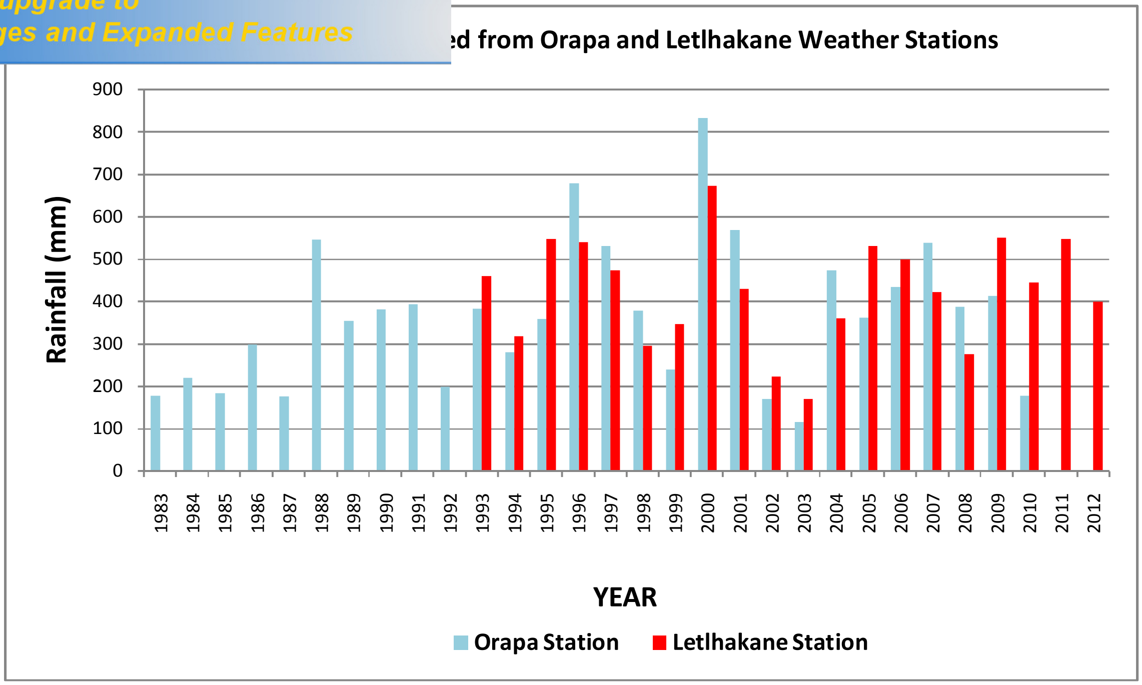

Figure 3.2: Annual rainfall for Orapa and Letlhakane area

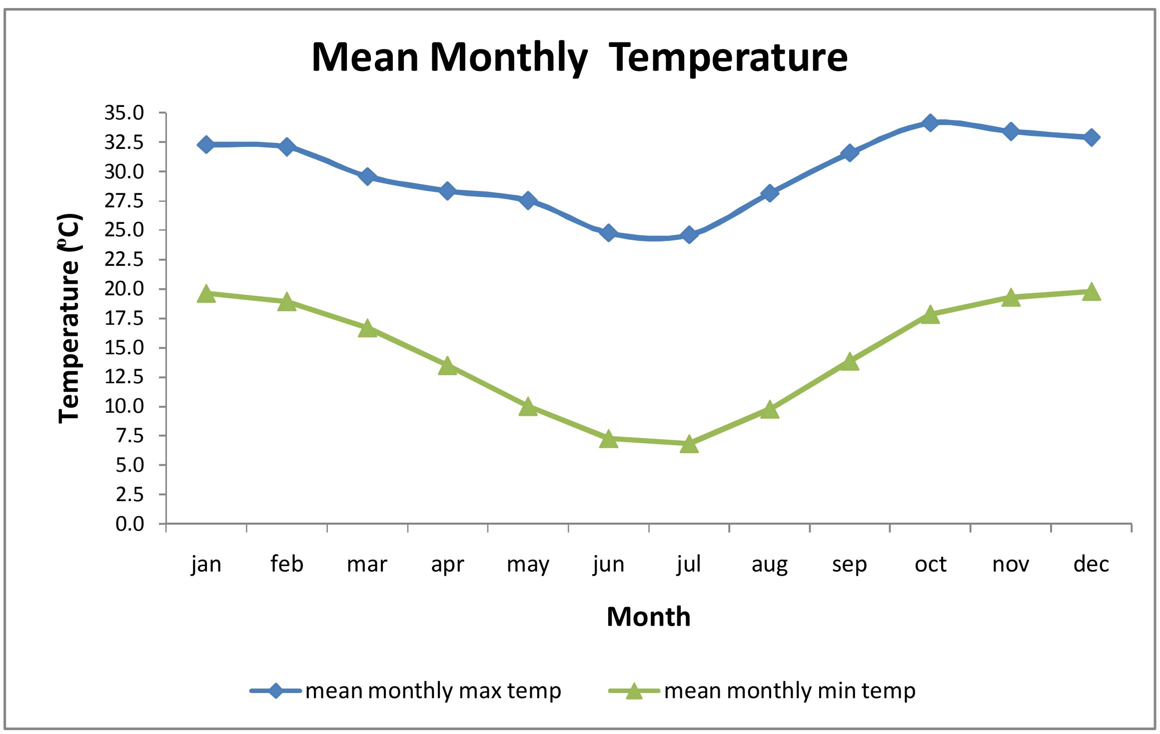

Figure 3.3: Mean monthly maximum and minimum temperatures for period 1994 to 2010

The regional geology of the area is shown in figure 2.4. Borehole information has been used to describe the lithologies in the area and the structures are inferred from aeromagnetic data and interceptions in some of boreholes drilled in the area. Drilling borehole logs show that the main stratigraphical units are Kalahari Group Sediments, Stormberg Lava Group and Karoo Supergroup. Graphic borehole logs for all the boreholes are shown in appendix 1.

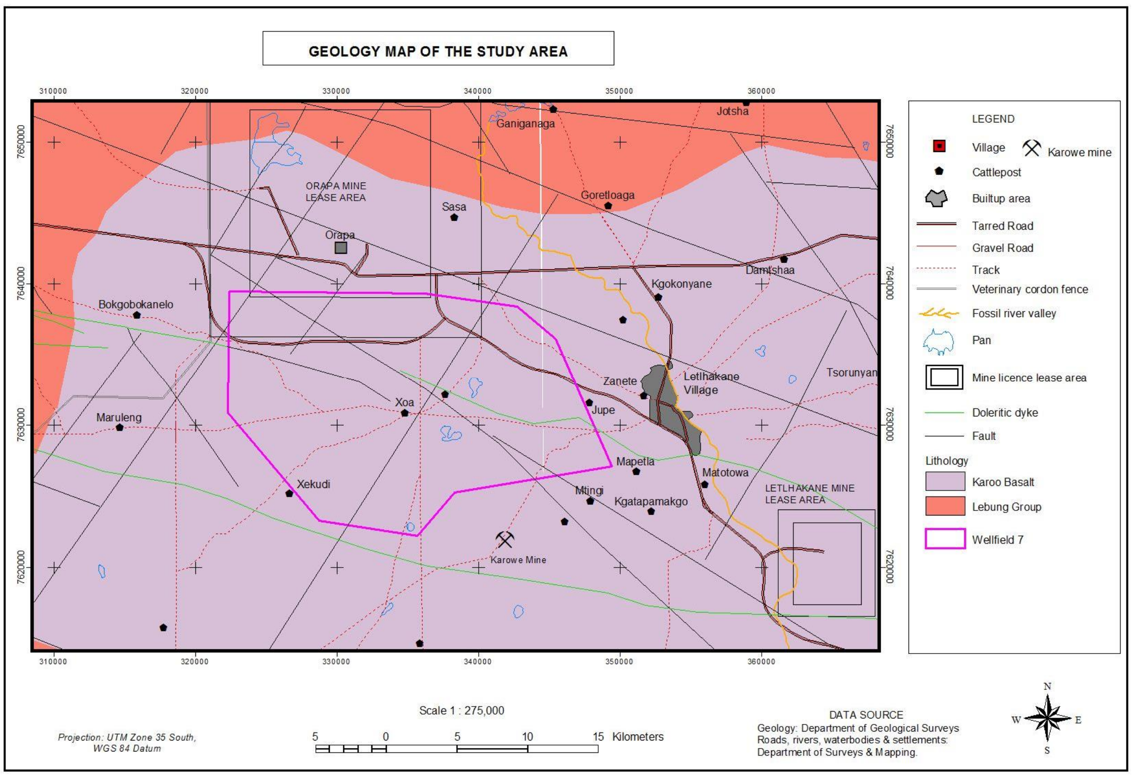

Figure 3.4: Regional Geology map of the study area

3.3.1 Kalahari Group Sediments

The youngest rocks in the area are that of the Kalahari Group Sediments. They unconformably overlie the Karoo Supergroup (Carney et al., 1994). This group is characterized by cream to whitish, fine Kalahari sands, gravels, and interlayers of pinkish e Kalahari beds have varying thicknesses, from 4m up to

3.3.2 Karoo Supergroup

Below the Kalahari beds are the poorly exposed rocks of the Karoo Supergroup, comprising of succession of sedimentary and volcanic rocks. Formations of the Karoo Supergroup include the Stormberg Lava Group, Lebung Group, Beaufort Group and Ecca Group.

3.3.2.1 Stormberg Lava Group

The uppermost unit of the Karoo Supergroup is the Stormberg Lava Group, deposited at the close of the Karoo basin deposition around the Jurassic (Carney et al., 1994). It consists of amygdaloidal basaltic lava flows, with occasional sandstone lenses. The basaltic sheets are weathered at the top and become fresh as you get to the base. They vary in colour, from greenish to purplish grey to greyish, and are intercepted as shallow as 4 mbgl and at depth at 51 mbgl. The basalt thickness varies between 12-129m averaging 92m. This group unconformably overlie the Lebung Group.

3.3.2.2 Lebung Group

Underlying the basalt are rocks of the Lebung Group with thickness range between 60-240m. The Lebung Group strata comprises of two formations, Ntane Sandstone Formation conformable on the Mosolotsane Formation (Carney et al., 1994).

3.3.2.2.1 Ntane Formation

The Ntane sandstones were formed in an arid aeolian environment (Smith, 1984). They typically comprise of pinkish to orangish to beige massive sandstones, with rounded and almost sorted fine to medium grains. The sandstones have siltstone intercalations at places as mented zones. The Ntane Formation is intercepted as hickness of 98m.

3.3.2.2.2 Mosolotsane Formation

At the base of Lebung group is Mosolotsane Formation. The Mosolotsane Formation was deposited on an erosional unconformity on top of the Tlhabala formation (Smith, 1984). It consists of intercalations of reddish siltstones, reddish to greenish mudstones and reddish to brown massive cross-bedded sandstones. The thickness of Mosolotsane varies from 6 - 119m.

3.3.2.3 Tlhabala Formation

Below Lebung are rocks equivalent to the Beaufort Group which, according to (Smith, 1984, Carney et al., 1994), were deposited in the lacustrine environments. This group is represented by Tlhabala Formation. It comprises of massive mudstones, silty and variegated at places, with calcareous layer facies and limestones. These mudstones are where most of the boreholes are terminated. Generally the boreholes were terminated about 5m into the mudstones but there are boreholes which went as deep as 19m within the Tlhabala. Summary stratigraphy of the area is given in table 3.1.

Table 3.1: Summary Stratigraphy of the Study area as modified from (Carney et al., 1994).

Age	Unit	Group	Formation	Lithology
Tertiaryï Recent 1-65 Ma	Kalahari sediments			Sand, silt, gravel, calcrete
Carboniferous ï Jurassic 65-205 Ma	Karoo sequence	Dolerite Dykes		dolerite dykes
		Stormberg Lavas		Basaltic lavas
		Lebung Group	Ntane	Sandstones, rare siltstones
			Mosolotsane	Siltstones , rare pinkish sandstones, rare mudstones, coarse sandstone
Neo Proterozoic 545-1000 Ma		Beafort Group	Tlhabala	Mudstones, silty mudstones
		Ecca group	Tlapana	Coaly mudstones with minor sandstones & siltstones
Archaen	Archaen basement		Basement Granite	Pale grey to white, fine to medium grained unfoliated granite

The study area lies in the Kheis Magondi Belt that resulted during the deformation of the Kalahari ï Zimbabwe Craton during the early Proterozoic (Carney et al., 1994). The aeromagnetic data is the best available data for the structural studies in this area as much of the area is covered by the Kalahari sands. Faults have been interpreted from the aeromagnetic data, running generally SE-NW and SW-NE across the area with a dominant W-N-W trend. The W-N-W trending features occur in the regional structural trend and there are horst and graben structures formed due to the deformation associated with this trend (Carney et al., 1994). This is where WF7 is developed.

Late to post Karoo period dolerite dykes were intruded along a number of the faults, particularly into those with a W-N-W trend. These probably control groundwater locally or regionally by acting as dams throughout the full thickness of the aquifer (WSB, 2013b).

