GROUNDWATER RESOURCES EVALUATION OF THE LOKALANE-NCOJANE KAROO BASIN (BOTSWANA) USING NUMERICAL MODELLING

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Dedicated to Mirriam, Wanjivwa, Salome, and Peter Jr

ABSTRACT

In most arid and semi-arid regions such as the Lokalane-Ncojane Karoo Basin (LNKB), in Botswana, evaluation and understanding of groundwater resource is vital for management purpose. An optimal way to evaluate groundwater resource is by numerical models which however requires accurate external driving forces as inputs and knowledge about the aquifer to be modelled such as their hydrogeological similarities and differences.

The main objective of the study was to evaluate groundwater resources in the Lokalane-Ncojane Karoo Basin (LNKB). To achieve this objective a 3-D litho-stratigraphic model was developed using Rockworks software for the Kalahari Karoo Basin (KKB) and different formations modelled after applying a cross sections to the model suggested by (Smith, 1984). These formations based on their hydrological properties, were then converted into five hydrostratigrapic unites, namely, the Kalahari Sand aquifer, Stormberg Basalt aquitard, Ntane Sandstone aquifer, Inter-Karoo Mudstone/Siltstone aquitard and Ecca Sandstone aquifer which were also applied by (Kisendi, 2016).

These hydrostratigraphic layers had varying thickness and spatial extent. The Kalahari Sand which was the first layer ranged from 0-86 m and has a continuous spatial extent. The Stormberg Basalt aquitard the second layer has a limited spatial extent and ranged from 0-78 m. The third and fouth layers were the Ntane Sandstone aquifer and Inter-Karoo Mudstone/Silitstone which both were spatially limited and ranged from 0-182 m and 0-190 m respectively. The fifth was the spatially continuous Ecca Sandstone ranging from 0-214 m.

With the layers in place and exported into an integrated hydrological model (IHM) using MODEFLOW-NWT under ModelMuse a steady state model was created. The driving forces to the model namely precipitation and potential evapotranspiration (*PET*) were applied as satellite based products downloaded as FEWSNET products which were later processed in a GIS environment. The simulation period was for three hydrological years from 1st October, 2012 -30th September, 2014 and mean hydrological measurements were applied as model inputs. The steady state model was calibrated using 40 observation boreholes (Appendix 5) with trial and error method. The main calibration variables used in calibration were the vertical (VK, VCKB) and horizontal (HK) hydraulic conductivities.

The results obtained in terms of the water balance components as fluxes in and out of model showed the total UZF recharge input was 0.28 mm yr^{-1} and 0.27 mm yr^{-1} was lost as ET_{ss} which gave a net recharge in the area of 0.01 mm yr^{-1}. Among the simulated aquifers, the hydraulic conductivity of the Kalahari Sand aquifer (3.40-7.65 m day^{-1}) was higher than Ntane Sandstone aquifer (0.1-5.95 m day^{-1}) and Ecca Sandstone aquifer (0.1-3.45 m day^{-1}). The study also found that the presence of seasonal water ponds have an influence on the groundwater fluxes (net recharge and ET_{ss}).

Key words: 3D- Stratigraphic model; 3D- Hydrostratigraphic model; Integrated hydrological model; Kalahari Karoo Basin; Lokalane-Nkojane Karoo Basin

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HK	Horizontal Hydraulic Conductivity
IHM	Integrated Hydrological Model
KKB	Kalahari Karoo Basin
LNKB	Lokalane-Ncojane Karoo Basin
m.a.s.l	meter above sea level
3D	Three dimensions
BNWMP	Botswana National Water Master Plan
UZF	Unsaturated Zone Flow
MODEFLOW-NWT	Modular finite-difference groundwater-flow model –Newtonian Solver
NE-SW	North East-South West
PET	Potential Evapotranspiration
DEM	Digital Elevation Model
GHB	General Head Boundary
VK	Vertical Hydraulic Conductivity
WCS	Wellfield Consulting Services
WLE	Water Limited Environments

1. INTRODUCTION

1.1. Background of the study

Groundwater is an important resources for human survival and is present almost everywhere below the ground surface (Margat & Gun, 2013). According to Wolf, Morris, & Burn, (2007) groundwater is a central element in the urban water cycle as it accounts for about 78 % of freshwater and it is the most widely used for activities such as mining, irrigation, industrial and source of drinking water.

In most arid and semi-arid regions such as the Lokalane-Ncojane Karoo Basin (LNKB), in Botswana, evaluation and understanding of this important resource is vital. According to Obakeng et al.(2007) understanding of such a resource in such an area can sometimes be difficult because of erratic rain with recharge only in years with good rains. The other factor is that most of the infiltrating water are taken up by the deep rooted plant species and also lost due to evapotranspiration caused by high temperatures. It is also argued by Lubczynski, (2009) that many tree species in water-limited environments (WLE) depend on groundwater by direct uptake from the groundwater body or from the capillary fringe using rooting systems that may extend to several meters depth. These trees are thus, able to capture soil moisture in the unsaturated zone, reducing groundwater recharge.

Apart from that, groundwater resource has been subjected to intensive exploitation which has resulted in the alteration of the natural hydrogeology of most aquifers thus, affect the ecological functions and services that depend on groundwater resource (Custodio et al., 2016). One such example of exploitation in arid regions is where there is high groundwater abstraction in especially low recharge regions resulting in declining groundwater levels which makes evaluation of such a resource of high priority. Although groundwater evaluation can be done in many ways but one way is the use of numerical groundwater models (Wei, H et al.,2013)

This study will focus on evaluation of the groundwater resource in the LNKB by developing an integrated steady state model which encompass both unsaturated and saturated zones. It will use spatio-temporally distributed satellite data precipitation and potential evapotranspiration, FEWSNET product already biased corrected as driving forces to the integrated model in the LNKB. This will help in quantifying groundwater resource from the available aquifers through net recharge, evapotranspiration and groundwater storage.

Most of the work done in the same area have used standalone and single aquifer models such as (Rahube, 2003). This study will update the steady state model by Kisendi, (2016) with driving forces that were not spatially distributed. This will also develop a new conceptual model based on a 3D hydro-stratigraphic model and boundary conditions of the Lokalane-Ncojane Karoo Basin (LNKB).

1.2. Problem identification

Groundwater is the only source of potable water in the Central Kalahari. The Karoo sediments which hosts the Lebung Sandstone and Ecca Sandstone have proved to be good aquifers in large parts of the area. This group formation makes these strata consistent and productive aquifers in Botswana (NWMP, 2006). The Botswana National Water Master Plan Review estimates 75% of the national water demand is fed by supply from groundwater resources thus, the hydrogeological systems of the LNKB have been stressed by groundwater abstractions with the projected water demand for 2006-2035 linearly increases (WRC, 2006).

To help understand resource in the area stand-alone and single aquifer models by Chilume, (2001) and Rahube, (2003) exist for small parts of the LNKB. Then Kisendi, (2016) did an integrated model which however, was run with different boundary conditions and applied ground measurement data which were not adequate.

1.3. Objectives and research questions

1.3.1. Main objective

To evaluate groundwater resources in the Lokalane-Ncojane Karoo Basin (LNKB)

1.3.2. Specific objectives

- To upgrade geological, structural and hydrostratigraphic model of the LNKB
- To develop and calibrate a steady state integrated hydrological model of the LNKB
- To derive groundwater evapotranspiration, groundwater recharge, storage and net recharge of the LNKB
- To evaluate water balances of the LNKB

1.3.3. Main research question

What is the most reliable way to quantify the groundwater resources in the LNKB?

1.3.4. Specific research questions

- What is the most reliable geological, structural and hydrostratigraphic model of the LNKB
- What is the most reliable hydrogeological conceptual model of LNKB?
- What is the estimated net recharge (groundwater fluxes) of the LNKB?
- What is the water balance in LNKB?

1.4. Hypothesis

Groundwater resource in LNKB can effectively and reliably be predicated using a calibrated integrated flow model

1.5. Novelty of the study

- The upgrade of the existing geological, structural and hydrostratigraphic model of the LNKB
- The use of new hydrological conceptual model and new boundary conditions of the LNKB
- The use of integrated model in the evaluation of the groundwater resource in the LNKB

1.6. Assumptions

- Satellite products used in this study provide spatio-temporal variability of rainfall and potential evapotransipiration with sufficient accuracy for groundwater evaluation
- The groundwater resources evaluation can be realistically done through use of an integrated hydro logical flow model calibrated at steady state condition
- Interception of Kalahari savannah, represents 8% of precipitation

1.7. Literature Review

For effective groundwater management, understanding of different hydrological processes involved in a system is important. One way these surface and groundwater processes that have an impact on the groundwater resource can be understood is by applying integrated groundwater models. Although there are other models that can be used to evaluate the groundwater resource, in this study an integrated groundwater model was chosen. This is because other models such as standalone models may only focus on saturated zones leaving out the unsaturated zone where equally important hydrological processes also take place. Rachid, A & Al-Bitar, A (2008) argued that standalone models stimulate individual systems and considers adjacent systems as boundary conditions thus, not factoring in impacts from adjacent systems. While integrated models on the other hand simulate all the main processes that happen in both unsaturated zone such as infiltration and unsaturated zone storage and saturated zone such as exfiltration. They also try to factor in some other driving forces to the system such as precipitation and potential evapotranspiration (*PET*) that are not simulated in standalone models (Sophocleous, 2002).
There many studies that have been conducted in the LNKB and used different methods. Therefore this section will focus on some of the hydrogeological research studies conducted in LNKB highlighting their findings and shortcomings and finally defining what this study will add to the previous research.

1.8. Previous Research

It is not surprising that a lot of studies have been conducted in the study area (semi-arid Kalahari) during the past century to try and evaluate the groundwater resource because it is the sole resource. Previous studies in the area had focused more on using mostly standalone models in assessing the possibility of recharge in the area and very little has been done regarding integrated groundwater numerical modelling on LNKB.
Many studies conducted in the semi-arid of the Kalahari have shown that there can be moisture fluxes as high as 12mm a year (Gieske, 1995). Obakeng et al., (2007) demonstrated that there is considerable recharge in the Kalahari environments in spite of the high potential evapotranspiration in the area. For the LNKB, evidence gathered by WRC, (2006) indicate that groundwater replenishment occurs mainly in the western part of the LNKB with less or no recharge in the rest of the area.

The study by Chilume, (2001) showed potential recharge in the Lokalane-Ncojane basin using a single layer (Lebung aquifer) standalone model. Then Rahube, (2003) study was extended to two aquifer layers (Lebung & Ecca). Also the unpublished report from the Government of Botswana, Ministry of Minerals, Energy and Water resources by WRC, (2006) on the Ncojane and the Matlho-a-Phuduhudu blocks, using 3 layer steady state models for the two areas were developed. The two aquifers that were evaluated are the Ntane Sandstone aquifer and the Ecca Sandstone aquifer respectively. Finally Kisendi, (2016) went further and for the first time used 5-layer model including unsaturated zone of Kalahari Sand using an integrated hydrological steady state model. However, his model used ground measurements that were not adequate and spatially limited.

