DEPARTMENT OF GEOLOGY

CHARACTERISATION AND GROUNDWATER FLOW REMODELING, DUKWI WELLFIELD PHASE II NORTH-EASTERN SUB-DISTRICT BOTSWANA

By

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STATEMENT OF ORIGINALITY OF AUTHOURSHIP

The work contained in this thesis has not been previously submitted for a degree or diploma at any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

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ABSTRACT

The Dukwi WellField phase II groundwater flow model has been audited, remodelled and updated to 2015. The current model (2015 DWM) is a three dimensional groundwater flow model. The model covers Phase II of the wellfield while the former were two dimensional groundwater flow models and covered the Dukwi regional wellfields of which some were decommissioned over time. The remodelling exercise serves to rationalize, update and upgrade the previous DWM, its audits and to incorporate them into one integrated model that will describe the entire area to greater detail. The exercise involved reconstruction of the Model slices and structures using the geological and hydrogeological data at hand. The most striking findings of the 2015 Dukwi wellfield Phase II model are its contrasting water resources quantitative simulations in relation to the former DWM. The current model reflects a simulated recharge of 2800 m^3/d, simulated abstraction of 4517 m^3/d and simulated available water resources of 1630 m^3/d, while the latest former Dukwi Wellfield water resource evaluation studies (DWA, 2008) reflected simulated values of 3493 m^3/d, 6758 - 10137 m^3/d and 3379 m^3/d, respectively. The former Dukwi Welfield water resources evaluation studies (DWA, 2008) further predicted maximum drawdown of 37m by the year 2059, for a close period by the year 2055 the current model predicted maximum drawdown of 13m. The minimum available drawdown for the Dukwi WellField is about 25m, the current model simulations therefore reflects that the aquifer system can sustain the demand beyond the year 2055. The 2015 DWM provides information that serves as a tool for understanding the aquifer system and its behaviour in its current state; it is also useful for predicting its responses (water levels and drawdowns) and volume fluxes of the ground water resources for implementation of management alternatives like increased or decreased abstraction.

DEDICATION

This thesis is dedicated to my mother Elisah Legadiko, for her kindness and devotion, and for her endless support throughout my years of studies.

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ABBREVIATIONS

Bicarbonate	HCO_3
Borehole	Bh
Centre for Applied Research	CAR
Calcium	Ca
Chloride	Cl
Cubic meters per day	m^3/d
Cubic meters per hour	m^3/h
Cubic meters per year	m^3/yr
Department of Environmental Affairs	DEA
Department of Water Affairs	DWA
Dukwi Wellfield Model	DWM
East	E
Geological surveys	GS
Graphical User Interface	GUI
Integrated Water Resource Management & Efficiency Planning	IWRM - EP
Iron	Fe
Kilometres	Km
Magnesium	Mg
Manganese	Mn
Maximum	Max
Metres	m
Metres above mean sea level	mamsl
Metres below ground level	mbgl
Milligrams per litre	mg/l
Millimetres	mm
Millimetres per day	mm/d
Millimetres per month	mm/month
Millimetres per year	mm/yr
Million years	Myr
Million cubic meters	Mm^3
Minimum	Min
North	N
Number	No
Partial Differential Equation	PDE.
Percent	%
South	S
Square meters per day	m^2/d
Square kilometres	km^2
Standard deviation	Std. Dev.
Static water level	SWL
Storativity	S
Swidish Consulting Company	SWECO
Total dissolved solids	TDS
West	W
World Health Organisation	WHO
Year	yr

1.0 INTRODUCTION

1.1 BACKGROUND

Water resources constitute the most critical issues for sustainable economic growth and the integrity of natural ecosystems and human societies that depend on them. Many countries including Botswana are facing a wide range of challenges directly or indirectly associated with the availability and distribution of water resources. The common challenges include but are not limited to; shortage of portable water, continuous degradation of water quality, inadequate sanitation facilities, climate change, increasing and competing demands for water resources across sectors such as mining and agriculture. Challenges of water resources management and use therefore require integrated approaches that address them holistically across all sectors.

Water resources occur in various ways that include groundwater, surface water, and treated wastewater. In Botswana groundwater varies widely in terms of quality with highly saline sources in the western part of Botswana and in terms of rates of replenishment of the aquifers (IWRM-EF, Volume 1, 2003). Many of the surface water sources in Botswana occur within shared (trans-boundary) river basins. Arid conditions are persistent in Botswana, summer seasons are prolonged (DEA & CAR, 2006) and thus increased evaporation rates adding to the unreliability in the few available surface water supplies. In an attempt to cope with the ever increasing demand for water resources under various sectors, Botswana had to exploit both groundwater and surface water resources for supplies. A review of Volume1 of the Main Report for Integrated Water Resources Management &Water Efficiency Plan published in May 2013 by the Department of Water Affairs reveals volumes of potable water the country receives from wellfields and storage dams. The estimated combined sustainable yield of Botswana's wellfields and storage dams was 165 Mm^3/a or 216 L/person/day, where by sustainable yield of aquifers constitutes 96 Mm^3/a or 125 L/person/day and sustainable yields of dams were 73.2 Mm^3/a or 95.89 L/person/day based on the 2011 national population census estimate of 2,024,904 people (Statistics Botswana, 2011). This is less than the current water demand of around 200 Mm^3/a (262 L/person/day). According to the report, New dams were to relieve the situation by increasing the overall yield to 317 Mm^3 (415 L/person/day), but this was to offer temporary relief.

Groundwater is a key source of portable water, in many towns, villages, mining industries, agricultural industries in Botswana and at large. This is because of its abundance, distribution, stable quality and relatively inexpensive exploitation (Morris et al., 2003) as compared to surface water exploitation which encompass constructions of storage dams and engineering activities to make the water reach the intended destination.

The vital component of groundwater studies is the investigation and analysis of its occurrence, distribution, quantity and quality over space and time. This includes a determination of its location for protection against contamination, its replenishment rates aimed at assessing the sustainability of the resource in coping with the demand, analysis and monitoring of the chemistry.

Groundwater modelling is performed with computer based programs to analyse groundwater flow and water balance in a given aquifer system (Brassington, 1998). It is a simulation method used to determine and predict response of the aquifer system to various pumping or injection scenarios. This includes estimation of hydraulic parameters, response of the aquifer to climate changes, water abstraction, and recharge influxes and to quantify the resource (Water Lines Report Series no 82, 2012). Groundwater flow is governed by an array of equations; the equations are commonly solved through numerical predictive groundwater models. The groundwater flow conceptual model is first laid down and later refined through numerical models.

Groundwater abstraction rates should be established with consideration to the aquifer's recharge rates to avoid mining of the resource (over exploitation) hence an encouragement for adaptation of sustainable abstraction rates. Groundwater occurrence, storage and distribution are governed by geology and structures, that is; porosity, fractures and thickness of the geologic units. The other crucial factor is considering that the aquifer is an open system hence needs to set boundaries to the zone of interest, but with an appreciation that the system is not isolated and therefore can be affected by activities outside the set boundaries which are in its vicinity. The factors which commonly affect groundwater resources include contamination and water table fluctuation in response to climate change and or recharge and discharge.

The Dukwi area is poorly endowed with surface water resources to meet increasing demand of a growing population. These accentuate the importance of groundwater resources in the area. The Dukwi regional wellfield has been identified by the Department of Water Affairs as one of the most important sources of potable water supply in the area (DWA, 1996). The Dukwi regional wellfield was developed between 1992 and 1995 and comprised of the Dukwi wellfield Phase I, Dukwi wellfield Phase II, Chidumela wellfield and Soda Ash Botswana boreholes. The Chidumela wellfield, Dukwi wellfield Phase I and Soda Ash Botswana wellfield were decommissioned in 2008 in response to diminishing water quality. The Dukwi wellfield Phase II is the only wellfield currently in operation. The wellfield comprises four production boreholes with an average sustainable yield of 30 m^3/h per borehole (DWA, 2008). The wellfield currently supplies Sowa Town, Soda Ash Botswana mine, Nata and Dukwi villages as well as the Dukwi Refugee camp and Quarantine Camp. The Dukwi wellfield boreholes extract groundwater from the Mea Arkose aquifer which is the main aquifer in north-eastern Botswana. The Mea Arkose is part of the Karoo Supergroup.

The other Karoo formation, the Ntane sandstone is also present in the region and like in other parts of the country where it has been intercepted it proved aquiferous, however, boreholes tapping water from this aquifer have reported TDS values of 1500mg/l which is above the limits for recommended domestic supply (DWA, 1996).

Sowa Town and Nata village have a history of boreholes drilled in their vicinity yielding saline waters, this has prompted for their potable water supply to be through a 30 km and 50 km pipeline from Dukwi wellfield, respectively (DWA, 2005).

At present the Dukwi wellfield Phase II in its current state exhibits no sustainable capacity to cope with the demand for water supply from the centers which are dependent on it. This is based on the outcomes of a review on Sustainability of Groundwater Resources in the Dukwi wellfields by the Department of Water Affairs (DWA, 2008). Table 1 reflects on the sustainability of the developed groundwater resources in the Dukwi wellfield just before the Chidumela wellfield, Dukwi wellfield Phase I, and Soda Ash Botswana boreholes were decommissioned.

Table 1. Sustanability of Groundwater Resources in Dukwi Wellfield.

Wellfield	Available developed resource (m^3/d)	Sustainable resource (m^3/d)	Current abstraction (m^3/d)	Annual abstraction (M m^3/year)
Dukwi	5700	600	6600	2.44

The abstractions for Dukwi wellfields were very high and unsustainable. Available developed resource in Dukwi Wellfield was estimated at 5, 700 m^3 per day. The estimated abstraction was around 6600 m^3 per day which was more than the available developed resource, estimated at 5, 700 m^3 per day. Dukwi Wellfield abstraction consisted of 1200 m^3, 1700 m^3 and 3700 m^3 per day being abstractions from Chidumela, Botash and the Dukwi wellfields boreholes, respectively. The existing groundwater flow models for the Dukwi wellfields predictions indicate that pumping at these high rates could be supported up to at least the year 2020 (Central Statistics Office, 2008). In 2008, the Dukwi wellfield Phase I, Chidumela wellfield and Botash wellfields were decommissioned due to decline in water quality. The current study is therefore carried out on the Dukwi wellfield phase II. The wellfield has four production boreholes under operation each pumping about 1000 m^3 per day, total yield of about 4000 m^3 per day (DWA, 2008). The current abstraction is therefore still very high considering the statistics in table 1.

1.2 PROBLEM STATEMENT

The Dukwi Regional Wellfield and its numerical ground water flow model were developed between 1992 and 1995. The wellfield has been running since, the model was last audited 12 years ago in 2003 by the department of water affairs (DWA, 2005). There have been changes (factors) that may have contributed to making the former groundwater models invalid at present. The factors include; Decommissioning of Boreholes or Wellfields as elaborated in section 1**,** Population growth and industrialisation hence increased abstraction**,** climate change and diminishing water quality.

There is need for up to date information to assess the consequences induced by the discussed factors and for proper management of the Dukwi wellfield Phase II going forward. A tool is therefore needed that will provide this information. The tool for understanding the system and its behavior and for predicting its response is a groundwater flow model. The model takes the form of a set of mathematical equations, involving one or more partial differential equations, such model is a mathematical model. There is need to carry out this project as it stands out that 12 years is a long period for an operating wellfield to take without being remodelled or audited.

1.3 THE OBJECTIVES

1.3.1 General Objective

To quantify and asses the available developed potable groundwater resources in the Dukwi wellfield Phase II in terms of total recharge, discharged and storage in the aquifer system under the current conditions as well as to analyse responses of the aquifer system under various scenarios and stresses over space and time.

1.3.2 Specific Objectives

The specific objectives of this project are fivefold**;** the first objective is to conceptualise hydrogeological setup of the study area through integration of the latest available geological, hydrogeological, geophysical and remote sensing data.

The second is to audit, remodel and update the 2000 Dukwi Wellfield numerical groundwater flow model and its audits to 2015 using the latest techniques and available data.

The third is to estimate and project the aquifer drawdowns and hydraulic head distribution over the next 45 years and therefore to assess sustainability of the groundwater resources in the Dukwi wellfield Phase II under current conditions.

The fourth objective is to analyse the current water quality data from the Dukwi Welfield Phase II production boreholes to evaluate its suitability for human consumption as per the 2009 Botswana Bureau of standards drinking water specifications and to delineate protection zones for the wellfield,

The last objective is to run various future wellfield development scenarios (locating potential wellfield extension site) to aid future planning and management of the groundwater resources in the Dukwi wellfield Phase II area.

1.5 HYPOTHESIS

1. Predicted head distribution and drawdown in the last Dukwi Welfield Model audits (DWA, 2005) are no longer valid at present.

2. Protection zones increase and get more spatially distributed over periods of aquifer exploitation.

2.0 LITERATURE REVIEW

2.1 GROUNDWATER

“Groundwater is the water located beneath the earth's surface in soil and rock pore spaces and in the fractures of rock formations. A unit of rock or an unconsolidated deposit is called an aquifer when it can yield a usable quantity of water to wells” (Rushton, 2003)**.**

Expanding the statement above, Groundwater is the subsurface water hosted by geologic units including porous (fractured) rocks and soils below the water table. This is the subsurface water in which fluid pressure is greater than atmospheric pressure. The water table is a boundary between the vadose zone in which the fluid pressure is less than atmospheric pressure and the saturated zone in which the fluid (water) pressure is greater than atmospheric pressure. The zone of saturation is where pores and fractures in rocks and soils are filled with water only while in the unsaturated zone they are filled with both air and water. Pores in rocks or soils may be isolated or interconnect. When pores are interconnected, they allow the flow of water through them. The subsurface can be categorised into hydrostratigraphic units with different hydrogeological characteristics. When the hydrostratigraphic unit stores and allows sufficient flow of water to wells it is called an aquifer and the opposite is an aquitard (Fetter, 1994). Aquifers can be further categorised into confined, unconfined, leaky, perched and so on. Confined aquifers are bound by impermeable units at the top and bottom while unconfined aquifers (water table aquifers) have no bounding unit at the top and have their thickness equal to the saturated thickness.

2.2 GROUNDWATER MODELS

A groundwater model is an approximated computation of a groundwater situation, aquifer or wellfield (Modified after Anderson and Woessner, 1992). Groundwater models represent the natural groundwater flow in the environment; this is a simplified conceptual representation of a component of the hydrologic circle. Models can be simple two dimensional analytical groundwater flow models or complex three dimensional numerical groundwater flow and solute transport models which model quality aspects of the groundwater system (Kresic, 1997).

Various types of groundwater models may be distinguished. These include abstract, physical, analog, and numerical models. Abstract models represent the groundwater system in a mathematical form. Numerical and mathematical models are abstract models. A mathematical model is a mathematical representation of a conceptual model for a physical, chemical and/or biological system. It consists of an equation (usually a partial differential equation) plus auxiliary conditions that describe the behavior of the real system (Anderson & Woessner, 1992). Physical models of groundwater systems were widely used before the advent of computers; these models include conceptual models of a groundwater system, an example being a sand tank used to simulate an aquifer system.

Groundwater models can be Transient groundwater models which simulate changes in heads and flows over space and time or steady state models which assume no change in heads and flows with time. Groundwater flow computations and approximations are governed by differential mathematical equations often solved by approximation method. The numerical models are usually based on the real physics the groundwater flow follows. These mathematical equations are solved using numerical codes such as visual MODFLOW, PMWIN, and FeFlow (Rushton, 2003).

Groundwater modelling requires that the water storage and transmission properties of the subsurface are expressed in quantitative terms. These models mainly aim at quantifying the resource; they take into consideration the inputs, outputs and what remains in a hydrogeological system (mass conservation). The principle of mass conservation can be expressed in mathematical terms and combined with the empirical laws (Darcy's law) that govern the flow of water and solutes in the subsurface in the form of differential equations.

The formulated differential equations can be solved using techniques of calculus that solve the governing differential equation where some simplifying assumptions are formulated. The other techinique is using numerical techniques where space and time are subdivided into discret intervals and the governing differential equation is replaced by piecewise approximations (Kresic, 1997). In solving governing differential equations, model boundary conditions, initial conditions and hydrogeological parameters need to be specified.

The methods of solving the governing differential equation include finite difference, finite element and analytical element method (Kahsay, 2008). The Finite difference method solves the governing differential equation by approximating them with difference equations in which finite differences approximate the derivatives, Finite element methods solve partial differential equations by subdividing the model domain into simpler parts called finite elements and variational methods in the calculus of variations to solve the problem by minimising the associated error function, while analytical element methods solve the partial differential equations by having only internal and external boundaries as the discretized boundary integrals, they involve superposition of analytic solutions. Heads are calculated in continuous space using a computer to do the mathematics involved in super - positioning, currently the method is limited to steady-state, two-dimensional, horizontal flow.

Historically, the Finite difference method was the first method to be used for the systematic numerical solution of partial differential equations and as result many numerical models of groundwater flow use finite-difference methods to solve the governing partial differential flow equation for groundwater flow and solute transport (Kahsay, 2008; Mehl and Hill, 2002). Furthermore, Modflow based modelling packages use finite-difference methods, the packages are in some instances freely available, this has contributed to the wide use of finite-difference methods to solve the governing partial differential equations for groundwater flow and solute transport.

The governing equation for groundwater flow in its general form is as follows (Anderson & Woessner, 1992);

For steady-state, heterogeneous, anisotropic conditions, without a source/sink term

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z})=0$$

With a source/sink term

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z})=-R*$$

General governing equation for transient, heterogeneous, and anisotropic conditions

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z})=S_s\frac{\partial h}{\partial t}-R*$$

Where; K_x, K_y and K_z -are directional components of hydraulic conductivity along the principal directions of anisotropy.

S_y -Specific yield = S_s b (Storage coefficient for unconfined aquifer)

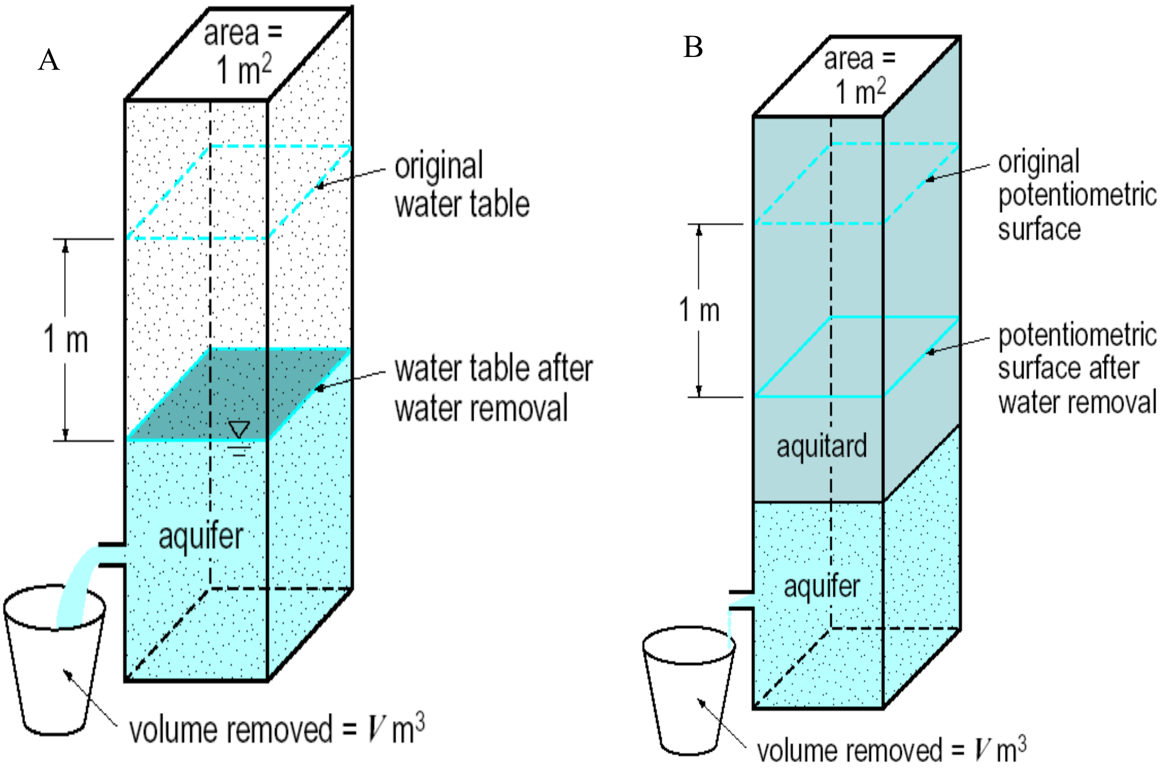
S_s - Specific Storage coefficient = $\Delta V / (\Delta x\ \Delta y\ \Delta z\ \Delta h)$ (Storage coefficient for confined aquifer)

R* source/sink term

h –hydraulic head

t –time

Storage coefficient for unconfined and confined aquifers are conceptualized in figure 1 and discussed in the proceeding text.



Unconfined aquifer - $S_y = S_s$ b Confined aquifer - [illegible]

Figure 1 (A and B) conceptualisation of storage coefficients (Saurce -Hornberger et al. 1998)

Figure 1A shows a unit of rock with the original water table and the water table after the unit of rock was dewatered under the influence of gravity. Specific yield (S_y) is the ratio of the volume of water that drains from a saturated rock under the influence of gravity to the total volume of the rock (Meinzer, 1923) that is S_y -Specific yield = S_s b (Storage coefficient for unconfined aquifer)

The specific storage is the amount of water per unit volume of a saturated formation that is stored or released from storage owing to the compressibility of the mineral aquifer skeleton and the pore water per unit change in head (Fetter, 1994), the phenomena is reflected by Figure 1B. Specific Storage (S_s) = $\Delta V / (\Delta x \ \Delta y \ \Delta z \ \Delta h)$ (Storage coefficient for confined aquifer).

2.2.1 Boundary Conditions

Groundwater system is a continuous and an extensive system, however, groundwater modeling usually focuses on a section of the system to be defined and therefore boundaries are assigned for simplification purposes. The external and internal environments of a groundwater system and their interaction determine the behavior of the system in question and such are referred to as boundary conditions (Franke and Reilly, 1987; Reilly, 2001). The features making up the internal and external environment include but are not limited to; streams, rivers, lakes and reservoirs, springs, recharge at the water table, earth materials of low hydraulic conductivity, inter-basin flow, groundwater evapotranspiration, groundwater divides, artificial boundaries that are not physical features, et cetera. Some of these allocated features have a significant impact on the behavior of groundwater systems and therefore have to be accounted for in the model (Reilly, 2001).

2.2.2 Modeling Code

Software packages for groundwater modelling are intended to solve the governing equations for groundwater flow and solute transport. Many assumptions are made to solve such equations as accurately as possible. A conceptual model of the hydrogeological system under investigation is first constructed and the governing equations are then solved numerically.

Modeling codes are interactive programs that implement a command or a sequence of commands and produces outputs (Anderson and Woessner, 1992). Software selection is a vital step in numerical groundwater modeling. There is a wide range of groundwater modeling packages which include; the modeling code that solves the equations for groundwater flow and/or solute transport, sometimes called simulation software or the computational engine, a graphical user interface that facilitates preparation of data files for the model code, runs the model code and allows visualisation and analysis of results (model predictions).

Some groundwater modelling software packages are readily available at no cost and can be modified by the user, while others are commecial and cannot be modified by the user. Some common groundwater modelling software packages include; visual MODFLOW and PMWIN. Feflow is applicable for Simulation of saturated and unsaturated flow, transport of mass (multiple solutes) and heat, with integrated graphic user interphase, HydroGeoSphere for Simulation of saturated and unsaturated flow, transport of mass and heat, SUTRA for Simulation of saturated and unsaturated flow, transport of mass and heat and many others not in the list.

All MODFLOW runs require input of the following parameters, conductivity, recharge, total porosity, specific storage coefficient, specific yield and effective porosity. The specific storage and specific yield are not required in steady state simulation while porosity is required for transport simulation.

2.3 PREVIOUS WORK

Detailed and thorough hydrogeological study were carried out in the study area by a hand full of researchers and organisations which include; Water Surveys Botswana (DWA, 1995a and b), SWECO (DWA, 1977) and WLPU (1984, 1991). These investigations entailed detailed geological, geophysical studies, drilling, test pumping, and groundwater resources evaluations, which culminated in the establishment of the Dukwi Wellfield (Phases I and II, Chidumela wellfield and Soda Ash Botswana Boreholes).

Following the establishment of the Dukwi Regional Wellfield which was developed between 1992 and 1995, a groundwater flow model was also produced by Water Surveys Botswana (DWA, 1995a and b) based on the software AQUA. The Model (Aqua Model) was then reproduced in 2000 by Geotechnical Consulting Services (DWA, 2000a and b) based on visual MODFLOW. The 2000 model was audited in 2003 by the department of water affairs (DWA, 2005). Monitoring and establishment of the Dukwi Wellfield monitoring report was also carried out by Geotechnical Consulting services (DWA, 2011). In addition, Post Graduate research authored by Mannathoko (1990) and Makobo (1996) have contributed the knowledge of the area through data compilation, analysis, and interpretation.