3.5 Hydrogeology

The main aquifer is the Lebung aquifer comprising of the Ntane Formation overlying the Mosolotsane Formation. The Ntane seems to be in more or less continuous contact, producing a continuous aquifer across the whole formation (WSB, 2013a). Borehole yields in Ntane sandstone vary between 0.3 and 100 m^3/hr. WF7 is located, generally, where the thickest Ntane formation occurs and the borehole yields tend to correlate with the thickness of Ntane sandstone. The thicker the sandstone unit the higher the yield and the thinner the sandstone unit the lower the yield (WSB, 2008). Although significant yields have been recorded at depth, the general trend is that borehole yields decrease with depth of the sandstone unit. Water quality has also been observed to follow the same trend, deteriorating with depth of Ntane (WSB, 2013b). The hydraulic conductivity is typically 0.1 to 0.3m/day with a transmissivity of between 5 and 20m^2/day but with local variations as high as 150m^2/day. From previous modelling studies, the aquifer has an effective specific yield of around 0.001 and a specific storage of around $5x10^{-5}m^{-1}$ (WSB, 2013a).

contain significant amounts of water, with yields of ...er coarse and sugary sandstone of this unit has proven to be an important aquifer. The water quality is extremely saline ranging between 8000mg/l and 18500mg/l. The hydraulic conductivity in the sandstone varies between 1 x 10^{-2} m/day and 0.5m/day. The red mudstone lenses marking the base of Mosolotsane forms an impervious layer inhibiting vertical flow to the units below. A zone of enhanced horizontal conductivity is developed between the mudstone layer and the sandstone above.

ods

The methods used in the research process were based on the objectives formulated above and general model development procedure. Table 4.1 summarizes the methods used in the research study.

Table 4.1: Summary of methods to be used in the research process

Stage	Activity	Data requirements
Desk top study	collect relevant secondary data	·Meteorological ·GW level ·Pumping tests ·Lithological and Geophysical logs ·Geological maps & cross sections ·Topographic maps
	Review of previous works on the area	·Hydrogeology and Geology reports ·Research papers / thesis ·Consultant works ·Journal articles
Data collection	Collect relevant primary data	·Groundtruth observations ·Water level measurements ·GPS coordinates
Data processing & Analysis	Data collected processed to fit into model (aquifer characterization & conceptual model)	·Layers ·Aquifer parameters (K,T) ·Aquifer thickness ·Boundary conditions ·Recharge ·Aquifer confined or unconfined
	Run the model ï achieve model convergence (model calibration and convergence)	·Calibration ·Predictive runs

The study was carried out in three phases; desktop study, data collection and then data processing and analysis phases. The activities carried out in each phase, as well as the sources of information and materials used are presented here.

4.1 Desktop Study

This was at the preliminary stage of the study where a desk top survey was done in preparation for the field work. At this stage, literature review of previous works done in the d are topographic maps, geological maps, groundwater well completion data) as well as the different reference materials (research papers, research thesis, manuscripts, consultant work & journal articles). All available data were gathered and a database for the project created. Geological, hydrogeological and geophysical data were revised and integrated.

4.2 Data Collection

A field trip was undertaken during the months of August and September. The trip entailed survey of all WF7 boreholes, taking GPS coordinates. Water level measurements were also taken during the field trip in order to define the groundwater flow gradient. The groundtruth observations were made to validate some of the data obtained in the desktop survey; geology, stratigraphy, geomorphology and discharge areas.

4.3 Data Processing and Analysis

All data obtained in the first and second phases were processed and analyzed. These data was then synthesized to use in the development of a conceptual model as well as develop and calibrate a numerical model. Figure 4.1 shows the schematic representation of the steps taken in the research process.

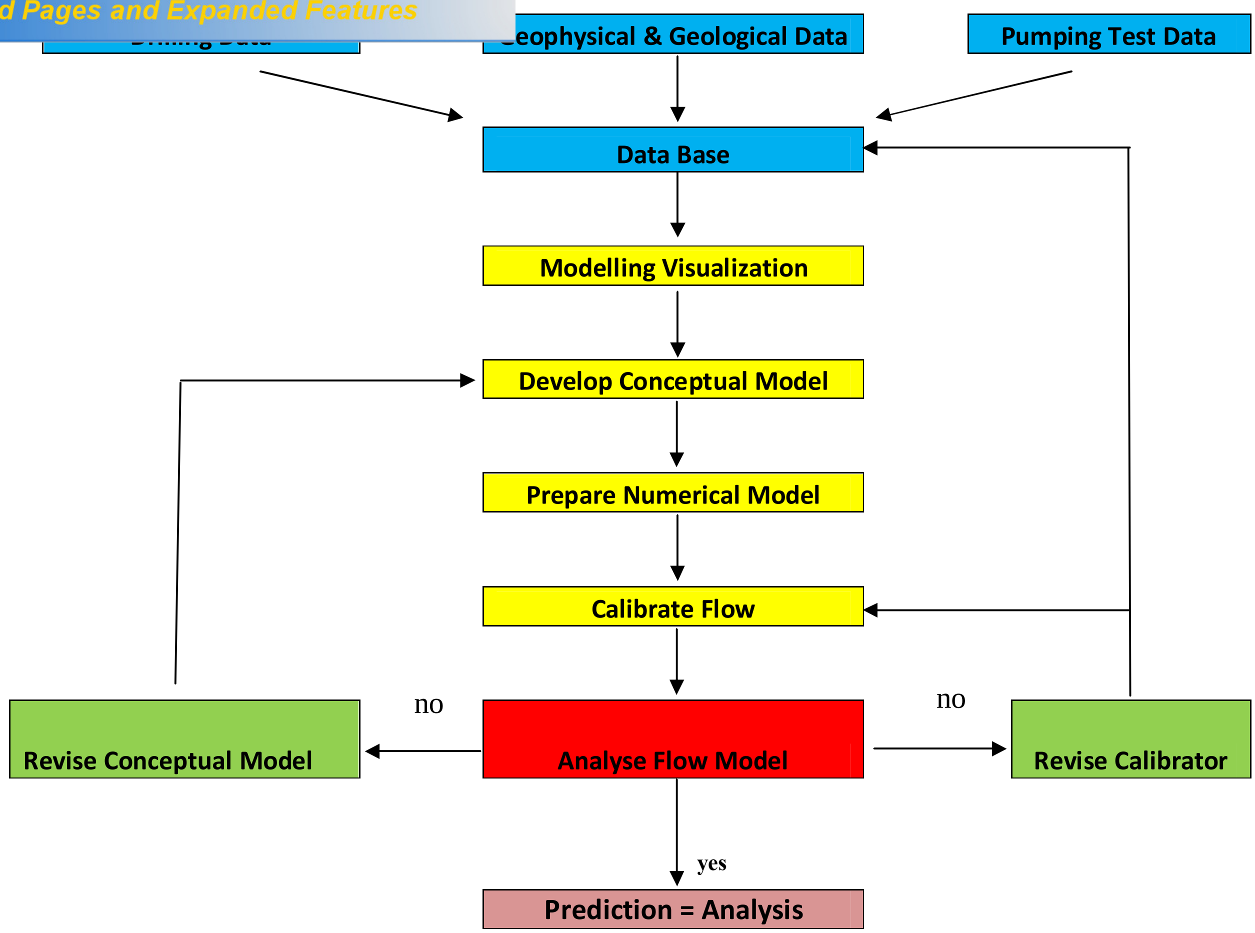

Figure 4.1: Schematic representation of the steps taken in the research process

4.4 Model Input Data Preparation

4.4.1 Recharge

Groundwater recharge can be defined in the general sense as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir (Vries and Simmer, 2002). Potential recharge estimation is important for any groundwater studies (Rushton et al., 2006). In this study area Stormberg basalt covers the Ntane sandstone in the Plan area and therefore direct recharge is unlikely to occur. This was, among others concluded by the Swedish geological AB from the isotope study in the Serowe Area (DGS, S values along the Letlhakane River corresponding fault eakage to the aquifer from the overlying basalt (DWA, 1993).

Generally, recharge rates in the area of study obtained during previous modelling exercises are in the range between 0.3 and 1 mm per annum. The 2001 steady state model was calibrated with a recharge of 0.7 mm/annum. (WSB, 2008) used a recharge value of 1mm/year for the regional model and (WSB, 2013b) found the model recharge to be 0.3mm/year for the EIA modelling report. However, DWA (2005) estimated, through chloride mass balance method, the annual recharge at 2.69mm/annum.

4.4.2 Well Abstraction

At WF7, there are about 29 production wells to be operated and 11 observation and monitoring wells. All well locations are shown in figure 4.2. The pumping boreholes are distributed throughout the area. Planned abstraction rates, as estimated from pumping tests, range from 140m^3/day to 1200m^3/day and based on these planned abstraction rates the average daily abstraction from the wellfield is estimated at 8040 m^3/day. Table 4.2 show planned abstraction rate for each well.

4.4.3 Elevation

A Hand Held GPS was used to measure and to define the ground elevation of the boreholes and water levels, to define the aquifer top and bottom, to construct cross-sections and help when defining the model boundary in the conceptual model formulation. The area is generally flat ranging between 986 ï 1019 meters above mean sea level (mamsl). Table 4.3 shows the ground elevations, together with rest water levels for each borehole.

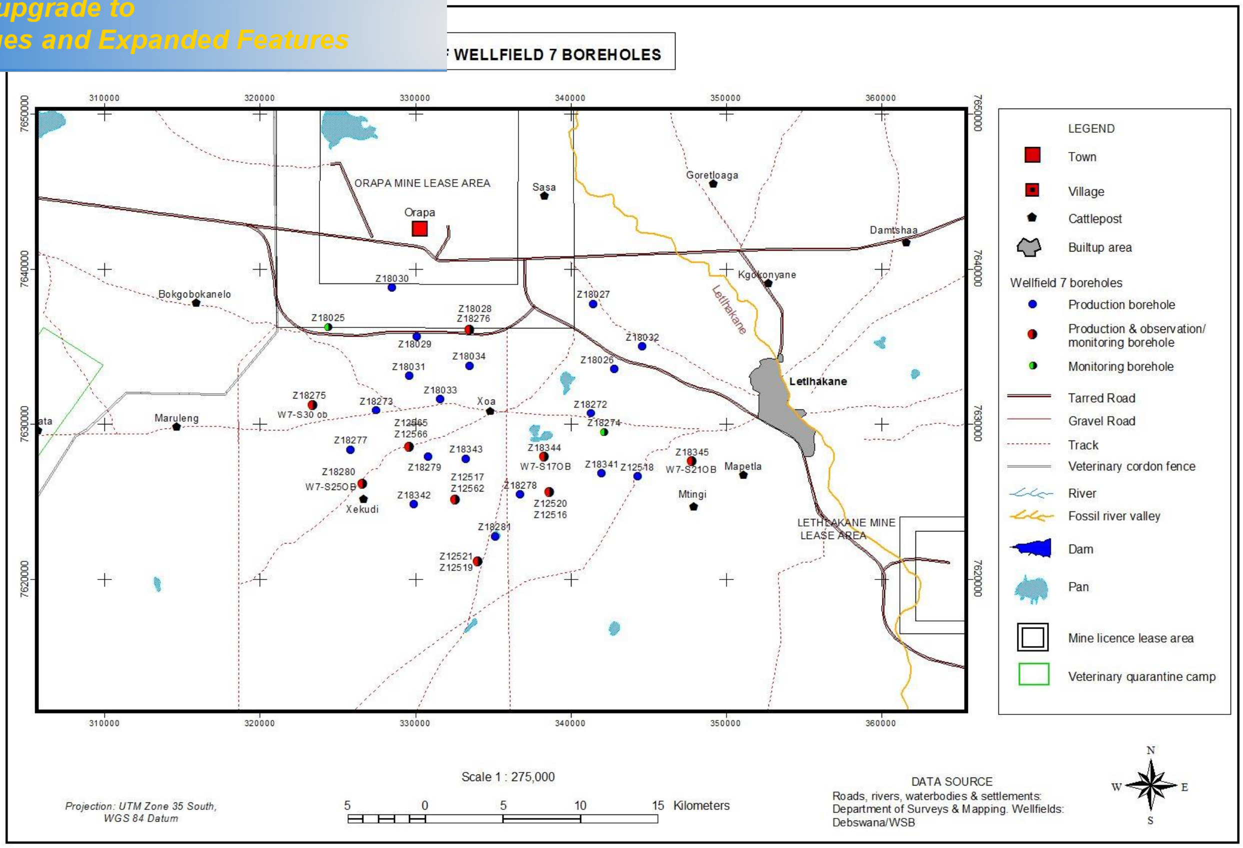

Figure 4.2: Geographic location for all WF 7 borehole

Table 4.2: Planned abstraction rates for all the WF7 production boreholes (WSB, 2013)

Borehole number	Recommended Abstraction Rate		Borehole number	Recommended Abstraction Rate	
	(m^3/hr)	(m^3/day)		(m^3/hr)	(m^3/day)
Z12517	14	280	Z18272	8	160
Z12518	12	240	Z18273	10	200
Z12520	55	1100	Z18275	20	400
Z12521	20	200	Z18277	18	360
Z12565	15	300	Z18278	25	500
Z18026	7	140	Z18279	18	360
Z18027	8	180	Z18280	22	440
Z18028	25	600	Z18281	25	500
Z18029	8	160	Z18341	22	440
Z18030	8	160	Z18342	8	160
Z18031	20	400	Z18343	20	400
Z18032	14	280	Z18344	18	360
Z18033	20	400	Z18345	60	1200
Z18034	25	500			

ter Levels (RWL) for all wellfield 7 boreholes

		(mbgl)	RWL (mamsl)	Borehole no.	Elevation (mamsl)	RWL (mbgl)	RWL (mamsl)
Z12515		41.7		Z18034	993	86.1	907
Z12516	1005	41.3	964	Z18272	997	34.2	963
Z12517	1007	37.5	970	Z18273	1003	41.6	961
Z12518	1000	39.0	961	Z18274	1000	37.9	962
Z12519	1019	43.2	976	Z18275	1000	43.8	956
Z12520	1005	46.7	958	Z18276	987	68	919
Z12521	1019	48.9	970	Z18277	1005	41.2	964
Z12522	1003	37.1	966	Z18278	1006	50.1	956
Z12562	1006	36.5	970	Z18279	1003	35.5	968
Z12565	1002	37.3	965	Z18280	1013	52.0	961
Z12566	1002	37.4	965	Z18281	1008	61.5	947
Z18025	987	37.85	949	Z18341	1001	44.3	957
Z18026	991	31.9	959	Z18342	1012	44.4	968
Z18027	978	50.2	928	Z18343	1001	34.8	966
Z18028	986	78.0	908	Z18344	1001	39.3	962
Z18029	991	83.6	907	Z18345	1005	54.7	950
Z18030	987	50.9	936	Z18346	1005	52.6	952
Z18031	998	35.4	963	Z18347	1002	39.0	963
Z18032	987	28.4	959	Z18350	1011	42.0	969
Z18033	999	37.3	962	Z18475	1000	45.0	955

4.4.4 Groundwater Level

Groundwater recharge and discharge, either natural or artificial, can result in fluctuation of groundwater level in aquifer system. (Van-Geer and Defize, 1987). Groundwater levels for all boreholes were measured and they range between 907 and 975 mamsl. A trend of rest water levels (RWL) is presented against the ground elevation in figure 4.3 below. Head measurements are also needed to establish groundwater flow during conceptual model development, initial head for the numerical groundwater model and for model calibration.