Although much work has been done in the LNKB by previous studies like Chilume, (2001) and Rahube, (2003) who showed potential recharge in the LNKB, they used single layer, standalone models. Therefore, they did not encompass recharge on the Ecca aquifer assuming all the recharge was into Lebung aquifer. WRC, (2006) conducted projects on behalf of the government of Botswana, Ministry of Minerals, Energy and Water resources in LNKB with focus on the Ntane Sandstone and Ecca Sandstone aquifers, also using standalone models and applied recharge as a value and not allowing the model to calculate. Kisendi, (2016) developed a 3D hydrostratigraphic model for the study area which this study will try and update using different conceptual model and boundary conditions. He modelled the five layers for his study and concluded that the area receives a net recharge of 0.03 mm yr-1. This was concluded by applying an integrated model which was run using a steady state model. WRC, (2006).

1.8.1. Value of this research

This research aim at appreciating the work conducted by previous studies and all their strong points. These include among others, the development of the 3D stratigraphic model since this will help in the conceptualization and discretization of the boundaries for the study area. But it will mostly focus on the gaps and try to address the short comings such as use of ground measurement data that is not spatially distributed and use of standalone models to simulate the flux in the study area instead of using integrated models. It will also try to enhance the calibration of the steady state model by using forty (40) monitoring boreholes (Appendix 5) which are spatially distributed in a quest to having a more representative model of the water resources in the LNKB.

1.9. Study area

1.9.1. Location (Lokalane-Ncojane Basin)

The LNKB falls within the Central Kalahari Karoo basin in the central part of Botswana and extends to Namibia in the western side. The study area covers about 35 000km^2 and is generally a flat area, with a gentle sloping towards the NE direction. Its elevation value range from 1030 to 1295 m, above sea level with no major connecting surface water bodies but presence of seasonal water ponds in the area Figure 1. The study area is just south of the Ghanzi Ridge, which is a prominent topographical feature running from the southwest to the northeast and is an elevated sequence of meta-sedimentary rocks that form part of the Ghanzi-Chobe fold belt. The main geomorphological feature of the study area are fossil dunes and pans and these crescent –shaped dunes are generally composed of grey calcareous material derived from the pan floors (Rahube, 2003). The climate is characterised by semi-arid conditions with rainfall restricted to the summer period between September and April. The Kalahari basin is filled with tens of meters of sandy deposits which are underlain by sedimentary rocks and basalt of the Karoo Super group formation (de Vries et al.,2000).

Since the area has no perennial water at the surface, groundwater is one important resource in the area thus, makes it a basin with an internal groundwater drainage system. Groundwater is mainly found in Karoo rocks with water tables ranging from 20 m below surface to more than 100 m. The main groundwater flow in the area is from southwest at a land surface elevation of 1250 m which is a water divide, to the lowest depression to the northeast at an elevation of 925 m (de Vries et al., 2000).

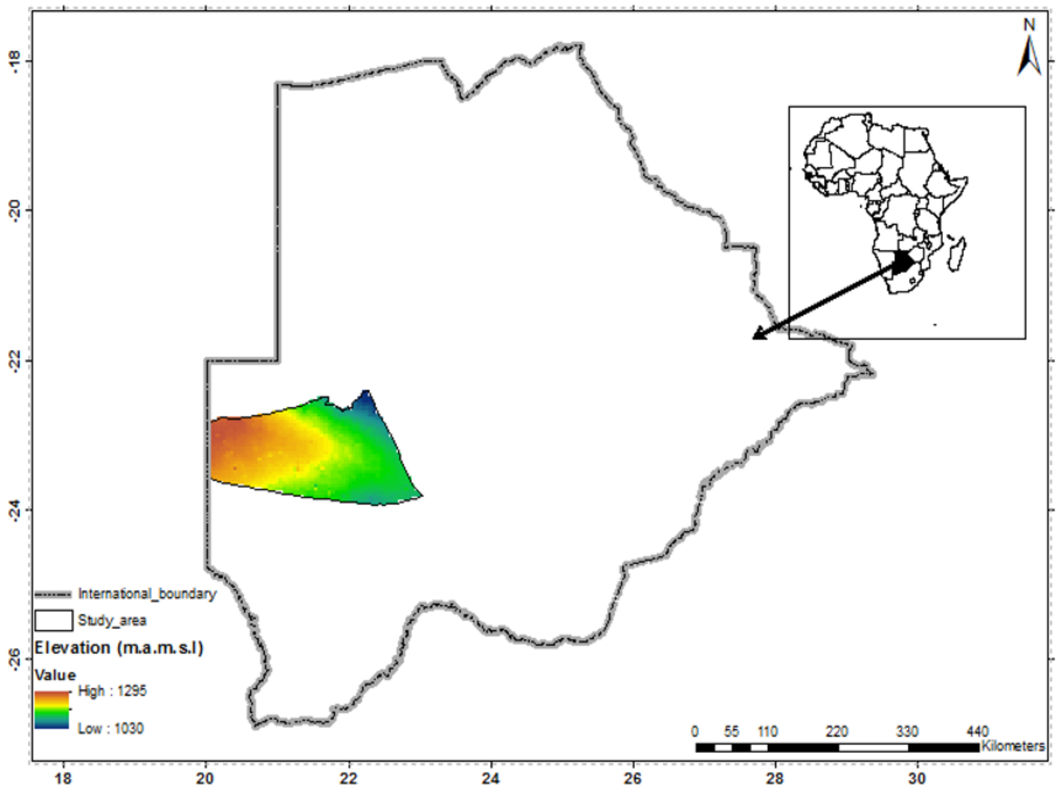

Figure 1 Location of study area

1.9.2. Climate

The study area lies in a semi-arid environment which is mainly characterised by dry cold winters and hot wet summers. Generally Botswana experiences seasonal rainfall, which occur mostly during the summers, from November to March. The period between months of April to September are transitional months, where the first one marks the dry season and the later is for the beginning of the wet season. Mostly the pattern shows that periods of higher than average annual rainfall are usually followed by periods of drought in erratic patterns. On the basis of the earlier study done by Rahube, (2003) the seasonal nature of the Botswana rainfall is mainly due to the extra-tropical waves and the troughs in the middle and upper airstreams and tropical systems, which include the Inter-tropical Convergence Zone (ITCZ), easterly waves, tropical storms and cyclones of the south west Indian ocean, Congo air mass boundary and the seasonal low pressure over Namibia, Botswana and Angola. The rainfall in Botswana is predominantly conventional. This is characterised by highly localised, high intensity thunderstorms/showers and hailstorms that are generally short lived. In the study area the highest temperature occurs during the summer and the coldest occur during the winter. The mean maximum monthly temperatures varies from 27 degrees Celsius to 35 degrees while the mean minimum monthly temperatures vary from 4 degrees to 10 degrees. There are high temperature changes within 24-hour period due to high temperatures during the day and low temperatures during the night. For the study area the annual mean rainfall and mean temperatures in the study area with reference from measurements from Ghazi station Figure 2

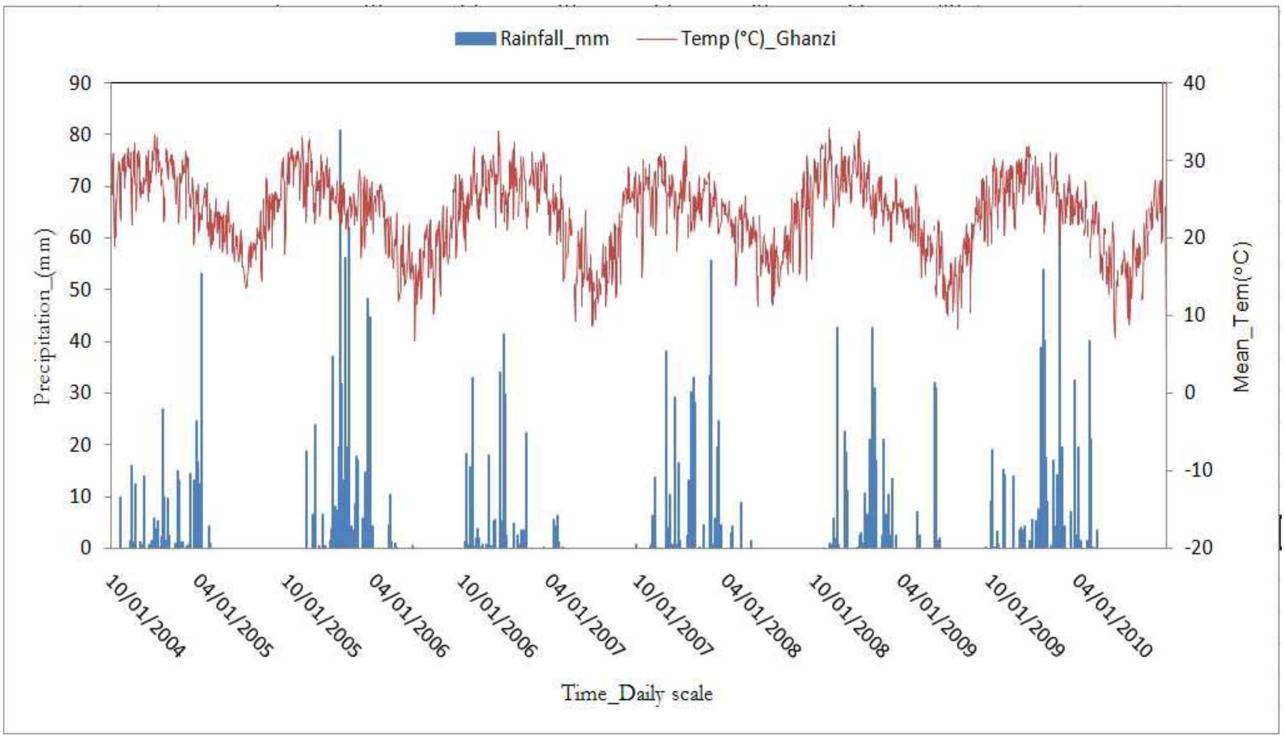

Figure 2. Daily precipitation and temperature at Ghanzi Airport stations (After Kisedi, 2016)

1.9.3. Land use and land cover

The LNKB is characterised with different types of land use such as residential settlements, wellfields, arable land, game reserve and commercial ranches. Land (cultivation areas) and cattle post (grazing areas) is a common practice in the area, although there are instances where cattle and posts are within one area (Kisendi, 2016).

In terms of land cover the study area has mostly savannah type with three main classes. These are tree savannah, mixed savannah and grass savannah. The three main tree species found in almost the all the area are Acacia Luderitzii/Boscia albitrunca association, Acacia melifera, and "Terminalia sericea while Lonchocarpus nelsii/ Acacia erioloba association", is generally found in areas of heavy Sand (Rahube, 2003). Mostly of these tress are able to survive such conditions due to having deep roots that are able to tap into the groundwater resource (Lubczynski, 2009).

The vegetation diversity shown in the study area is primarily due to the extensive and homogeneous Kalahari sand cover and the relatively flat gentle undulation topography. Local structural vegetation differences occur due to grazing and bush fires and areas where vigorous grazing is practiced tend to have less herbaceous tress and more of woody tree vegetation.

1.10. Regional geological setting

The geological setting of the study area is an extract and follows that of entire regional geological setting of Botswana. The major structural feature in the sitting on the eastern part outside the study area is known as the Kalahari Line. It is one of the major structural feature in the region mostly found at the edge of a Mid-Proterozoic Continental Craton trending north south along the longitude 22 °E, in the Eastern portion of the LNKB. There is also the EEN trending Zoetfontein –Fault which extends across Botswana into South Africa and its position is unclear in the vicinity of the Kalahari Line (Smith, 1984). The main geological structures and setting in Botswana and that are part of the LNKB are discussed in detail below;

1.10.1. Pre- Karoo Group

These are mainly made up of two groups the Transvaal (interbedded reddish, grey and purple quartzite, carbonaceous siltstone and shale, cherty, limestone, ironstone and volcanic) and the Waterberg group (Reddish siliciclastic sedimentary rocks, mostly quartzite sandstone and conglomerate) and are Proterozoic in age with such rocks (Smith, 1984).