The former modelling activities main outputs involved mainly water resource quantification and predictions of future drawdowns and hydraulic head distributions under the then wellfield conditions. No documented groundwater flow modelling was done following the operational amendments which led to the decommissioning of the Dukwi Wellfield Phases I, Chidumela wellfield and Soda Ash Botswana wellfield.

Other works outside of wellfield establishment have also been carried out. Such include rehabilitation works in nine of the production boreholes drilled during 1994 (DWA, 1995a). The works were aimed at rehabilitating the boreholes which had screen problems. These were achieved through removal of the casing or screen to install a basal metal plug and stabilisers. Further rehabilitation encompassed borehole development using air and subsequently step test to assess the performance of such boreholes (DWA, 1996).

Other works on the study area not necessarily about groundwater investigations include the 1962 to 1963 exploration for coal by the Department of Geological Survey (DGS, 1973). The earliest geological observations recorded for the area are those of McGregor (1930) taken during a visit to the Makgadikgadi Pans. Green (DGS, 1966) published a comprehensive description of the Karoo in Botswana based on research on the Karoo System of South Africa. Stansfield (DGS, 1973) provides an initial assessment of the lithostratigraphy for the Karoo in the area around Dukwi and Tlalamabele. Smith (DGS, 1984) published a detailed stratigraphy of the Karoo Supergroup in Botswana. In his work he defines the Dukwi Basin as a sub-basin around Nata where the pre-Karoo lies at approximately 400 m below ground level and shallows towards the south, where the Archaean Basement outcrops south of Dukwi.

3.0 METHODOLOGY

The standard modelling approach was adopted, the process was five staged where the preceding step (s) laid foundation to the succeeding step (s). The initial stage involved identification of the problem. The problem solving strategies were outlined and the feasible ones were adopted. The second stage involves the conceptualization, organization and simplification of the modelling data for easy visualisation and analysis. The third stage involved solving the governing partial differential equation through the use of computer based programs in this case to simulate distribution of hydraulic heads and drawdowns as a function of space and time. In stage four the simulated parameters beforehand were compared to observed parameters for evaluation of the reliability of the simulation strategy adopted. The last stage involves application of the evaluated strategy (model) to solve the outlined problem hence a comprehensive presentation of the outcome. Figure 2 shows detailed groundwater modelling research approach adopted followed by detailled explanations.

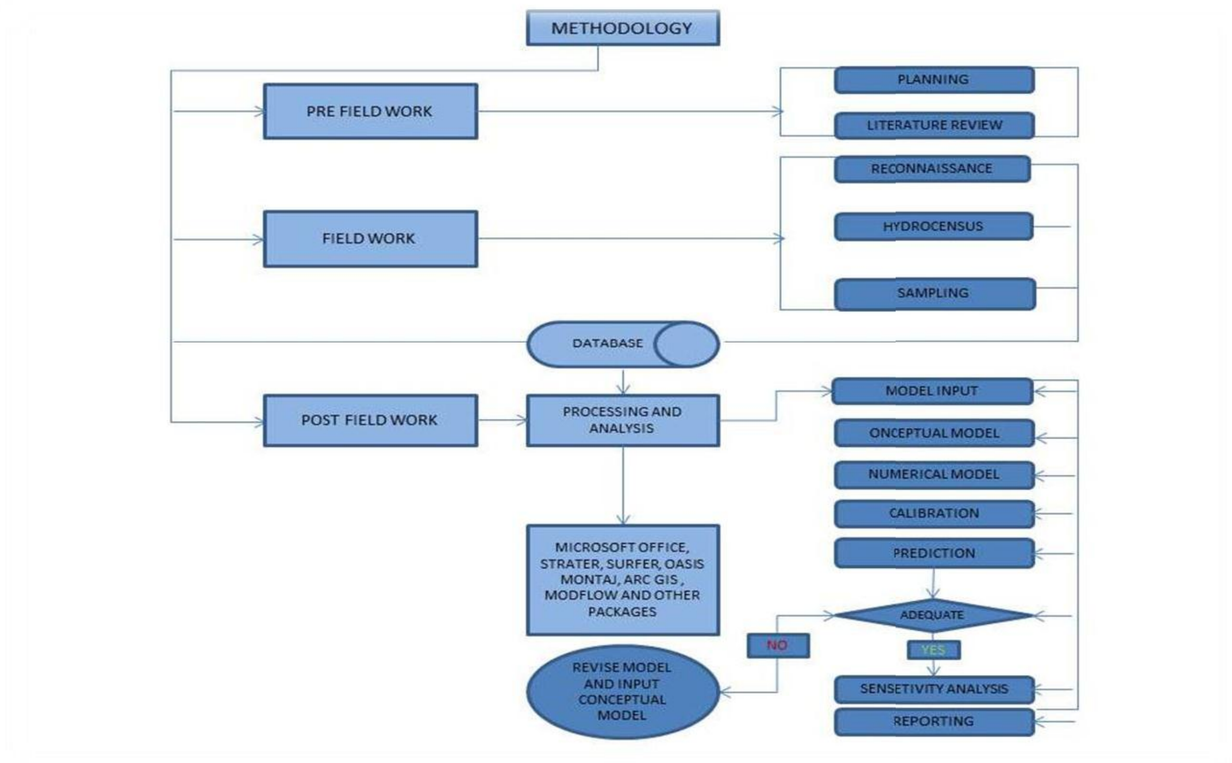


Figure 2. Groundwater Flow Modelling Approach

3.1 PRE FIELD WORK

3.1.1 Planning

This is the most critical stage of any research project. It lays a foundation for all the other subsequent stages of the research exercise. The problem statement was outlined and refined and hence the purpose of the modelling exercise was outlined, project objectives were stated to guide and confine the research exercise to make it feasible and practical. Data availability, time constraints and resource availability assessment was carried out to derive the confidence level on the research results.

3.1.2 Literature review

Literature review or intensive desk top study was carried out to inquire on data availability and on previously or running research projects in the vicinity of the project area. The desk top study stage also involved an assessment on availability and affordability of modelling codes applicable to the research project, extent of area of interest and the data format required for the modelling exercise.

3.2 FIELD WORK

3.2.1 Reconnaissance Survey

This encompassed exploring the study area to gain vital information on features of the environment for later analysis and or dissemination. The first step of reconnaissance survey was to find all available existing maps that show the area to be reconnoitred Studying the existing maps and aerial photographs, helped in eliminating challenges such as further consideration of an unfavourable route, thus saving much time. The maps and aerial photographs helped in the assessment and recording of the in situ positions of environmental features and their relation to other sites in their vicinity. The features of interest entailed access points, features such as outcrops, geological structures and other topographic features such as elevations, streams, slopes, flood plains, et cetera.

3.2.2 Hydrocensus

This literally means “water census”. It involved gathering information on water features (water audit), sources of water supply and water quality. This was an exercise intended at presenting information on location of water features and sources which were mainly boreholes. The exercise aimed at; identifying water related features which encompassed erosion gullies, storm water channels and diversion embankments, features where water could collect during rainy seasons such as ponds, lakes, quarries and huge barrow pits, potential sources of contamination such as dumping sites and pit latrines as well as water points or sources which included boreholes.

3.2.3 Hydrosampling

This stage encompassed bailing out a few water samples for chemical analysis (TDS, EC and pH) *in situ* and for more detailed laboratory test. Water samples at each production borehole were collected; each water sample was collected in two parts or bottles, one acidified and the other non-acidified. One bottle is acidified so that certain chemical elements such as iron (Fe) and manganese (Mn) do not precipitate but remain in solution until the sample is analysed in the laboratory. Appropriate sampling bottles were used and samples were stored in a cooler box with ice packs to slow down chemical reactions during transportation. The water samples collected from each production borehole in the Wellfield area were submitted at WUC laboratory for detailed analysis. The outcomes of water quality analysis results were made available for the current study by the Department of Water Utilities Cooperation.

3.3 POST FIELD WORK

3.3.1 Data Processing and Analysis

A compilation of all the data that was collected in both pre - field work and during field work helped in producing a database. The data was processed into maps (contour maps, geology maps, and scatter maps), graphs, models and many other data formats. Many software packages were employed in data processing and analysis, such packages include Microsoft office, Strater, surfer, Grapher, oasis Montaj, and MODFLOW. In instances where there were gaps in recorded data, averages of recorded data were used to estimate the missing data. The following stages were followed when carrying out the data processing, analysis and production of the numerical model.

3.3.2 Conceptual Model

Conceptualisation is a descriptive representation of groundwater system operating across the study area, its interaction with external systems and the resulting outcome (Water Lines Report Series no 82, 2012). This stage involved data analyses to derive and compute physical processes governing groundwater flow and occurrence in the study area. The data was acquired through field measurements and observation. The collected data was integrated with data retrieved from existing databases and was analysed and presented. Some specific aspects of the physical environment were therefore represented in the model. In cases where available data was not sufficient, conceptualisation seemed challenging and hence additional data was acquired or other approaches were used and or the set objectives were refined or modified.

The most significant aspects of the physical environment which were considered in the conceptualisation stage include but not limited to:

Hydrostratigraphic units and boundaries: this is mainly about rock types on the study area, their distribution and extents. The degree of weathering and fracturing of the rocks observed or expected in such rocks were very important since they influence hydrogeological coefficients or parameters such as storage parameters, conductivity and transmissivity coefficient.

Structures; the structural features controlling or influencing groundwater flow includes but not limited to bedding, faults, fractures and joints. Hydrogeological data also forms part of the conceptualised aspects: regional and local water table levels, flow directions and the storage, transmissivity and conductivity coefficients were considered. Topography aspects were also considered in the conceptualisation stage since geomorphological aspect of the study area has significant effects on groundwater behaviour.

The conceptualisation stage was a very important stage, it is perceived as a pseudo representation of the actual groundwater system. Construction of a good conceptual model makes it easy to implement the numerical model. Field visits were made during this stage and they motivated the adaptation of reality which exerted a positive influence on the subjective decisions made during this stage.

3.3.3 Selection of Modelling Code

This stage involved choice of modelling package, extracting and allocating the initial conditions to be modelled or to help in building the overall numerical groundwater flow model. The conditions were presented in a format that is compatible with the modelling code. Verification of the modelling code and the governing equation was also carried out in this stage.

3.3.4 Construction of Numerical Model

In this stage the governing partial differential equation was solved using visual MODFLOW (Schlumberger Water Services). The results obtained were compared to observed data. This stage is known as the calibration stage. If simulated and observed values are acceptable, this step is followed by the prediction phase. Numerical model construction involved use of the modelling code (modelling software). Model dimension were chosen based on the objectives of study, the model can either be 1, 2 or 3 dimensional. In this research project a 3 dimensional model was considered suitable to achieve the objectives and hence was chosen. This stage also involved making decisions on the size of the model (areal extent), formulation of model grids for numerical computations, simulation time, assigning boundaries to represent interaction between groundwater and surface water features. Other aspects that were considered during model construction include rainfall, evaporation and evapotranspiration, groundwater abstraction and hydrogeological properties.

3.3.5 Calibration of the Model

Calibration was undertaken by trial and error approach and by means of parameter estimation code and convergence was judged using data for the piezometric surface generated at monitoring wells.

The aim of this exercise is to find parameter values that allow the model to match or reproduce historical measurements to enable the model to be useful in projection or extrapolation.

3.3.6 Prediction

This stage involved making projections on the working system (groundwater flow model) on how the climatic, abstraction and drainage stresses will affect water levels and chemistry after given stress periods outlined under the objectives.

3.3.7 Sensitivity Analysis

A sensitivity analysis was performed to assess response in groundwater head induced or imposed by changes in hydraulic parameters. This was implemented by varying the Transmissivity (T) and Storativity (S) parameters within the range 0.1 to 10 times the values used for resource modelling. Recharge was not used since the model was calibrated on fixed recharge. This approach was adopted since recharge is relatively easy to estimate based on chemistry, rainfall data and many other methods. Model verification was then carried out using a set of calibrated parameter values and stresses to further establish confidence in the model.

3.3.8 Model Reporting

This stage encompasses documentation and communication of different stages of the modelling process through a written technical document. The report describes the model, all data collected and the results obtained through the modelling process. The report may be accompanied by an archive of all the model files and all supporting data so the results presented in the report can, if necessary, be reproduced and the model used in future studies.

4.0 THE PROJECT AREA

4.1 LOCATION AND ACCESS

The Dukwi WellField Phase II is located in the North-eastern region of Botswana about 130 km Northwest of Francistown city. The wellfield covers an area of approximately 480 km^2. The project area is bound by lines of longitude 26°21’E and 26°29’E and lines of latitude 20° 31’ S and 20° 35’S. The wellfield is bound by Mosetse River to the south and Nata and Semowane to the North and is in proximity of the Makgadikgadi inland basin to the eastern edge (DWA, 1995a).

This Dukwi Wellfield Phase II consists of four production boreholes which are currently in operation and supplying water to Dukwi, Nata, the Refugee Camp, and the Soda Ash Botswana (SAB) Plant. The access to this wellfield is possible via the Francistown – Nata road, and through gravel and muddy roads; the access varies in difficulty from time to time and generally more challenging during rainy seasons. Routine manual water level monitoring, water sampling for water chemistry analysis and local farmers helps in keeping the routs in existence. Figure 3 is a section of map of Botswana showing the project area and boreholes comprising the Dukwi wellfields.

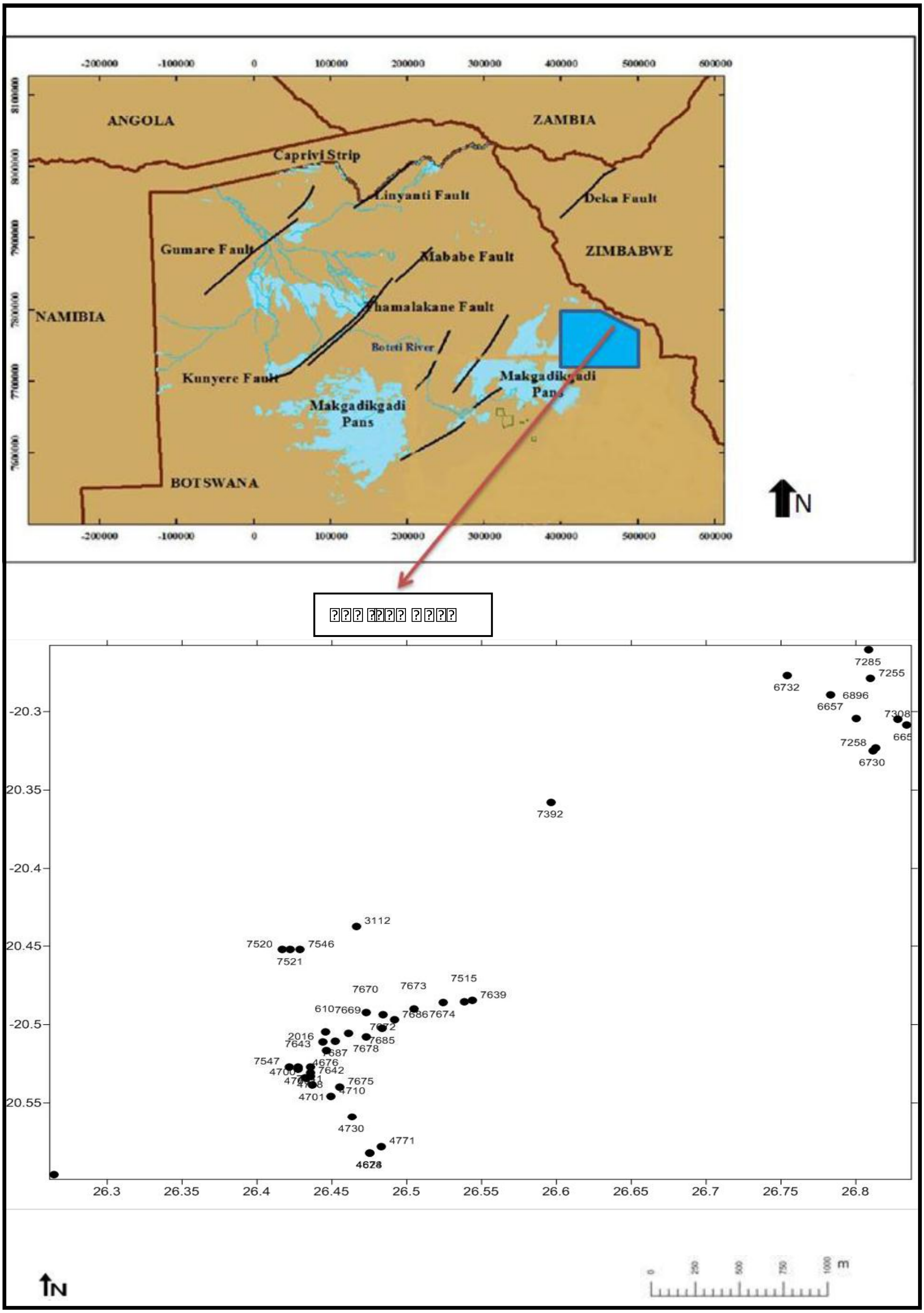


Figure 3. Location of the Project Area

4.2 PHYSIOGRAPHY

The study area is generally flat and dips gently towards the west (regional ground surface gradient is 1.7 m/km) to the Makgadikgadi depression at which the aquifer system of the study area discharges. The ground elevation has a maximum variation of up to 100 m amsl with the highest elevation of about 1000 m amsl to the east and minimum elevation of approximately 900 m amsl at the edge of Sua Pan.

Surface drainage is dendritic and is dominated by the Mosetse River to the south, Tutume River, Semowane River and Nata Rivers to the north. The streams run south-east to north-west and ultimately draining to the Makgadikgadi Pans as these form a regional surface water sink. Low gradients control the deposition patterns resulting in wide braided plains and inland deltas where the rivers enter Sua Pan. The 940 m amsl ground surface contour line represents the eastern-most limit of the palaeo-Makgadikgadi Lake. Upstream of this elevation, the river channels are highly sinuous, whereas downstream the channels are anastomosing (DWA, 1995a).

There are no perennial rivers in the project area, although streams may flow for all or part of their length after heavy rains. The study area is dominated by well-developed plains with a thick sand cover of up to 20 m in most parts. There is however some significant topographic features occurring to the south east of the wellfield area where a linear ridge (Kgwana Hills) of quartzitic inselbergs trending north – south dominates part of the project area. The hills are features of highest elevation of the project area at about 1065 m amsl.

4.3 CLIMATE

The climate of north-eastern Botswana (study area) as interpreted based on data acquired from the department of Botswana Meteorological Services shows that the area is generally similar to the rest of the country. The climate of the country is semi-arid and dry. The Rainfalls are unreliable and unevenly distributed. Its best rains are found to the north-east, and rainfall decreases further west and south. Most of its rains are received during the rainy season between the months of October and March. (Figure 4).

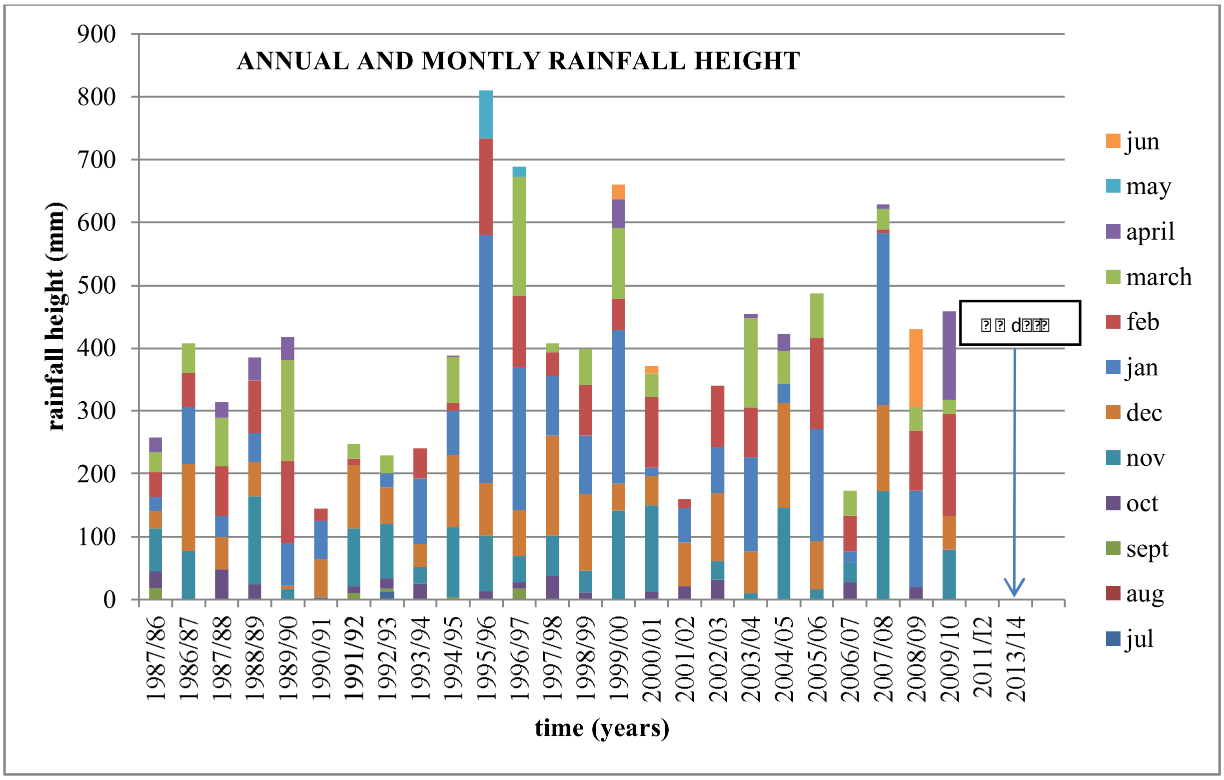


Figure 4. Annual and Monthly Rainfall of the project area (1987 to 2010).

There are three air streams which are primarily feeding rain in to Botswana. These comprise of the Inter-tropical Convergence Zone which brings mainly the January rains, the south-eastern trade which brings the December rains and the one which is dominant in the study area is north-eastern monsoon winds associated with the Mozambique’s monsoon cycle (Bhalotra, 1984).

The climate of Botswana including the study area is characterised by two seasons: the wet season and the dry season. Summer is a subdivision of the wet season; the Dukwi area receives its rains during this period around the month of October through to the month of March (Figure 4). A combination of hot and wet conditions leads to high humidity in the study area during these months particularly in the afternoons. The months of April and May represent the climatic transition period from wet season to dry season. They are therefore characterised by moderate conditions of temperatures, humidity and rainfall. The dry season (winter) commences during the month of June or sometimes a bit early towards the end of May through to late September or early October. The winter period is pronounced mainly between the period of late May and early August. The rainfall is almost absent and temperatures fall below 25°C with very low humidity, approximately half of what is observed during the wet season. The area dries up and only dew makes it wet in the early mornings. The months of September and October experience transition from winter to summer, the temperatures start to rise and can reach up to 40°C in late October.

4.4 VEGETATION AND SOILS

The information on the vegetation of the study area was compiled based on reconnaissance reports of the project area and from old reports done on the study area notably a report by Water Surveys Botswana (DWA, 1995a). The vegetation of the area is influenced by the geomorphology of the study area. Vegetation cover on the study area is dominated by Mopane followed by shrubs species. Mopane woodland dominated relatively good drainage soils while shrub land dominated where the soils have poor drainage and mixed woodlands dominated areas where drainage improves and the soils are shallow. In areas of deep sands, Mopane is replaced by the sandveld plant species. Grassland characterises the vicinity of Sua Pan, where the high salinity prevents the occurrence of trees (DGS, 1973).

The soils in the area vary widely according to the parent material and formational processes relating principally to the Palaeo Makgadikgadi Lake and the present day pans (DWA, 1995a). Saline lacustrine clays and silts mainly as vertisols (black cotton soils) occur to the west near Sua Pan and grade into calcareous soils on the pan fringe areas. These are gradually replaced by deeper sandy soils to the east.

4.5 LAND USE

Northeast District is dominated by small villages, no major economic activities; neither manufacturing nor wholesale establishments except at Sowa town where there is Soda Ash and salt mine. Subsistence Agriculture is a dominant activity in the study area and this kind of agriculture however has been on the decrease manly due to the persistent drought that has ravaged the area during the last few years. Low crop production and small livestock heads comprise the major land use carried out on communal lands (free hold land), such activities rely on rainfall seasons and low yielding small hand dug wells utilizing shallow perched aquifers present in the study area. Low crop yields are also thought by extension workers in the agriculture as due to lack of commitment by farmers.