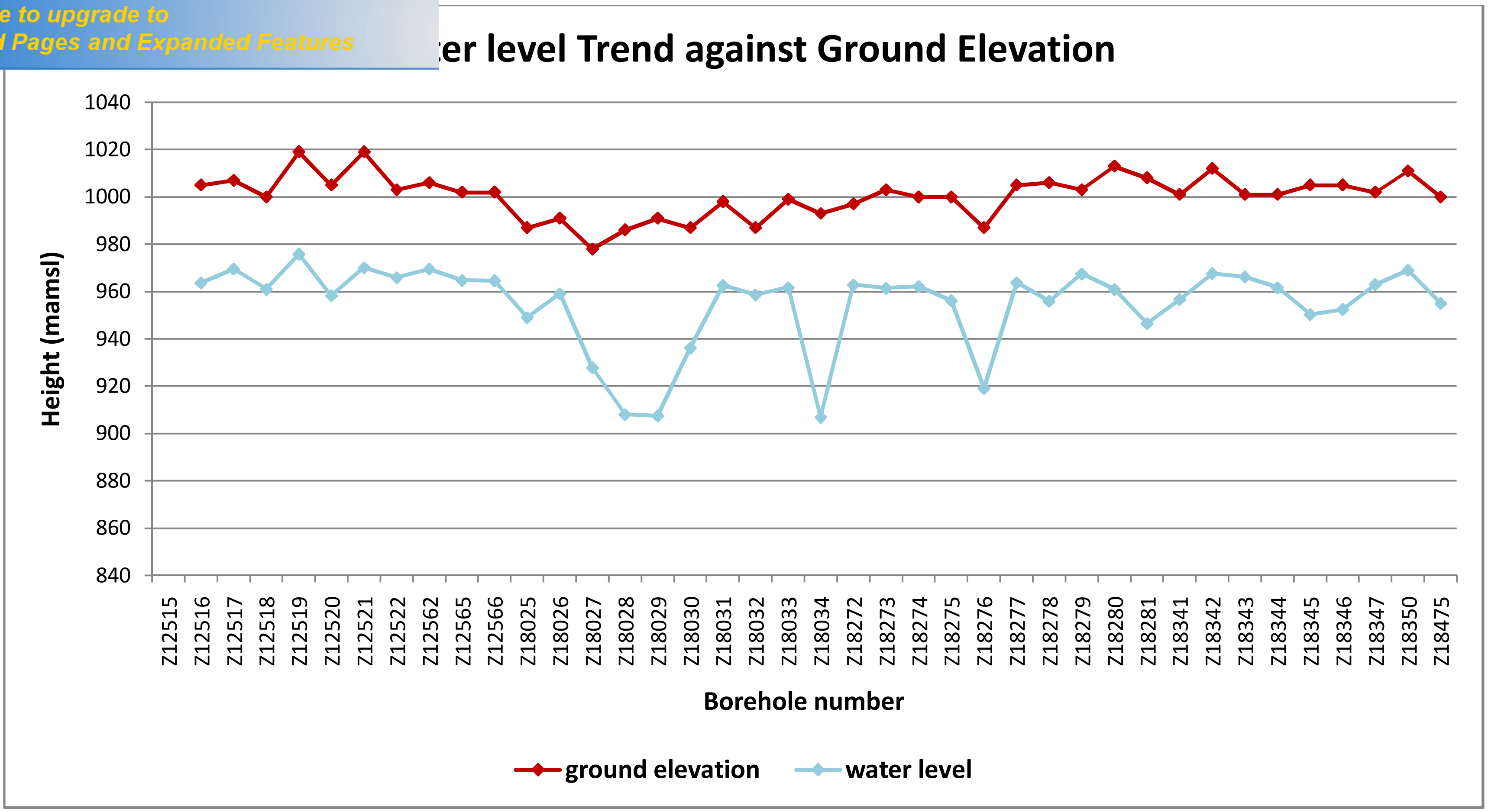

Figure 4.3: Rest water level for all WF7 borehole

Fluid transmissivity, hydraulic conductivity, storage and thickness of aquifer are fundamental properties for characterizing an aquifer and as (Leven and Dietrich, 2006) have indicated, one needs to master the distribution of these parameters for any successful hydrogeological study. Accurate characterization of aquifer properties is also fundamental to understanding and predicting aquifer responses to development and management of the groundwater resource. In particular, these parameters are essential elements of dynamic models which have become standard tools for sustainable development and optimal resource management (Rotzoll et al., 2013).

The most effective way of estimating hydraulic properties of an aquifer is through pumping tests that are carried out on certain boreholes (Kahsay, 2008). Pumping tests accurately estimate hydraulic properties of an aquifer because the results reflect the average value across the geological formation and takes into account natural variability (Davidson and Wilson, 2011). According to (Kruseman and Ridder, 1990), discharge and drawdown values measured in pumping and observation wells, during a pumping test, can be used to accurately calculate the hydraulic characteristics of the aquifer.

For WF7, single well pumping tests were carried out at most of the boreholes after they were drilled. These data were collected and analyzed to understand the well and aquifer system behaviour of the area. The tests carried out were calibration test, step drawdown test, constant rate test (CRT) and recovery test. The interpretation results of the aquifer parameters are given in table 4.4.

4.4.5.1 Transmissivity

Transmissivity (T) is measured as the rate at which groundwater can flow through an aquifer section of unit width under a unit hydraulic gradient (Fetter, 1994). It describes the ability of the aquifer to transmit groundwater throughout its entire saturated thickness and it is also strictly a 2D phenomenon necessitated by averaging the hydraulic head in a vertical direction. Flow through the aquifer is assumed

...y not hold for all cases. Aquifer tests performed during previous aquifer characterization campaigns provide estimates of transmissivity for the Lebung aquifer. The pumping tests results performed here give an average transmissivity of 9.6m^2/day.

Table 4.4: Wellfield 7 Aquifer parameters as interpreted from pumping tests for each borehole

Borehole no	Aquifer Thickness (m)	Yield (m^3/day)	Specific Capacity (m^3/day/m)	Transmissivity Pumping Well (m^2/day)		Storage	Transmissivity Observation Well (m^2/day)		Storage
				Pumping	Recovery		Pumping	Recovery	
Z12517	60	14	0.29 - 0.44	6.5	6.15	0.00015	15.4	16.2	0.0019
Z12518	7	12	0.21 - 0.25	5	3.8	0.0016	62	188	0.86
Z12520	6	55	0.78 - 0.87	20	12	0.004	7.3	66	0.0005
Z12521	11	10	0.18 - 0.23	4.6	5.5	0.007	80.2	126	0.003
Z12565	20	15	0.33 - 0.43	6.7		0.000042			
Z18026	43	8	0.13 - 0.18	2.6	1.4	0.000002			
Z18027	58	10	0.27 - 0.36	7	7.3	0.00018			
Z18028	83	45	0.87 - 1.38	17	12.3	0.0005			
Z18029	81	8	0.15 - 0.22	2.8	3.5	0.000015			
Z18030	103	9	0.09 - 0.18	3.7	4.4	0.00009			
Z18031	73	22	0.38 - 0.47	8	9.6	0.0035			
Z18032	64	20	0.32 - 0.35	6.3	7.3	0.001			
Z18033	68	25	0.37 - 0.64	9.5	13.6	0.000012			
Z18034	29	45	0.67 - 0.84	14	4.5	0.0012			
Z18272	56	10	0.18 - 0.22	2	2.3	0.009			
Z18273	80	10	0.14 - 0.26	5	4.6	0.00006			
Z18275	105	20	0.34 - 0.45	10	14.6	0.000035	50	58	0.0015
Z18277	119	20	0.58 - 0.64	11	4.9	0.000025			
Z18278	74	25	0.81 - 1.12	12	9.4	0.000017			
Z18279	95	22	0.97 - 1.12	15	24	0.00028			
Z18280	56	25	0.42 - 0.58	11	9.1	0.00012	18.3	10.9	0.00007
Z18281	113	25	0.32 -0.44	8	10.4	0.007			
Z18341	79	25	0.36 -0.40	9	9.1	0.006			
Z18342	99	9	0.2 - 0.21	4	3.9	0.0001			
Z18343	87	25	0.56 - 0.67	13	10.9	0.00003			
Z18344	64	20	0.000019	12.5		0.001			
Z18345	79	60		27	26	0.0018			
			min	2.0	1.4		18.3	10.9	
			max	27.0	26.0		50.0	58.0	
			average	9.6	9.2		34.2	34.5	

Hydraulic conductivity (K) is the ease with which water can move through an aquifer (Fetter, 1994), and it can be determined by dividing the transmissivity of the aquifer by the thickness of the aquifer. The hydraulic conductivity can vary in a geological unit relatively short distances, particularly in fractured aquifers. Typical values for hydraulic conductivity for different geological units are shown in table 4.5.

Table 4.5: Typical Hydraulic conductivity values for different geological units as adapted from (Freeze and Cherry, 1979).

Geologic Unit	Hydraulic Conductivity (m/day)
Fine sand	1 - 5
Coarse sand	20 ï 100
Sandstone	0.001 - 1
Basalt	0.0003 - 3

4.4.5.3 Storativity

(Fetter, 1994) defines storativity (S) or storage coefficient as the volume of water released or absorbed from storage with respect to the change in head (water level) and surface area of the aquifer. The value of the storage coefficient is dependent upon whether the aquifer is confined or unconfined. Water released from storage in a confined aquifer is from compression of the aquifer and expansion of water when pumped. Pressure is reduced but the aquifer is not dewatered. In an unconfined aquifer, water is predominantly from gravity drainage as the aquifer materials are dewatered during pumping. Storage coefficient of a confined aquifer ranges from 0.00001 to 0.001 compared to 0.01 to 0.30 for an ed aquifers can produce more water for a small change in head compared to confined aquifers.

At WF7, the storage coefficient in the Lebung aquifer as determined from the pumping tests range between $2x10^{-6}$ and $9x10^{-3}$.

A conceptual model is a pictorial representation of the groundwater flow system. It is usually in the form of a simplified diagram or hydrogeologic cross section (Anderson and Woessner, 1992). The conceptual model is simplified according to the assumptions made relative to the objectives of study, ascertaining that it incorporates the important hydrogeological conditions. A conceptual model gives the direction to the numerical model, its design and geometry, so an inaccurate numerical model can often be attributed to an inaccurate conceptual model.

Developing a conceptual model helps the modeller to formulate a better understanding of a site condition, to define the groundwater problem, to develop a numerical model and to aid in selecting a suitable computer code. The conceptual model area is developed by integrating available data from hydrostratigraphy, well and geophysical logs, Geologic maps and geologic cross-sections.

5.1 Well Log Data and Geology

Well log data are important to develop better understanding of aquifers and groundwater flow direction in that it contributes to proper characterization of the hydrogeological condition. Drilling log data of the boreholes in the wellfield were collected from the mine database and applied to demarcate the hydrostratigraphic zones of the area. The information from the drilling lithologic logs indicates that the Ntane and Mosolotsane sandstones are the main water bearing geologic units. At the top and bottom of the sandstones are the basalt and mudstones respectively. These units are less permeable than the sandstones, so they may form a barrier to groundwater flow. The summary drilling borehole graphical logs are shown in appendix 2. Figure 5.1 shows the NW-SE geological cross section of the area.

5.2 Hydrostratigraphy

Geologic formations with similar hydraulic properties can be combined to form a single hydrostratigraphic unit or a geologic formation may be subdivided into several units (Anderson and Woessner, 1992). Drilling logs and geologic knowledge gained from previous studies were used to

…s as follows; Kalahari Group sediments, Stormberg Basalt, Ntane Sandstone and Mosolotsane Sandstone.