1.10.2. Dwyka Group

Another group is the Dwyka group which is represented by the Dukwi Formation and is the Basal unit of the Karoo Super group. According to Smith, (1984) this formation rests on Proterozoic Transvaal and Waterberg Super group and also on the Archaean basement strata. This unit mainly forms part of the basement in the hydrogeological layers.

1.10.3. Ecca Group (Middle Karoo)

Another important group is the Ecca Group. The setting which has been adopted for this study was done by Smith, (1984)who argues that the group is divided into three separate conformable formations, namely the Bori, Kweneng and Boritse in respective order from oldest to youngest as follows;

i. The Bori Formation is mostly an accumulation of mud deposited from suspension in a post glacial lake, which shows forms of the early Karoo glacial depositional environment and it overlies the Dwyka Formation. It mostly comprises of the basement in the study area.
ii. The Kweneng Formation (Middle Ecca) is mostly comprised of massive, poorly bedded, coarse to medium grain quartz-feldspathic gritty arkoses becoming finer grained and silty towards the base. This also forms part of the basement in the study area and is a transition from the argillaceous units of the Bori Formation to grits and coarse sandstones.
iii. The Boritse (Upper Ecca) is part of the fifth layer in the groundwater flow model of the LNKB and comprises of alternating sequence of fine to coarse grained feldspathic sandstone, alternating with carbonaceous mudstones, muddy siltstones and silty mudstone intercalations, dull and bright coals and coaly carbonaceous mudstones.

1.10.4. Beaufort Group (Middle Karoo)

Also the Beaufort Group of the Karoo is mostly dominated in the southern parts of the Kalahari Basin by the Kwetla Formation. It is characterised by a largely argillaceous non-carbonaceous multi-coloured, (yellow, brown, green, greenish grey, purple, cream, white and light grey) sequence of mudstones and subordinate siltstone, with minor fine to coarse grained sandstone intercalations and the Mosolotsane Mudstone, It forms the fourth layer Mosolotsane- Kwetla of the LNKB, which is an aquitard, confining the Ecca aquifer (Smith, 1984).

1.10.5. Lebung Group

The Lebung Group lies on the uppermost Ecca Group and Kwetla Formation throughout the country of Botswana. It is mostly made up of two divisions namely, the lower Mosolotsane Formation and the upper Ntane Sandstone Formation. Among the two the Ntane Sandstone Formation is the mostly studied, widely understood and the most predictable aquifer in the Karoo sequence. This makes it the principal target for groundwater development in many regions of the country, especially the Central and Eastern part of Botswana as argued by (Smith, 1984). In this study, Ntane Sandstone forms the third hydro geologic layer of the LNKB. Smith, (1984) further suggests that on the other hand the Mosolotsane Formation is the lowermost subdivision of the sequence of continental sediments and volcanic that comprises the Lebung group. It's mostly mudstones -siltstones with occasionally intercalations of coarse sandstones. In this study, the Mosolotsane was combined with the Kwetla unit of Beaufort Group, to form a fourth hydro geologic layer (aquitard) of the LNKB.

1.10.6. Stormberg Lava Group

It forms the uppermost unit of the Karoo Super group and has been formally designated the Ramoselwana Volcanic Formation. The Stormberg manily consist of a very extensive, and often very thick, sequence of tholeiitic flood Basalts which mark the end of the Karoo sedimentary succession and the Basalt is black to greenish grey, but reddish brown in the amygdaloidal zones. This is mainly found in the small part of the Eastern LNKB and forms the second hydro geologic layer, confining the Ntane Sandstone aquifer(Smith, 1984).

1.10.7. Kalahari Group

This group is part of Post-Karoo superficial deposits of the Kalahari Group (commonly termed 'Kalahari Beds' or 'Kalahari Sands'), it mainly comprises of loose to poorly consolidated sand, silcrete and calcrete intercalations of variable proportions, subordinate to minor Ferricrete, silcretized/calcretized sandstones and mudstones which is the most widely spread in the study area(Smith, 1984). In the LNKB, this unit forms the first layer, mainly unconfined and considered to be unsaturated zone.

1.11. Geology of study area

The geological arrangement in the study area has evolved over time and a general stratigraphic setup for the area is highlighted in table 1. According to Matgen, et al, (2007) the central part of the large Kalahari basin is composed of younger sediments of the Kalahari Group and the Karoo Super group ranges in age from Late Carboniferous to Early Jurassic. The Proterozoic Okwa basement forms the oldest rocks in the area and this basement is made of the younger Okwa basement complex which is composed of intrusive meta-igneous rocks, and the older Okwa Supracrustal basement assmblages, which mainly consists of porphyrite felsites and possibly sericite quartzite.

The Cretaceous sediments of the Karoo Super group overlie the basement. Basalt deposits cap the Karoo Super group in the north-central and north-eastern parts of the study area and these basalts are characterised by weathered, green to reddish purple, amygdaloidal lava flows that are dark grey in colour Figure 3. The basalts oversteps the Lebung Group strata and overlie rocks of the Okwa Group in the east and Ecca Group in the west (Rahube, 2003).

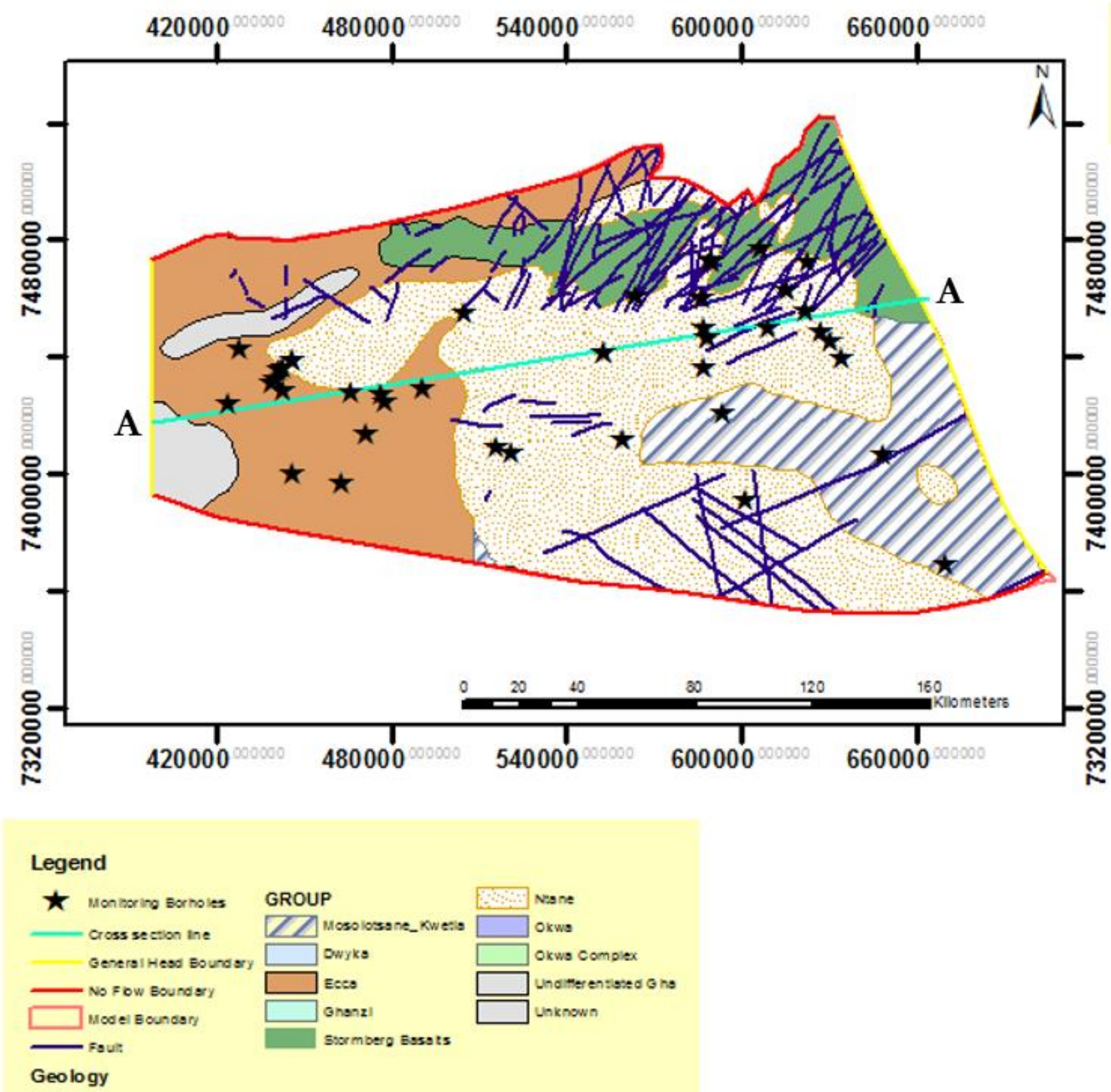

Figure 3. Geology of the study area and its physical boundaries

Table 1: The Karoo stratigraphy of the study area (adapted from Smith, 1984)

Age	Group Series		Formation	Lithology
Caenozoic	**Kalahari Group**		Kalahari Group	Lose sands, calcrets, silcretes, calcareous sandstones and mudstones
Mesozoic	**Karoo Super Group**	**Stormberg Basalt Aquitard**	Stormberg Basalts / Lava	Variably weathered, green or reddish purple amygdaloidal lava flows
Upper Palaeozoic		**Ntane Aquifer**	Ntane Sandstone Formation	Fine to medium grained,clean,friable sandstone, brownish red/pink
		Mosolotsane-Kwetla Aquitard	Mosolotsane/Kwetla Formation	Red/brown mudstones and siltstobes with minor sandstones/Grey mudstones/siltstones with minor sandstone. Arenaceous to the west and the north
		Ecca Aquifer	Boritse Formation	Fine to course, white, quartz sandstone interbedded with coal, carbonaceous mudstones and siltstone
			Otshe Formation	Ffine to coarse, brown/grey, felspathic, micaceous sandstone interbedded with carbonaceous mudstone and rare coal seams
			Kweneng Formation	Predominantly medium to coarse grained feldspathic sandstone, grits with subordinate silystone aand mudstone. Minro coals
		Dwyka Basement	Dukwi Formation	Massive, dark grey, sandy mudstone and siltstone.
			Mmalogong Formation	Tillite, conglomerate with quartzite/granite clasts in sandstone matrix.
			Khuis Formation	Purple mudstone rythmites/varvites with dropstones.
			Middlepits Formation	Purple siltstone and very fine sandstone.
			Bori Formation	Dark, micaceous siltstone/mudstone and minor sandstone.
			Kobe Formation	Dark micaceous siltstone/mudstone and minor sandstone

1.12. Hydrogeology

In the study area the main aquifers considered where the Kalahari Sand aquifer, Ntane Sandstone aquifer and Ecca Sandstone aquifer. The other two layers that are namely the Stormberg basalt and Inter-Karoo Mudstone/Siltstone aquitards were also considered. This section will try to focus at each hydrostratigraphic unit of the study area.