The local farmers have developed and utilized small tracks to move around the study area, such tracks are temporary and may disappear when not in frequent use.

4.6 POPULATION

The current DWM considers mainly a 12 year nominal period from 2003 to 2015. The population situation for the project area from 2001 to 2011 is presented in Table 2. The pattern of increase is similar to the rest of Botswana, that is the annual rate of increase, which is the surplus of births over deaths, has however, been increasing at a decreasing rate. The population has been increasing but the increase has been declining over the decennial censuses that have been held since 1971. The percentage increase for Sowa Town and North eastern villages from 2001 to 2011 is 25% and 22%, respectively (Table 2). The observed declining growth trends might be reflecting the interactive outcomes of; declining fertility rates associated with increasing economic development; increasing female literacy and their participation in semi-professional and professional occupations and successful family planning programmes (Central Statistics Office (CSO), 2011). The population will nonetheless continue growing in response to the population momentum attributed to past high fertility and the youthful population structure of north-eastern Botswana (Central Statistics Office (CSO), 2011).

5.0 GEOLOGY

5.1 REGIONAL GEOLOGY

The study area (Dukwi wellfield Phase II) belongs to the north-eastern Karoo sub- basin portion of the Karoo basin in Botswana. A review of the literature by Green (DGS, 1966), Stansfield (DGS, 1973) and Smith (DGS, 1984) shows that the Karoo rocks in the study area (Northeast Botswana) continue eastwards into Zimbabwe and Northwards into Zambia and the Caprivi Strip. The faulted edge of the stormberg cover overstepping the Ghanzi – Chobe fold belt marks the western boundary of the Karoo supergroup of North-eastern Botswana, while to the south; the boundary is marked by a Precambrian basement outcropping as ridges south of Dukwi, coinciding with major post – Karoo dyke swarms through Makgadikgadi pans. The ridges have significantly influenced sedimentation in the study area and they are recognised as the lower Karoo starter hence the Dwyka and Ecca Groups have been encountered only at the southern margins of the study area (Smith, 1984).

The Karoo supergroup in the study area is poorly exposed due to the thick Kalahari sand cover going up to 60 m in most areas. The geology of this area was therefore compiled based on data from a few outcrops present on the study area and a limited number of deep boreholes drilled during search for coal by Geological Surveys (Green, 1973), Anglo Botswana Coal (Barnard and Wittaker, 1975) and Shell Coal (Ellis, 1973).

Based on the works of Green (DGS, 1966), Stansfield (DGS, 1973), and Smith (DGS, 1984), The stratigraphic distribution and succession of the Karoo supergroup of North-eastern Botswana is shown in Figure 5, summarised in Table 2 and shown on the geological map presented in Figure 6.

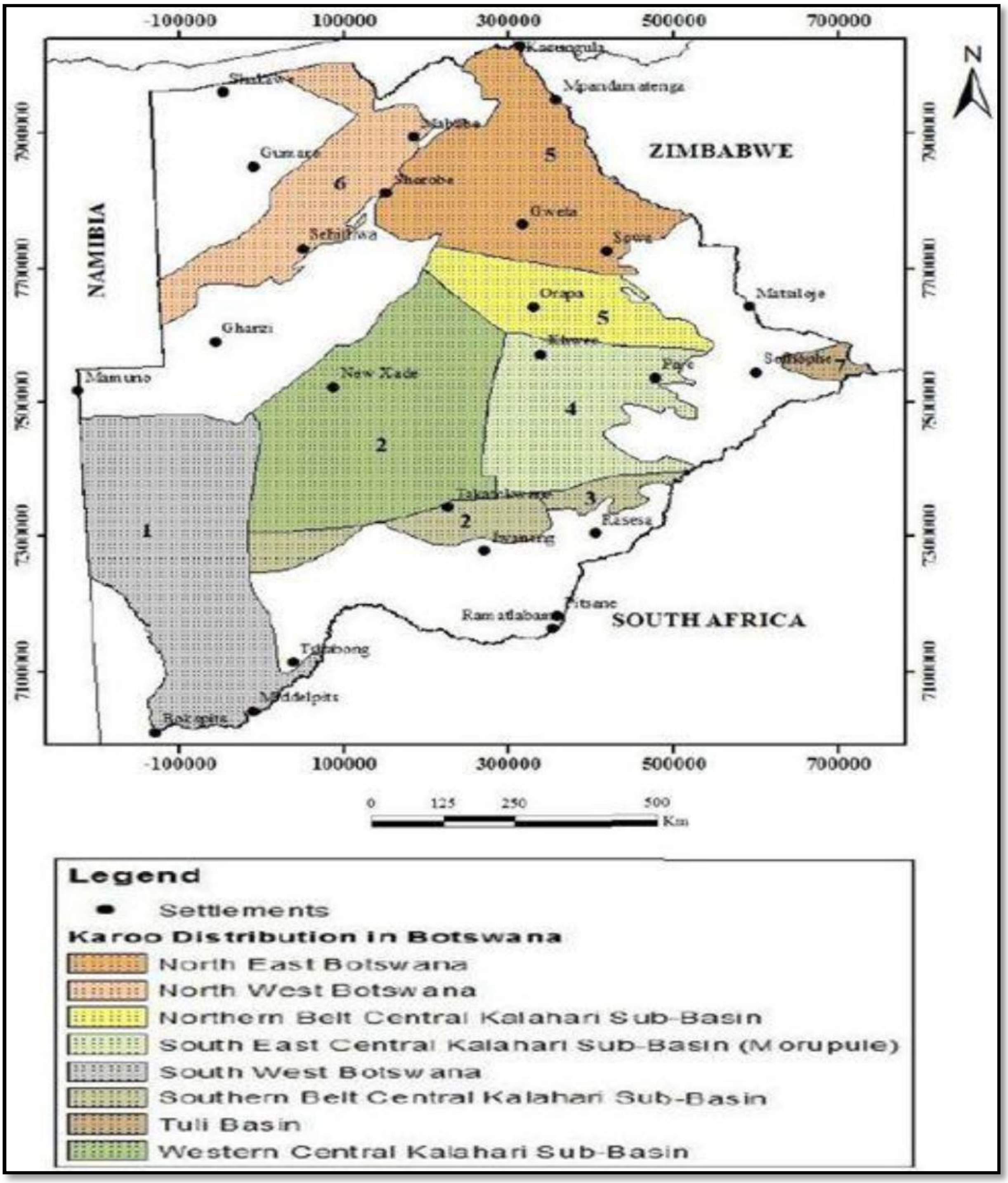


Figure 5. Occasion and Distribution of The Karro Supergroup in Botswan (Smith, 1984).

The Karoo Supergroup is widely distributed in Botswana, this supergroup covers up to about 70 % of the country's area and about 80 % of north-eastern Botswana (Figure 5). According to Smith (DGS, 1984), the formations of the Karoo Supergroup are generally similar, but vary significantly locally.

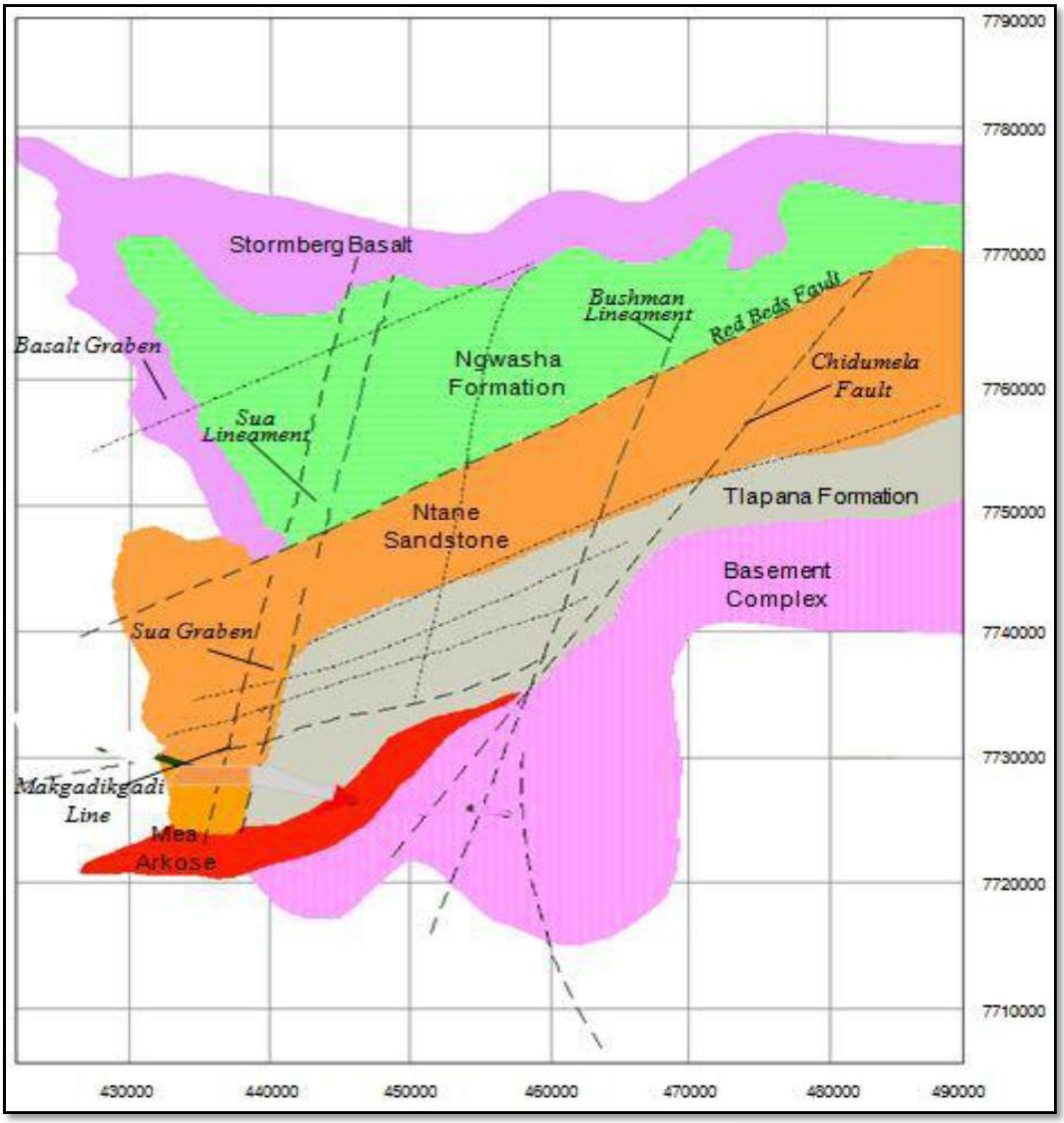


Figure 6. Geological Map of the Study Area. (Adopted from DWA, 2000)

Figure 6 shows that the structures in the study area generally trend northeast – southwest and the formations have contacts generally trending parallel to the major faults. These are interpreted to be as a result of the major tectonic activities which contributed to the complexity of the geology and structural geology of the study area.

Table 2. Lithostratigraphic succession of the Dukwi region.

Age	**Stratigraphic Unit**			**Lithology**
	Supergroup	**Group**	**Formation**	
Tertiary & Recent	-	Kalahari	-	Alluvium, calcrete and silcrete
Post-Karoo	Dolerite intrusions (dikes and sills)			
Late Carboniferous to Early Jurassic	Karoo	Stormberg		Basaltic flood lavas
		Lebung	Ntane Sandstone	Aeolian and fluviatile sandstone
			Ngwasha	Red to purple mudstone and sandstone
			Pandamatenga	White coarse sandstone
		Ecca	Upper Tlapana	Variegated mudstones
			Lower Tlapana	Dark carbonaceous shales & coals
			Mea Arkose	Fluvio-deltaic sandstone with insubordinate coals
		Dwyka	Dukwi	Grey varved mudstone and shale
Archaean Basement	Mosetse River Gneiss Group			Quartz, feldspar gneisses, migmatites and granitic gneisses
	Greenstone Belt Rocks			Chlorite-talc schists and amphibolites, characteristically green

The main stratigraphic units in the area are presented in Figure 5 and in profile in Table 2.

A description of the stratigraphy of the study as presented starting from the basement (Archaean basement) through the Late Carboniferous, Early Jurassic and the Post-Karoo age groups to the uppermost Tertiary & Recent age groups is as follows:

5.1.1 Archaean Basement

The Archaean basement is a complex of crystalline rocks which belongs to the Greenstone Belt Rocks Group and Mosetse River Gneiss Group. Greenstone Belt Rocks uncomformably underlies the Mosetse River Gneiss Group and are characterised by the non-granitic schists or metasediments. The metasediments of this group are typified by the indurated greenish Chlorite-talc schists and amphibolite. The Greenstone Belt rocks were intercepted at variable shallow depths in boreholes drilled in the study area, no record of outcrops of these rocks was found in the literature on the study area. These rocks form large raft-like bodies. The greenstone type rocks can be traced back by interpretation as part of the Archaean and Proterozoic belts of Zimbabwe, which truncate in the south against the Makgadikgadi Line (DGS, 1978 and Mason, 1998).

The Mosetse River Gneiss Group overlying the Greenstone Belt rocks outcrops south of the Dukwi along the Mosetse River. The Mosetse River Gneiss Group is represented by Quartz, feldspar gneisses, migmatites and granitic gneisses (DGS, 1970) and is exposed in the southern part of the area represented by the Kgwana hills. The Kgwana hills consisting largely of grey variegated dolomitic limestones and graphic schists. The limestones are sheared and brecciated and show copper mineralisation. The granitic gneisses predominate and are thought to be the product of granitisation of fine-grained quartz-feldspar-biotite rich sediments. Amphibolite and subordinate schists and limestone's occur widely throughout the gneiss group, but in trace amounts.

5.1.2 Karoo Supergroup

The Karoo rocks of northeast Botswana are poorly exposed but form part of the largest sedimentary sequence in the study area. The sedimentary sub-basin in the study area is identified as the "Nata Sub-Basin" by Smith (DGS, 1984), which extends eastwards into Zimbabwe and northwards into Zambia and the Caprivi Strip. The lithological units in the Dukwi area are described below.

The lower Karoo strata are represents by the Dwyka Group rocks which uncomformably overly the Archaean basement. The sediments sequence of this group forms the oldest sequence of the Karoo stratigraphy and were deposited under glacial conditions. The group is represented by rocks of the Dukwi Formation (DGS, 1973). The Dukwi formation is typified by beds of sandstone and tilloids and an upper member of Grey varved mudstone and shale.

The Dwyka Group is in turn uncomformably overlain by rocks of the Ecca Group**.** The Ecca Group in the Dukwi area is represented by Mea Arkose Formation and the Tlapana Formation.

The Mea Arkose formation forms the basal strata of the Ecca Group in the Dukwi area and according to Stansfield (DGS, 1973); it has an average thickness of 136 m. This formation is represented by white, gritty arkoses and sub-arkoses which exhibit iron banding in some observed rock samples. The feldspars are fresh in the unweathered rock, but when weathered they deteriorate to a white powder, probably kaolin. Pebbles are found throughout the sequence, either with a scattered distribution or confined to distinct beds. According to Stansfield (DGS, 1973) fluviatile conditions prevailed during the sedimentation.

The Tlapana Formation uncomformably overlies the Mea Arkose formation and has an average thickness of about 177 m. This formation is characterised by non-carbonaceous mudstones, siltstones and carbonaceous mudstones. The formation is subdivided into Lower Tlapana and Upper Tlapana Formation after Smith (DGS, 1984).

The Lower Tlapana is typified by a carbonaceous division of sediments. The more prominent rocks include carbonaceous shales, mudstones and coal and some carbonaceous streaks associated with the carbonaceous units in these zones. Coals and carbonaceous horizons containing siderite and pyrite are generally subordinate in quantity to grey mudstones. A highly variable depositional environment is indicated by the lateral inhomogeneity of the formation.

The Upper Tlapana is typified by non-carbonaceous division of the formation. The more prominent rocks of this division include, fine-grained massive mudstones, they range in colour from purple, yellow, and brown to grey (DGS, 1984).

Top of the Ecca group is the Lebung Group which is composed of the Pandamatenga, Ngwasha, and the Ntane Sandstone Formations.

The lower most member of the Lebung group is the Pandamatenga Formation. The formation consists mainly of fine- to medium-grained calcareous sandstone and mud-flake breccias and conglomerates (DGS, 1973).

The Ngwasha Formation is uncomformably sandwiched between the Pandamatenga Formation and the Ntane Sandstone Formation. The Ngwasha Formation is typified by heavily oxidised sedimentary rock and consists of red thick muddy siltstones with calcareous nodules.

Above the Ngwasha Formation lies the Ntane Sandstone Formation also called the Cave Sandstone (DGS, 1966) which is characterised by a range of sandstone layers ranging from coarse, gritty, cross-bedded sandstones changing upwards to thinly bedded, medium- to coarse-grained sandstones of cream-brown to red colour. The sandstone is quartz-rich and contains feldspar and quartz pebbles up to 1 cm in diameter. An Aeolian deposition is suggested based on the nature of this formation (DGS, 1984).

5.1.3 Stormberg Group

The Stormberg Group comprises the youngest rocks of the Karoo Supergroup and is represented by basaltic lavas. The group is present mainly to the north of the wellfield area. A narrow graben controlled by northwest trending lineament extends south-eastwards from the north into the wellfield area. Within this basalt graben some 30 m of highly weathered tuffaceous lava are present. The lavas are typically grey-green to purple-grey, are fine-grained, and contain amygdales and vesicles. Their widespread distribution suggests a non-explosive deposition.

5.1.4 Post-Karoo Intrusions

The post Karoo intrusions are dominated by the dolerite intrusions, such intrusions are not common in the study area except in a few cases. These intrusions took place after deposition of the Karoo super group (Stansfied, 1973). The doleritic dykes of the post Karoo intrusions exhibit a preferential trend or orientation towards WNW. These observations were made on intrusions just outside the study area. The intrusions in some localities occurred in the form of sub- horizontal sills.

5.1.5 Kalahari Beds

Calcretes and duricrusts of the Kalahari beds represent Tertiary and Recent Deposits, they have a wide distribution, and they almost conformably overlie the Ntane Sandstone. Other members of the Kalahari beds include sandstones (especially in the northern part of the Sua Pan) and alluvial sands along the riverbeds.

5.2 Local Geology

Local geology of the study area was derived from analysis of borehole logs. The logs were extracted from borehole certificates which were more generalised and less detailed. Some wells terminated within the Mea Arkoses aquifer and that makes it difficult to derive the aquifer thickness from such wells and to know the underlying geological formation. Further effort encompassed doing more lithological logs and correlations using the more recent and better detailed borehole logs from Chidumela wellfield which forms part of the regional Dukwi wellfield. The data from such lithological logs were compared to the old less detailed ones from the Dukwi wellfield phase II borehole log. The lithological log data exhibited no major difference to the regional geology. The produced borehole logs are presented in figures 8, 9 and 10. The boreholes selected for logs were taken along trends from a list of boreholes shown on figure 7. Trends were generated with an attempt to make them perpendicular to the trends of geological structures and the general flow direction, represent most of the project area and to sample well detailed borehole logs. Figure 7 is the Dukwi wellfield map showing trend of boreholes sampled for graphical lithological logs.

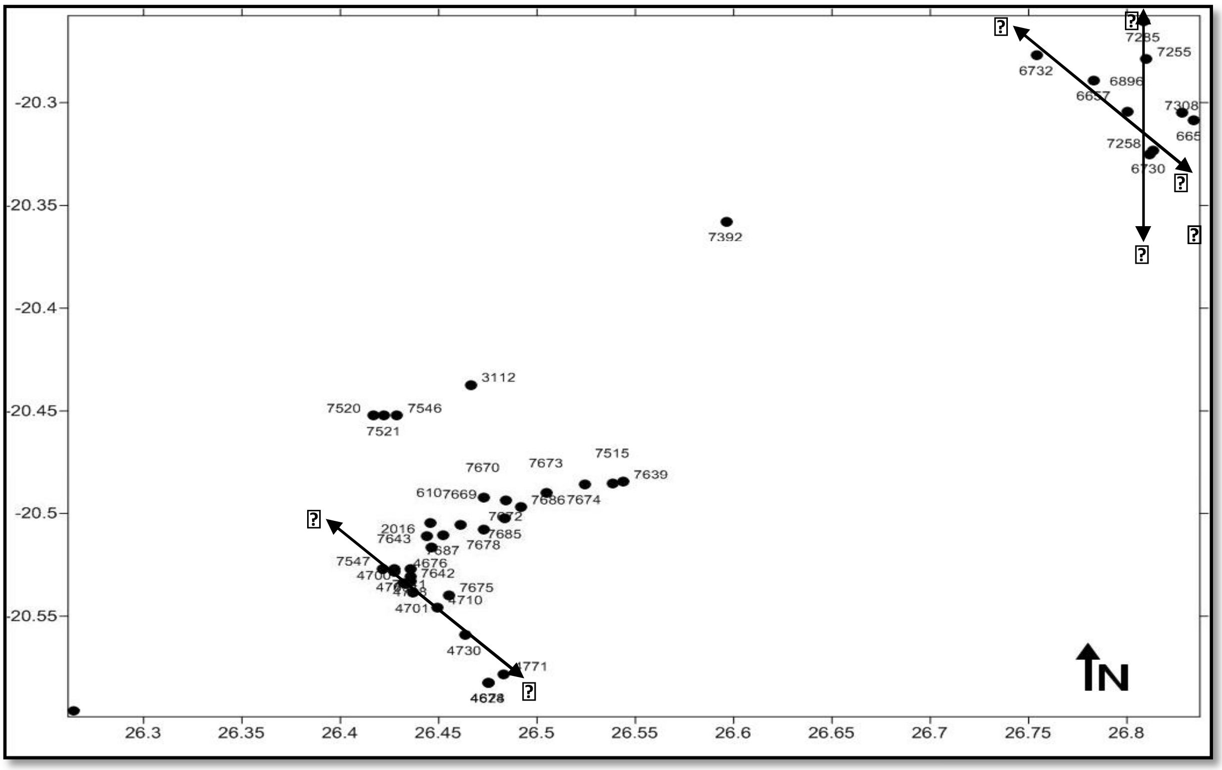


Figure 7. Trends for boreholes sampled for geological crossections

A-B cross section represents northwest – southeast trending Dukwi wellfield lithostratigraphical borehole logs

C – D and **E-F** represent northwest – southeast trending and north –south trending Chidumela wellfield lithostratigraphical borehole logs, respectively.

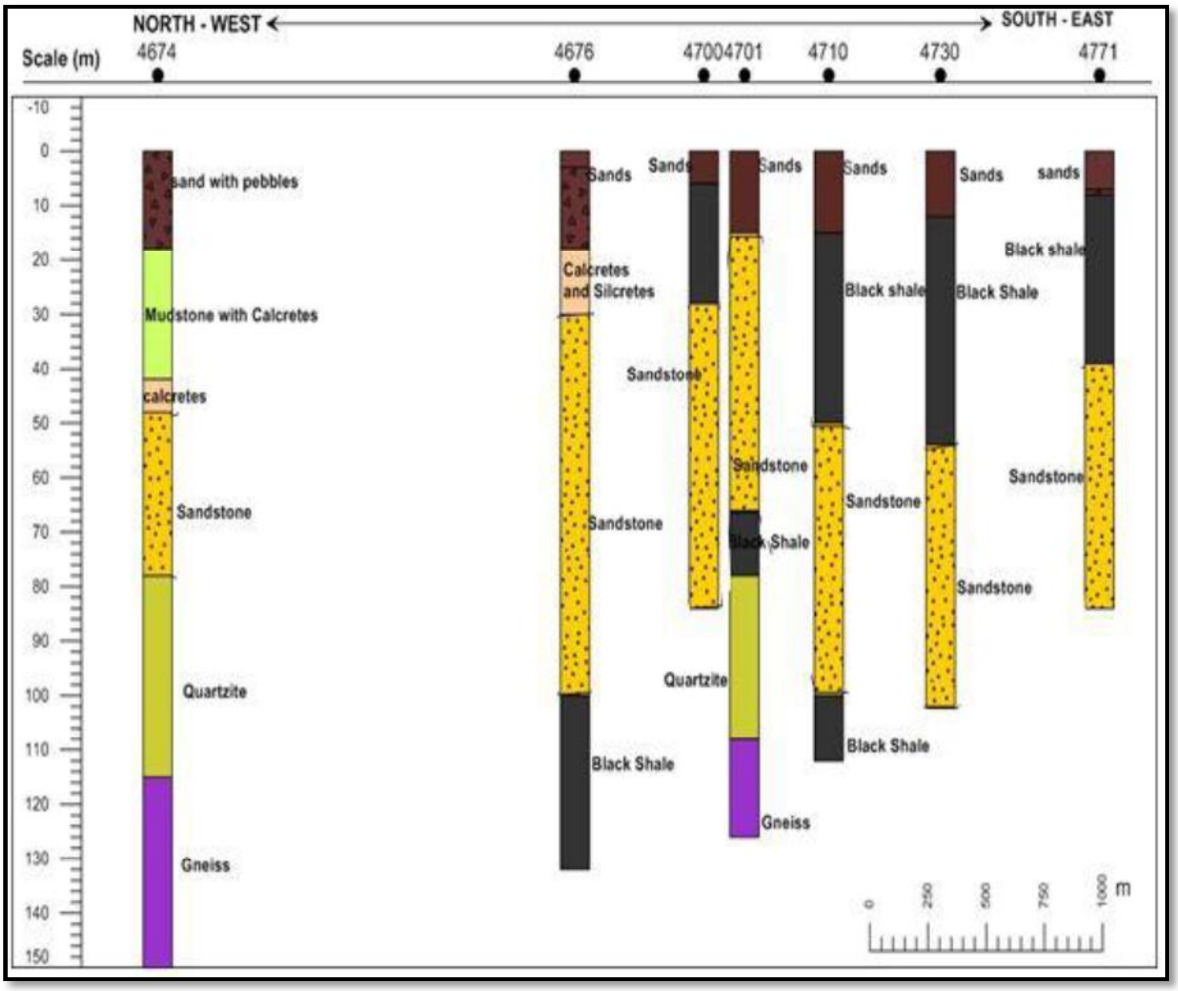


Figure 8 Dukwi Wellfield Phase II Borehole Logs.