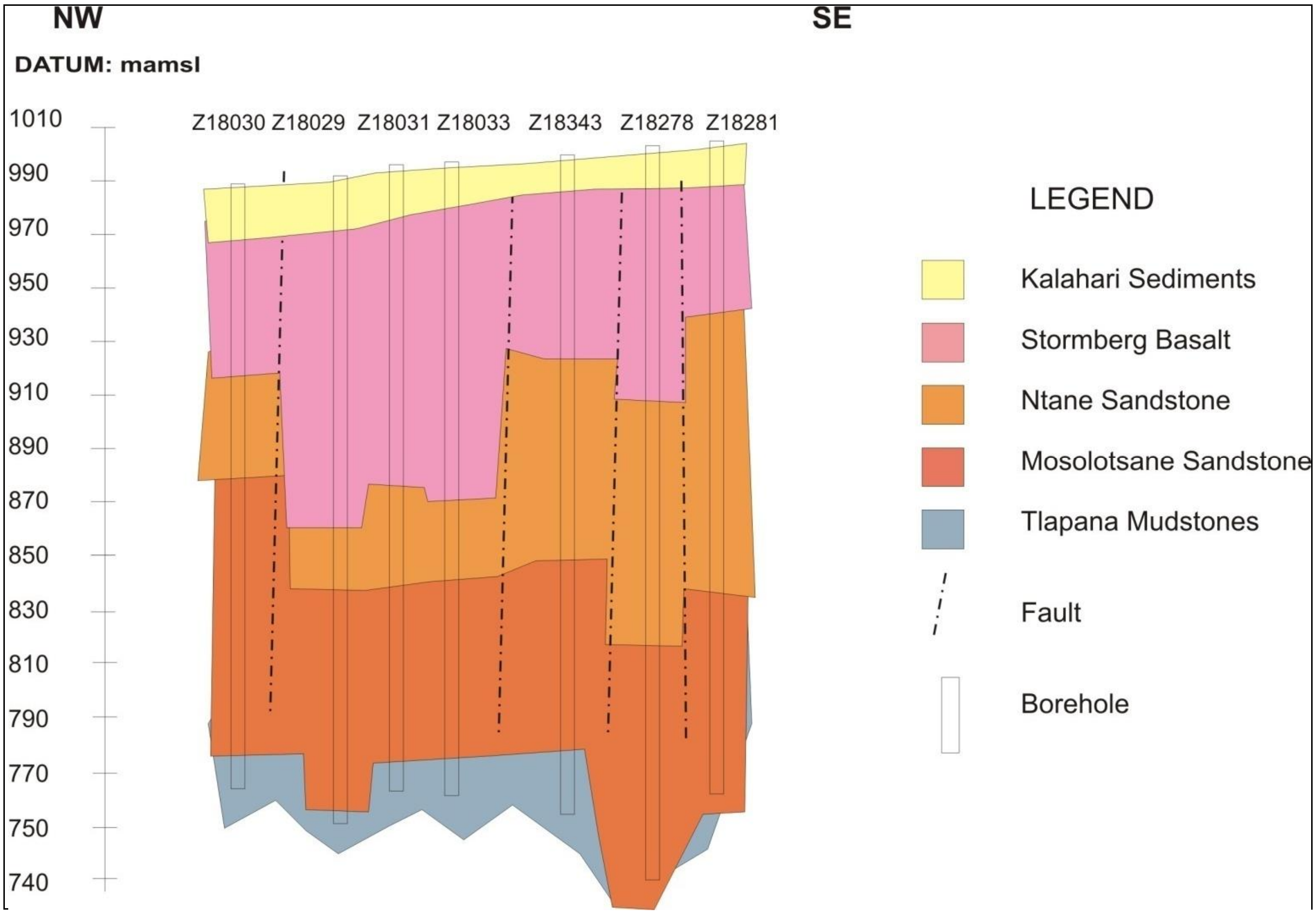

Figure 5.1: NE-SW geological cross section of the study area

5.3 Hydraulic Properties of stratigraphic units

Hydraulic properties are key components of the conceptual groundwater model. These include both hydraulic conductivities and transmissivities. As already stated above, the hydraulic property data for WF7 was derived from aquifer pumping tests carried out in previous studies.

5.4.1 Groundwater Recharge

Recharge is the process whereby groundwater is replenished by water draining into the groundwater system (Fetter, 1994). It does not include water held in the soil in the unsaturated zone that may be evaporated, taken up by plants or discharge at topographic lows. Rainfall, evapotranspiration and soil type are the major factors contributing to the groundwater recharge of an area. Recharge to confined aquifers occurs where the aquifer is exposed at the surface, or leakage through confining layers. It can occur directly where it outcrops such as at higher elevation where it is unconfined or via slowdown seepage through an overlying leaky aquitard. For this study area, recharge is adopted from previous studies. The recharge is estimated at 0.765mm/year.

5.4.2 Groundwater Discharge

Discharge is the process whereby groundwater leaves the aquifer (Fetter, 1994) Discharge can occur through groundwater pumping (well abstraction), leakage to surface water bodies as base flow, or spring seepage. The main groundwater discharge will take place through pumping from the production wells and is estimated at 8040m^3/day which translates to about 2,9Mm^3/year.

5.5 Groundwater Flow System

A groundwater flow system is a set of flow paths with common recharge and discharge areas, basically describing the movement of water in the subsurface from the point where it enters the ground to where it leaves (Fetter, 1994). Identifying these entry and exit points is critical to conceptualizing the system and developing an accurate model. The Groundwater flows from recharge to discharge areas through pores and fractures in sediment and rock in the zone of saturation, moving from high to low elevation and from high to low pressure. The rate of flow depends on the hydraulic gradient and hydraulic conductivity. The greater they are the more rapid groundwater will flow.

...lot a potentiometric surface map of WF7 area. Figure 5.2 ...ed heads. The map shows the flow direction to the north eastern part of the study area.

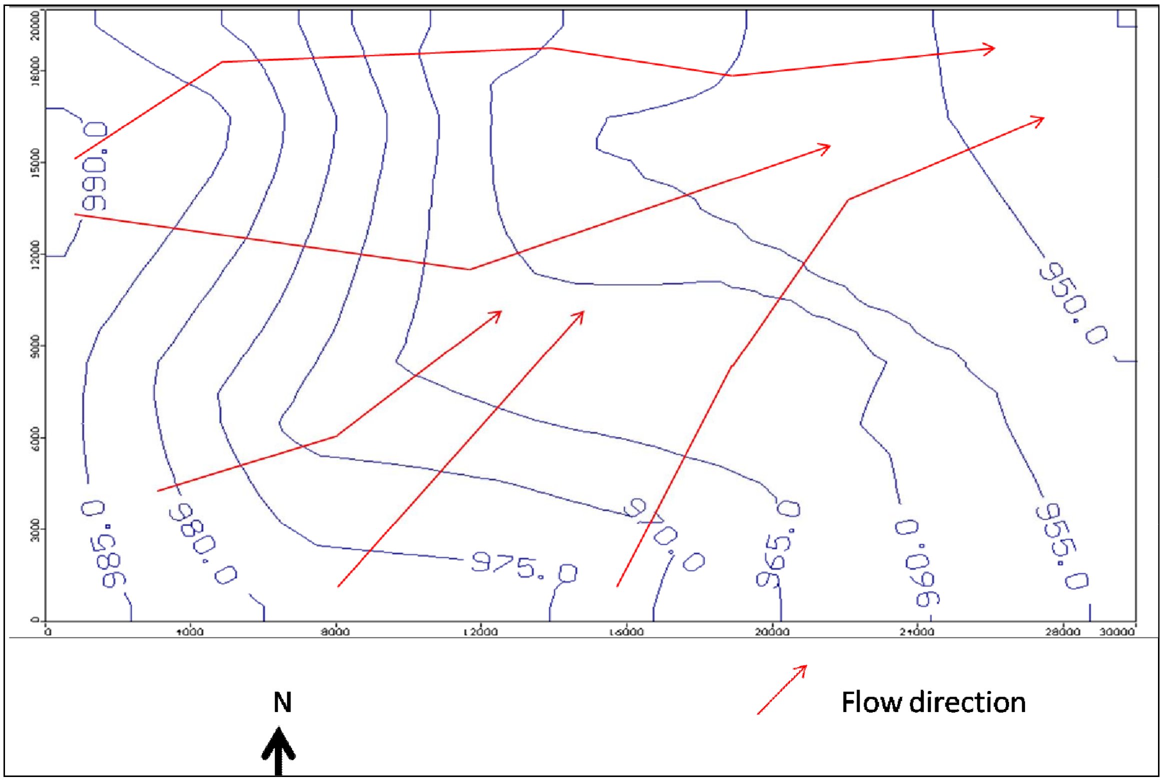

Figure 5.2: Potentiometric surface map of WF7

5.6 Model Boundaries

Model boundary is the interface between the model calculation domain and surrounding environment and only a specific part of the real world system is of interest. The boundaries largely determine the flow patterns, so care must be taken when choosing the boundary conditions wrong boundary conditions generate wrong water balance of the system under study (Anderson and Woessner, 1992) . Model boundaries could be physical (impermeable geologic formations and surface water bodies) or hydraulic boundaries (groundwater divides and flow lines) (Kahsay, 2008). Establishment of the model boundaries acquired from the geology topography and flow system prevailing in the area.

No physical boundaries have been established for this model, so hydraulic boundaries shall be used.

5.7 Simplification

Complete reconstruction of the field system is not feasible and so it is necessary that it be simplified. Although the conceptual model should be simplified as much as possible, it should still remain complex enough to represent the systemôs behaviour (Anderson and Woessner, 1992), and in order to achieve this simplicity of the complex real world, some basic assumptions about the model area are normally made.

For this study, the following assumptions were made;

- a steady-state condition for the 20 years period
- the basalt and mudstones are considered to be impermeable

The conceptual system of WF7 area is shown in figure 5.3.

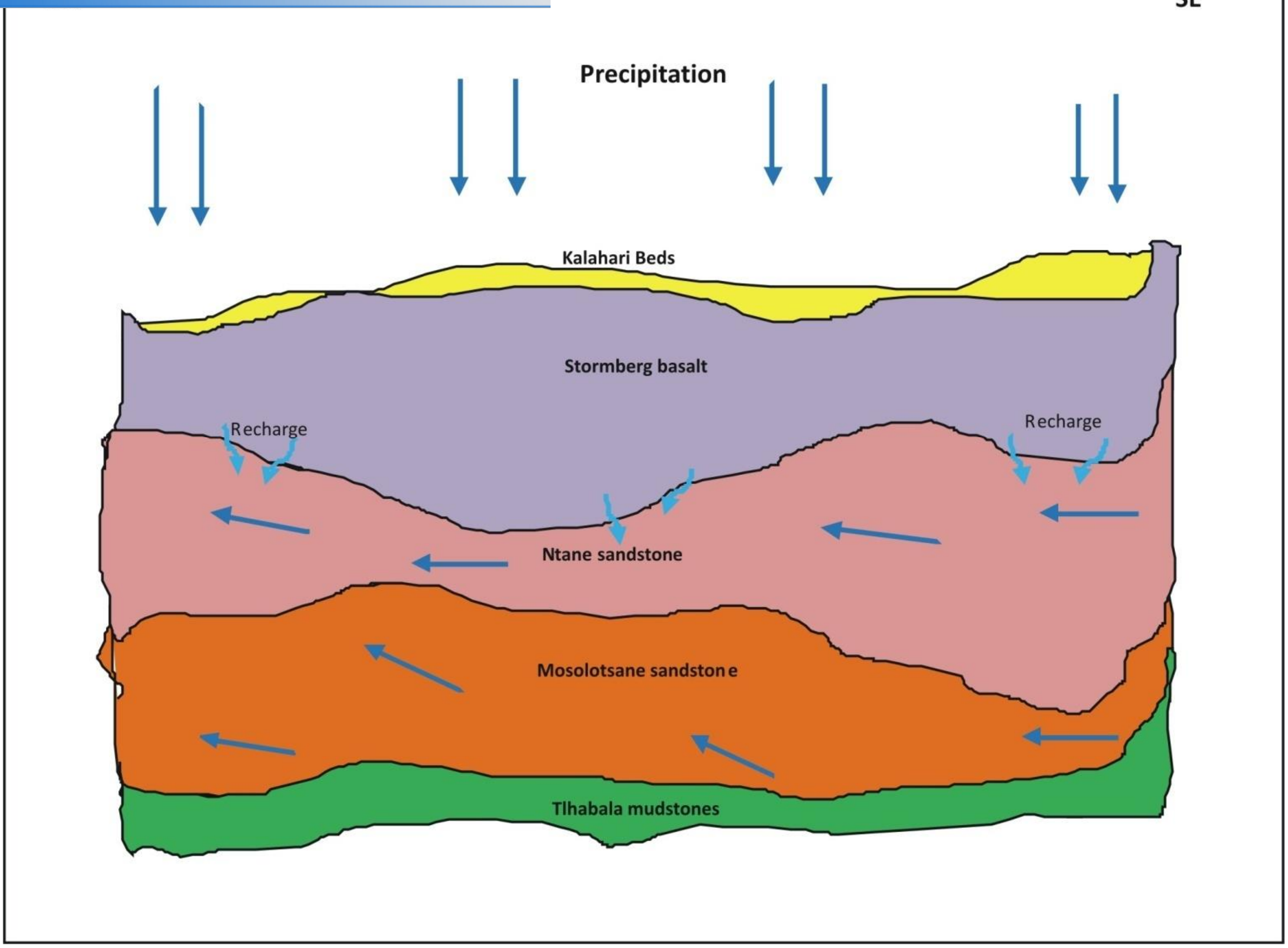

Figure 5.3: Conceptual model of WF7 aquifer system

6.1 Code Selection

Selection of a computer code depends on the objectives of the study area and reliability of the code, available field data as well as the available resources in terms of time and/or money (Anderson and Wang, 1982). The code selected for this exercise is Visual MODFLOW Pro Version 4.3, a MODFLOW graphical user interface which can be used to describe and predict the behaviour of groundwater flow system.

6.2 Model Geometry

Horizontal Extent

The horizontal extent of the model domain is bounded by 320000 & 350000 UTM East and 7620000 & 7640000 UTM South, making the total area of the model domain to be 600 km^2.