1.12.1. Kalahari aquifer

The Kalahari Sand aquifer in most places directly overlie the Ntane aquifer expect in places where the basalt is present. Generally these are shallow aquifers and mostly exploited by hand-dug wells and mostly water strikes might occur between 10 m and 40 m below surface were water is contained in primary pores and dissolution of calcrete may provide enhanced storage and permeability (Rahube, 2003).

1.12.2. Stormberg Basalt aquitard

According to WRC, (2006) although these basalts have recorded some water strikes but it's not such significant yield thus this formation does not have any considerable signs of saturation and is considered as an aquitard in the study area. From the geological date this formation acts as a confining bed and overlie the part of the Ntane aquifer especially in the northern part. It is not spatially continuous but makes it one the important formation to be evaluated during this study.

1.12.3. Ntane Sandstone aquifer

From the geometry of the Ntane Sandstone aquifer which was interpreted from geological data shows that it is not spatially continuous and extends eastwards into the Central Kalahari. This is formed by the top Ntane Sandstone formation and overlying the Inter-Karoo Mudestone/Siltstone formation with a general water flow from west to east appendix 1. This was derived from potentiometric maps by using the hydraulic head from reports with borehole logs in the study area. The Ntane Sandstone aquifer varies has a saturation thickness varying from 10 m in the west to 80 m in the south and north while the centre records a thickness of about 130 m (Rahube, 2003).

1.12.4. Inter-Karoo aquitard

This is also referred to as the Kwetla formation which is mainly composed of mudstones. They are not spatially continuous and are mainly thicker in the southern parts of the study area and act as confining bed for the Ecca Sandstone aquifer. This limits the flow of groundwater between the Ecca Sandstone and the Ntane Sandstone(WRC, 2006).

1.12.5. Ecca Sandstone aquifer

This is one of the most documented formations in the Kalahari and mainly composed of the Boritse formation which is characterised by some fine coarse, clean quartzo feldspathic sandstone, coals and carbonaceous mudstones and siltstones. According to WRC, (2006) the Ecca aquifer is mostly confined with the exception of the western side of the aquifer where the Inter-Karoo Mudstones /Siltstone thins out. It contains variable water quality with estimated yields of 50 m^3/hr and a general flow pattern of from west to east.

1.12.6. Dwyka aquiclude

The Dwyka aquiclude mostly intercepted in the north-western part of the study area are highly localised with very low yields recorded. This makes it of very low hydrological importance to this study area but wealth considering.

1.13. Hydrochemistry

1.13.1. Ntane Sandstone aquifer

As discussed earlier the general flow of groundwater through the Ntane aquifer is from the west to east as shown in appendix 2. Rahube, (2003) suggest that the low hydraulic conductivities recorded in the aquifer coupled with low hydraulic gradients do not facilitate rapid groundwater movements but rather help have prolonged rock water interaction. Therefore, this aquifer have shown predominantly high amounts of cations Ca^{+}, Na^{+} and Mg^{2+} and anions HCO3- in solution. The total dissolved solids (TDS) is generally low with values of about 150mg/l which is indicative of some fresh water.

1.13.2. Ecca Sandstone aquifer

The trend in water chemistry in the Ecca is not much different from the pattern in the Ntane. The aquifer also shows low total dissolved solids (TDS) especially in the western part. While a prominent increase in TDS occurs in the southeast indicating very low hydraulic conductivities resulting in prolonged rock water interaction and pronounced increase in TDS and the water chemistry in the western part is characterised by Ca-HCO_3 indicative of recently recharged water(Rahube, 2003).

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2. METHODOLOGY

This section will focus on methods that will be applied in order to help answer the above highlighted research questions. This will be done by developing a 3D hydro-stratigraphic model which will help build a reliable conceptual model for the area and later calibrate a steady state model that will help in the evaluation of the groundwater resource in the study area. Because of the importance of the resource in the area many studies ranging from geological, hydrogeological studies and also models have been conducted to help in the assessment of groundwater resource. Although some models have been conducted in the area most of them have been standalone models, focusing on single aquifers. Some of the notable studies that have been done in the area include a standalone steady state numerical model on the Hunhukwe/Lokalane which focused on the Ntane aquifer done by WRC, (2006) which was later upgraded to two aquifers Ntane Sandstone and Ecca Sandstone aquifers by (Rahube, 2003). Kisendi, (2016) also did a more recent study that was conducted using ground measurement data although not spatially distributed thus, the importance of this study to address such shortcomings.

Therefore, this research will take into account what previous studies have done but the focus will be on assessing groundwater in the Lokalane –Ncojane Karoo Basin, (LNKB) using an integrated steady state model with different boundary conditions. Also it will focus on using satellite products namely precipitation and *PET* as model inputs and driving forces which was not applied by other studies. The highlights of the methodology are shown in Figure 4. To help achieve this MODEFLOW-NWT under Model Muse will be used with UZF1 package which will help simulate an integrated hydrological model.

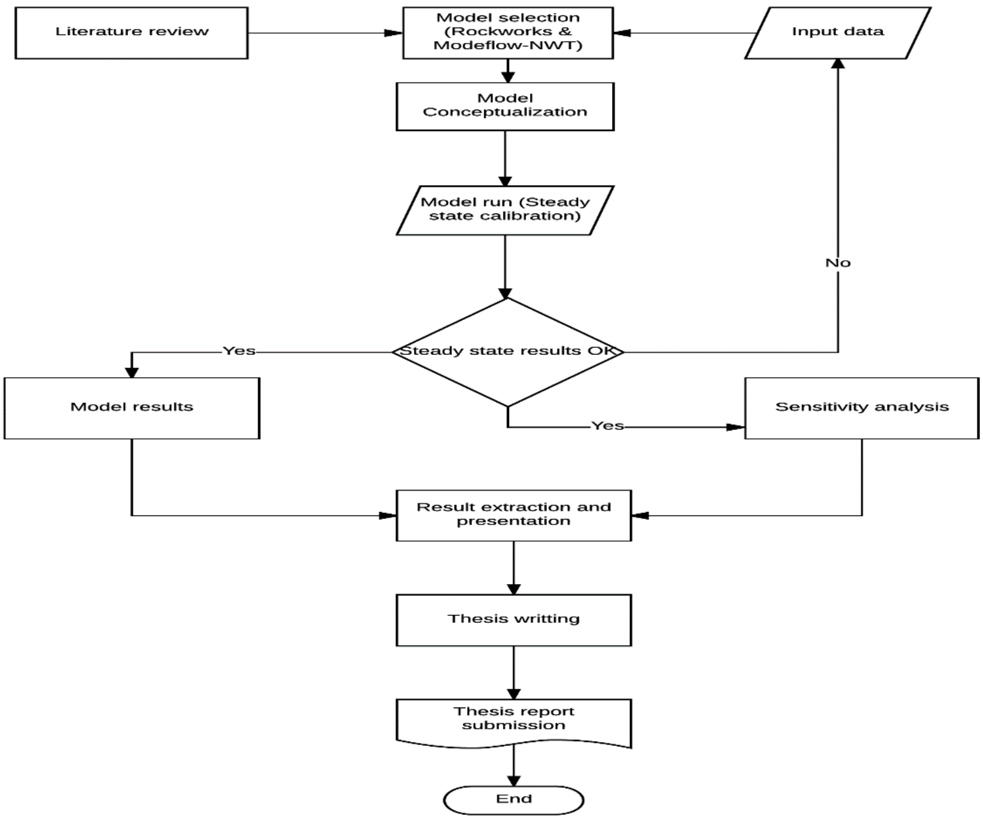

Figure 4 Summarized research methodology

2.1.1. 3D stratigraphic and hydro-stratigraphic models

In this study to address the issue of building a reliable conceptual model a summarised flow chart of the procedure which was applied is shown in Figure 6. For this study to build such a model, available borehole geological logs were used and compared to other methods studied in the area. According to WRC, (2006) most of the bedrock geology in the study area is obscured by unconsolidated Kalahari beds sediments of variable thickness and lithology. Apart from using a model to understand the geology such data and other methods that have also been applied in the area such as aeromagnetic, ground geophysics and remote sensing were reviewed.

To help simulate such a model Rockworks 17th version software was used to process the borehole data. This software is mainly used for sub surface visualization especially in the petroleum, environmental, geotechnical and mining industries. It has popular tools which include maps, logs, fence diagrams, solid models and volumetric. It has a 3D plot window which is used to view and manipulate the solid model to bring a meaningful interpretation and also has provision to incorporate physical features such as faults which helps give a meaningful representation.

The development of a 3D stratigraphic and hydro-stratigraphic models involved using all the available data namely borehole locations, elevations and down-hole intervals. These were imported in Rockworks software and layer thicknesses were interpolated by inverse distance and subtracted accordingly from the DEM as top of the model. A cross section was drawn in the study area following the available boreholes labelled as A-A Figure 3 above.

For both 3D stratigraphic and hydro-stratigraphic model the following lithological units were applied which included the post Karoo Stratigraphy (Kalahari Beds), Karoo Stratigraphy (Stormberg Basalt, Ntane Sandstone, and Inter-Karoo Mudstone,Siltstone, Ecca and Dwayka) and the Pre-Karoo. Thus the arrangement for the hydro-stratigraphic units were Kalahari Sand aquifer, Stormberg Basalt aquitard, Ntane Sandstone aquifer, Inter-Karoo Mudstone/Siltstone aquitard and the Ecca aquifer respectively. While the other units below the Ecca Sandstone were taken to be basement of the study area Figure 5.

By use of inverse distance, interpolation of the layer thickness for each stratigraphic unit and using the DEM as top of the model for the study area the different hydrostratigraphic thickness were obtained and subtracted from each other to get the individual thickness of all the layers. These thicknesses were then exported in ArcGIS as X, Y, Z data. The X, Y, Z data was processed in GIS environment by plotting them as points which were later interpolated to raster maps of the five hydrostratigraphic units which were converted to ASCII files and exported into Model Muse.