The logs show sand cover of up to 20m in thickness, underlain by Calcretes and Mudstones and in some cases by black shales. The shales in turn overlie the sandstones categorised as the aquiferous Mea Arkoses which terminates into black shales and quartzite in some cases. The underlying deepest formation is the granitic gneiss though some boreholes terminated in shales and in worst cases sandstone.

Figure 9 and 10 was produced using more recent and relatively more detailed and accurate data for Chidumela wellfield boreholes. Interpretation of the geological logs reflects that the sandstone is less extensive than what was reflected by less detailed geological logs for the Dukwi wellfield Phase II. The set of lithological logs from Dukwi wellfield phase II and

Chidumela wellfields generally reflects similar rock units across all trends in both scenarios; this is what was expected at local scale.

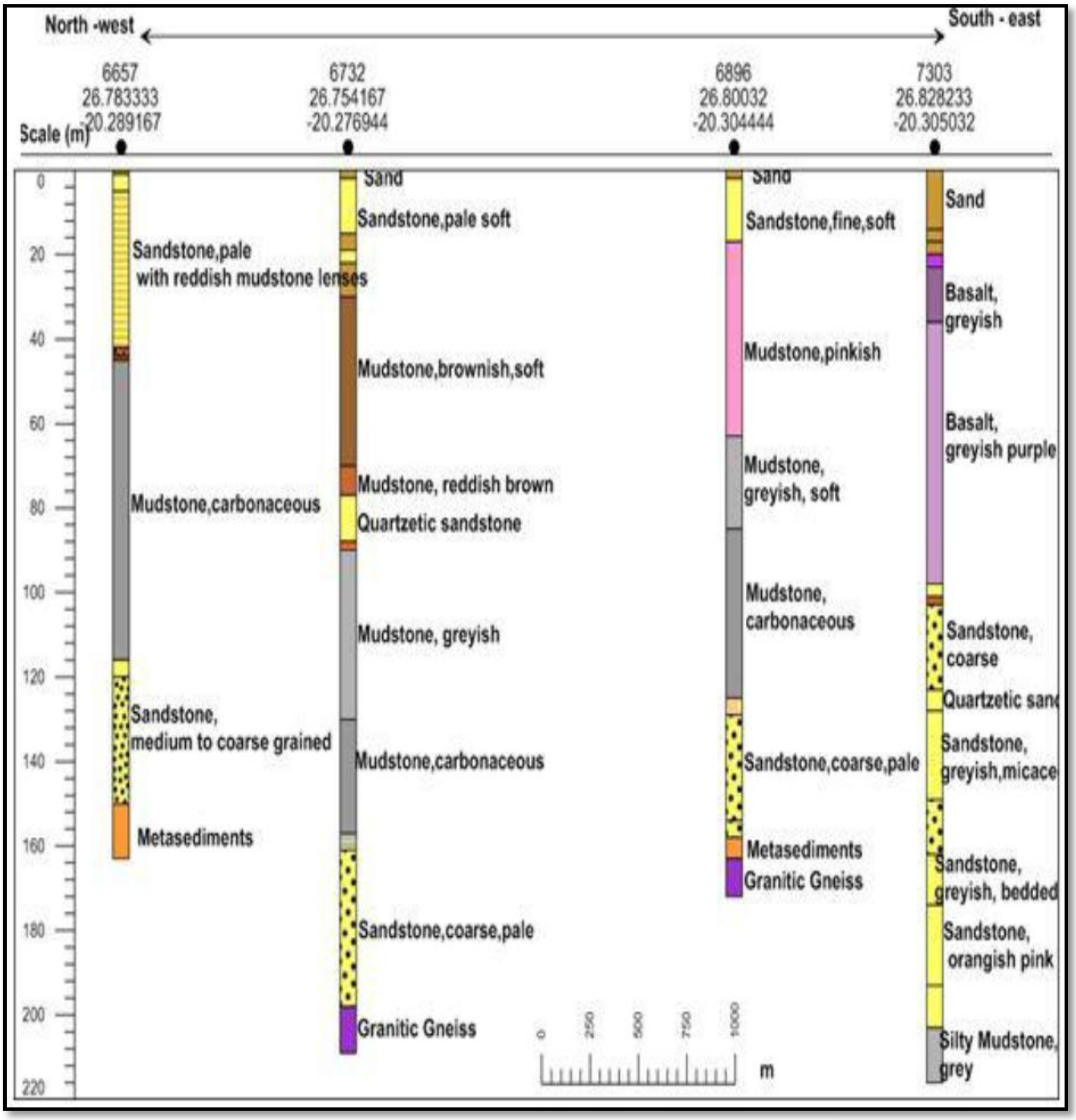


Figure 9 Chidumela Wellfield Borehole Logs along the Northwest - Southeast trend.

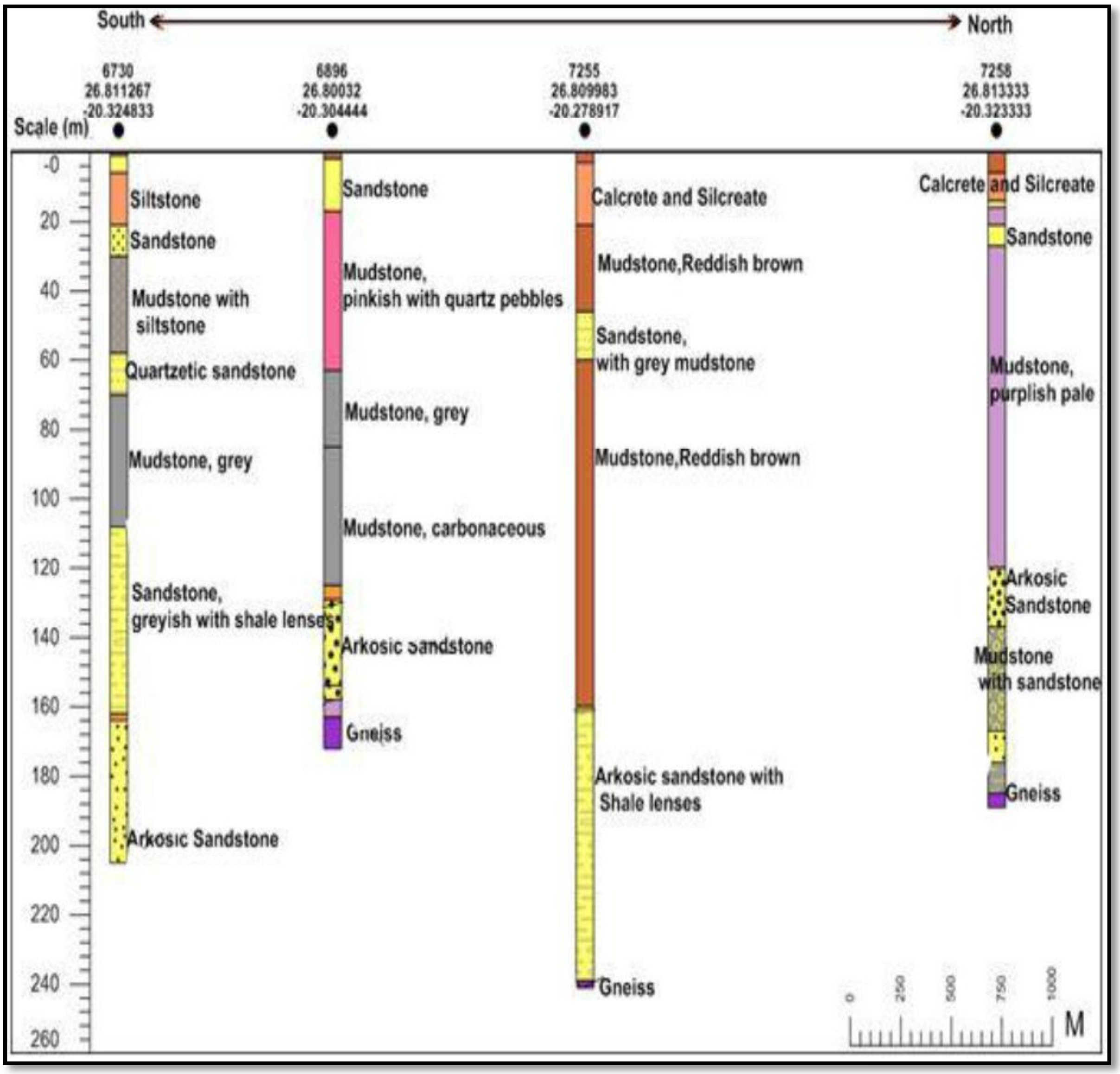


Figure 10 Chidumela Wellfield Borehole Logs along the South - North Trend Direction.

The borehole logs exhibit great variation in depth of same rock formations, the most significant ones being depth to the Mea Arkose sandstones. This variability in depth of same rock formations locally account for the highly variable water strikes in the project area**.**

Most of the boreholes terminate into the granitic gneiss which is classified as the lower most rock formation of the project area. This basal rock type is also intercepted at variable depths in boreholes distance about 1000m to 2000m apart. The presence of the granitic gneiss in majority of the boreholes reflects that the formation almost conformably underlies rocks of the study area.

5.3 GEOLOGICAL STRUCTURE

The structural geological setting of the study area was covered by Stansfield (1973) under the tectonic history of the Dukwi area. The structural geology results from three tectonic episodic events, that is, ancient episodes, inter- Karoo episodes and post – Karoo episodes. Ancient episode tectonics affected only rocks of the basement complex and the pre-existing pile of sediments were altered to gneisses which now comprise the basement. The inter- Karoo episodes caused the unconformity that occurred at the base of the Mea Arkoses and Ntane sandstone. The Post- Karoo episodes resulted in faulting which resulted in displacement of Karoo formations in the study area and can be demonstrated by cross- bedding on rocks of such formations. The examination of aerial photographs by Stansfield (1973) revealed some lineaments of which many were interpreted as fault traces across the area. The Bushman and Sua Lineament are the most prominent structures shown on the geologic map of the study area (Figure 6). Groundwater hydrodynamics in the study area (Dukwi area) is essentially determined by geological structures basically tectonic structures and basin sedimentary infilling. The main structural features that heavily influence the hydrogeology of the area (DWA, 1995a) are tabulated in table 3.

Table 3. Major Structures and Lineaments within the Welfield area.

Structure	Trend	Age of Structure	Age of Reactivation
Sua Lineament	NNE	Pre-Cambrian	Carboniferous, Permian Quaternary
Bushman Lineament	NNE	Pre-Cambrian	Not active Carboniferous to Quaternary
Chidumela Fault	NE	Pre-Cambrian	
Makgadikgadi Line	ENE	Pre-Cambrian	Carboniferous and Permian
Basalt Graben	NW	Permian	Triassic and Jurassic
Red Beds Fault	ENE	Permian	Triassic
Dolerite Dykes (Tuli Swarm)	WNW	Jurassic	

Water Surveys Botswana carried out a detailed study on the structural geology of the study area (DWA, 1995a). The study included satellite imagery, regional geophysics, and drilling activities. The study was a basis for all the previous modelling studies, and this study was also used to supplement the structural analysis carried out in this report.

The major conclusions made during the project regarding structure are as follows:

The western edge of the Dukwi basin was defined by the Sua lineament. This lineament belongs to a group of N and NNE trending lineaments which are spread across the study area. The Sua lineament was singled out as the most significant lineament of its group and was reflected by an aeromagnetic low interpreted to be a narrow graben. The fault coincides with the extension of the Makgadikgadi Palaeo Lake of the quaternary period and was considered active.

The southern edge of the Dukwi basin was defined by the Chidumela fault belonging to a group of NE trending faults. This faults coincides with a change in basement type from paragneisses to the east to volcanic greenstone to the west.

The eastern edge of the Dukwi basin is defined by a NNW- SSE trending fault which runs normal to the Bushmen lineament.

The Northern edge of the basin is defined by a lineament belonging to a group of ENE trending structures, which started from the middle of the study area and was traced until it coincided with NE trending structures. The ENE trending structures run parallel to the Makgadikgadi line.

The N-S faults dominating the eastern part of the study area run normal to the amphibolites and Meta limestone of the Matsitama Greenstone.

Dykes of the Tuli dyke swarm intercept the Makgadikgadi line and are an evidence of major crustal rifting event (DGS, 1978). The northern edge of the Tuli Dyke Swarm in the study area is marked by ESE-WNW trending lineaments dominant in the southern part of the area

NW-SE trending lineaments in the northern part of the area form a graben structure to the west of the wellfield area.

The conclusions made from analysis of literature (DGS, 1978, DWA, 1995a) on structural geology of the Dukwi wellfield area is that; major lineaments of the study area are, the Chidumela fault, Red Beds Fault and the anonymous NE-SW trending faults, Sowa Lineament and Sowa Graben that trend N to S and Basalt Graben that trends NW to S. These lineaments act as barriers to groundwater flow and divide the project area into compartments. The Makgadikgadi Line acts as a conduit to the north due to enhanced hydraulic conductivity and as a barrier to the south due to the depth change in the Basement. A series of minor faults and fractures oriented in NE and NNE directions have developed the secondary porosity in the aquifer rocks. These minor faults do not influence the groundwater regime of the Mea Arkose Aquifer and are therefore not modelled explicitly in the current study.

6.0 HYDROGEOLOGY OF THE DUKWI AREA

Hydrogeology section of the study encompasses analysis of the water occurrence in different rocks and sediments, its distribution and quality within the study area. The occurrence is judged based on water strikes, the geologic units in which water was intercepted. Rocks and sediments that are classified as being aquiferous or contributing to the aquifer system in the study area are categorised as Hydrostratigraphic units.

6.1 HYDRO STRATIGRAPHIC UNITS

The study area comprise essentially of a wide range of hydrostratigraphic units dominated by an extensive sedimentary sequence of the Karoo supergroup. The hydraulic heads before abstraction were recorded and range between 28 and 40 mbgl (DWA, 1995). The formations comprising the hydrostratigraphic units of the study area encompass;

6.1.1 Archaean Basement

The basal stratigraphic units in the Project Area is typified by rocks of the Archaean basement dominated by granitic gneisses and associated sediments. Granitic gneisses are generally crystalline and hence limited in primary porosity, such rocks utilise secondary porosity to qualify as aquifers. The basement rocks are generally deep and challenging to explore and extract water from. There are few boreholes on record that has reported water strikes in the Archaean basement, therefore, this unit is not considered in the numerical modelling. The Archaean basement is however appreciated as an aquifuge and vital in determining the thickness of the aquifer.

6.1.2 Ntane Sandstone

The Karoo rocks forms part of the largest sedimentary sequence in the north-eastern Botswana as previously envisaged. The Ntane sandstone is well spread in the Karoo sequence of Botswana, though generally fine grained, this formation has proved aquiferous on record in other areas. However, the Ntane sandstone on the Dukwi area does not show resourceful groundwater yields. On few occasions where substantial yields were intercepted in it around the study area, TDS values were too high for use as potable water for human consumption.

6.1.2 Mea Arkoses

From analysis of existing information and reference from a report by Stansfield (1973), it was concluded that the Mea Arkoses member of the Karoo supergroup is the most suitable formation for groundwater extraction in the study area. Lithostratigraphic logs of wells drilled in the study area exhibit that this formation is extremely complex and variable locally both horizontally and vertically. The formation is characterised on a macro scale by a more argillaceous basal member overlain uncomformably by a more arenaceous middle horizon underlying a top member comprising of argillaceous and arenaceous strata. Lithological variability of a formation increases chances of high porosity, permeability and hence good storativity and transmissivity.

The variability of this sequence on a more local scale is of hydrogeological vitality since the variation may be at a well domain and hence will certainly be within the range of influence of any multiple well developments. Due to the extensive variability of this formation, no particular horizon or position within the sequence is considered more yielding since water is intercepted randomly during drilling at variable levels. However, bulk accumulated data reflects that the grits and arkoses of the lower middle Ecca (Mea Arkoses) formation generally constitute the most wide spread and better aquifer horizons within the sequence. This conclusions are further supported by GS10 project (1981) following their intensive investigation on Karoo hydrogeology in Botswana while Jennings (1974) confirmed the productive nature of this coarse to medium grained sandstone on middle Ecca in Botswana.

Interpretation of current wellfield borehole data shows that the wells penetrate through about 24 meters of Ntane sandstone, 30 metres of Tlapana mudstone and then into Mea Arkose formation. The main aquifer (Mea Arkoses) contains significant thickness of medium to coarse grained arkosic sandstone which forms the high yielding aquifer of the project area. The aquifer thickness as reflected by lithological borehole logs (Figures 8 – 10) averages 58 m on the study area.

6.1.3 Dolerite Intrusions and Kalahari Group

Stormberg Group Basalts and dolerites contain water with extremely high salinity ((TDS) > 20,000 mg/l) and therefore not utilised in the Dukwi wellfield.

Calcretes and silcrete horizons of the Kalahari Group and montmorillonite-rich soils, which facilitate the occurrence of localised perched aquifers that are exploited by hand dug wells along the Semowane River (DWA, 1977), are also not utilised in this project area due to their anticipated short lived characters and hence not considered in modelling.

6.2 GROUNDWATER OCCURRENCE AND MOVEMENT

The spatial and temporal presence and distribution of groundwater on the study area is very important in groundwater flow modelling. The study put sufficient effort in surfacing such aspects for construction of the conceptual model.

6.2.1 Groundwater occurrence

Water occurrence and movement in the wellfield area was mainly derived from a database created from borehole certificates and wellfield hydrographs. Table 4 reflects the no of water strikes intercepted in each formation and the average yields per formation.

Table 4. Water occurrence and yields from wellfield water points.

FORMATION	NO OF WATER STRIKES	AVERAGE YIELD (M^3/H)
Mea Arkose	98	22
Stormberg	3	2
Ntane sandstone	7	6
Ngwasha	12	11
Pandamatenga	2	9
Tlapana	21	5
Dwyka	2	3
Basement complex	4	2

Generally, all intercepted formations had scenarios of water being struck in them, it is mainly with consideration to yield and number of water strikes that the Mea Arkoses is categorised as the main aquifer in the study area. The Ngwasha formation and the Pandamatenga formations come second and third, respectively, after the Mea Arkose in terms of average yield. The Pandamatenga formation and the Dwyka formation reflect lowest probabilities of water interception with water having been intercepted only two times in each of them. The rest of the formations reflects generally low yields and in some cases low probabilities of intercepting water in them. It is concluded that The Mea Arkose Formation is the major aquifer and exists throughout the study area. The aquifer is highly heterogeneous and anisotropic. This conclusion is supported by the variability and a wide range of transmissivity values that were reported by Water Surveys Botswana in the main report (DWA, 1976). The transmissivity values were reported to be ranging from; 1.5 m^2/d to 1760 m^2/d. The Mea Arkose aquifer is generally confined mostly towards the North by the Tlapana formation. Water levels rise above the depth of interception as expected under confining conditions. Towards the southern part of the study area, the aquifer is reportedly exposed and hence unconfined, the shales of the Tlapana formation are absent in this section of the wellfield.

6.2.2 Ground Water Movement and Flow Direction

Generally, water flows from point of high head to point of lower head, but on ground it is more complex due to inhomogeneity of hydrogeological units and presence of barriers or boundaries. Potentiometric contours for the study area reflect that regionally, hydraulic heads are lower on the western side as compared to the eastern side (Figure 11). It is concluded that water generally flows in a westerly direction and discharges to the Sua pan as previously envisaged. The maximum initial head difference in the study area is 70 m amsl. The huge hydraulic head differences across the study area are due to presence of barriers or boundaries and this is in convergence with the outcomes of a study carried out by water Surveys Botswana (DWA, 1995) where they made deductions that the study area has geological compartments which are poorly interconnected. Each compartment has a unique local flow pattern different from other adjacent compartments. Figure 11 shows hydraulic head distribution recorded on the study area before the wellfield was formally under operation.

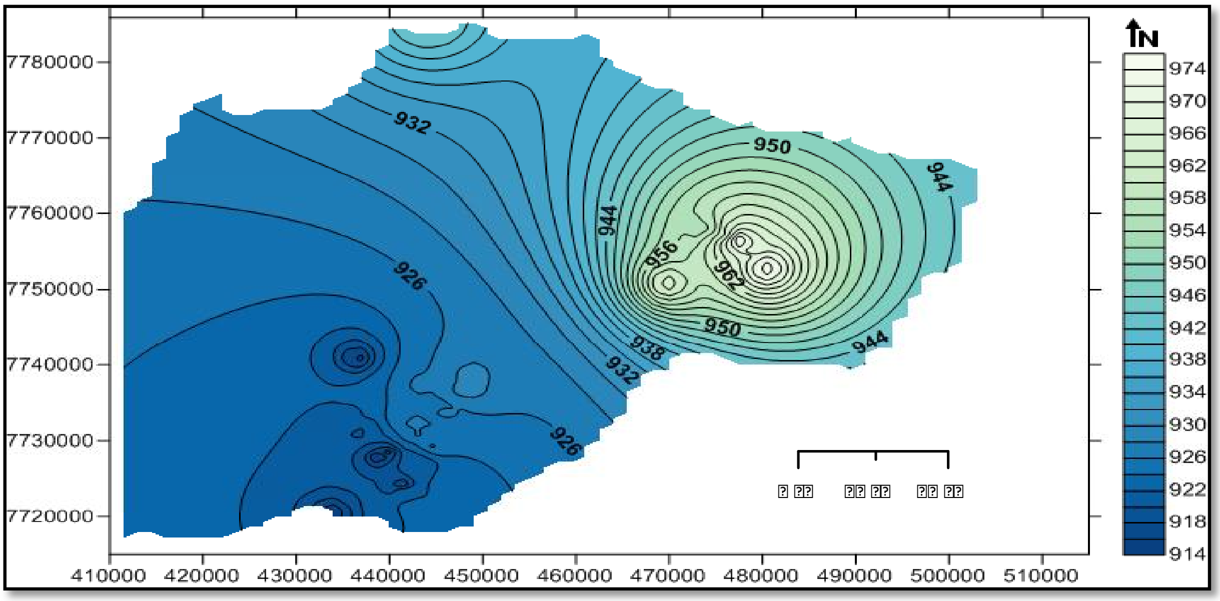


Figure 11. Initial Hydraulic Head Distribution.

On a regional scale, it is very difficult to derive a flow direction due to the variability of transmissivity values within the study area and presence of compartments which were interpreted to be controlling flow (DWA, 1976).