Vertical Extent

From the conceptual model, and based on the geologic and well completion data, 4 layers were used to in this exercise, layer 1, 2, 3 and 4 representing kalahari sediments, basalts, sandstone and mudstones respectively. Point elevation data for each borehole in the study area was interpolated over the model domain to create elevation files for inputting into the modelling programme. The top and bottom elevations of the aquifer system are 1020 mamsl and 750 mamsl respectively, giving a total maximum thickness of 270m.

There are three most important aspects of model design; spatial domain, initial conditions and boundary conditions.

6.3.1 Discretization

A 30*20 (30000m by 20000m) grid was used in this exercise consisting of 2400 active cells.

6.3.2 Boundary Conditions

Boundary conditions give the head or flux at the boundary of the model. General Head boundary (GHB) package was employed to simulate groundwater flow through the E - W boundary and N - S boundary (figure 6.1). These were specified in layers 2, 3 and 4.

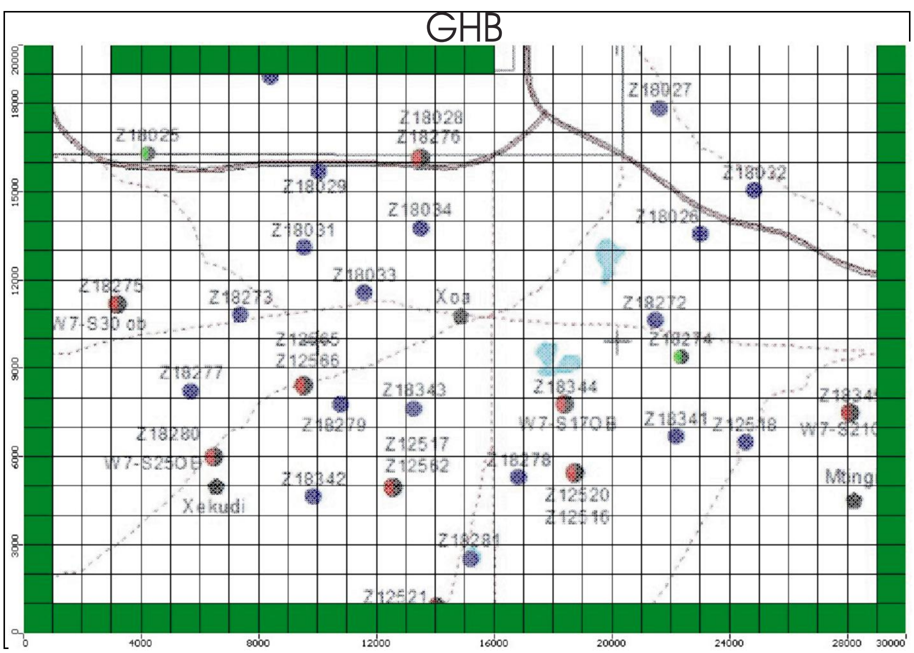

Figure 6.1: General Head boundaries assigned to the model in layers 2, 3 and 4.

Initial conditions specify the boundary conditions with respect to time. They give the spatial distribution of the hydraulic heads in the system at the beginning of the simulation (Anderson and Woessner, 1992). They are used for model convergence so the initial conditions should be within the range of the boundary conditions.

SWL for the observation boreholes were interpolated to obtain the initial heads for the entire model.

6.3.4 Aquifer parameters

Hydraulic conductivity and storage are key parameters required for the flow model. The hydraulic conductivity and storage values estimated from the pumping test results were applied before being adjusted during the calibration process. Hydraulic conductivity was set equal in all directions (X, Y and Z) in all layers. The parameter values assigned to the model are shown in table 6.1.

Table 6.1: Parameter values assigned to the model

Layer	Conductivity			Storage			
	k_x	k_y	k_z	Ss	Sy	Eff. porosity	Total Porosity
1	20	20	5	1E-5	0.2	0.4	0.45
2	0.00173	0.00173	0.0008	1E-5	0.15	0.05	0.07
3	1.73	1.73	1.0	1E-7	0.1	0.15	0.2
4	0.86	0.86	0.4	1E-6	0.05	0.15	0.2

n wells

Boreholes are spatially distributed throughout the wellfield area. The data base of the boreholes was collected from previous reports on the area, and compiled in excel for input into the model. There is no time series monitoring groundwater level data for all the boreholes as they were just recently drilled. Out of the 29 pumping wells, only 21 were applied in the model and all the 11 observation wells were used.

6.3.6 Recharge

The model was assigned a recharge input of 0.765mm/year, assigned only to the top layer, and is adjusted to 0.4mm/year during model calibration.

6.4 Model Calibration

Adjustments in the model input data are required to improve the reliability of the model results. This is done, normally, because the model does not reflect the real world with enough accuracy, resulting from ambiguity of the input data, and thus does not give satisfactory results. The adjustment is made, manually or automatically, until the model results approximate or equal the selected field conditions. (SWS, 2004).

In the case of WF7, RWL were set as target points to match with calculated model heads. Since pumping has not started in the wellfield, and there are no drawdown data, calibration was only carried out for the non-pumping scenario. Parameter optimization was conducted through PEST by manually varying hydraulic conductivity, storage and recharge, and then comparing calculated heads to those measured in wells.

Part of the observation points used in model calibration is set aside for use in model validation. There is, often, too short set of observed data, which will be used for calibration, and so there is no data available to validate the model. This was the case with this study.

7.1 Conceptual Model Results

Conceptualization of the Orapa WF7 system was attained through integration of hydrogeological data and field observations (figure 5.3). The main source of groundwater recharge in the area is rainfall although it is considered to be minimal. Other than rainfall, no other sources were identified within the WF7 area so, most recharge is thought to occur outside the model area. Discharge will be from abstraction from the pumping wells. Flow is mainly restricted to the Lebung aquifer (Ntane and Mosolotsane) sandstones, mainly northwards, as indicated by the potentiometric map in figure 5.2. No physical boundaries were identified so GHB were established to the north, south, east and western sides of the model domain.

7.2 Calibration Results

Calibration results were evaluated both qualitatively and quantitatively. A scatter plot of measured against simulated heads is used to show the calibrated fit. The graphs were examined to see how the points are distributed along the straight line of a perfect fit. Figure 7.1 shows the plot of calculated vs. observed hydraulic heads before pumping. A correlation coefficient of 66% was achieved during calibration.

Equipotential maps interpolated from observed and simulated heads were also analyzed to see if they give flow directions that compared to one another. Figure 7.2 shows a potentiometric surface map derived from interpolation of simulated heads. The simulated head contour map shows reasonably similar regional groundwater flow directions as the observed head contour map from the conceptual model.

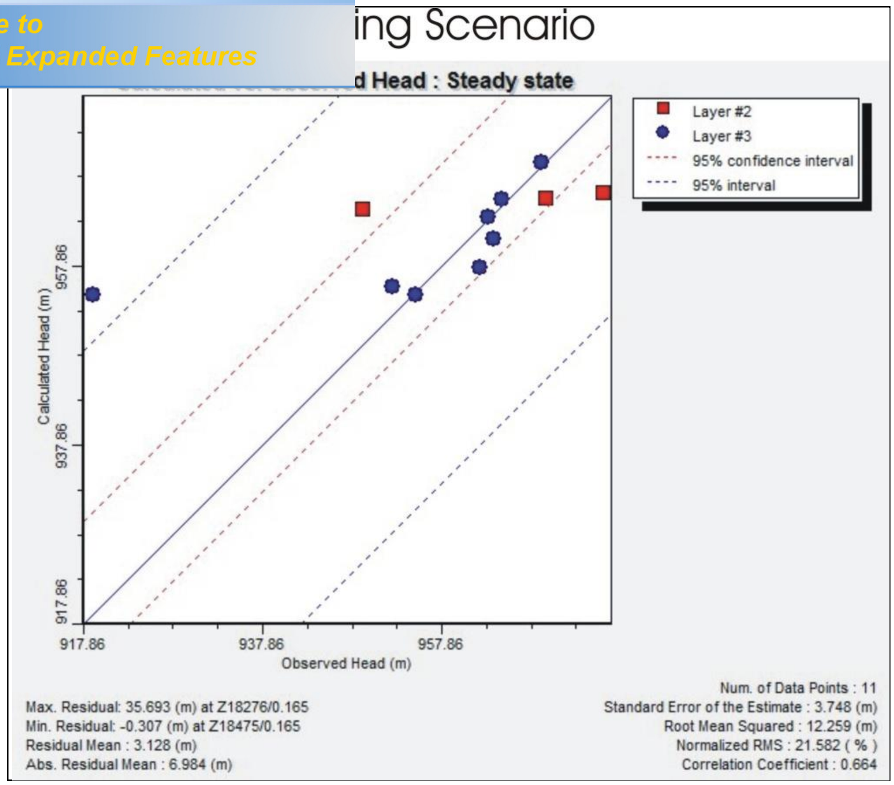

Figure 7.1: Scatter plot for the simulated vs. observed heads for the non-pumping scenario.

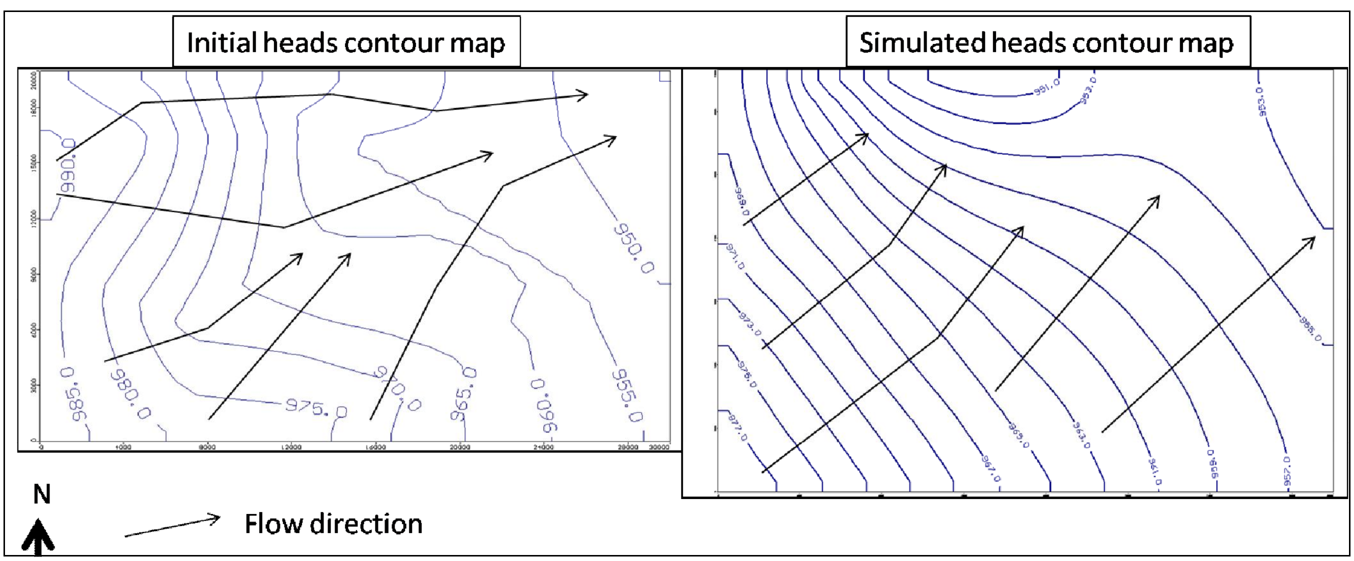

Figure 7.2: Equipotential lines interpolated from simulated heads showing similarities to the contours interpolated from observed heads.

…n absolute error and Root Mean Squared error) were used to …s are shown in table 7.2. The measure of the errors is in an acceptable range according to the pre- determined error criteria. The results show the simulated heads diverged from the observed heads by 12m.

Table 7.2: Results error quantifying methods

borehole no.	observed head (mamsl)	simulated head (mamsl)	obs - sim	|obs - sim|	$(obs - sim)^2$
Z12516	963.70	960.88	2.82	2.82	7.95
Z12519	975.80	966.17	9.63	9.63	92.74
Z12562	969.50	965.52	3.98	3.98	15.84
Z12566	964.60	965.27	-0.67	0.67	0.45
Z18025	949.00	964.22	-15.22	15.22	231.65
Z18074	962.10	957.64	4.46	4.46	19.89
Z18276	919.00	954.69	-35.69	35.69	1273.78
Z18346	952.40	955.57	-3.17	3.17	10.05
Z18347	963.00	963.36	-0.36	0.36	0.13
Z18350	969.00	969.51	-0.51	0.51	0.26
Z18475	955.00	954.69	0.31	0.31	0.10
				ME	**-3.13**
				MAE	**6.98**
				RMSE	**12.26**

7.3 Water Budget

It is very important for the inputs and outputs to balance out in any accurate groundwater flow model. Comparison of inflow and outflow components of the Orapa WF7 groundwater flow system is shown in figures 7.3 before pumping and figure 7.4 for the pumping scenario. Recharge remains constant at 672m^3/day for both scenarios. The recharge compares with the values estimated for the area in the conceptual model. The outflow component through the head dependent boundary reduces by 3085m^3/day when pumping. This is because more water will now be discharged through the wells rather than through the boundaries. Both plots show that total inflows equal total outflows.