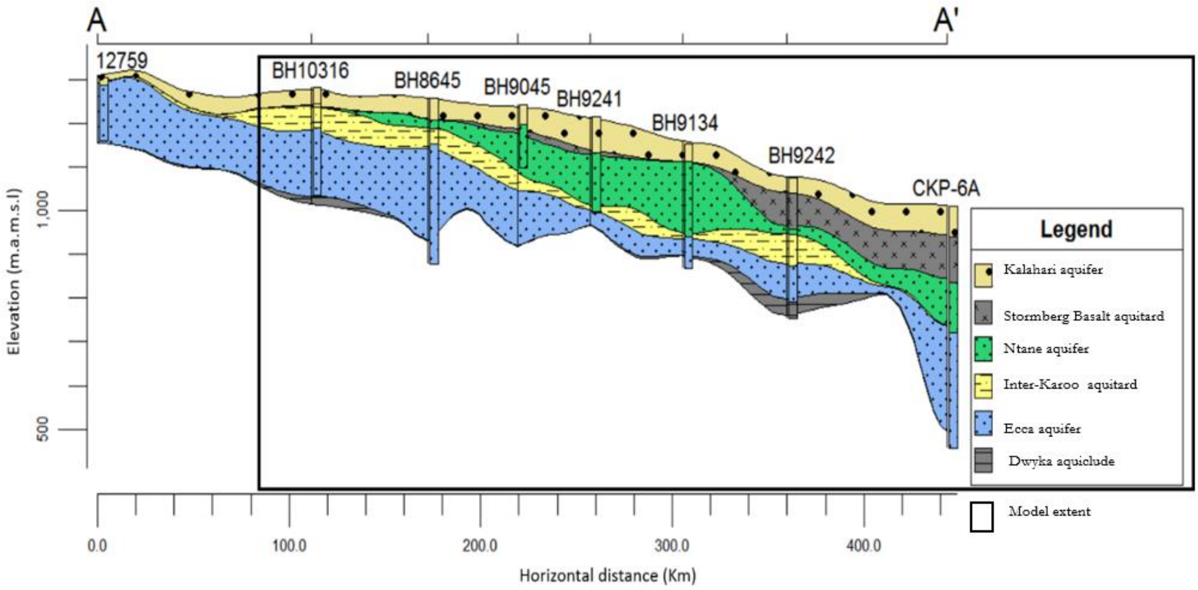

Figure 5. Cross section of the study area and flow direction (for location see Figure 4)

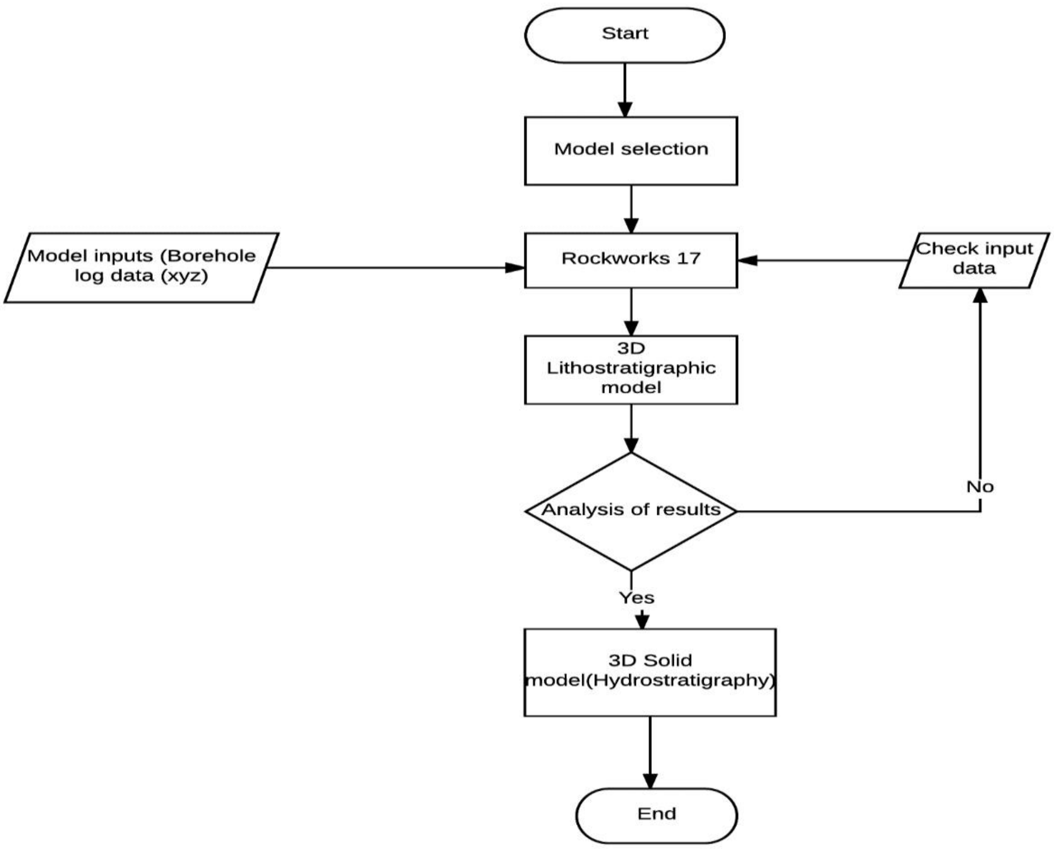

Figure 6. Summarized flowchart for the 3D Stratigraphic model

2.2. Data processing

In this study different data processing techniques were performed to help achieve the objective of this study. The LNKB model required different hydrological data sets which are inputs to the hydrological model. This included the development of the five hydrostratigraphic units which was done using the borehole log data in rockworks 17. Other variables included daily climatic data such as precipitation and potential evapotranspiration *(PET)* which are independent variables that vary in time. Also state variables such as measured hydraulic heads for the study area were also used in steady state calibration. In this study the major hydrological parameters that were applied are discussed in the following sub sections.

2.2.1. Precipitation

Spatio-temporal FEWSNET, satellite, daily precipitation product at 11km spatial resolution, was downloaded from earlywarning.usgs.gov/fews/datadownloads, website. Continental Africa was selected on a daily scale for the all simulation period 1st October, 2012 to 30 September, 2014 with 1095 images processed. This was done in a GIS environment by resampling to a 1 km grid to conform to the study area and clipped to the LNKB boundary map. Then an average for the all simulation period was obtained and applied for the steady state condition.

2.2.2. Potential evapotranspiration

For *PET* also spatio-temporal FEWSNET, satellite daily product with also 11 km spatial resolution was downloaded from earlywarning.usgs.gov/fews/datadownloads, website. The same simulation period was maintained 1st October, 2012 to 30th September, 2014. In order to apply such data sets for steady state condition an average for both input data sets was calculated.

2.2.3. Hydraulic Heads

These are state variables derived from borehole elevation and groundwater levels data. In the study area such data has been obtained since the 1980's in Botswana by manually measuring and also using automated groundwater level recorders (WRC, 2006). For this study about forty (40) boreholes with average monthly data head measurements were used for steady state calibration.

The boreholes have data running from 1st January 2004 till 31st December, 2014 but for this study the simulation was only for the period 1st October, 2012-30th September, 2014. This period was chosen because it showed consistence in the data with less gaps. Part of the time series boreholes were plotted against daily satellite extracted rainfall from FEWSNET for the same period and the trend in groundwater hydrographs show that piezometer BH9244 shows slightly corresponding increase in water level from November to March of all the years after some precipitation. While piezometer BH7763 shows a trend of delayed recharge in the boreholes in shown in Figure 7 and Figure 8. The other set of analysed heads against rainfall are shown in Appendix 4

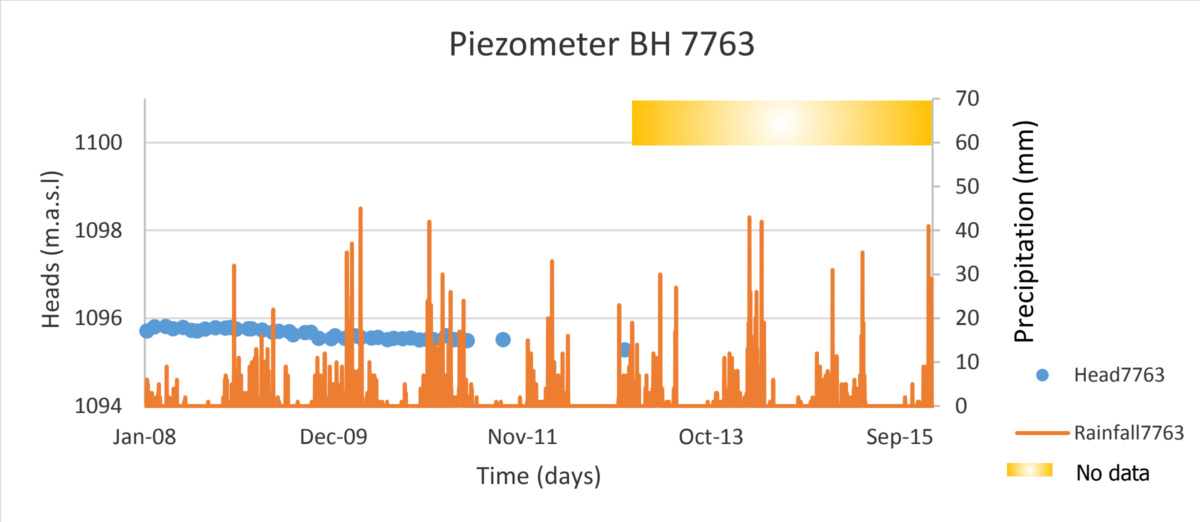

Figure 7. Example of groundwater hydrograph; BH7763 daily head measurements Vs FEWSNET satellite daily rainfall.

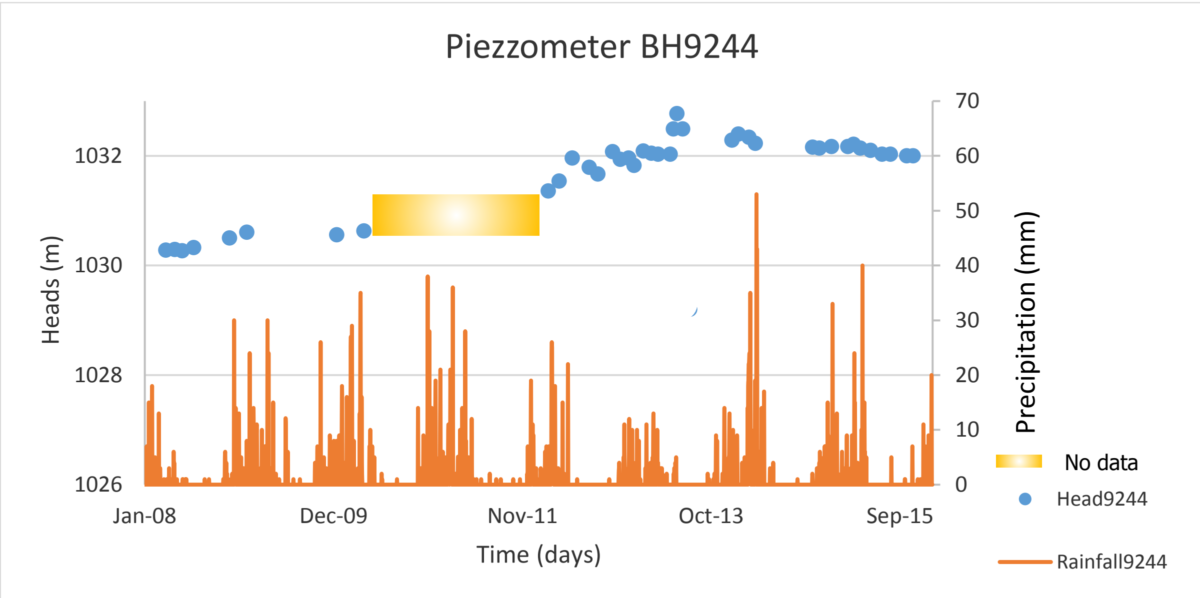

Figure 8. Example of groundwater hydrograph; BH9244 daily head measurements Vs FEWSNET satellite daily rainfall.

2.3. Conceptual model

A conceptual model helps a modeller have a pictorial view of the area interested to be studied or modelled. This becomes the transition to an effective numerical model. It can be represented in different ways one of them being the use of a cross section with some of the major field characteristics captured as presented in Figure 9. Anderson et al , (2015) argues that the conceptual model helps the modeller simplify and communicate what is already known such as hydrogeology from acquired field data. For an effective and well represented conceptual model some important aspects need to be implemented. Some of these factors which were also considered for the LNKB include the following;

2.3.1. Hydrostratigraphic units

The hydrostratigrahic units form one of the primary units for building a conceptual model. These are mostly units with more or less identical hydrological properties that can be combined to form a single unit (Anderson et al., 2015). This study area had five hydrostratigraphic layers composed of three main aquifers and two aquitards which were evaluated. These are the Kalahari Sand aquifer, Stomberg Basalt aquitard, Ntane Sandstone aquifer, Inter-Karoo Mudstone/Siltstone aquitard and Ecca Sandstone aquifer respectively. The boreholes that were evaluated in this study tap from the two aquifers namely the Ecca Sandstone and the Ntane Sandstone. A detailed highlight of the hydrostratigraphic units for the study area have been discussed in Table 1.