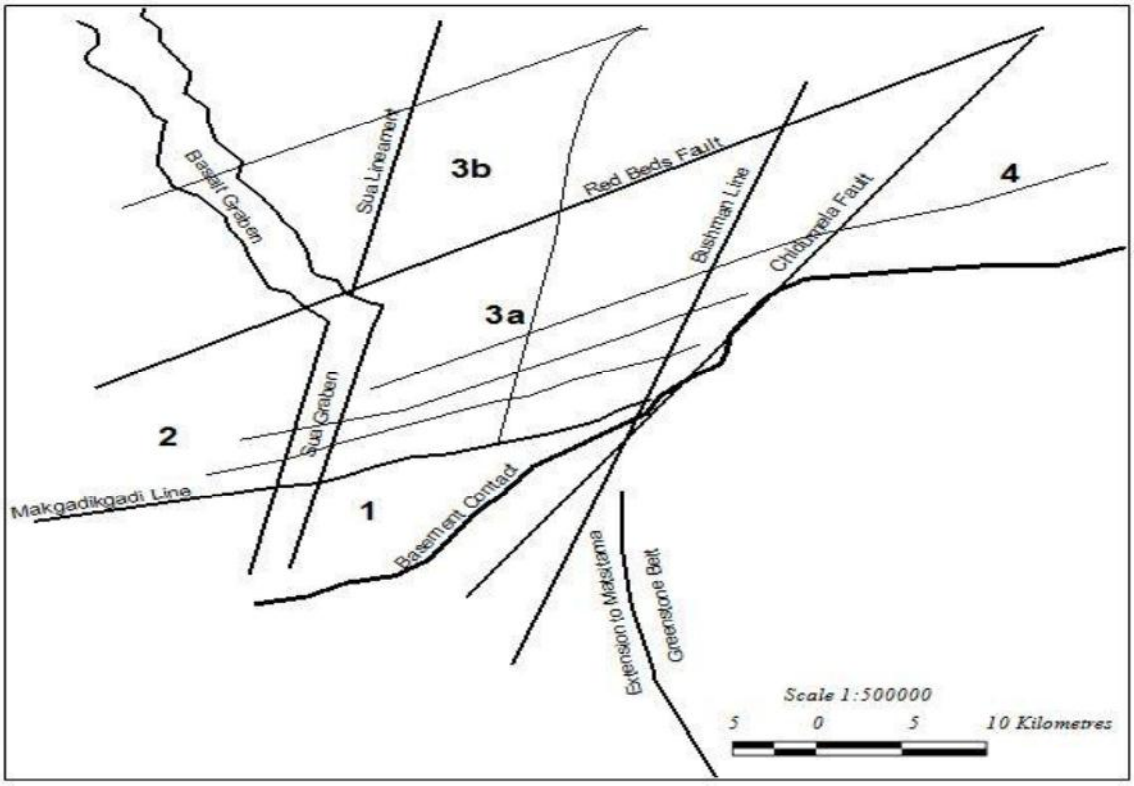


Figure 12 Aquifer compartments (adapted from Water Surveys Botswana)

A zone of enhanced transmissivity oriented south west – north east exists in the south-western part of the study area. This zone is bounded to the north by the Makgadikgadi Line (figure 12) which has transmissivity values significantly higher than elsewhere in the study area (DWA, 1995b).

The general flow direction in the southern part of the Dukwi basin is to the southwest with flow parallel to the ENE structural features like the Makgadikgadi Line. In the northern part groundwater flows westwards towards Sua Pan. The south-eastern part of the area up to the zone with high transmissivity forms a groundwater compartment (Compartment 1 in Figure 12). The hydraulic gradient was found to be very flat (approximately $5x10^{-4}$) and it is even lower in Compartment 2 (DWA, 1995a).

Compartment 3, located to the north of Compartment 1 is an almost isolated sub-basin containing old water discharging slowly towards the southwest, as reflected by water chemistry data (DWA, 1995b) The report further states that Compartment 3 is largely isolated from Compartment 1, but is thought to receive flow from the north. Compartment 4, located in the NE, includes the Chidumela Wellfield and is isolated from the other compartments by the Chidumela Fault hence not considered in the current study.

6.3 WATER QUALITY

Water chemistry for the study area is very complex and characterises different water types hence challenging to conceptualise and derive originality of such water types which are highly variable at a local scale. A series of reports which contributed to the understanding of water chemistry for the study area include the first investigation by SWECO (DWA, 1977), followed by Mannathoko (1990), and Water Surveys Botswana (DWA, 1995). Analysis of the reports led to a general conclusion that there are three different types of water found in the area, which are: Type I: Ca-Mg-$HCO_{3,}$ TDS < 1000 mg/l, Type II: Na-$HCO_{3,}$ TDS between 1000 mg/l and 1500 mg/l, and Type III: Na-Cl, TDS >1500 mg/l (often > 5000 mg/l).

The current study also retrieved the latest water quality data collected from the DWA Water Quality Database, through Water Utilities Corporation. The current water quality analysis was done to assess how the chemistry values for water samples representing the four production boreholes for the Dukwi wellfield Phase II compare to the Botswana Bureau of Standards (BOS 32:2009) drinking water Specifications. These specifications classify water based on quality into two classes which are “Class I (ideal) and Class II (acceptable). Class I is usually the maximum allowable drinking water standards for surface water resources and Class II is usually the maximum allowable drinking water standards for groundwater resources. The classes represent certain maximum quantities of Total Dissolved Solids (TDS), pH, turbidity, conductivity, cations and anions present in a representative water sample.

The chemistry analysis results reflect that all parameters fall in Class II which is the acceptable Botswana Bureau of Standards (BOS 32:2009) Drinking Water Specifications for groundwater resources. The present water quality for the project area is therefore (Class II) generally suitable for human consumption. According to the Botswana Bureau of Standards (BOS 32:2009) recommendations, water quality for groundwater need to be monitored frequently, at least quarterly in a year.

The presence of water of acceptable quality in the Dukwi wellfield Phase II, while the adjacent wellfields have been decommissioned in response to decline in water quality is in line with the deductions made in previous study (DWA, 1995) that the area is compartmentalised. The reports further reported that these compartments have unique water types and the waters do not mix (DWA, 1995). This deduction is supported by the fact that the Dukwi wellfield Phase II has been in operation since 1998 and has been in operation for 18 years but still supplies water of acceptable quality. The current study furthered the investigations through analysis of geomorphology of the study area and made deductions that this is due to the Dukwi wellfield Phase II‘s close proximity to recharge zones.

Table 5 shows the Dukwi wellfield Phase II water chemistry results by November 2014 and Botswana Bureau of Standards (BOS 32:2009) drinking water quality specifications.

Table 5. Dukwi wellfield Phase II water chemistry results – November 2014.

Parameter	**Units**	**BH 7678**	**BH 7675**	**BH 7687**	**BH 7674**	**CLASS I**	**CLASS II**
pH		7.62	7.25	7.21	7.16	5.5 – 9.5	5 - 10
Conductivity	Us/cm	1516	1377	1488	1530	1500	3100
TDS	mg/l	985.4	895	967.2	994.5	1000	2000
Sulphate	mg/l	125.41	112.49	121.92	115.15	250	400
Chloride	mg/l	217.02	216.55	229.2	107.1	200	600
Nitrate	mg/l	0.8	0.43	0.94	ND	50	50
Fluoride	mg/l	0.79	0.64	0.78	0.66	1	1.5
Calcium	mg/l	28.09	94.34	11.28	97.42	150	200
Magnesium	mg/l	6.59	44.53	46.50	44.42	70	100
Potassium	mg/l	0.52	2.20	3.28	2.39	50	100
Sodium	mg/l	167	238.10	238	254	200	400
Iron	ug/l	300.2	ND	10.11	23.65	300	2000
Manganese	ug/l	109.4	1.61	2.26	1.94	100	500
Turbidity	NTU	0.19	0.24	0.16	0.14	1	5
Zinc	mg/l	0.61	ND	ND	ND	5	10
Alkalinity	mg/l	381.57	345.33	389.78	360	-	-
Nickel	ug/l	5.66	0.99	0.62	1.14	70	70
Chromium	ug/l	5.42	ND	ND	ND	50	50
Cobalt	ug/l	4.72	3.86	3.95	3.76	500	500
Cadmium	ug/l	2.56	2.64	2.56	2.60	3	3
Bromide	mg/l	0.90	0.94	1.02	0.60	-	-
Aluminium	ug/l	ND	ND	ND	0.84	200	200
Copper	ug/l	1648.29	ND	35.28	26.37	2000	2000

ND – Not done

Though within acceptable drinking water quality specification of the Botswana Bureau of Standards (BOS 32:2009), the Total Dissolved Solids (TDS) and chloride concentrations for waters of the study area are generally high. The high TDS and chloride concentrations in waters within the area are mainly due to residual salinity from the ancient Makgadikgadi Lake (DWA, 1995).

Further water chemistry analysis reflects that waters within the study area are potentially corrosive as indicated by the Ryznar Index values ($RI = 2^* pH_s - pH$; where pH is the measured water pH and pHs is the pH at saturation in calcite or calcium carbonate). Ryznar (Table 7) gives only an indication about the aggressiveness of the water but carrier (Table 6) gives an indication about the scale and corrosion potential of the water.

Table 6 Ryzna Index and water corrosivity and scaling characteristic indication

RI	Indication (Carrier 1965)
4,0 - 5,0	Heavy scale
5,0 - 6,0	Light scale
6,0 - 7,0	Little scale or corrosion
7,0 - 7,5	Corrosion significant
7,5 - 9,0	Heavy corrosion
>9,0	Corrosion intolerable

Table 7 Ryzna index and water aggression characterisation

RI	Indication (Ryznar 1942)
RI<5,5	Heavy scale will form
5,5 < RI < 6,2	Scale will form
6,2 < RI < 6,8	No difficulties
6,8 < RI < 8,5	Water is aggressive
RI > 8,5	Water is very aggressive

The water chemistry results values in table 6 were used to calculate Ryznar Index values for each sample representing the respective production borehole. The Ryznar Index values were

8.1, 7.5, 9.3, and 7.3 for boreholes 7678, 7675, 7687 and 7674, respectively. The Ryznar Index values of above 6.8 (table 6) indicate that the waters in the study area are over saturated with respect to $CaCO_3$ and are potentially corrosive (Driscoll, 1986). Values close to seven (table 6) indicate that the waters on the study area are less incrusting or corrosive. Based on the categorisations in table 6 and 7, the water in borehole 7687 is very aggressive and of an intolerable corrosion. The fact that the water is pumped from the four boreholes in to the same storage may induce delusion factor and hence a better overall water quality.

6.4 CURRENT WELLFIELD LAYOUT

Three wellfields comprising the Dukwi regional wellfield have been decommissioned over time due to deterioration in water quality. The decommissioned wellfields include the Dukwi Wellfield Phase I, Chidumela wellfield and Soda Ash Botswana boreholes. The Dukwi Wellfield Phase II is the only wellfield that is currently under operation on the study area and it has four production boreholes which are BH 7674, BH 7675, BH 7678, and BH 7685 supplying water to Nata, Sowa, Dukwi and Dukwi Refugee Camp. There is monthly water level and quarterly chemistry monitoring conducted on 28 monitoring wells which are well distributed across the study area. The production boreholes abstractions are through electrical submersible pumps which are connected to Telemetry system. The down to hole depth for the production boreholes range from 125mbgl to 198mbgl. The boreholes were gravel packed to the top of the water strikes and beyond the entire aquifer thickness and pressure grouted to the surface. These boreholes were cased and screened for the total lengths with 20 slot stainless steel wire wound screens. The four production borehole details are presented in Table 8.

Table 8 Drilling and Construction Detailes for the Production Boreholes

Borehole Number	Depth (mbgl)	Drilling Details (Interval (m) / Diameter (mm))	SWL(mbgl	Screen Details (Interval (m) / Diameter (mm))	Pump Intake (mbgl)
7674	197	0 – 91 m / 381 mm 91 – 197 m / 305 mm	49.9	90 – 125 m / 205 mm	90.20
7675	198	0 – 100 m / 381 mm 100 – 198 m/ 305 mm	52.82	103 – 135 m / 205 mm 135 – 159 m / 205 mm	87.30
7678	125	0 – 38 m / 381 mm 38 – 124 m / 305 mm	35.47	70 – 93 m / 205 mm	73.80
7687	145	0 – 59 m / 381 mm 59 – 145 m / 305 mm	36.82	63 – 86m / 205 mm 86 – 112 m / 205 mm	69.70

6.5 PODUCTION BOREHOLES ABSTRACTION

The Dukwi regional wellfield comprise of phase I and Phase II, Chidumela wellfield and Soda Ash Botswana boreholes which were commissioned between 1995 and 1998. There are about 32 private boreholes in vicinity of the wellfield, this boreholes abstract water for domestic use and livestock water supply and therefore represent minor abstraction volumes of about 3m^3/h that are neglected in the modelling exercise. There are two production boreholes hosted by Soda Ash Botswana on the western part, monitoring data indicate that they also have low effect to drawdowns in the study area. The available abstraction data for Dukwi Wellfield is of poor quality and has some gaps in the records. The production boreholes have been either, decreased, increased, changed or pumping rate varied over the years. The data exhibit that the abstraction rates are highly variable but generally increasing over most of the years up to the year 2007. The rates started dropping in 2008 but a gap in records over the years 2009, 2010, 2011 and

2012 makes it difficult to interpret the trend beyond 2008. Abstraction rate estimates are used where the data is totally missing, and this is done by averaging recorded abstractions data. The historic annual abstraction data retrieved from the Water Utilities Corporation database for 1999 to July 2014 is presented in Figure 13. The abstraction data was presented as annual rather than monthly abstraction because the wellfield exhibit significant response to abstraction over years of abstraction rather than monthly. The monthly and daily abstractions reflect significant effect at borehole domain rather than wellfield scale and do not show significant effect on the water table response.

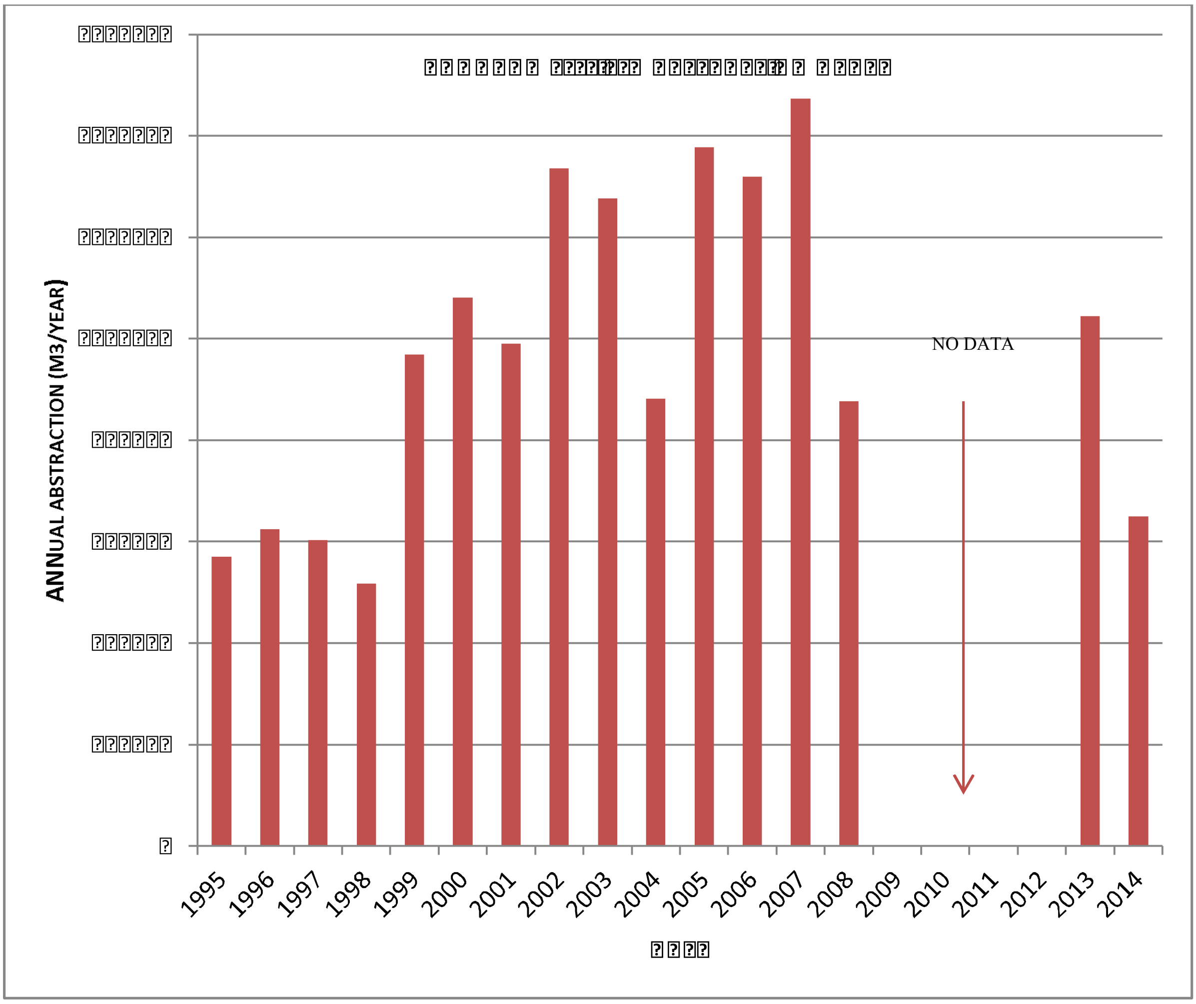


Figure 13. Annual Dukwi Wellfield Abstraction Plots (1995 to 2014).

6.6 WATER LEVEL FLUCTUATIONS

Groundwater systems are generally open systems and interact extensively with their environment. The hydrogeological system comprise of input, storage and output processes, if recharge to and discharge from the groundwater system at all places and at all times remain the same, the water table would remain in a fixed position and groundwater reservoir would be in equilibrium with its environment. However, in nature the water table is always fluctuating in response to injection or extraction of water from the system. The degree of fluctuation is governed by many factors which include the intensity of addition or extraction of water to or from hydrogeological system. The Dukwi area is therefore no exception to these natural phenomena and such fluctuations were observed from hydrographs derived from the wellfields monitoring data.

6.6.1 Observation Borehole Monitoring

Department of Water Affairs take record of water levels at twenty eighty observation boreholes manually on a monthly basis. The monitoring data was obtained from DWA database and was plotted to produce hydrographs (Appendix 3).

The produced hydrographs generally exhibited significant ground water level fluctuations in the Dukwi wellfields. The fluctuations can be due to climatic circles, wellfields abstraction and many other factors hence challenging to correlate it to one aspect. The other aspect that makes it challenging is that of lag time, it may take unspecified time for each well to respond to effective conditions or phenomena. The distance of a borehole form recharge zone or abstraction point also influence the response of water table level at that specific well. A few hydrographs that represented the various trends in water table fluctuations were picked and discussed and the rest of the hydrographs were presented in appendixes 3. The hydrograph in figure 14 shows a rise in water level from 907.29 m amsl to 908.54 m amsl between August 1999 and April 2001. This scenario coincides with a high annual rainfall height of 650 mm recorded between the year 1999 and 2000 (Figure 4). Abstraction rates during this period were generally low (Figure 14). Figure 15 shows the hydrograph produced from monitoring data at observation borehole 7547.

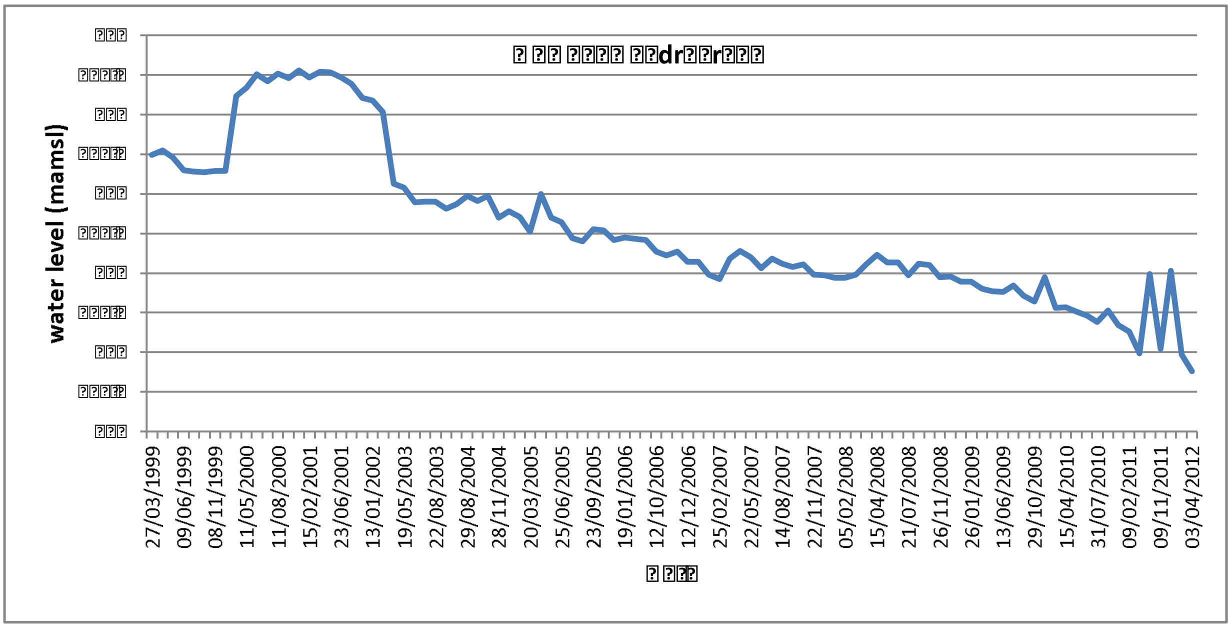


Figure 14 Observation Borehole 7547 Hydrograph

There was a steep drop in water level from 908.18 to 907.13m amsl between May 2002 and April 2003. This coincides with a very low annual precipitation of 155mm (Figure 4) between the years 2001/02 and makes the second lowest annual rainfall height between the years 1987 and 2010. Abstraction rate during this period was generally increasing; hence the most probable cause of a steep drop in water level is a drop in annual rainfall height combined with increased abstraction rate. Beyond this point the water level exhibited consistency but was generally going down while abstraction rates and rainfall patterns were variable. The other borehole hydrographs exhibited a more consistent water table depth throughout the record period, boreholes with such response are generally located relatively far from the pumping wells or and adjacent to water bodies or recharge zones. Borehole 7487 is located far north of the pumping wells, borehole 3129 is located on the south-western side of the production wells along Mosetse River, and borehole 7545, 7516, 7513 and 7393 are located to the eastern side along Semoane River. This observation boreholes exhibit a similar trend, the consistency in water level for such boreholes which are adjacent to rivers is due to recharge flux and hence consistent head for most of the time. However, though these streams are seasonal and flow only after heavy rains, there are shallow hand dug wells utilised by farmers which are adjacent to the streams. The wells utilise shallow perched aquifers which contribute to the Dukwi wellfield Phase II Recharge as reflected by the flux in water level from observation points adjacent to the streams.

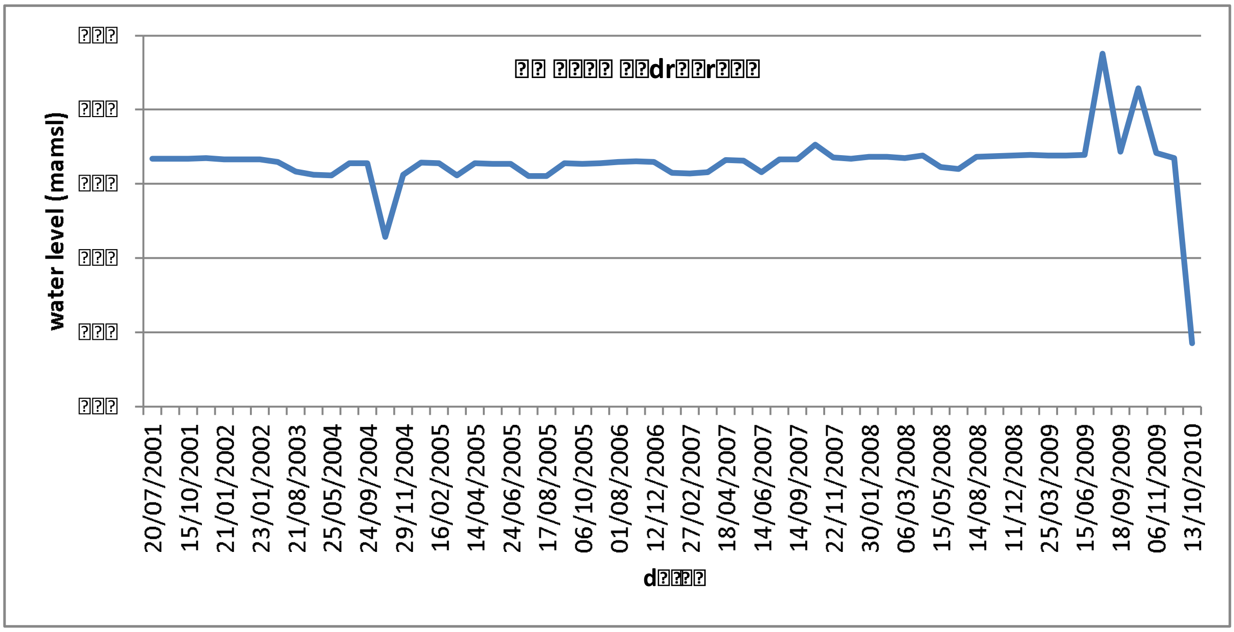


Figure 15 Observation Borehole 7487 Hydrograph

6.7 AQUIFER RECHARGE

The primary form of recharge to the Mea Arkose aquifer is rainfall which is generally distributed evenly across the study area. However, not all rainfall received on the wellfield area percolates and replenishes the aquifer system. Although water levels in the confined portion of the aquifer may respond to periods of heavy rain, these fluctuations are unlikely to be the result of direct recharge and may be attributed to pressure responses from recharge that occurs at different recharge zones. The geology and geomorphology of the study area is therefore scrutinised to delineate sections of groundwater replenishment and therefore derive a quantitative estimate of recharge to the aquifer system.