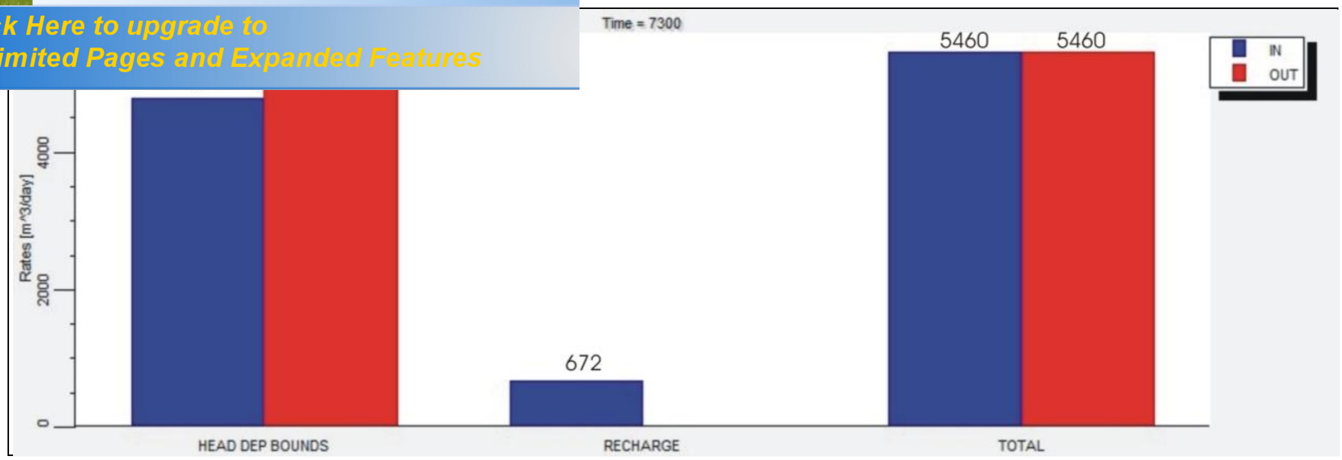

Figure 7.3: mass balance flow for the non-pumping scenario.

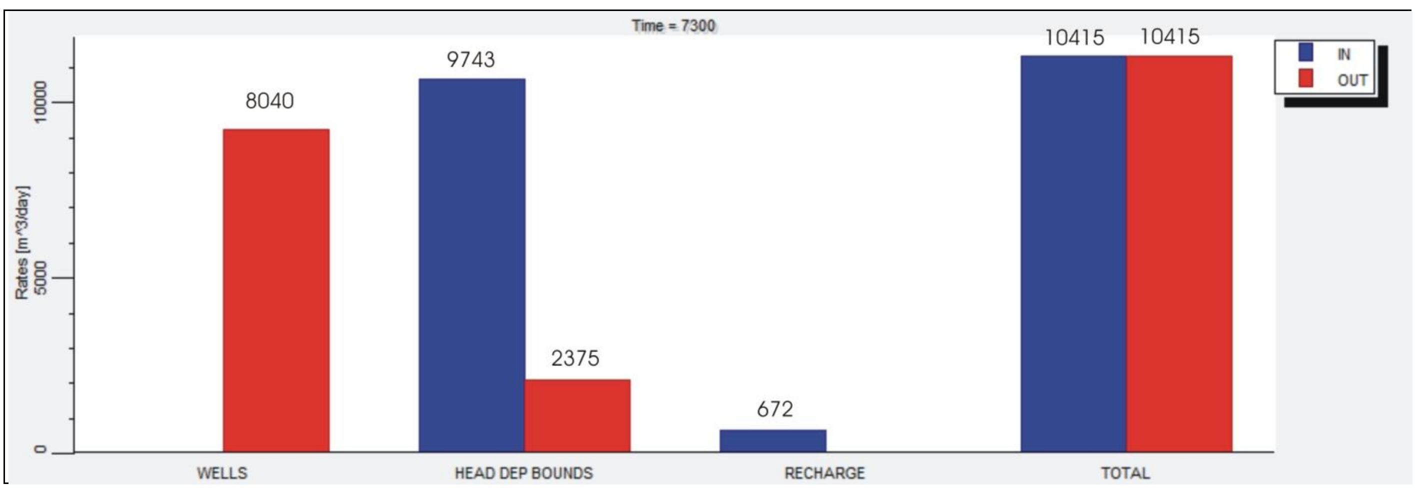

Figure 7.4: mass balance flow for the pumping scenario

7.4 Hydraulic Heads

Simulated hydraulic heads contour maps for the non-pumping and pumping scenarios are shown in figure 7.5. In both cases, the general trend for the hydraulic gradient is towards the NE, in line with the general flow system of the area as shown by the plot (figure 5.2) in the conceptual model. The hydraulic head from the pumping scenario range between 978 and 951mamsl. After pumping, the head range

.6 show a plot of drawdown after pumping. The effect of pumping is largely around the wells and this will result in groundwater decline of up to 30m, when abstracting at a rate of 8040m^3/day for the entire 20years period. The average available drawdown is about 67m, which gives about 45% of the total drawdown being reached. This is a satisfactory result as for sustainable groundwater management; the target is to extract at maximum 50% of the total water available. The largest amount of drawdown will be to the NW of the wellfield, which may be associated with Orapa mine dewatering taking place just north of the model area.

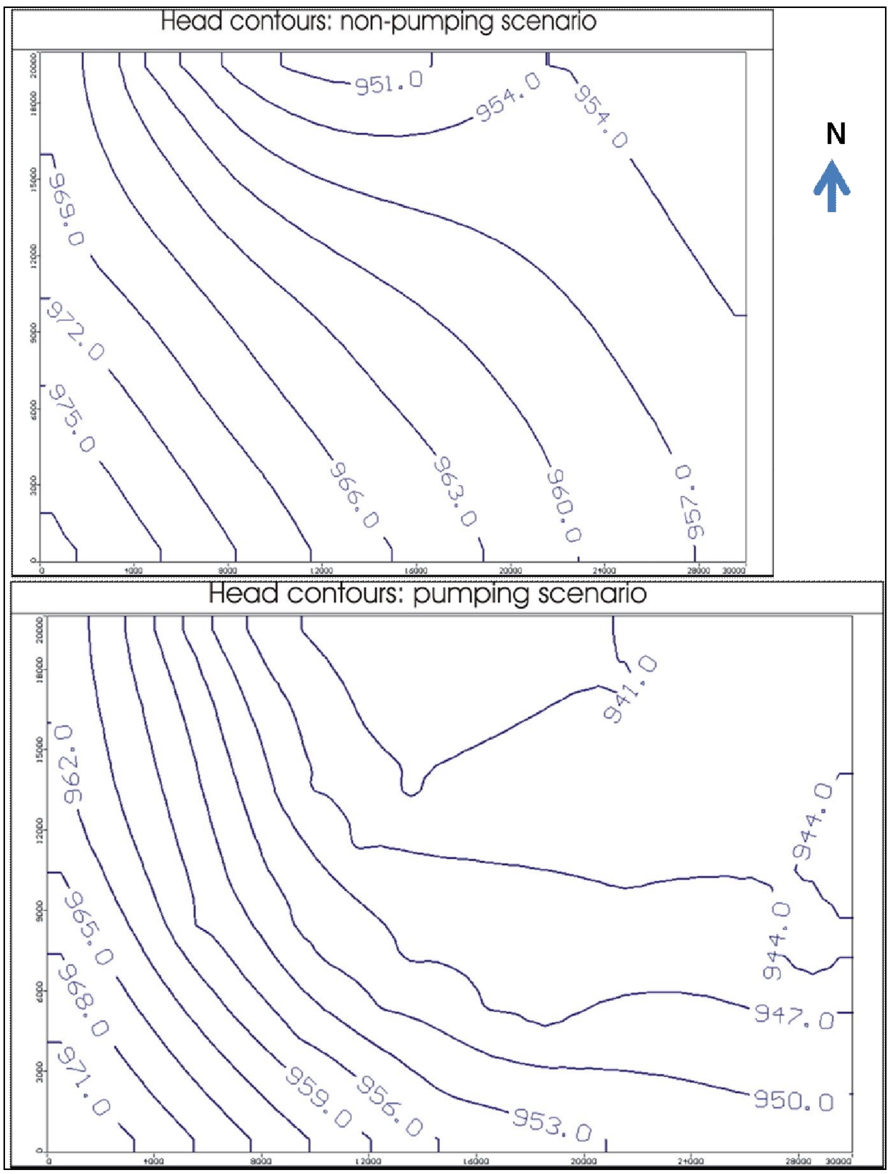

Figure 7.5: simulated head contours for the non-pumping and pumping scenarios

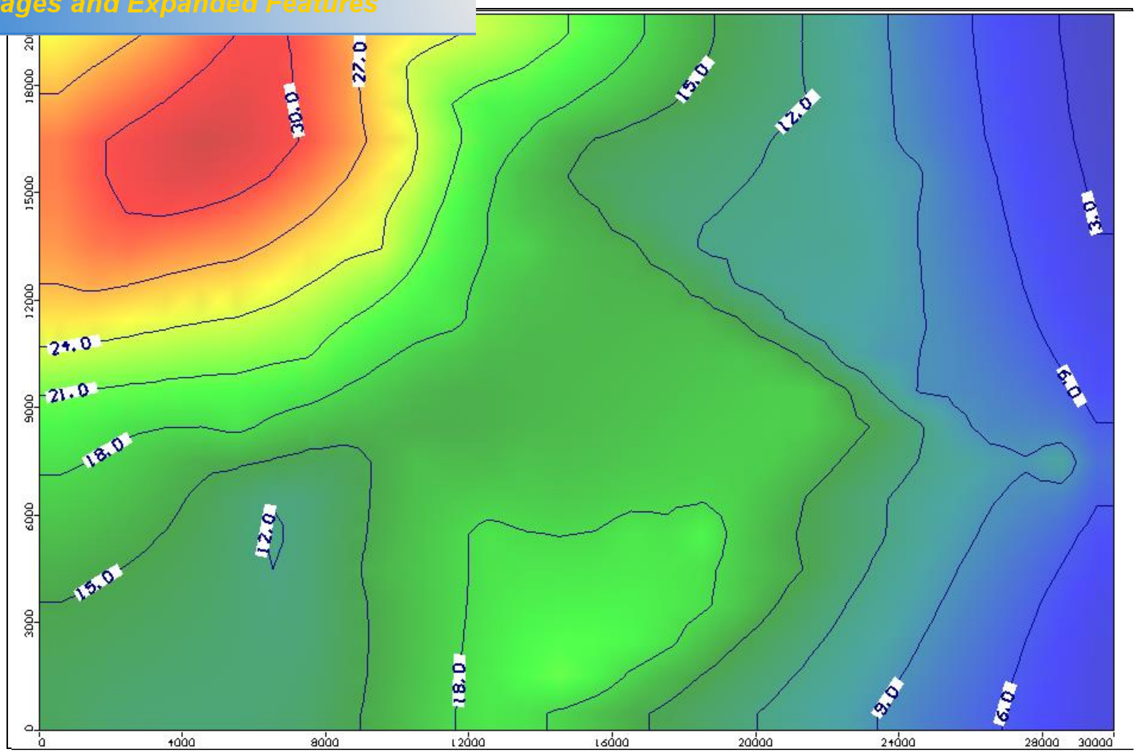

Figure 7.6: Drawdown contours after pumping scenario

7.5 Model Limitations

Although the model results are realistic and reasonable, the following limitations may apply:

- Simplifications and assumptions of the field system made during conceptual model may introduce errors and uncertainties
- The different steps in model build up, real world - conceptual model - mathematical model, may each introduce errors to the model.
- Lack of time series data may render the model inaccurate as is calibrated to a set of conditions not entirely representative of the real system.
- The model was not validated because of insuffient data.

endations

8.1 Conclusion

1. The steady state numerical model is ideal tool for groundwater management in the area. It can be used as a decision making tool with regard to determining the responses of the system to abstraction and estimating aquifer properties. This model was able to accurately simulate the WF7 groundwater flow system with insufficient data.

2. The steady state flow model made use of well data to simulate the observed hydraulic heads with a correlation coefficient of 66%, showing a highly correlated data. The standard deviation is 12m, also giving a high confidence in the result. The inflows and outflows balance out, leaving no water unaccounted for.

3. The model results show that a daily groundwater abstraction of 8040m^3 from the wellfield will result in a drawdown of up to 30m, after pumping for a period of 20 years. This is less than 50% of the available drawdown, making it sustainable to abstract water from this wellfield.

8.2 Recommendations

This study is a good basis for detailed groundwater modelling works in the wellfield in the future and as more data becomes available, accuracy of the model can be improved. In order for this to happen, the following recommendations are made:

1. Carry out an improved model that takes into account abstraction from dewatering in the nearby mines (Orapa, Letlhakane and Karowe Mines), other wellfields as well as private boreholes.
2. A transient simulation be carried out for better predictions of the impact of the large scale abstraction from the wellfield

vells evenly distributed within the wellfield, to improve calibration values

4. Documentation of time series of abstraction rates once pumping starts
5. Implications on other water uses
6. Modelling without validation is not totally reliable, so it is recommended that further work consider validation of the model to improve its reliability.