2.3.2. Flow systems

The general groundwater flow in LNKB is towards the NE direction where the basin water might be discharged as shown from the potentiometric maps Appendix 1-3. In IHM the main flow systems are the unsaturated zone and saturated zone flow. In this study groundwater flow is mainly in three aquifers namely the Kalahari Sand, Ntane Sandstone and Ecca Sandstone aquifers respectively. Apart from the horizontal flow in the three aquifers there is also vertical flow in the confined layers through leakage therefore, the model was set to simulate in quasi 3-D. In quasi-3D model flow through confining beds is taken to be only in vertical direction and no release of water from storage within the confining bed (Anderson et al., 2015).The groundwater flow was simulated using steady state flow condition where there is no change in storage with time for the aquifer.

2.3.3. Preliminary water balance

Precipitation is the only source of water input in the LNKB although most of it is evapotranspired due to high temperatures in the area and water uptakes by 'thirsty' Kalahari vegetation. Only small fraction of that input end up as recharge which infiltrates into the aquifer system. According to de Vries et al., (2000) very little precipitation ends up as aquifer recharge despite high infiltration rates because most of the water is evaporated and transpired from thick (>60 m) unsaturated zone.

2.3.4. External and internal physical boundaries

For any groundwater model to have meaningful results one of the aspects that need great consideration are the boundary conditions. In this study, there are no abstraction boreholes, therefore, only physical boundaries (Figure 3) are considered. The external, no-flow boundaries are assigned on the northern part of the LNKB, along the geological contact with the Dwyka Karoo rocks in the north, north-east and the quartzite rocks in the north- west .The Southern part of the Kalahari also have a no flow boundary due to the parallel direction to streamlines of groundwater flow pattern. To justify the assignment of the two above mentioned boundaries, relevant potentiometric maps are presented in Appendix 1-3

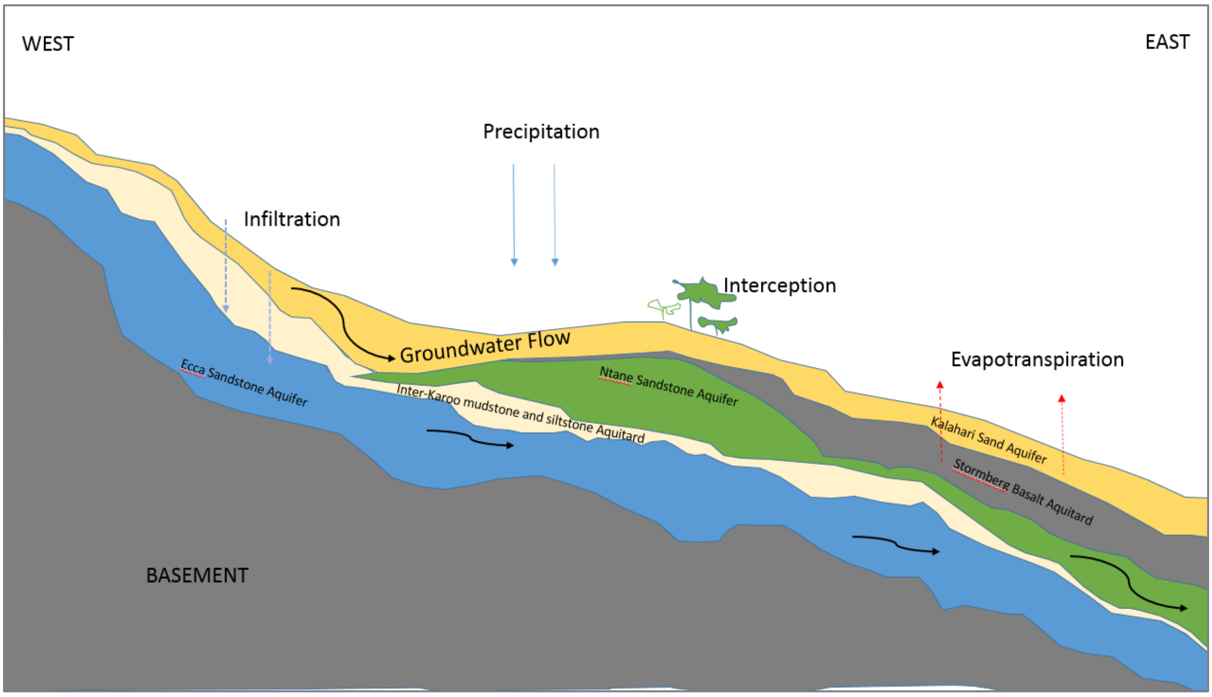

Figure 9. Conceptual model of the study area

2.4. Numerical model

2.4.1. General concepts

The developed conceptual model helped to move into a setting of the numerical, integrated hydrological model (IHM). Such models can be simulated in steady state or transient state. In this study, multi-layer, steady state, IHM was carried out over the LNKB.

2.4.2. Software selection

In this study the software used is the MODEFLOW-NWT with unsaturated zone flow (UZF1) Package under ModelMuse environment. According to Niswonger et al,(2011) the UZF1 package assumes that unsaturated flow occurs in response to gravity potential gradients only. It tries to simplify the vertical dimension by using precipitation, ET, Infiltration and extinction depth as input parameters. In UZF1, the infiltration is calculated by subtracting interception. The package also calculates recharge as equal to infiltration, subsurface evapotranspiration and unsaturated zone storage. The proposed software has the following advantages;

- It can estimate recharge and evapotranspiration internally within the (MODFLOW-NWT facilitated by the UZF1) package.
- It deals with nonlinearities problems (drying and wetting) which cause a lot issues of convergence failures by keeping active the model cells within a simulation.

2.4.3. Grid Design

The model grid used during modelling was a uniform 1km by 1km with a grid network of 171 rows and 311 columns which made the total grid cells 35,000 km^2 with a WGS_1984_UTM_Zone_34S as the projected coordinate system.

2.4.4. Numerical model layers

This involves the building up of the model with the numerical model with the exact layers to match it with the physical stratigraphic units of the aquifer system. In this study a model was built on five layers using the provided database for the boreholes logs for the study area. The top of the model was defined from the DEM 90 meters resolution that was downloaded from https://lta.cr.usgs.gov/SRTM1Arc website of USGS, (2015) and resampled to 1km to conform with the grid selection. The model thickness for the different layers was defined in Rockworks for the aquifer and aquitard bottoms that were interpolated using inverse distance in rockworks and exported as X,Y,Z files to ArcGIS. They were converted to raster maps and imported in model muse as ASCII files as discussed in section 2.2. The defined layer structures are Kalahari Sand which forms the first unconfined layer, then the Stormberg Basalt aquitard which is the confining layer and the second, the Ntane Sandstone aquifer which is partly confined by the Stormberg Basalt aquitard mostly from the central to the eastern parts of the study area. Then followed by the fourth layer comprising of the Inter-Karoo Mudstone/ Siltstone aquitard which is the confining layer for the Ecca Sandstone aquifer and the Ecca Sandstone is the fifth and last layer for the study as shown in Figure 9. In ModelMuse once imported these layers are automatically defined once the UZF and Upstream Weighting (UPW) packages are activated and assigned convertible layers were the heads in the model cells determine the status of the cells. Therefore, when the heads are on top of the cell top the model assumes a confined layer structure and the opposite is for unconfined layer structure. While the two aquitards were considered to be non- simulated confining layers but allow vertical flow. Therefore, the model was structured as a quasi-3D which strictly allows vertical flow through the confining beds.

2.4.5. Potentiometric heads

The heads for this study were derived from using the available borehole logs for the LNKB. This was done by using the elevation data and the provided water level data that helped to calculate exactly hydraulic heads. It was found most of the monitoring boreholes were tapping from the Ntane Sandstone and Ecca Sandstone aquifers respectively. The hydraulic heads applied to the project were used during calibration process in steady state.

2.4.6. Driving forces

These normally depend on the model type and purpose of the model thus, are different from one model to the other (Kisendi, 2016). In the numerical model for this study the driving forces that were focused on were; precipitation, potential evapotranspiration *(PET)* and interception. Precipitation data was used to derive infiltration which was calculated after applying an interception factor of 0.08 of the calculated mean precipitation. These were spatio-temporal FEWSNET satellite data for precipitation and *PET* downloaded on a daily scale from earlywarning.usgs.gov/fews/datadownloads, website. The data was for the simulation period 1st October, 2012 -30th September, 2014. Average mean images for both driving forces were processed in a GIS environment to obtain raster maps that were applied to the model.

2.4.7. Unsaturated zone flow (UZF) package

Since the focus of the study was simulating IHM, the UZF package was ideal tool to help simulate flow and storage in the unsaturated zone which happens to be the transitional boundary of exchange flux between saturated and unsaturated zones. In this study the major input parameters to this package are infiltration rate which is calculated by subtracting interception from precipitation while land surface runoff was not accounted due to luck of stream and rivers in the study area, evapotranspiration demand which has been discussed in section 2.3.3, extinction water content was assumed equal to 0.03 (m^3/m^3) and equal to the soil residual water content, the soil saturated water content was assumed to be 0.3 (m^3/m^3), Brooks Corey was assumed to 3.5 (m^3/m^3) and 70 m for the extinction depth which is the depth below which ET cannot be removed. For this study the extinction depth was set at 70 m considering two things the thickness of the Kalahari and also that it should be set in the first layer to avoid converging problems. Also what other studies in the area applied was taken into consideration. Obakeng et al., (2007) suggested that the maximum depth of most vegetation roots in the area is 70 m and also argued by (Kisendi, 2016). For this study to ensure that this was achieved some conditions had to be applied in ArcGIS field calculator Equation 1.

$$ED=70: Kth>70m \qquad \textit{Equation 1}$$

$$ED=Kth: Kth<70m$$

Where ED-Extinction depth and Kth-Kalahari Thickness

This condition helped to have spatially variable extinction depth within the first layer and avoided model converging problems which were experienced in Kisendi, (2016) especially that the Kalahari has no uniform thickness.

2.4.8. Interception

The study area is mainly dominated with mostly savannah vegetation which include; tree savannah, shrub savannah, mixed savannah and grass savannah which intercept incoming precipitation. Interception refers to fraction of precipitation trapped by the leaves and branches of plants and forests and evaporated. This study adopted an interception value of 0.08 which is based on the study by Werger,et al (1978) who argued that the annual precipitation loss by mature forests in the study is about 8-12%.

2.4.9. Infiltration rate

Infiltration rate calculated as mean precipitation (see 2.4.6) minus interception (*Equation 2*) was applied as input of UZF package. According to Niswonger, (2011) the infiltrating water was converted to water content, and the water content is set to the saturated water content when the specified infiltration rate in the UZF package exceeds the saturated hydraulic conductivity.

$$I=P-(0.08*P) \qquad \textit{Equation 2}$$

Where I-Infiltration and P-Precipitation

2.4.10. Model parameterization

In MODEFLOW-NWT in oder to simulate flow in the unsaturated part two packages were used namely UZF and Upstream weighting (UPW) package. In steady state condition, zones were created and defined the horizontal and vertical hydraulic conductivities (HK and VK) of the aquifer layers and only vertical hydraulic conductivity of the confining bed (VKCB). Within the UZF package other important parameters that were activated and necessary for the study included (IETFLG) for simulating evapotranspiration, (IFTUNIT) for calculating surface leakage and the print summary of the UZF budget terms. The number of wave sets (NSETS2) and the number of trailing waves (NTRAIL2) were set to 40 and 15 respectively. Conductance for the general head boundaries (GHB) was also assigned to all the three aquifers namely Kalahari Sand, Ntane Sandstone and the Ecca Sandstone aquifers with values of 0.001 m^2 d^{-1}, 0.002 m^2 d^{-1} and 0.001 m^2 d^{-1} respectively.