The technic applied to estimate recharge include application of hydrometry, numerical modelling , satellite imagery, review of geology and hydrochemistry data from the Department of Water Affairs Database and old reports of previous modelling exercises notably a report by Water Surveys Botswana, (DWA, 1995). Based on an intensive application of these technics, it was concluded that recharge of the Mea Arkose aquifer occurs primarily in the eastern to the south- eastern part of the area where the aquifer is unconfined, along the contact between the Mea Arkose Formation and the Basement, and along certain stretches of the major rivers.

There is significant recharge from Mosetse river into the aquifer system, the conclusion is derived from observations made from recent water level data. Boreholes adjacent to the river shows relatively increased hydraulic head when the area receives rainfall as compared to other boreholes away from the river as elaborated in section 6.6.1 of chapter 6. These observations were also discovered by Water Surveys Botswana in their studies that lead to the establishment of the first Dukwi wellfield model (DWA, 1995).

The report shows a one year qualitative comparison of monthly rainfall from July 1993 to October 1994 with borehole water level responses adjacent to and away from the river courses. In the current report borehole hydrographs were used to arrive at this deduction, that is more pronounced water level increases are in boreholes located adjacent to Mosetse River.

Water Surveys Botswana (DWA, 1995) also carried out a detailed hydrochemistry analysis of water samples from the study area and made the following deductions which were also reviewed and adapted in the current study.

Water samples from different compartments (Figure 12) were sampled and analysed. Water type in Compartment 1 along the contact between the Mea Arkose Formation and the basement rocks was a Na-Ca-HCO_3. This water type was interpreted to be reflecting an active recharge. This is because this water type is characterised as fresh water.

The radiocarbon analyses were also carried out to verify recharge along the basement contact and where the Mea Arkose is unconfined. The results indicate that relatively modern waters (0 – 10 pmc ^{14}C and relatively light values of ^{18}O) were found in these areas, while more stagnant waters (50 – 88 pmc ^{14}C and heavier values of ^{18}O) were found to the north of the high transmissivity zone.

To further scrutinise the outcomes from the former reports, the current study involved a Steady state calibration which was carried out to estimate recharge on the study area using latest rainfall data. Previous reports confined recharge to the unconfined section of the aquifer and along structures. This may lead to discrepancies since some structures could have been missed or misinterpreted. In addition to recharge estimates on such areas, a recharge value was assigned to the whole study area to account for discrepancies that may lead to underestimation of recharge. The initial main recharge areas were therefore assigned to the basement contact; Mea Arkoses outcrop as well as following the river courses of the Mosetse, Tutume River, and Gwedebi Rivers and to the general study area. A total recharge of 4085 m^3/d was adopted for the whole model area and was to be further scrutinised in the numerical modelling calibration stage.

7.0 RESULTS

7.1 CONCEPTUAL MODEL

The conceptual model was built to organize and simplify the modelling data for easy visualisation and analysis. It was instrumental in the determination of the dimension of the aquifer as well as the design of the grid. Conceptualisation of flow regime and mode of flow played a vital role in choosing the dimensions of the current model, hence a three dimensional model was found appropriate for achieving the objectives of the study. The major and vital components of the conceptualisation process of the study area include; demarcation of the area of interest, identification of the hydrostratigraphic units, allocation of the surface and subsurface drainage which is generally to the west towards Sowa pan, identification of recharge zones which are mainly through the rivers into the aquifer as it was reflected by data from observation boreholes adjacent to the rivers and through unconfined sections of the aquifer, allocation of precipitation, evapotranspiration and discharge. Figure 16 is a not to scale summary of the conceptual model of the study area.

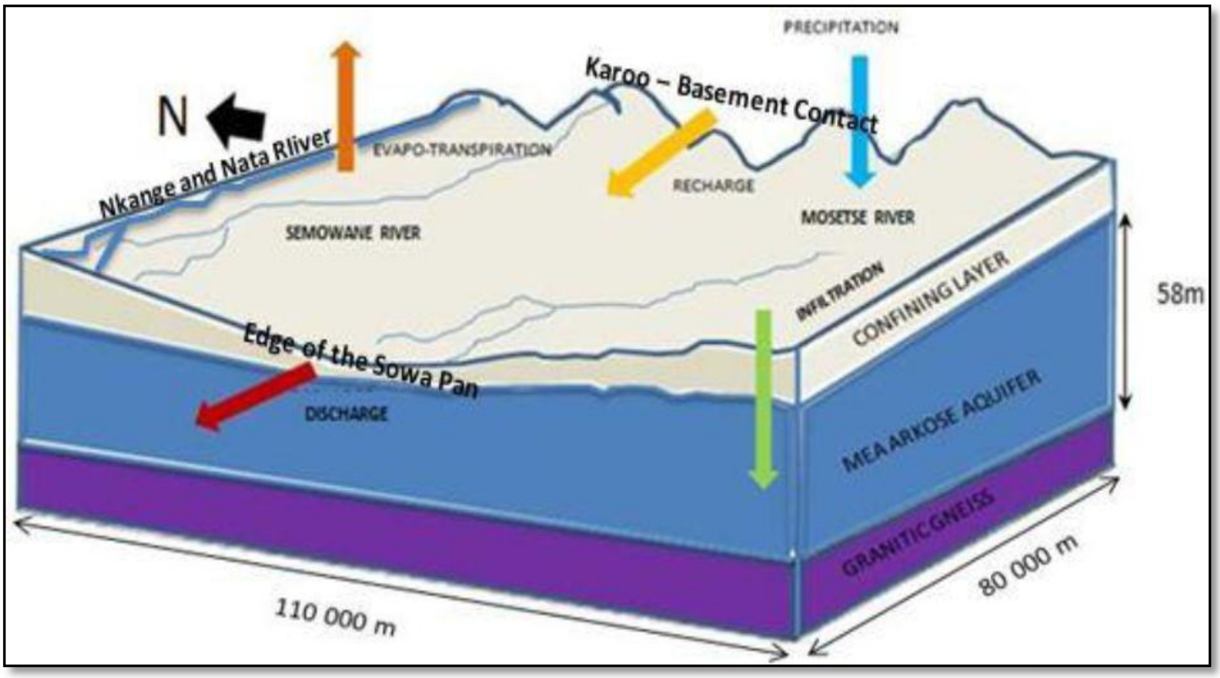


Figure 16. Schematic Conceptual Model of the Project Area.

7.1.1 Assigned OF Model Boundaries

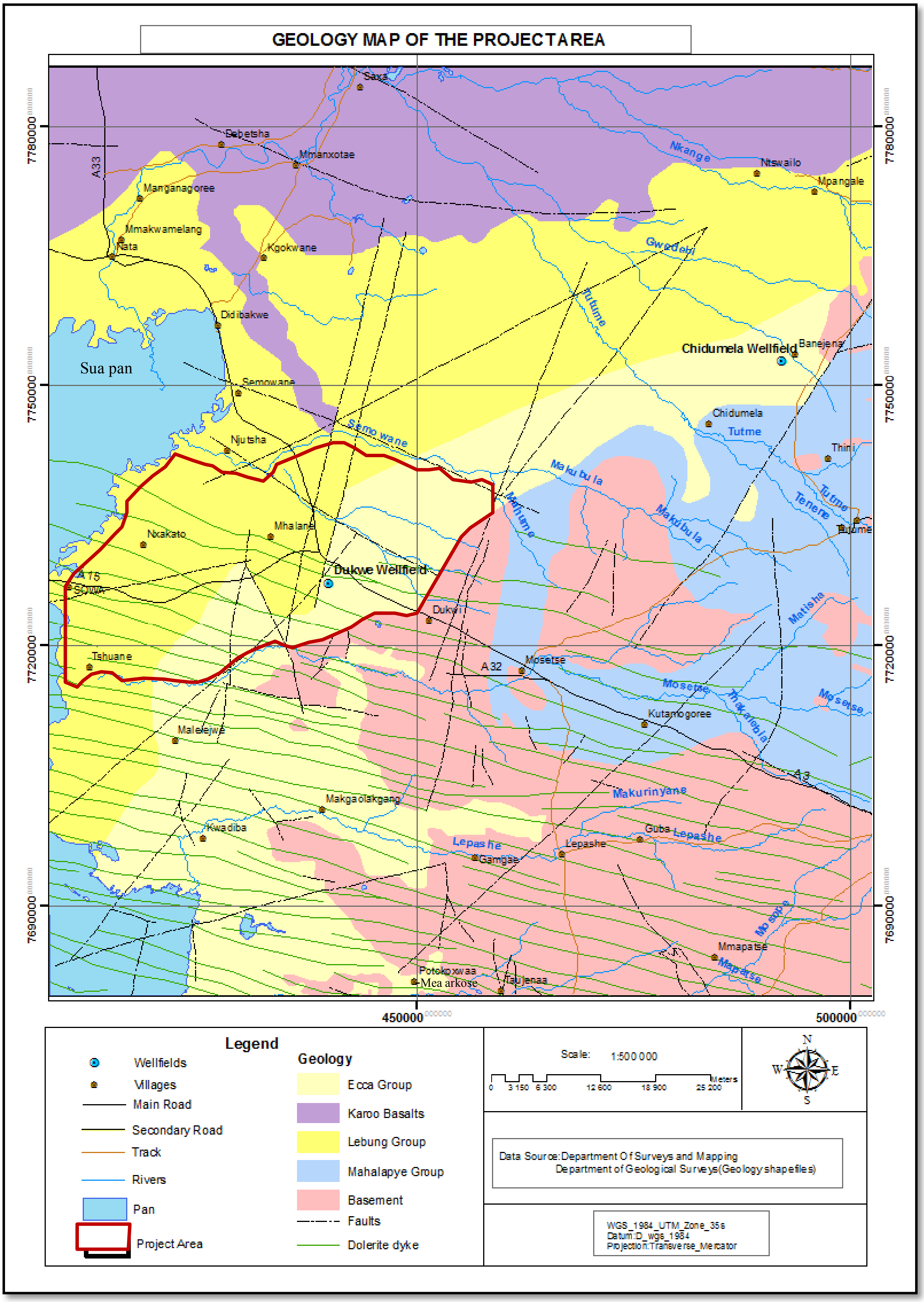


Figure 17. allocation of model baundaries.

The boundaries of the model domain are based on physical structures and features and geology of the study area (Figure 17). The model domain is bound to the north by Semoane River, contact between the Basement and the Mea Arkose Formation of the Ecca group defines the eastern edge of the aquifer, it is recognised that some recharge from rain enters the aquifer along this contact, trending along Mosetse River to the Sua Pan confines the aquifer to the south and to the west the aquifer terminates along the edge of Sua Pan at an altitude of 900 m amsl representing the ground elevation of the pan surface. The regional discharge of the aquifer occurs via evaporation at the pan.

7.2 NUMERICAL MODEL

The conceptual model produced for the study area laid a foundation for the mathematical model. The main purpose of the current numerical model was to audit, refine, upgrade and remodel the 2000 Dukwi wellfield model. The methodology outlined in chapter 3.0 was followed

7.2.1 Numerical Modelling Packages

The modelling package used in this study is a Modflow based Modelling package called Visual Modflow. Modflow is interactive computer simulation software used for 2-Dimensional or 3-Dimensional modelling of steady or transient state groundwater flow, mass transport and heat transfer for groundwater systems. It employs the finite difference method in solving the differential governing equations for groundwater flow, mass transfer and heat transfer. This graphical based interactive software is GIS compatible and was chosen for the development of this three dimensional model because Modflow based packages are common and are used broadly around the world on similar projects. They are also well documented and available for IBM – compatible personal computers at nominal costs. The package also has the capability to handle large scale regional problems.

7.2.2 Previous Models

The original Dukwi regional model was constructed in 1995 (DWA, 1995) using the modeling software AQUA and the model was referred to as the 'Aqua Model'. The wellfield was then remodeled by Geotechnical Consulting Services (DWA, 2000b) using a MODFLOW based software Processing Modflow for Windows, Version 4.1, (Chiang and Kinzelbach). The Department of water affairs audited the model using visual modflow (DWA, 2005) in 2003. The other latest Dukwi wellfield study was a wellfield monitoring exercise hence the 2011 Dukwi Wellfield monitoring report (DWA, 2011) which covered monitoring for the year 2003 to 2008.The wellfield has not been audited or remodeled for the past 12 years.

7.2.2.1 Previous modeling results

The latest modeling exercise of the study area prior to the current study was the 2003 Dukwi wellfield auditing of groundwater flow model and protection zone. The study was based on wellfield abstraction from 12 production boreholes of the Dukwi wellfield Phase I, Chidumela wellfield and Soda Ash Botswana wellfield. The study considered a 17 year stress period of up 2020. The head distribution and drawdown maps reflected that the water level in the model area will not subside below the screened zones of the production boreholes during the period. A regional water budget was also established based on available and assumed data on abstraction. The budget covered the period up to the year 2020. The water balance computation reflected a linear relationship between increased abstraction and the volume of water that comes from aquifer storage. The study made deductions that the aquifer was being mined and recommended adaptation of sustainable abstraction rates. Aquifer protection zone was also redefined since the former was considered invalid.

7.2.3 Current Model

The current study is intended to remodel the wellfield and update the model to 2015 Dukwi Wellfield Phase II Groundwater Flow Model.

7.2.3.1 Model Assumptions

The current study used the model assumption for the previous study as a base for deriving the model assumptions for the current study.

It is assumed that:

1 despite being locally fractured, the aquifer can be modelled using Darcian flow equations for flow in porous media;

2 the aquifer can be modelled as a single layer;

3 the aquifer discharges in the Makgadikgadi pan;

4 recharge on the study area occurs at rates that vary according to the strata and structure underlying the Kalahari Beds, but to the east where the Mea Arkoses outcrops the recharge is assumed to occur directly though the Mea Arkoses sandstone Beds***;***

5 evapotranspiration on the aquifer system is considered insignificant; and,

6 Both horizontal hydraulic conductivities (K_x and K_y) are equal and isotropic.

7.2.3.2 Model Domain and Discretisation

The model domain was set as in the previous models and was also homogeneously discretised using a one-kilometre grid for the whole area. The areal extends were 110 kilometres in the east-west direction and 80 kilometres in the north-south direction.

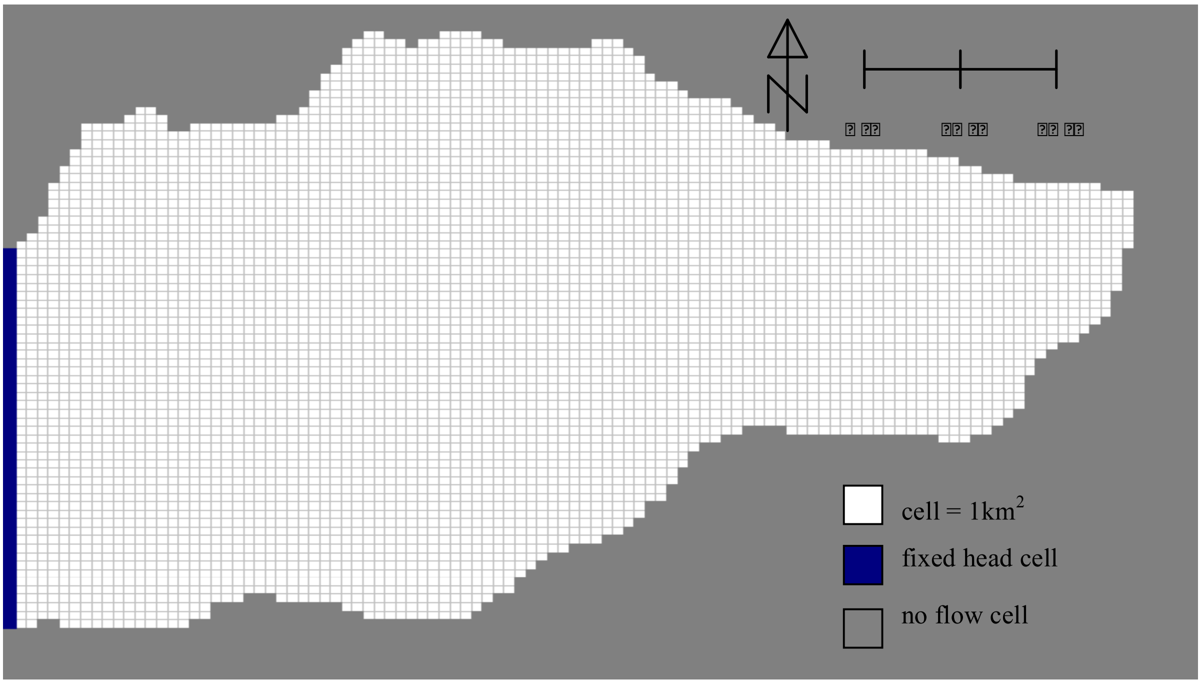


Figure 18. Model Grid and Boundary Conditions.

7.2.3.4 Boundary Conditions

The model boundaries adapted in the new model are a modification of the ones used in the Aqua Model and in the reproduced Modflow Model as well as the Audits. The decision on adapting the boundaries used in the former models was for consistency. The boundaries are based on physical structures and features which were allocated and discussed in the conceptual model of the study area (Section 7.1). The adopted boundaries at this stage were not yet final as they were to be subjected to scrutiny under the calibration stage. The fixed head cells were set to 900 m amsl along the edge of Sua Pan since borehole data from observation boreholes adjacent to the edge of the pan reflected water levels averaging 900 m amsl.

The adapted model boundaries are as follows:

- **North:** A no-flow boundary condition is assigned along the Nata River and the Nkange River.
- **East:** A no-flow boundary condition set at a distance of ten kilometres from the Karoo-Basement Contact which is also assigned as a recharge zone

- **South:** A no-flow boundary along the bed of the Mosetse River to the Sua Pan.
- **West**: Constant head boundary condition along the edge of Sua Pan at an altitude of 900 m amsl representing the ground elevation of the pan surface.

7.2.3.3 Generation of Layer Data

The upper model surface was generated from topographic maps of the study area and was incorporated into the model through importing and georeferencing. The lower surface was generated by setting the base to 0.058 km derived by averaging the aquifer thicknesses from lithological borehole logs of the study area (figure 8, 9 and 10). The initial thickness was yet to be scrutinized in the calibration process. Being relatively small in thickness and relatively broad in length and width, the one layer concept adapted was considered reasonable and hence used in the current model.

7.2.3.5 Initial Conditions

Initial head conditions for the steady state calibration were set by importing the initial head for the observation boreholes recorded before operation of the wellfield. Calculated hydraulic heads from the calibrated steady state flow model were used as initial head conditions for transient flow modelling.

There are no well-defined values for hydraulic conductivity or transmissivity and storage. The combinations between these parameters are of a wide range with variations in different rock units. Rather than fix the values the model was run in steady state inverse mode using PEST (Parameter Estimation by Sequential Testing, (Doherty, 2005)). Target ranges were assigned to the hydraulic conductivity and storage based upon the regional geology, which in turn was derived from Botswana Geological Survey data amended as appropriate by data gathered during the investigations and analysis of test pumping data.

7.2.3.6 Model Calibration

It is more meaningful to calibrate on fixed recharge instead of calibrating on fixed transmissivity, as recharge data is considered more reliable than transmissivity data, recharge values could be changed towards the end of calibration stage when the results are close to convergence. Transmissivity is a log-normal-distributed parameter and thus varies locally in a large range, whereas recharge is a normally distributed parameter and fewer variations locally. While recharge could be estimated from the groundwater chemistry and many other methods, the transmissivity are only known as point values from pumping test sites which are not representative of the mean values for the zones used. Therefore this strategy of calibration was implemented in the current study.

The use of many degrees of freedom (for example a large number of different transmissivity and recharge zones as presented in the 1995 Aqua Model (DWA, 1995) and the 2000 Modflow model (DWA, 2000) always allows for a close steady state fit to the observed head data. Creating a separate zone for each borehole (as in the former models) which has pumping test data leads to an over-parameterisation and over-interpretation of existing data and the resultant solution is certainly not unique. The number of parameters must be reduced to obtain a stable solution where the parameters are independent from each other. To achieve this or adapt this strategy, initial input transmissivity values were reduced in number and distributed over relatively larger areas; it was during the calibration process where values were altered to achieve the desired fit.

7.2.3.6.1 Steady State Calibration, Non-pumping Condition

Steady state calibration was initially undertaken by hand; despite a high level of man-hour input a close fit (convergence) could not be achieved. A Modflow built-in version of PEST (Parameter Estimation by Sequential Testing) was then adopted. The parameter limits were set for values of hydraulic conductivity, recharge, and storage and Convergence was judged against the 42 observation wells. Some wells did not exhibit convergence even with the use of PEST; such wells exerted an undue influence on the PEST solution. It was tempting to remove such boreholes from the steady state calibration observation borehole list, but this was not done since data from such boreholes was consistent, the other reason was to retain steady state workups as in previous Dukwi wellfield models for easy correlation and comparison of the output.

Groundwater abstractions were set to zero; calibration hydraulic heads were adapted from observation data that was acquired before the wellfields started running. Though there were scenarios of private boreholes or undocumented abstractions, the rates were however considered insignificant.

The primary roles of the calibration process were to infer absolute values of hydraulic conductivity (or transmissivity), storativity and recharge. The wellfield aquifer system had no measured discharge; absolute values of discharge were not known and must be balanced by the model. A set of 42 boreholes were used in the calibration, Table 9 gives their IDs, coordinates and rest water levels that were imported in the model for steady state calibration while Figure 19 shows the distribution of observation points on the study area.

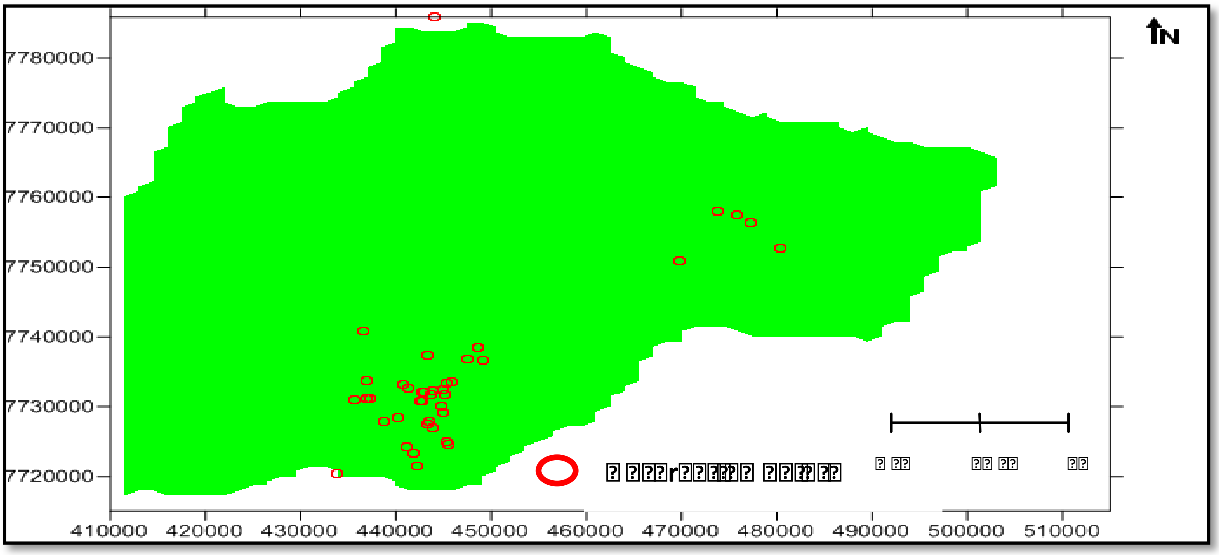


Figure 19. Distribution of Observation Boreholes Used For Callibration.