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Appendix 1: Meteorological Data

Appendix 1.1: Monthly maximum temperature for Orapa-Letlhakane area for years 1994 – 2010

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Avg
Jan	30.3	34.4	30.3	30.7	31.2	33.8	30.6	35.1	34.4	35.2	32.2	33.7	30.0	32.2	29.8	31.9	32.9	32.3
Feb	30.6	32.7	28.6	32.0	33.3	34.8	30.3	30.7	33.8	33.8	30.8	33.5	29.5	34.1	32.1		32.1	32.0
Mar	33.8	31.1	30.0	30.2	34.5	33.6	31.0	29.1	33.7	33.1	27.6	31.8	28.4	3.5	30.5	29.1	31.2	29.5
Apr	31.3	29.8	28.3	28.5	32.3	32.5	29.4	29.3	31.2	31.4	29.0	29.3	29.0	3.0	30.0	29.5	27.7	28.3
may	28.2	26.0	26.1	26.2	28.7	30.1	27.0	27.0	28.5	27.9	26.8	28.9	26.3	27.3	28.3	27.3	27.5	27.5
Jun	23.4	24.1	24.6	25.4	26.8	27.2	23.1	24.9	23.8	23.7	23.6	27.3	24.3	24.9	25.5	24.5	24.0	24.8
Jul		25.4	23.6	24.8	25.9	26.0	23.0	23.7	26.5	24.5	24.0	25.2	25.6	24.2	25.1	22.0	24.1	24.6
Aug	27.3	28.3	28.1	29.1	27.0	29.0	26.9	29.3	28.2	27.4	29.2	30.6	26.8	28.0	28.7	26.7	27.3	28.1
Sep	31.9	31.4	31.8	31.0	32.0	31.0	31.0	32.1	30.3	31.9	30.3	32.7	30.0	33.0	32.8	31.1	32.0	31.6
Oct	32.8	35.0	35.7	32.5	34.2	34.6	33.5	33.9	33.5	34.1	33.8	35.7	34.1	32.1	35.4	33.1	36.1	34.1
Nov	33.7	33.0	32.6	34.2	32.8	34.6	32.5	30.5	33.4	35.2	35.9	34.3	33.2	33.5	33.0	31.9	33.4	33.4
Dec	34.6	30.9	33.4	34.4	32.6	33.2	32.3	32.2	33.4	34.7	33.1	30.5	34.7	29.3	32.9	34.8	32.4	32.9

Appendix 1.2: Monthly minimum temperature for Orapa-Letlhakane area for years 1994 – 2010

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Avg
Jan	19.2	20.8	20.0	19.9	19.6	16.4	18.1	19.0	19.8	21.1	20.6	20.8	19.9	18.8	18.9	20.34	21.10	19.7
Feb	18.3	19.1	18.4	18.2	18.3	15.8	19.0	19.6	19.7	20.9	19.7	19.8	19.9	18.5	17.1		20.20	18.9
Mar	17.5	17.9	15.1	18.4	18.5	15.5	17.9	17.2	18.7	18.2	18.9	19.0	16.1	1.9	17.4	16.92	18.08	16.7
Apr		14.5	12.3	12.5	15.0	11.8	13.5	15.8	15.1	15.1	15.1	16.5	14.2	1.5	14.4	12.42	16.82	13.5
may	9.4	12.4	10.0	8.9	7.5	9.1	8.2	10.0	10.4	10.5	9.3	12.4	7.7	9.3	11.2	11.08	12.79	10.0
Jun	5.7	6.2	6.4	5.7	4.9	5.2	8.9	7.9	7.7	10.0	8.0	9.7	6.8	8.3	7.0	8.50	7.19	7.3
Jul		7.3	4.2	8.1	7.0	5.1	6.2	6.8	6.6	7.2	6.2	8.0	7.3	6.1	7.3	7.39	9.19	6.9
Aug	9.0	11.4	9.2	9.7	7.5	9.1	8.9	11.0	11.9	9.3	11.4	12.9	8.9	8.5	9.8	8.76	9.58	9.8
Sep	14.0	15.8	13.2	15.1	13.1	12.1	13.1	14.6	13.5	14.4	12.9	14.4	12.7	15.2	12.8	14.42	14.32	13.9
Oct	14.6	19.2	18.9	17.0	17.3	16.3	17.8	18.0	17.4	18.7	17.6	17.0	19.2	18.3	18.8	18.49	18.82	17.8
Nov	20.3	20.0	19.4	19.3	16.6	18.9	17.3	19.2	18.1	20.9	21.1	20.1	18.9	19.2	20.3	18.12	20.37	19.3
Dec	20.0	18.9	20.1	20.8	16.9	19.3	19.3	19.2	20.5	21.3	20.4	19.3	21.0	19.2	20.4	20.10	20.22	19.8

rom Letlhakane station for period 1993 - 2012

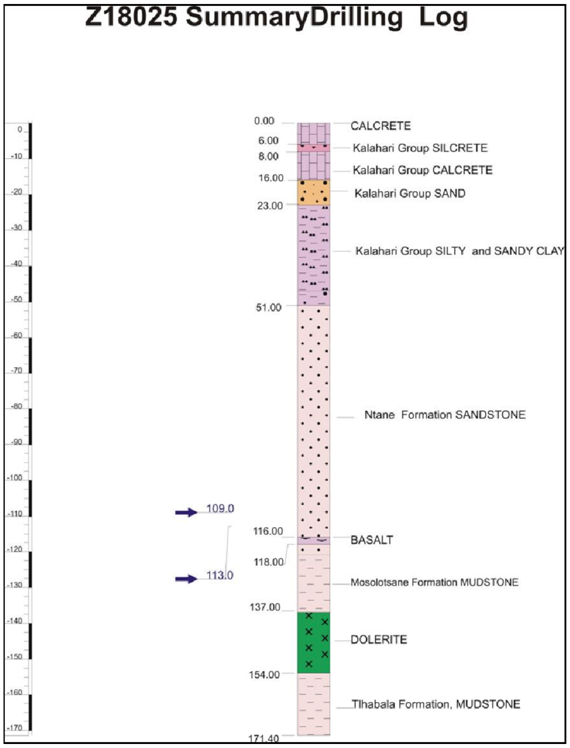
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1993	208.5	86.9	37.9	5.4	0	0	3.2	0	17.7	4.3	14.8	81.7
1994	106.8	96.6	8.7	0	0	0	0	0	0	3.1	82.7	20
1995	16.7	228.9	85.6	0	7.8	0	0	0	0	17	87.4	105
1996	157.8	221.7	14	0	18.2	0	0	0	0.6	20.6	50.3	56.7
1997	105.8	25.6	198.7	0	11.8	0	0	0	4.9	3	65.2	58.4
1998	96.7	44.7	8.3	4.4	0	0	0	0	0	16.8	35.9	88.7
1999	15.7	33.7	35.6	0.8	12.5	0	0	0	0	0.4	40.3	207.2
2000	241.5	156.4	80.5	7	9.4	49.3	0	0	0	9.1	47.6	71.7
2001	21.3	66.7	109.3	4.1	9.1	0	0	0	0	25.9	164.8	29.6
2002	31.1	24.3	3.8	4.4	6.2	0	0	3.5	15.3	1	29.8	102.8
2003	21	41.6	37.3	1.3	0	1.5	0	0	0	10.2	9.5	47.9
2004	112.9	84.6	45.6	2.2	0	0	0	0	0	21.2	6.8	87
2005	61.9	47.5	60.7	95.4	0	0	0	0	0	0	196.3	69
2006	151.7	190.5	24.8	5.3	4.1	0	0	1	0	0	18.7	102.6
2007	48.3	33	96.8	0	0	0	0	0	17.2	59.3	22.3	144.5
2008	90.5	14.6	77.1	42.4	0	0	0	0	0	0	25.3	25.7
2009	150.1	70.3	42.2	0	22.3	180.7	0	0	5.1	19.3	49.9	10.4
2010	66.4	96.9	20	115.3	0	0	0	0	0	6	91.9	48.4
2011	144.8	94.4	4	83	0	0	5.8	0	0	24	102.2	90.4
2012	145.2	67.8	37	0	0	0	0	0	0	75.8	14.6	57.8

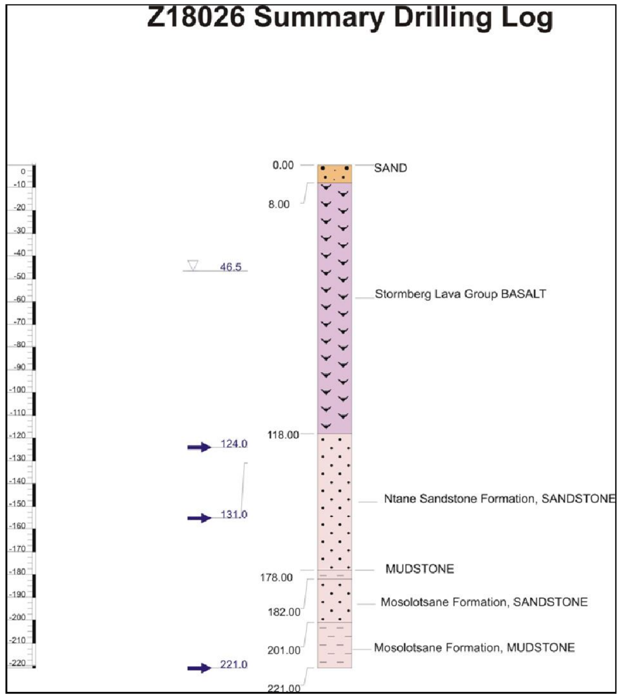
Appendix 1.4: Monthly rainfall measured from Orapa Power station for period 1983 - 2010

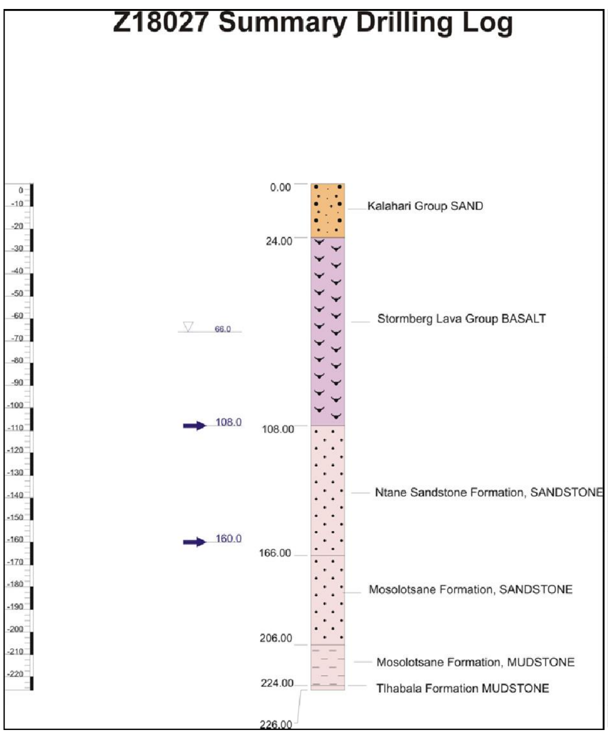
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1983	17.5	28	10.9	7	17.5	4.5	0	0	0	14	32.1	46
1984	24	45.3	48.5	3.3	0	0	2	0	11.1	11	64	11.3
1985	35.8	37.6	49	0	0	0	0	0	0	24.3	0.5	35.9
1986	95.6	34.2	35.3	36	0	0	0	0.8	7	27.8	42.5	18.5
1987	3	11	14.5	0	0	0	0	0	0	0	54.2	93.6
1988	70.5	153.8	104.2	37.6	0	0	0	0	3.6	88.7	0	86.9
1989	41.3	117	12.2	58.3	0	0	0	0	0	28.8	65.7	30.2
1990	135.2	54.6	54.5	7.5	46.5	0	0	0	0	12.2	24.5	46
1991	153	115	47.5	0	0	0	0	0	0	13	28	37
1992	42	12.5	41	7.6	0	1.5	0	0	0	3.5	50.5	40.5
1993	101.5	128.5	7.5	1	0	0	2	0	19	15	28	81
1994	109.5	62.5	4.5	0	0	0	0	0	0	1.5	74	28
1995	60.5	54.5	61.5	0	0	0	0	0	0	24.5	62	95.5
1996	251	295.5	14.5	2.5	12	0	0	0	0	0.5	45.5	56.5
1997	109.5	24	168	0	0	0	0	0	11.5	41.5	103	74

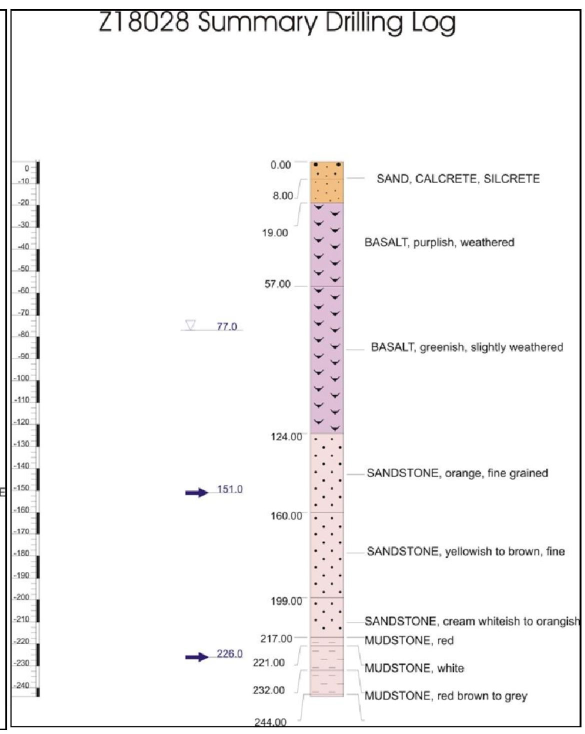
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	19.5	113	90
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	0	0.5	16	104
2000	251	210	185	8	3	32.5	0	0	0	12	49.5	82.5
2001	14.5	139	186.5	9.5	0	0	0	0	0	36.5	96.5	86
2002	39.5	4.5	22	4	5.5	0	0	2.5	20	2	1	70
2003	0	53	13	2	0	4.5	0	0	0	2	5.8	34.6
2004	64.9	122	158.6	1.3	0	0	0	0	0	13.2	15.8	96.5
2005	99.7	42.7		0	0	0	0	0	0	0	102.5	116.4
2006	106.7	164.9	48.8	0	5	0	0	0	0	0	31.4	77.1
2007	107	45.6							26	95.7	61.2	202.6
2008	149	6.1	56.9							10.4	155.1	10.5
2009	141.5	15.4	15.1	0	14	174.1	0	0	0	0	53.6	
2010	33.5	76.5	68	0								