Other initial values for the parameters in the model were used based on the previous studies conducted in the area by Rahube, (2003) and (Kisendi, 2016). Some of the initial values assigned to the model included saturated water content at 0.3 m^3 m^{-3}, residual water content at 0.02 m^3 m^{-3}, the vertical hydraulic conductivity range from 0.55 m d^{-1} to 1 m d^{-1}, horizontal hydraulic conductivity for the aquifers ranging from 0.001 m d^{-1} to 2.1 m d^{-1} which were also used as calibration parameters for steady state. All these values were used as the initial ones for model calibration. The DEM with a 90 meters resolution was used to help assign the model top or land surface and help calculate different model layers.

2.4.11. Model boundary conditions

The boundary conditions used for the model are highlighted in Figure 3 and potentiometric maps for the area are presented as justification for such boundary conditions have been attached in Appendix 1-3.The hydro-geological assessment of the area was one of the aspects that helped develop the boundary conditions for the domain. A no-flow boundary are assigned on the northern part of the LNKB, along the geological contact with the Dwyka Karoo rocks in the north, north-east and the quartzite rocks in the north- west .The Southern part of the Kalahari also have a no flow boundary due to the parallel direction to streamlines of groundwater flow pattern. The western and eastern side was assigned general head boundaries (GHB) following the potentiometric lines allowing groundwater to flow from west to east thus allowing flow into the model domain and discharge from the east respectively. These are head dependant flow boundary with two values namely the hydraulic conductance (m^2d^{-1}) and hydraulic head at the boundary (m) as highlighted in Equation 3. The other two aquifers namely the Ntane and the Ecca were also assigned the same boundary conditions with no flow in the northern and southern parts. While the eastern and western parts had general head boundaries.

$$Q_h = C_b\ (h_b - h) \qquad \text{Equation 3}$$

Where Q_b -flow through the general head boundary (m^3d^{-1}); C_b- hydraulic conductance (m^2d^{-1}); and h_b- Hydraulic head at the boundary (m).

2.4.12. Time discretization

The time frame that was set for this model simulation was three hydrological years from 1st October, 2012 to 31st September, 2014. For steady state the data for this period was averaged to get a mean value for Precipitation and *PET* which were applied to the steady state model. Then the acquired results after calibration was assessed for and errors using the hydraulic heads.

2.5. Numerical model calibration

Model calibration was applied to the model to ensure that the calculated hydraulic heads match the observed hydraulic heads with a smaller margin of error. To help with this computation in MODEFLOW-NWT a Newtonian solver was used and the maximum number of iterations was set to 1000 and model complexity set to medium. Although automatic calibration is possible using PEST, for this study calibration was done on a trial and error method which was done on steady state model calibration. This method was preferred because it helped understand how model behaviour and how to address challenges by applying site specific knowledge an argument also supported by (Hassan, et al 2014)

As pointed model calibration aims at getting the good match between observed and measured values of heads. The calibration parameters used in this study were the vertical and horizontal hydraulic conductivity of the confined and unconfined layers which were assigned for the different zones. The initial values for vertical and horizontal hydraulic conductivity were assigned based on previous studies conducted in the study area. Before calibration process, the steady-state model was achieved by calculating mean average values for the simulation time frame (1st October, 2012- 30th September, 2014) of the driving forces. These are precipitation and evapotranspiration. Calibration during modelling is an important step and can be done using either inverse or forward calibration. The difference between the two is that with inverse procedure, from known heads parameters and hydrologic stresses are determined while in the forward procedure which was applied the model calculates heads after specifying the parameters such as hydraulic conductivity, specific storage, specific yield and hydrologic stresses. To achieve acceptable range of error between the observed and the simulated heads the parameters and hydrologic stresses are adjusted (Anderson et al., 2015). The try-and-error method was adopted for this study, in which model parameters (hydraulic conductivity) were adjusted.

To assess the degree of reliability and uncertainty in the calibrated model, a sensitivity analysis was conducted to evaluate the uncertainty of the optimised parameter distribution during the study. This analysis was done by systematically changing one parameter of the model at a time and observing the changes that occur in the result of the model. Models have different uncertainties which cause difficulties in obtaining the exact model parameters thus, makes it important to carry out a sensitivity analysis. The sources of uncertainties in groundwater may include; described model parameters, conceptual model, observation data and the boundary conditions (Anderson et al., 2015). The more sensitive parameters in the model were given more attention during the calibration. In this study steady-state calibration, the reliability of calibrated parameters was assessed by the three cost functions, which are mean error (ME), mean absolute error (MAE) and root mean square error (RMSE).

2.6. Water budget

In assessment of groundwater one important tool used is the analysis of the water budget. For this model Modeflow-NWT which is run under ModelMuse was used. It uses two ways in which the calculation of the water budget is done. One is by using the listing file that provides a composite water budget mostly in (m^3 day^{-1}) for the all area in this case all the three aquifers namely the Kalahari Sandstone, Ntane Sandstone and the Ecca Sandstone. Thus, does not account for the contribution that each aquifer makes to the total water budget.

The second method is that it also calculates using the zone budget option. Unlike the first option this one calculates what each individual aquifer contributes to the total water budget. This helped to understand the potential of each aquifer namely the Kalahari Sandstone, Ntane Sandstone and the Ecca Sandstone by using the ZONE BUDGET tool in Modeflow-NWT. Therefore, for this study both methods were applied in the assessment of groundwater.

3. RESULTS AND DISCUSION

3.1. Structural Modelling

3.1.1. Model hydro-stratigraphic units

The nomenclature for the cross section presented Figure 3 above follows the one suggested by Smith, (1984) for the stratigraphic units of the Karoo units as table 1 illustrates. The cross section A-A (which runs from NW-SE) was selected to help present the hydrostratigraphic units that were obtained as presented earlier in Figure 5. From the presented hydrostratigraphic units in the area it can be concluded that only the Kalahari Sand and Ecca Sandstone are spatially continuous throughout the study area. While the other three namely Stormberg Basalt, Ntane Sandstone and Inter-Karoo Mudstone/Siltstone are not spatially continuous in the study area. This formation is so unique and important for this area since both confining layers the Stormberg Basalt and the Inter-Karoo Mudstone/Siltstone are pitching not completely overlying the Ecca Sandstone. Therefore this allows contact with the Kalahari Sand and makes recharge possible for the Ecca Sandstone aquifer especially the area between BH 12759 and BH 10316 Figure 5. The same is true with the Ntane Sandstone were it is in contact with the Kalahari Sand around BH 10316 unlike further Southeast were both the Stormberg Basalt and Inter-Karoo Mudstone/Siltstone overlies both the Ntane Sandstone and the Ecca Sandstone. For unites beyond the Ecca Sandstone (Dwyka) they were considered as the model basement and were not simulated due to lack of borehole data in the area.

3.1.2. Hydrostratigraphic layer thickness

Interpolation using inverse distance of the lithology performed in Rockworks helped to have the layer thickness for the model which were later rasterized in GIS environment to have spatially variable thickness for the Kalahari Karoo Basin (KKB) as presented in Figures 12- 16.

Kalahari Sand

According to Smith, (1984) the Kalahari Sand is mainly composed of homogenous sandy material that differs in colour, size and texture while colour ranges from orange, white, yellow, cream greyish brown and brown. Mostly loose and poorly consolidated fine sand and considered the upper hydrostratigraphic layer which was also applied in the model. Most of it is unsaturated and is a post Karoo eaolian sand unit of the Cenozoic as presented in Table 1. The Kalahari Sand presents a spatially variable but continuous thickness thicker in the SE and it thins towards the NW with range from 0.4 - 86.9 m as presented in Figure 10. The Kalahari thickness is of great importance in the basin since it determines how much of the groundwater percolates as groundwater recharge. From the presented thickness it can be argued that where thickness is higher it restricts how much of the water percolates especially in the eastern side while much of the recharge happens in the western part where it is thin. This was also suggested by previous studies(WRC, 2006).

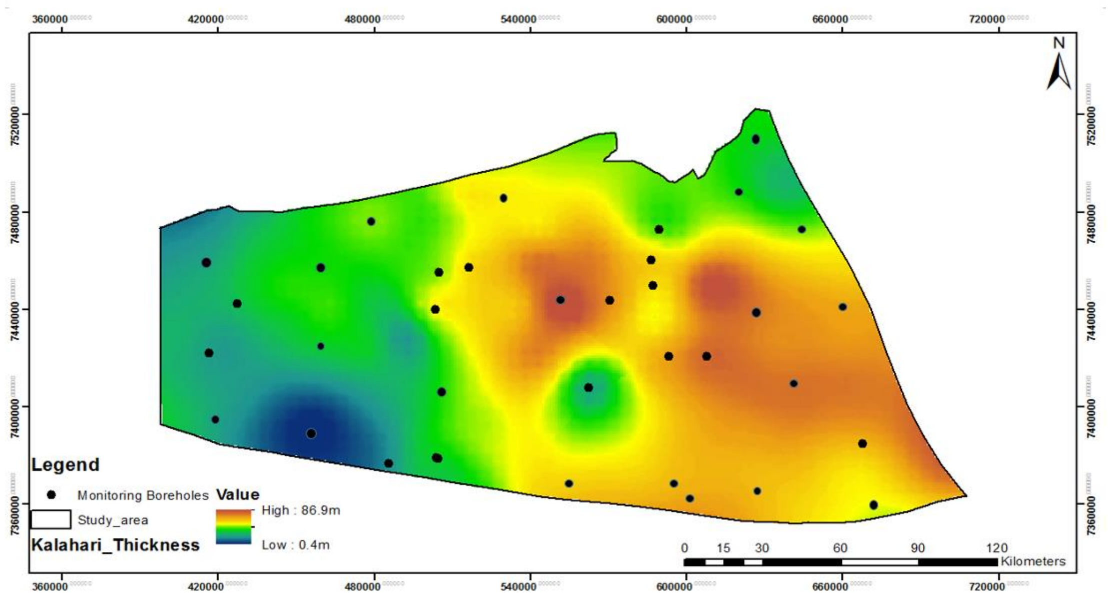

Figure 10. Spatial thickness variability of the Kalahari Sand and boreholes used for interpolation

Stormberg Basalt

The Stormberg Basalt is mostly thicker on the eastern and the northern parts of the study area thus, it is not spatially continuous in the all entire area and acts as part of the confining layer for the Ntane Sandstone. It was presented in the model as the second layer with a thickness ranging from 0.9 m to 78.2 m Figure 11. WRC, (2006) argues that in most parts of Botswana the Stormberg Basalt is not continuous mostly due to structural movements especially in area where it received an uplifting. This has resulted in considerable amount of the thickness being eroded. Generally the Stormberg Basalt does not have hydraulic connection to qualify it as an aquifer although some localised water strikes due to fractures have been recorded (WRC, 2006). Therefore, for this model it was also simulated as an aquitard.