Table 9 Location and water level details for Boreholes used in the Calibration Process

Borehole No.	Easting (m)	Northing (m)	Observed hydraulic head [mamsl]
586	445512	7724640	924
604	442780	7730850	927
616	442890	7732145	928
1186	442837	7732123	926
1239	443850	7732280	928
1662	445290	7724894	921
2008	444950	7729210	928
2016	441241	7732594	926
2017	445090	7731750	923
2028	445816	7733505	928
2036	443318	7737293	927
2037	444850	7730140	925
2070	469813	7750860	963
2146	447592	7736753	929
2157	448701	7738472	930
2165	449100	7736650	929
2979	436908	7731228	920
2980	435580	7730920	920
2981	436906	7731228	920
2982	443850	7726900	920
2983	443380	7727550	921
2985	436517	7740899	915
3067	440187	7728473	915
3071	441781	7723311	922
3074	443490	7727860	921
3087	441120	7724310	915
3098	437357	7731230	919
3106	436987	7733707	922
3107	438850	7727820	913
3112	440747	7733245	925
3128	448570	7738427	928
3129	433888	7720460	914
3130	445030	7732429	927
3141	445305	7733282	921
3156	442651	7730749	925
3181	443687	7731694	926
6730	477262	7756416	972
6732	475756	7757443	962
6733	473749	7758015	954
7258	480372	7752768	973
Z3056	442295	7721464	923
Nata River	444104	7785868	945

Though calibration was successful, not all model solutions converged and the solution plane for the model convergence was vast with a few solutions satisfying low convergence criteria where the parameters returned are outside their acceptable ranges. Poorly modelled boreholes may be due to error in data for the borehole or that the model badly reflects the geology and hydrogeology in that particular location (WSB, 2008). These boreholes were kept in the calibration list with an appreciation of the poor convergence they reflected so as to keep consistency with previous models being audited and remodelled. Boreholes with poor convergence can be noticed as being distant from the 45 ° line on the calibration plot (figure 23).

To alleviate the problem of the model being dominated by Layer 1, it was reduced to a single layer representing the Mea Arkose only, which is thought to be reasonable as the model covers around 8,800km^2 in area but only 0.058km in thickness.

For most PEST runs, hydraulic conductivity, recharge and storativity coefficients was limited to the permitted ranges based upon those determined from the analysis of testing pumping data and other investigations such as from geology and previous reports. Table 10 shows recharge and storage values and Table 11 shows transmissivity values that were assigned to the demarcated zones. The parameters were initial inputs for steady state calibration.

Table 10. Racharge and Storativity Values for Model Zones.

MODEL ZONE	RECHARGE	STORAGE
Zone of known high transmissivity	2.5 mm/year	
Inflow along basement contact	0.25 mm/year	
Mea Arkose outcrop	5 mm/year	0.002
Makgadikgadi line		0.008
Background		0.001

Table 11. Input Transmissivity Values.

Transmissivity Zones	Transmissivity values Value (m^2/d)
Background	48
Major Faults	0.8
Zone of known High Transmissivity	1618
Makgadikgadi Line	290
Basement Complex – Mea Arkose contact	47

7.2.3.6.1.1 Steady State Calibration Results

The results of the steady state calibration include, hydraulic head distribution maps, transmissivity values and statistical parameters reflecting on the degree of accuracy or confidence of the calibration. A plot of modelled against observed heads is presented as a scatter graph in Figure 20, the data points represent hydraulic heads. The 45° line trending northeast – southwest is the reference line. Points laying exactly on this line represent a perfect fit. Data points above the line reflects that the model is over predicting the hydraulic heads in the system while those below the line reflects that the model is under predicting the hydraulic heads in the system. Tolerance of statistical outputs is mainly influenced by the purpose of the model and scale of the model. Regional groundwater flow models are likely to have relatively high error values as opposed to small wellfield model. A rough rule of thumb is to have a Normalised Root Mean Square value of 10% or less and a low Mean Error of less than 0.2 but there is no general consensus on that. The output statistical parameters derived from the calibration include; a fit with a Correlation coefficient (R^2) value of 0.97. The residuals have weighted and root means squared values of (wRMS and RMS) of 6.7 and 4.0m respectively. The residual mean and absolute residual mean were 0.216 m and 2.9 m, respectively, while the standard error of the estimate was 0.9.

The result obtained in the statistical analysis is considered reasonable and acceptable considering spatial distribution of the observation points and the size of the model. Not all transmissivity zones had measurements of hydraulic heads. This may affect the correlation coefficient of the fit. The quality of the data was very poor, les flexibility is present in model auditing and remodelling and therefore there was an effort to stick to the observation points used in the previous model. Considering the head difference of up to 70 m in the model area, the residual mean of 0.216 m and absolute mean of 2.9 m are considered reasonable and acceptable.

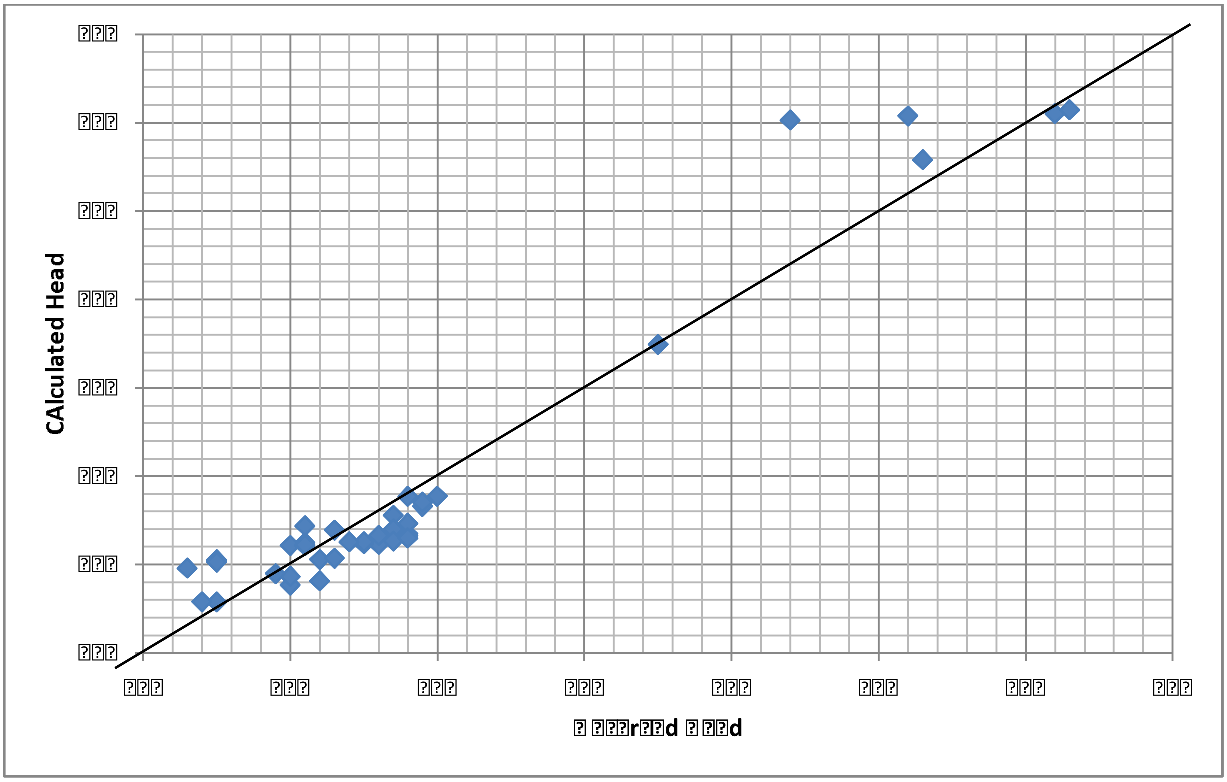


Figure 20. Scater Plot of Modelled Versus Observed Heads.

A Calibration Residual Histogram was also produced for analysis of relative frequency of observations for specific intervals of the normalized calibration residuals. A rule of thumb is that for good calibration output, the lowere vulues of the normalized calibration residuals should be more frequent than high value normalized calibration residuals. The high frequency in lower values of the normalized calibration residuals indicates that majority of observation points have high convegence between observed and interpolated hydraulic heads. The callibration risdual histogram in Figure 21 reflects that the more frequent normalized calibration residuals are lower values hence good convegence between culculated and observed head. The callibration outcome is again considered good and acceptable based on interpretation of calibration residual histogram.

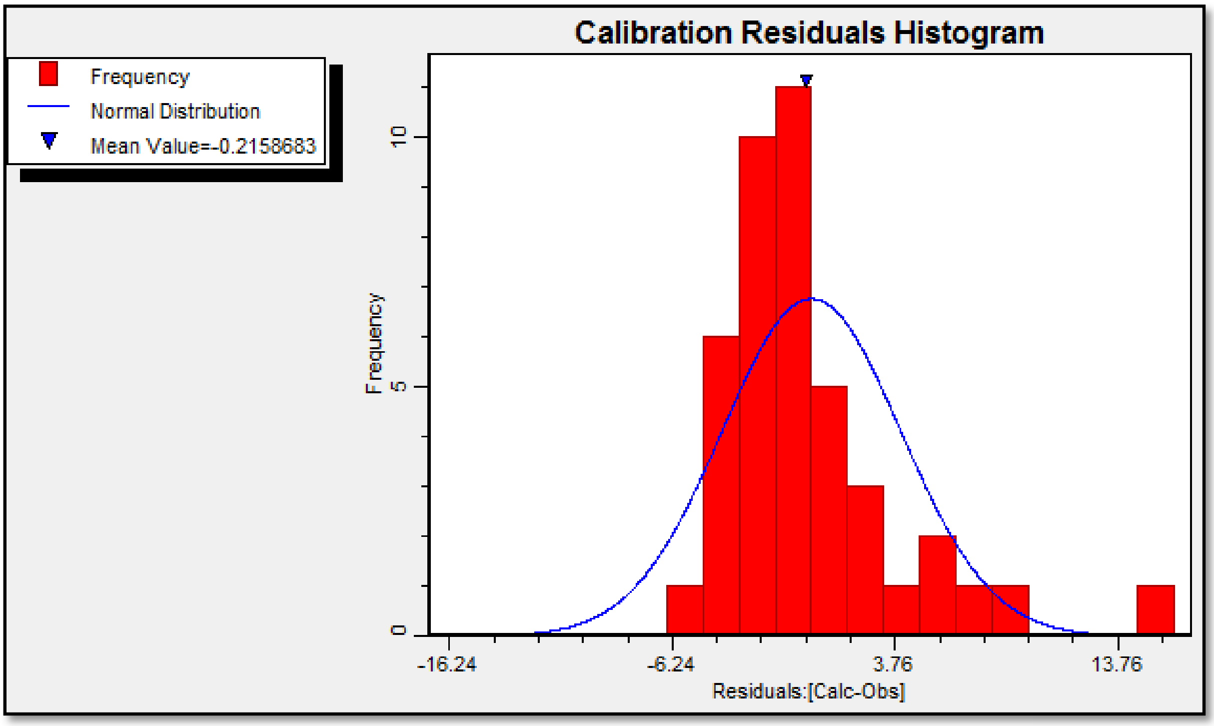


Figure 21. Calibration Residuals Histogram.

The effective transmissivity values obtained by calibration were presented in tables for easy comparison with the ranges that were used in the initial stage adopted from regional geology data and amended as appropriate by data gathered during the investigations and analysis of test pumping data.

Table 12 shows comparison of input transmissivity values and calibration values while Figure 22 shows allocation of transmissivity values to the project model area after calibration.

Table 12. Input and Calibrated Transmissivity Values.

Transmissivity Zones	transmissivity Value (m^2/d)	
Background	initial	calibrated
	48	58
Major Faults	0.8	0.58
Zone of known High Transmissivity	1618	1305
Makgadikgadi Line	290	290
Basement Complex	47	40.6

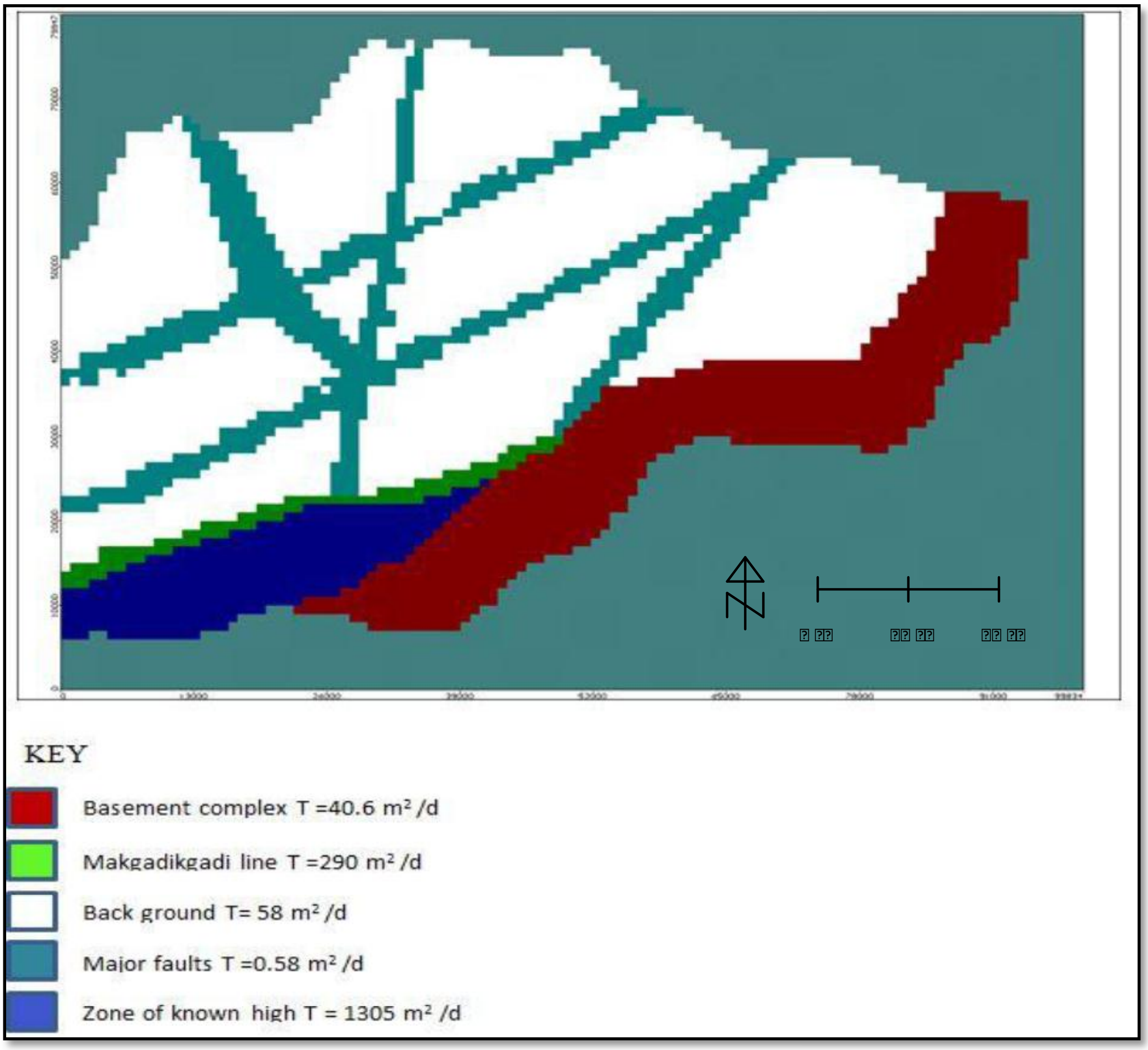


Figure 22. Effective Transmissivity Values.

The calibrated transmissivity values for the Basement Complex seem to be high but in fact correspond to a hydraulic conductivity that is lower than the hydraulic conductivity of the background. This is what was expected as this was discovered from a review of analysed test pumping data and as it was the case in the previous modelling reports. Major faults exhibit lower transmissivity values and this coincides with the deductions made in chapter 6 that they act as flow barriers. The area labelled as the zone of high transmissivity followed by the Makgadikgadi line reflects highest and higher transmissivity values, respectively. These were the case in other investigations and previous reports though the actual values differ significantly.

An output map of net recharge for the Dukwi wellfield as balanced by the model reflects a relation between transmissivity and recharge rates. The higher the transmissivity the higher the recharge rate, this improves confidence in the calibration results since basic expectations comprise the outcome. Figure 23 shows a map reflecting net recharge for the study area.

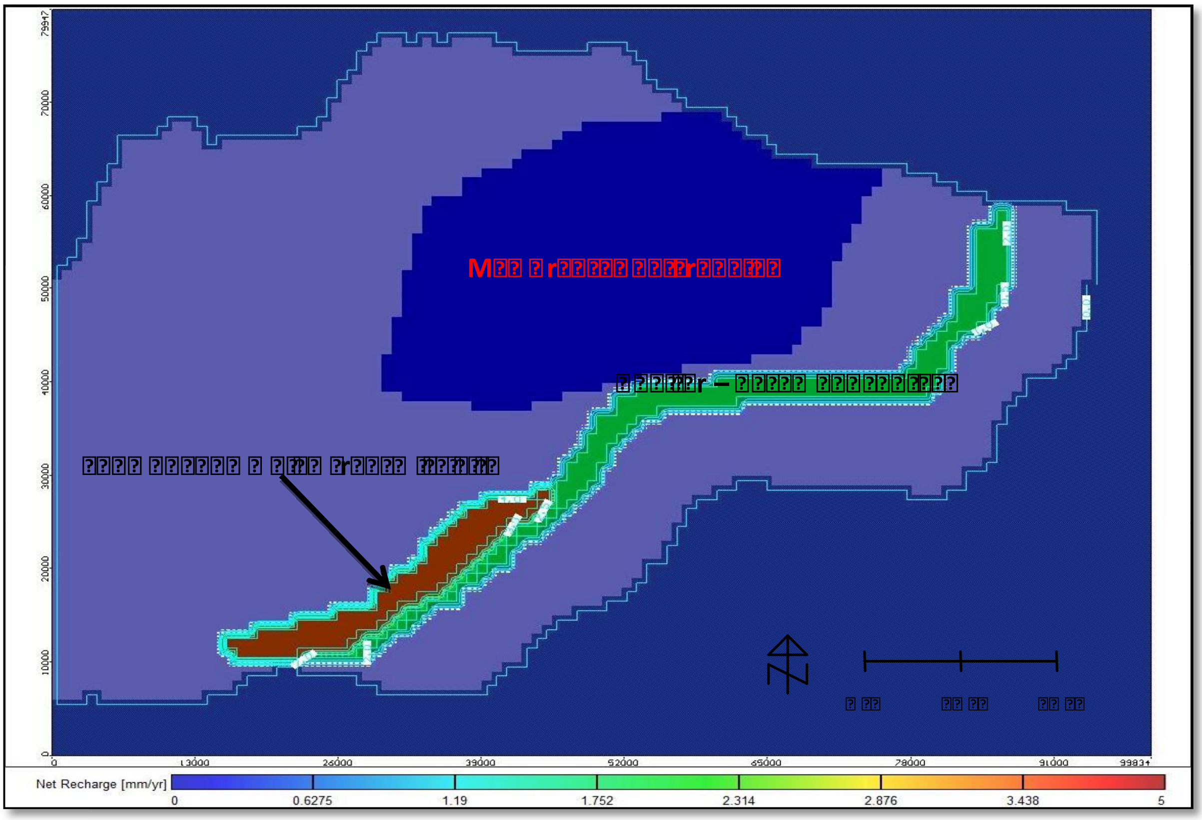


Figure 23. Net Recharge for Dukwi Wellfield Phase II.

Table 13 shows comparison of input recharge values and calibration values, the outcome reflects generally the opposite of what was derived from rainfall and climate data. The discrepancy is however reasonable given the data quality.

Table 13INPUT AND CALLIBRATED RECHARGE VALUES

MODEL ZONE	RECHARGE VALUES	
	INPUT	CALLIBRATED
Zone of known high transmissivity	2.5 mm/year	2.8 – 5 mm/year
Inflow along basement contact	0.25 mm/year	1.19 – 2.8 mm/year
Mea Arkose outcrop	5 mm/year	>1.19 mm/year

Table 14 shows the comparison between input storage values and calibration storage values. The output storage values were relatively very small to the initial values.

Table 14 Input and Callibrated Storage values

MODEL ZONE	STORAGE	
	initial	calibrated
Mea Arkose outcrop	0.002	$3.45 *10^{-5}$
Makgadikgadi line	0.008	0.00014
Background	0.001	$5 *10^{-5}$

A map of hydraulic head distribution for steady state calibration was also produced (figure 24); the map reflects high hydraulic head distribution on the eastern part of the study area that lowers to the western part. The map reflects that the study area discharges at the Makgadikgadi pan as it was previously envisaged. This is with the assumption that groundwater flow behaviour on the study area follows the general rule of thumb; the rule assumes that groundwater generally flows from area of higher hydraulic head to area of lower hydraulic head.

A three dimensional hydraulic head distribution representation of the model area was also produced to help in conceptualisation and visualisation of the hydraulic head distribution. The map reflects presence of flow compartment on the study area as discussed in section 6.2.2 of chapter 6, as well as the major faults. The zone of high transmissivity and Makgadikgadi line is reflected and more pronounced on the three dimensional part of Figure

24 as the lowest section, this coincides with lower hydraulic heads on the model area. The zone is a path of easy flow for water out of the aquifer system as much as is the easiest section for water to infiltrate into the system due to its hydraulic parameters.

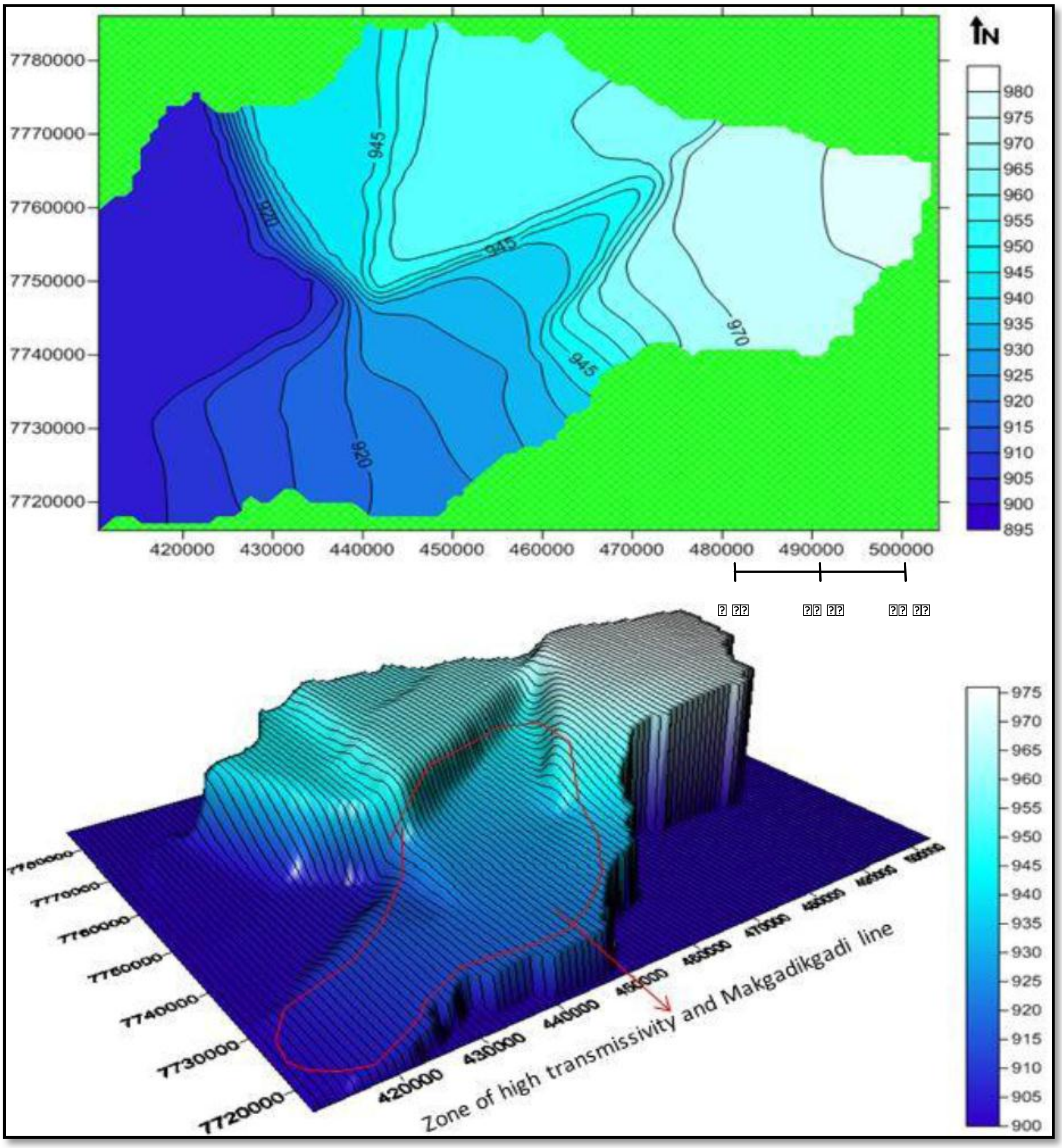


Figure 24. 2Dimensional and 3Dimensional Head distribution maps.