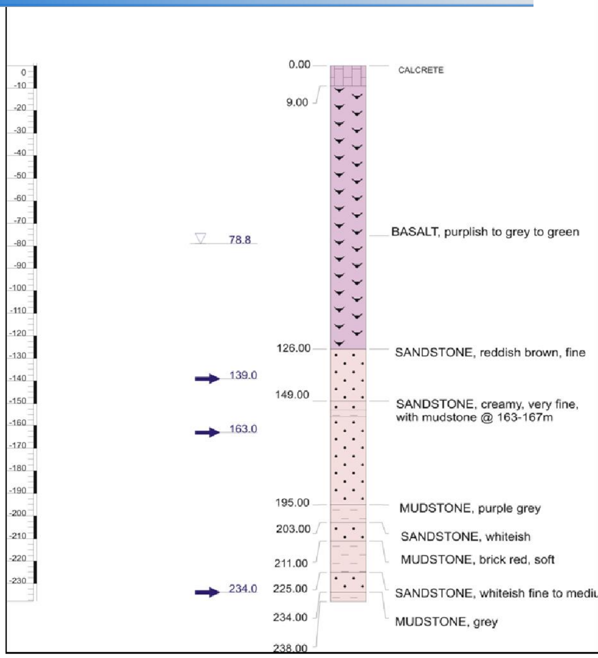
...gical Logs


Z18025 SummaryDrilling Log
0.00
CALCRETE
6.00
Kalahari Group SILCRETE
8.00
Kalahari Group CALCRETE
16.00
Kalahari Group SAND
23.00
Kalahari Group SILTY and SANDY CLAY
51.00
Ntane Formation SANDSTONE
109.0
116.00
BASALT
118.00
113.0
Mosolotsane Formation MUDSTONE
137.00
DOLERITE
154.00
Tlhabala Formation, MUDSTONE
171.40

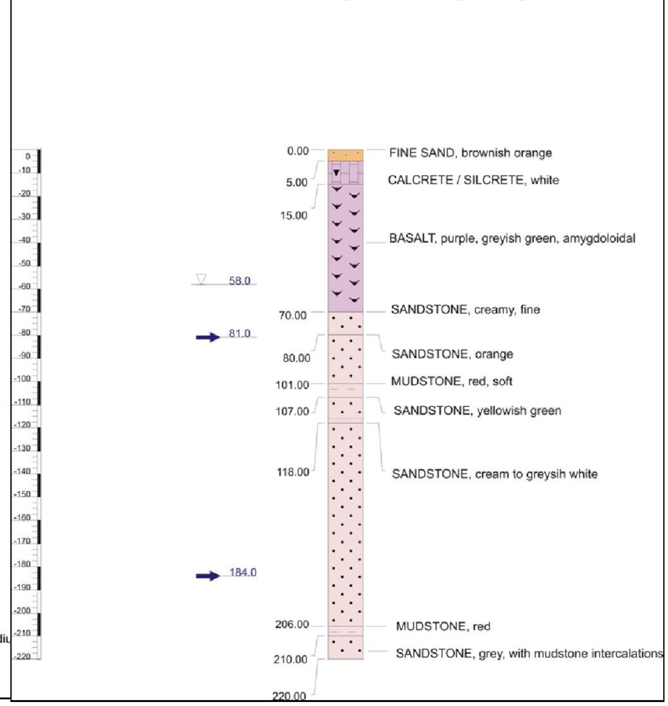

Z18026 Summary Drilling Log
0.00
SAND
8.00
46.5
Stormberg Lava Group BASALT
124.0
118.00
131.0
Ntane Sandstone Formation, SANDSTONE
MUDSTONE
178.00
182.00
Mosolotsane Formation, SANDSTONE
201.00
Mosolotsane Formation, MUDSTONE
221.0
221.00


Z18027 Summary Drilling Log
0.00
Kalahari Group SAND
24.00
Stormberg Lava Group BASALT
108.0
108.00
Ntane Sandstone Formation, SANDSTONE
160.0
166.00
Mosolotsane Formation, SANDSTONE
206.00
Mosolotsane Formation, MUDSTONE
224.00
Tlhabala Formation MUDSTONE
226.00

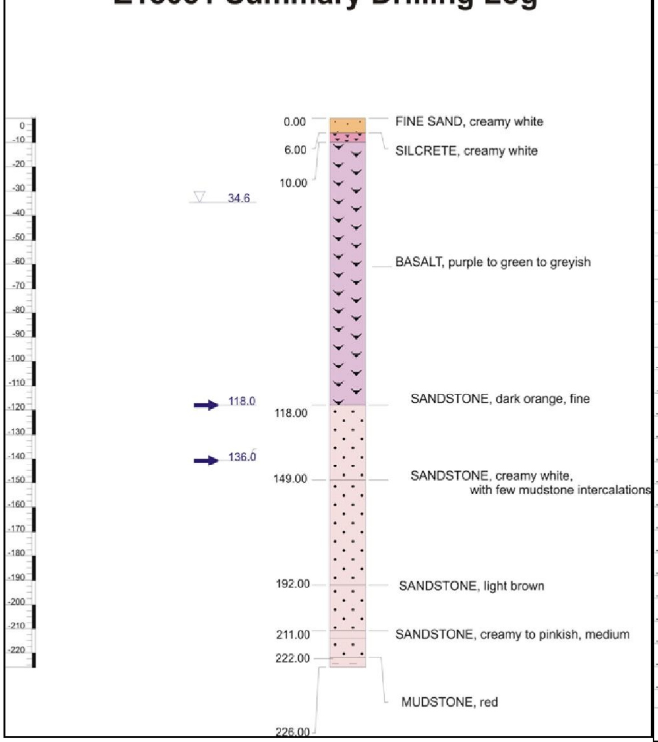

Z18028 Summary Drilling Log
0.00
SAND, CALCRETE, SILCRETE
8.00
19.00
BASALT, purplish, weathered
57.00
77.0
BASALT, greenish, slightly weathered
124.00
SANDSTONE, orange, fine grained
151.0
160.00
SANDSTONE, yellowish to brown, fine
199.00
SANDSTONE, cream whiteish to orangish
217.00
MUDSTONE, red
226.0
221.00
MUDSTONE, white
232.00
MUDSTONE, red brown to grey
244.00



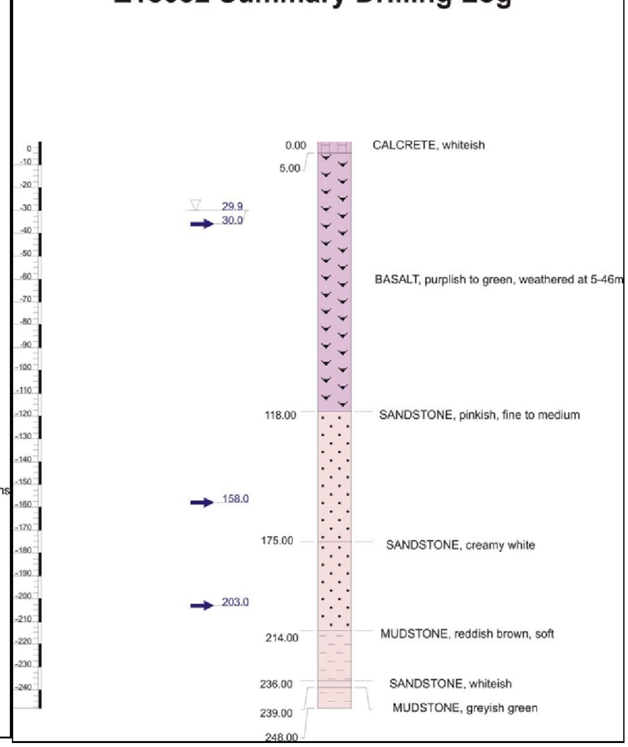
Z18030 Summary Drilling Log

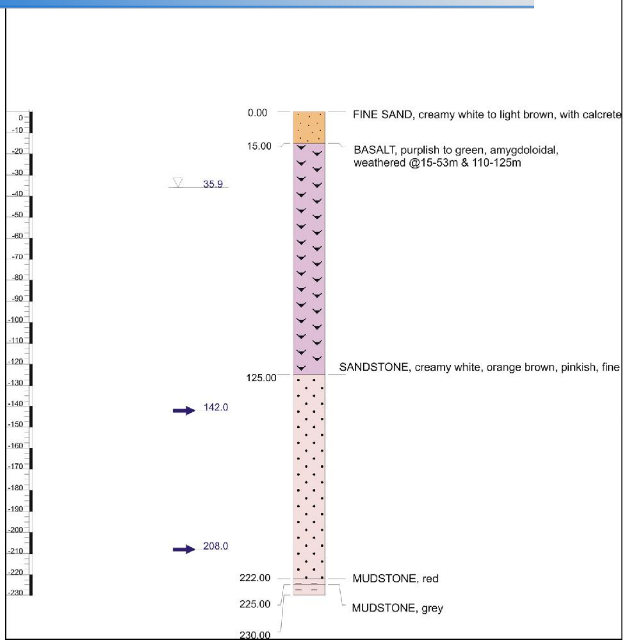


Z18031 Summary Drilling Log

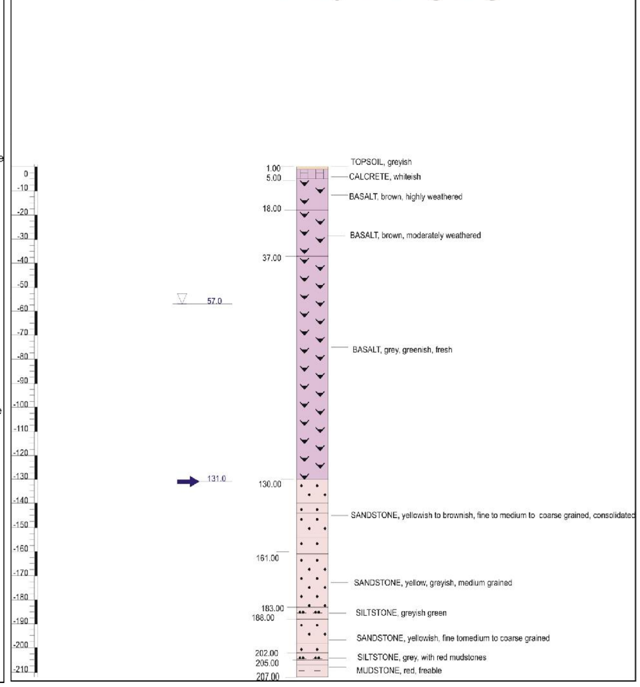


Z18032 Summary Drilling Log





Z18034 Summary drilling Log



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Borehole	PROJECTION	EASTING	NORTHING	Ground Elevation (mamsl)
Z12515	UTM 35 S, WGS 84			
Z12516	UTM 35 S, WGS 84			1005
Z12517	UTM 35 S, WGS 84	332601	7625149	1007
Z12518	UTM 35 S, WGS 84	344317	7626660	1000
Z12519	UTM 35 S, WGS 84			1019
Z12520	UTM 35 S, WGS 84	338648	7625631	1005
Z12521	UTM 35 S, WGS 84	334044	7621180	1019
Z12522	UTM 35 S, WGS 84			1003
Z12562	UTM 35 S, WGS 84			1006
Z12565	UTM 35 S, WGS 84	329632	7628572	1002
Z12566	UTM 35 S, WGS 84			1002
Z18025	UTM 35 S, WGS 84	324385	7636274	987
Z18026	UTM 35 S, WGS 84	342842	7633595	991
Z18027	UTM 35 S, WGS 84	341488	7637782	978
Z18028	UTM 35 S, WGS 84	333508	7636127	986
Z18029	UTM 35 S, WGS 84	330115	7635712	991
Z18030	UTM 35 S, WGS 84	328525	7638848	987
Z18031	UTM 35 S, WGS 84	329622	7633165	998
Z18032	UTM 35 S, WGS 84	344647	7635053	987
Z18033	UTM 35 S, WGS 84	331634	7631643	999
Z18034	UTM 35 S, WGS 84	333504	7633810	993
Z18272	UTM 35 S, WGS 84	341305	7630719	997
Z18273	UTM 35 S, WGS 84	327522	7630913	1003
Z18274	UTM 35 S, WGS 84	342150	7629486	1000
Z18275	UTM 35 S, WGS 84	323403	7631283	1000
Z18276	UTM 35 S, WGS 84	333498	7636162	987
Z18277	UTM 35 S, WGS 84	325851	7628368	1005
Z18278	UTM 35 S, WGS 84	336783	7625488	1006
Z18279	UTM 35 S, WGS 84	330825	7627930	1003
Z18280	UTM 35 S, WGS 84	326621	7626166	1013
Z18281	UTM 35 S, WGS 84	335146	7622805	1008
Z18341	UTM 35 S, WGS 84	342023	7626839	1001
Z18342	UTM 35 S, WGS 84	329939	7624866	1012
Z18343	UTM 35 S, WGS 84	333271	7627790	1001
Z18344	UTM 35 S, WGS 84	338341	7627908	1001
Z18345	UTM 35 S, WGS 84	347848	7627652	1005
Z18346	UTM 35 S, WGS 84			1005
Z18347	UTM 35 S, WGS 84	338384	7627911	1002
Z18350	UTM 35 S, WGS 84	326620	7626166	1011
Z18475	UTM 35 S, WGS 84	323438	7631287	1000