A vector map was also produced (Figure 25) to map and visualise the steady state flow pattern of water in the study area. It reflected that flow was generally to the west and the highest magnitude of flow was dominant in the central part of the model domain where major faults dominated. The map also reflect that flow is locally unique in most sections of the model area, this was interpreted to be reflecting presence of the compartments as previously invisaged.

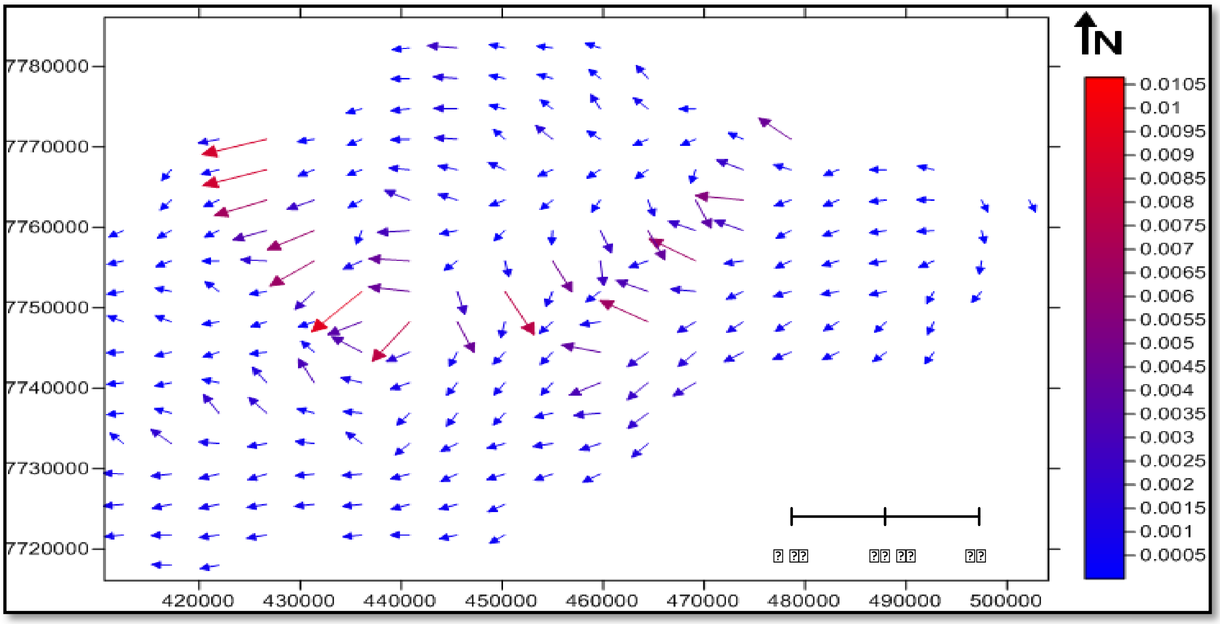


Figure 25. Flow Vector Map.

The flow vector map shows that major structures have a massive influence to flow and flow magnitude. An appreciation is therefore made at this stage that majore faults have significant influence on the model out put and a deliberate effort can be made in future studies to closely characterise them.

7.2.3.7 Steady State Simulation

Pumping wells were introduced in the model and a steady state simulation was run to investigade head distribution. A map of steady state simulation was then produced and presented in Figure 26. The map reflected that the abstraction influenced less than half of the model area. Head distribution exhibit high hydraulic head to the east and lowere hydraulic head to the west as was the case in steady state runs with zero abstraction. A three dimensional representation of head distribution was also produced and it reflects the cone of depression induced by the pumping wells on the model area which was absent when steady state runs were carried out with no abstraction wells.

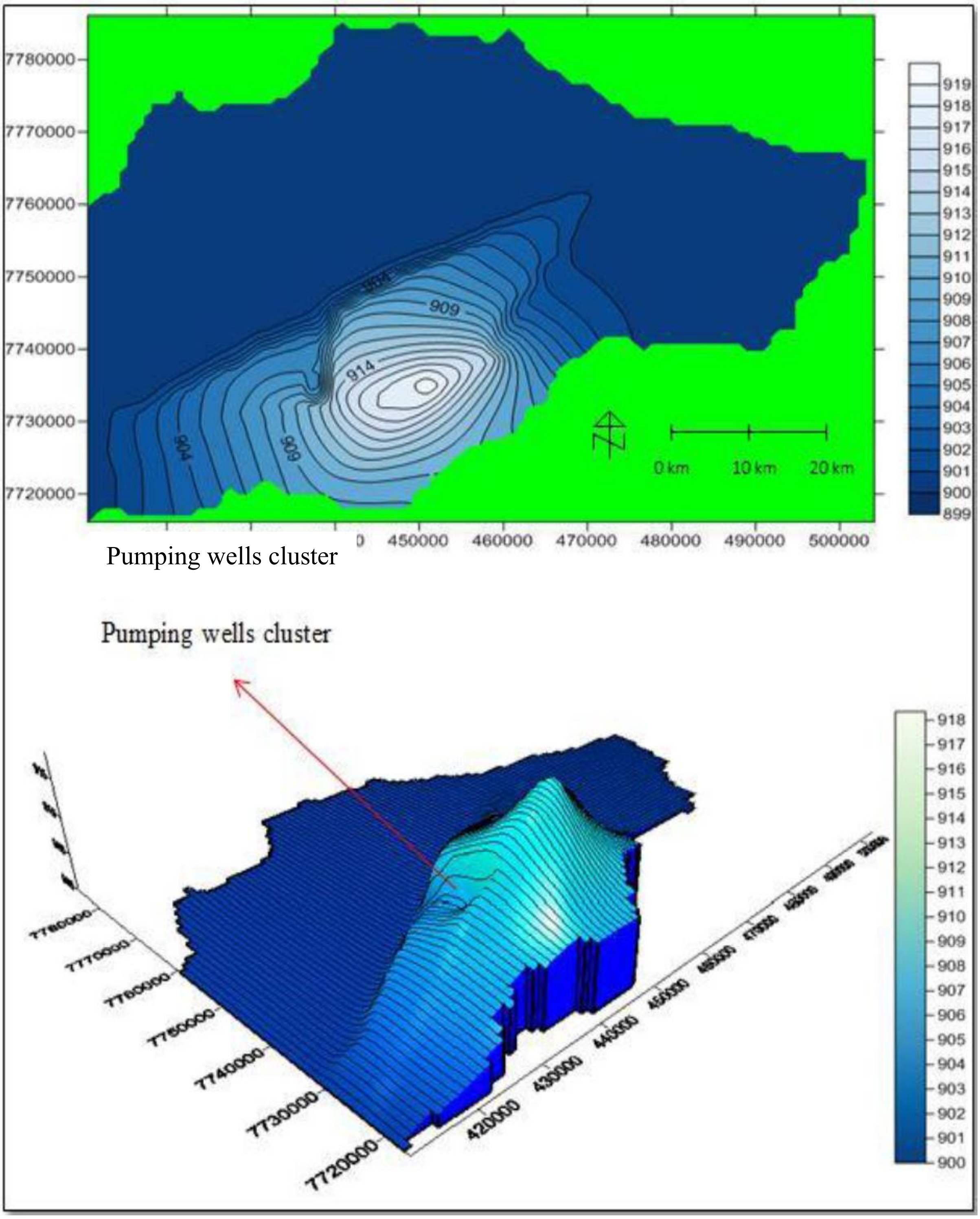


Figure 26. Two - Dimensional and 3Dimensional Steady State Head Distribution.

7.2.3.8 Transient Flow Modelling

The primary aim of transient flow modelling is for prediction of future aquifer scenarios which include hydraulic head distribution, resource quantification, drawdowns and water table behaviour under natural conditions. The natural conditions are characterised by unsteady processeses influencing groundwater water ocurrence, distribution and quality. This include varriable recharge and discharge scenarios.

7.2.3.8.1Transient Callibration

The transient calibration was performed as the initial stage of transient modelling and was carried out to derive or estimate aquifer parameters through the utilisation of monitored groundwater head data and abstraction scenarios. The aquired parameters were then used for transient flow simulation. The 25 wells used as observation points in the transient calibration are presented along with the corresponding location data in table15.

The transient model was run for 7920 days in a 360 30-day time steps, which covers the nominal period 01 January 1992 to 01 January 2014. Initial heads were taken from steady state runs of the model beforehand. The water levels measured in the observation boreholes were fitted during the transient calibration. Assuming that recharge is constant for the period of calculation, (1992 - 2014), movements in water level can be attributed to changes in the pumping rates. Due to an incomplete record of abstraction data, the transient model was developed using estimates of the absent pumping rates. The adopted pumping rates for the Dukwi Wellfield are summarised in Appendixes 1.

PEST, in Visual Modflow 4.0, does not operate in transient mode therefore the calibration must be by hand. The hydraulic parameters derived during steady state calibration were used as initial inputs for transient calibration. The groundwater abstraction considered in the model included that from all abstraction wells in the Dukwi wellfield for their respective periods of operation.

The calibration stage comprised of two runs with different scenarios, the runs were categorised into Run A with a zone of internal barriers running along Makgadikgadi line included and Run B was without the internal barrier. Run B exhibited relatively low residuals and was therefore chosen for transient groundwater flow simulation. Table 15 shows observation boreholes, their IDs, coordinates that were imported in the model for transient calibration and table 16 shows Estimated Residuals (m) for Transient Run B.

Table 15. Transient Calibration Observation Wells Locations.

BH-No	X	Y
610	7733051	441526
2016	7732595	441242
3112	7733243	440747
4628	7727958	443031
4649	7727907	442989
4702	7728601	442234
4768	7729327	441395
4769	7730274	439863
4788	7729671	441094
7392	7748858	457823
7515	7734864	452492
7520	7738550	439136
7521	7738549	439735
7546	7738550	440434
7547	7730294	439672
7639	7734987	452502
7641	7730295	439674
7642	7729624	441153
7643	7730248	440315
7669	7732678	443802
7670	7734145	445024
7672	7733998	446227
7673	7734506	448389
7685	7733024	446174
7686	7733628	447001

Table 16. Estimated Residuals (m) for Transient Run B.

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
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The zone of internal barriers running along Makgadikgadi line has been given a directional hydraulic conductivity of K_h = 0.01 m/d, perpendicular to its alignment. Specific storage was $5\text{x}10^{-5}\text{m}^{-1}$ for the background, $3.45\text{x}10^{-5}\text{m}^{-1}$ for zone of known high conductivity and 0.00014 m^{-1} for Makgadikgadi line, while specific yield was 0.0001 for the current model.

There were boreholes which exhibited maximum residual values. Removal of this borehole decreases the residual sum of square residuals and reduces the root mean squared residual. Removal of such boreholes would have improved the statistical work ups for the model and hence minimise residual values. The borehole exhibiting maximum residual values were however retained since the data from such points is consistent and therefore by rule of thumb they are a vital component of the statistics.

Despite their differences in values, the residual distribution behaviour in the current model is similar to the former models with the main errors around boreholes 2016, 3112, 610 and 7686. Figure 27 shows the residuals distribution for Run B and has been coloured to indicate zones of ‘reliability (actually contoured residuals) and has the locations of the representative observations wells superimposed.

The observation data in boreholes reflecting high residual (bh2016, bh3112, bh610 and bh7686) is consistent as discussed and therefore compelling for plotting in the residual distribution map, also the data projection into the model for such boreholes was interpreted as being reliable.

Convergence during Model calibration (steady state calibration and Transient calibration) is judged at borehole domain; hence most parts of the WellField are not tested and are dominated by extrapolated hydraulic data. Figure 27, illustrates the points on which the model has been tested, which despite attempts to distribute them across the model domain and are still clustered around pumping wells. The placement of observation borehole around the pumping well is important and convenient for test pumping exercise; it is however a setback in the modelling exercises.

There are areas in which the predictions become increasingly unreliable either because the models predict a bigger drawdown than is observed (Dark blue areas) or a smaller drawdown than is observed (Purple areas). In such areas the discrepancy may reflect that geology and aquifer thickness were poorly conceptualised and misinterpreted. Such zone carries a greater degree of uncertainty and further investigations must be implemented. Whenever changes in pumping strategy are implemented, the failed observation boreholes need to be closely monitored.

The Green areas are areas where the models deviate from the observed data by up to ±5m and indicate areas where, at the current time, the model is reasonably reliable (judged as ±5m) at the observation points.

The errors in all areas increase with increased abstraction and increased prediction periods and therefore predictions relating to long term resource evaluation, for example, should be viewed with caution because if the error in the model is of the order of 50% of the aquifer thickness, predictions about head distribution and drawdowns will be unreliable and unacceptable.

Lastly, the current model confines its predictive applications to ground water resource evaluations to the map area. Confirmatory verification of the predictions and simulations by the model is highly recommended.

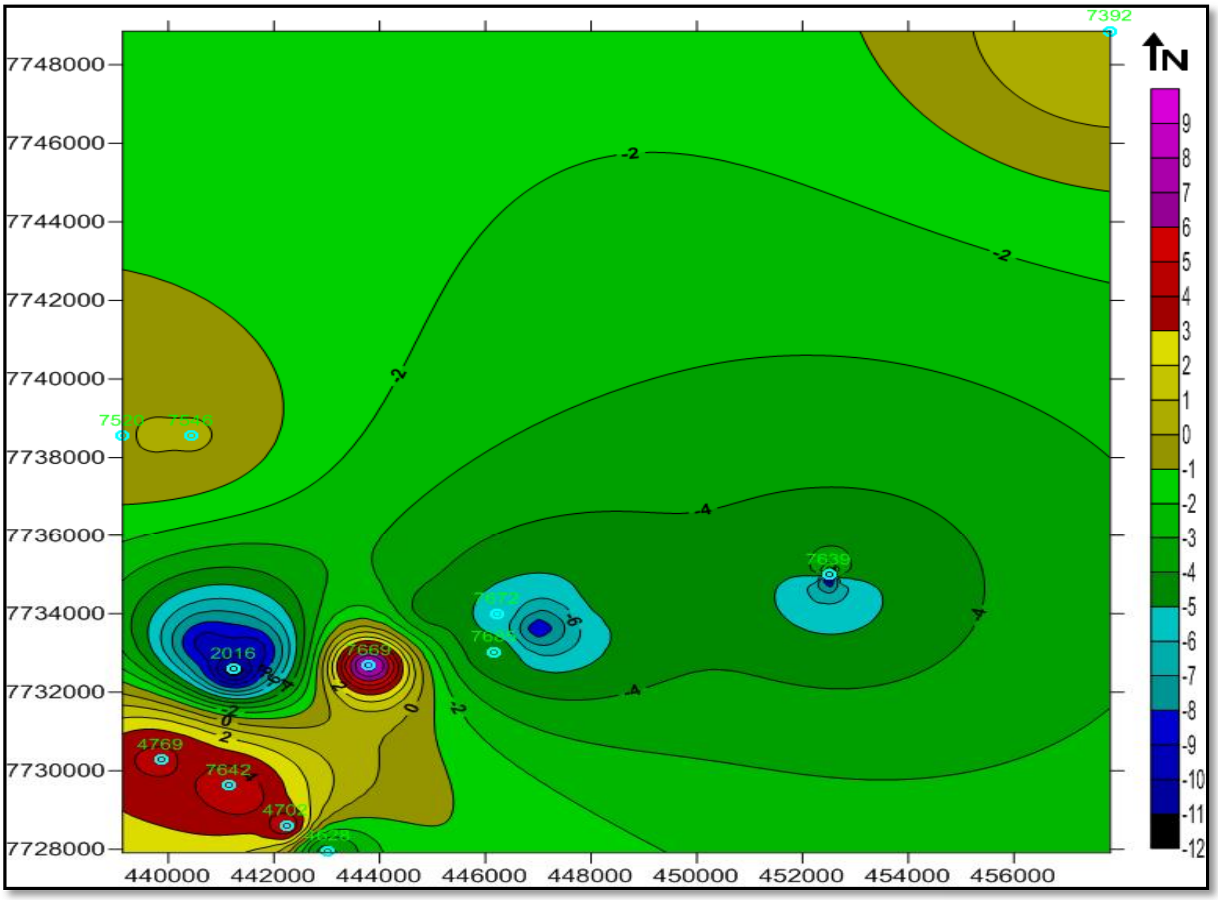

Figure 27. Residual Distribution Map.

7.2.3.8.2 Transient Modelling Output

Following transient model calibration, the 2015 transient groundwater flow model output reflecting groundwater heads and drawdowns distribution was produced. The modelling exercise was carried out using the abstraction rates retrieved from a database acquired from Department of Water Affairs, estimates were made where data was missing. The model covered a 61-year nominal period which runs from 1992 up to 2014. The results show that the water levels vary within the model area during the period. The hydraulic heads are of higher elevation to the east of the model area and declines westwards as was the case in steady state runs beforehand.

Drawdowns were also derived. Negative drawdown values represent recovery of the aquifer section due to decommissioning of Chidumela wellfield and Dukwi wellfield Phase I. The highest drawdown that the 2014 groundwater flow model reflects is 8.5 m (Figure 28) which is after a period of 61 years of simulation from 1992 to 2014. The Dukwi wellfield Phase II (study area) came under operation in 1998 though, for most part of the 61 years period, the Dukwi wellfield Phase I, Chidumela Wellfield and Soda Ash Botswana boreholes were under operation. It was after the decommissioning of the other wellfields in 2008 that the Dukwi wellfield Phase II experienced high and unsustainable abstraction of about 1000 m^3/day per borehole.

These drawdowns reflected by figure 28 are not at well domain and therefore should be interpreted with caution, the expectation is that drawdowns at well domain are relatively high and may differ from well to well. At wellfield domain, the drawdown data reflect a good performance of the aquifer considering that the aquifer thickness is 58 m and the maximum head difference is 70m. However, these results will be put under scrutiny in the prediction section, where observed and predicted head at well domain are correlated for a given period.

The hydraulic head distribution reflects that the study area ‘s current discharge is to the west into Makgadikgadi pans as previously envisaged. Figure 29 shows groundwater head and drawdown configuration at the end of transient modelling (December 2015).

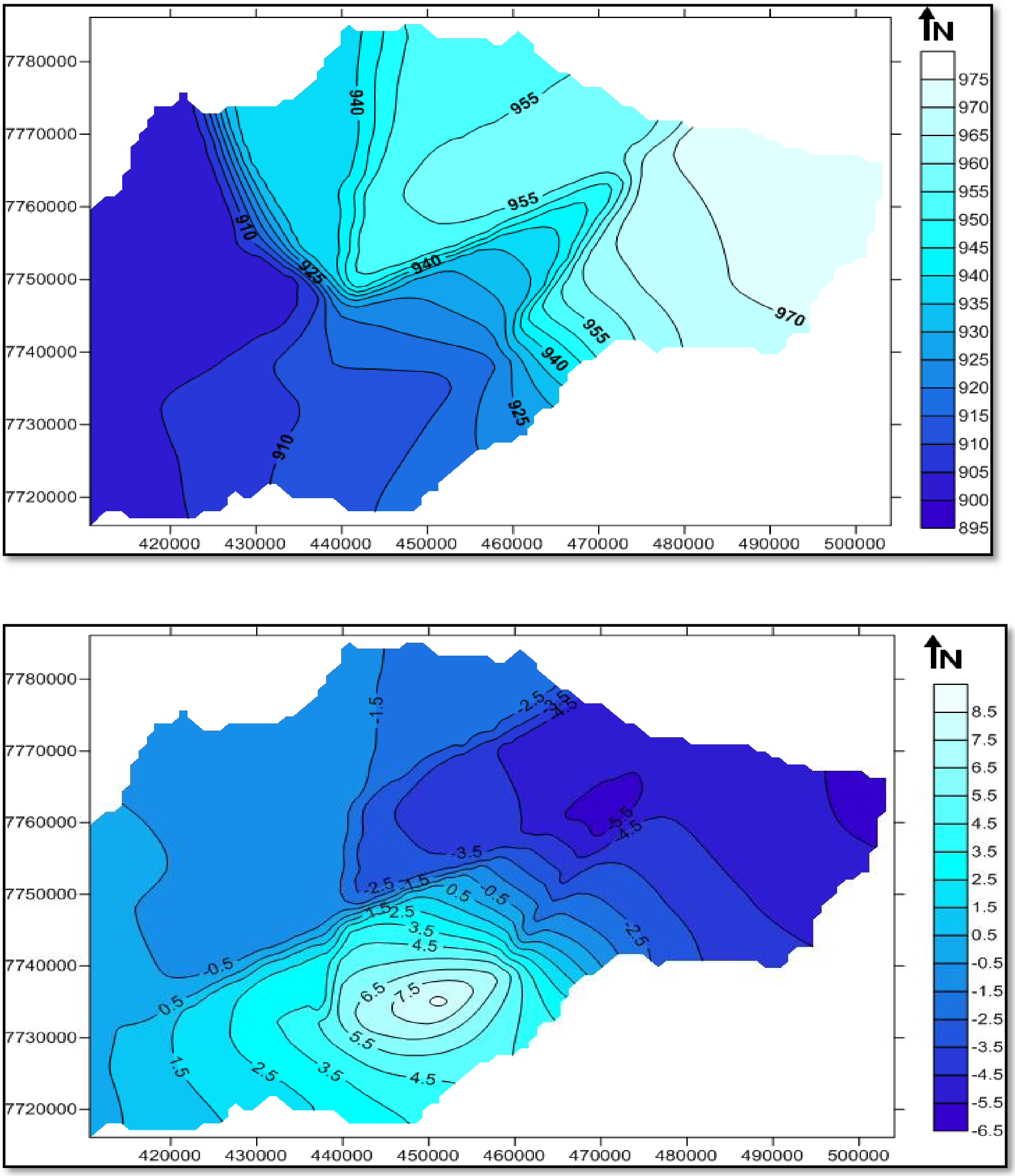

Figure 28 Groundwater Head and Drawdown Configuration at the end of Transient Callibration (December 2015).

7.2.3.9 Prediction

Well head monitoring commenced in 1992 by Department of Water Affairs, this exercise involved measuring water levels on a monthly basis in observation boreholes. Water Utilities Corporation (WUC) was later commissioned to carry out the task of monitoring both observation and production boreholes in Dukwi Wellfield Phase II (study area) in 1998 on behalf of DWA (DWA, 2005). However, Water Utilities Corporation discontinued measuring water levels in production boreholes after September 2003. Monitoring of the production boreholes was re-established again five years later and was done on four production boreholes (BH 7674, BH 7675, BH 7678, and BH 7687) which are currently running in Dukwi Wellfield Phase - II on a daily basis. These boreholes were connected to Telemetry system and measuring only abstraction data. In addition, data loggers were installed in all the four production boreholes in July 2008 to measure the water levels and are connected to the Telemetry (DWA 2011). The report (DWA, 2011) further reveals that from July 2008 onwards Water Utilities Corporation was measuring both water levels and abstraction. A request for water level data was made during the establishment of the current model (2015 DWM) but was unsuccessful, only groundwater levels data for twenty five observation boreholes which were monitored by Department of Water Affairs on a monthly basis was retrieved. This data was however sufficient to achieve the set objectives of the study.

The retrieved water level data was used for further evaluation of transient calibration results based on convergence between modelled hydraulic heads and observed. Hydraulic head versus time curves were therefore produced for the dual purpose of further evaluating calibration and for prediction of future hydraulic heads. Generally, the curves exhibited a good convergence with a maximum error of ±10 m amsl. Some curves exhibit unexpected trend though the data was found consistent and the data projection to the current model thought reliable.

The plots were therefore classified into three categories representing one of the three trends which were picked in these plots. The trends were classified as; high convergence, medium convergence and low convergence plots. High convergence plots have a maximum error (difference between observe and interpolated head) of ± 5 m amsl, this borehole plot on the green zone of the map in Figure 27 reflecting zone of high reliability, medium convergence have a maximum error of ± 10 m amsl while low convergence plots are characterised by intersection of the two plots representing observed water level and modelled. Medium convergence and low convergence boreholes plot on the purple and blue zones of the map, respectively, in Figure 27. The three types of plots were further characterised and examined in detail to understand their behaviour.

7.2.3.9.1 High Convergence Plots

The plots show high or good convergence between the observed well head and the modelled well head, such boreholes are bh 610, bh 2016, bh 3112, bh 4628, bh 7513, bh 7639, bh 7669, bh 7676, bh 7686. Figures 29, shows the type of curves reflecting the high convergence represented by observation borehole 7686. The rest of the plots with a similar trend are presented in the appendix 2 section. The difference in head is ±5 m amsl; this is good given the size of the modelled area, aquifer thickness of 58m and the challenges brought by unreliability of the data. Abstraction boreholes have been decommissioned over time, there are currently four abstraction boreholes operating in the Dukwi wellfield Phase II, and such is reflected by the stabilising predicted head change over time of the plots. The trend can be affected by change in abstraction rates over time, either increase or decrease in abstraction rates leading to the going down or going up of the plot, respectively, assuming fixed recharge.