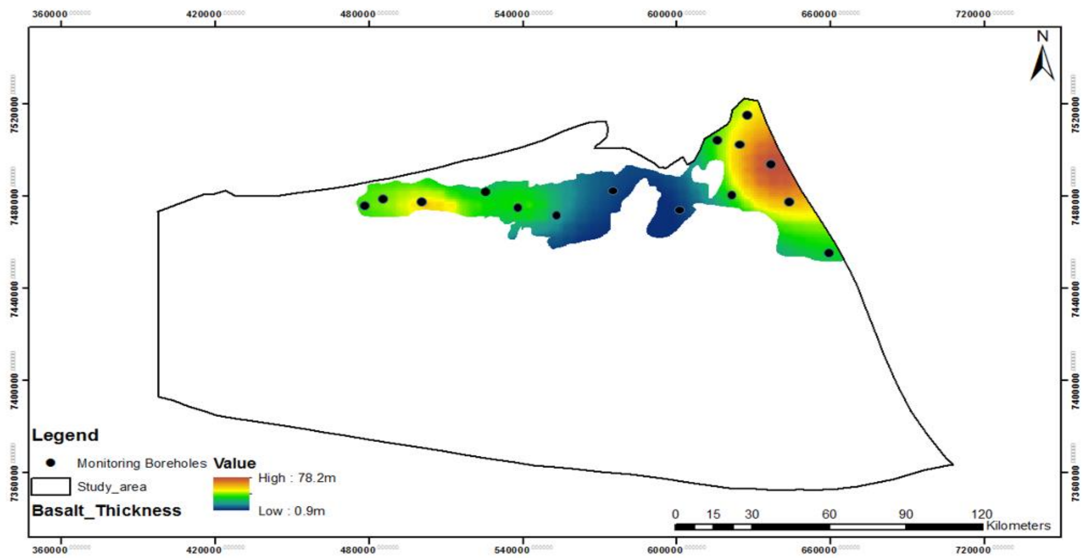

Figure 11. Spatial thickness variability of the Stormberg Basalt aquitard and boreholes used for interpolation

Ntane Sandstone

The Ntane Sandstone was simulated as the second aquifer for the model (Figure 12) with thickness range from 5.2 m to 182.9 m. It is mostly thicker in the central part and running from NE-SE of the study area. Although it is partly confined by the Stomberg Basalt it is in contact with the Kalahari Sand on the western side which allows recharge of the aquifer. The Ntane Sandstone although varies spatially in thickness it is also not spatially continuous for the entire study area. Some of the boreholes used in the evalution tap from this layer. Mostly characterised by medium to fine texture and range in colour from brownish to red/pink. It is one of the most productive aquifers in the area and most studied with more water strikes been recorded were the aquifers receives stress from the Stormberg Basalt (WRC, 2006).

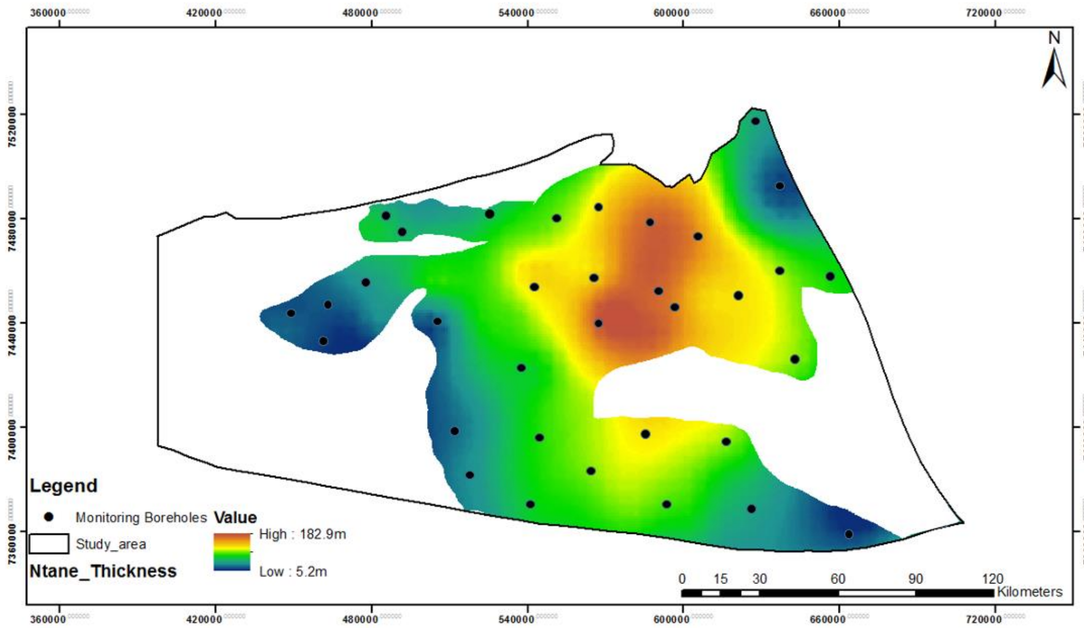

Figure 12. Spatial thickness variability of the Ntane Sandstone aquifer and boreholes used for interpolation

Inter-Karoo Mudstone/Siltstone

The Inter-Karoo Mudstone/Siltstone simulated as an aquitard and fourth layer of the model has thickness range from 4.7 m to 190.2 m as presented in Figure 13. The layer records low permeability which restricts the water exchange between the Ecca Sandstone and the Ntane Sandstone mostly due to its formation of the Inter-Karoo Mudstone/Siltstone of Lebung Group and the Beaufort Group which are mostly semi permeable (WRC, 2006). They are mostly comprised of intercalated sandstones, red/brown greenish mudstones with basal some basal conglomerate (Smith, 1984). The Inter-Karoo Mudstone/Siltstone is not equally spatially continuous and mostly present running from central to eastern part of the study area. This arrangement then allows the Ecca to have hydrological contact with the Kalahari Sand and allows for recharge of the Ecca Sandstone mostly from the western side.

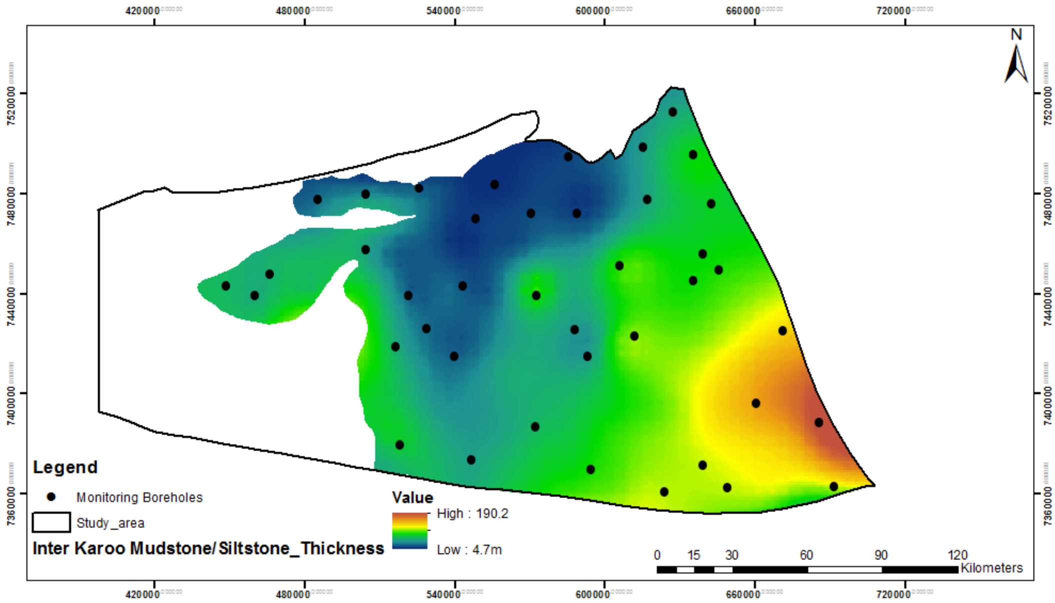

Figure 13. Spatial thickness variability of the Inter-Karoo Mudstone and Siltstone aquitard and boreholes used for interpolation

Ecca Sandstone

The Ecca Sandstone is the most deep and third productive aquifer and was simulated as the fifth layer. The Ecca Sandstone mostly comprise of the Boritse, Kweneng and Bori formation. It consist of coarse sandstones, carbonaceous mudstones, muddy siltstones and coaly carbonaceaous mudstones. The thickness range from 5.5 to 214.5 m (Figure 14) which is spatially variable and continuous with a low thickness in the central part. There are also boreholes that were used for this study tapping from the Ecca Sandstone.

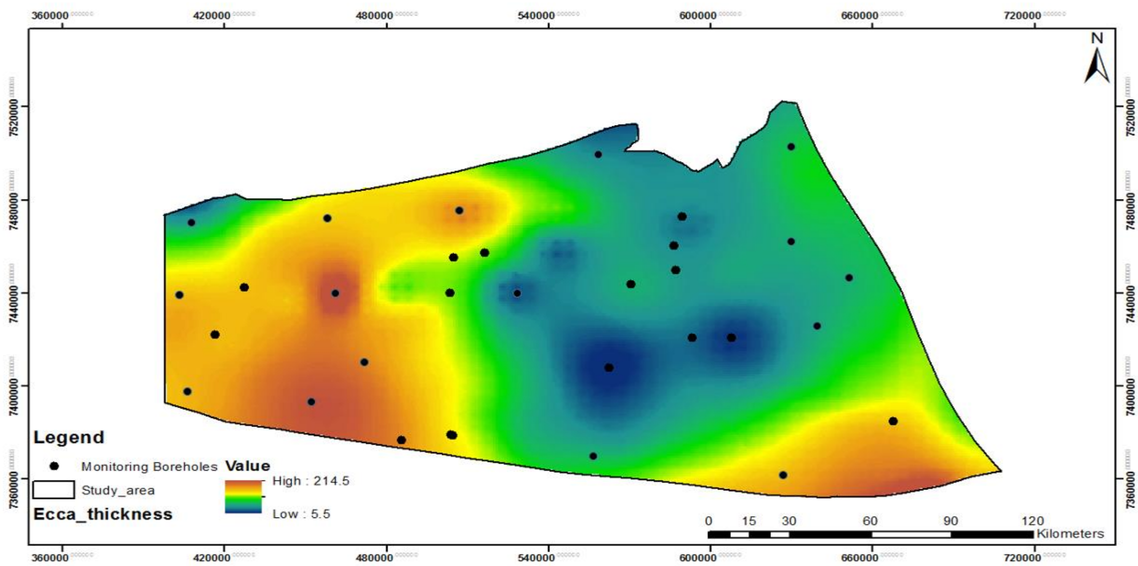

Figure 14. Spatial thickness variability of the Ecca Sandstone aquifer and boreholes used for interpolation

3.2. Hydrological fluxes

The downloaded satellite products for precipitation and *PET* were resampled from 11km resolution to 1km to align with the chosen grid seize. Single daily maps were downloaded for the three years simulation period 1st October, 2012- 30th September, 2014. The obtained spatio-temporally variable precipitation and potential evapotranspiration was averaged and used as input data for the steady state. For precipitation the obtained average image for the all simulation period was calculated and obtained an image that was applied to run steady state. For potential evapotranspiration the mean average for the simulation period 1st October, 2012 – 30th September, 2014 (Figure 16) was also calculated and applied to the model which ranged from 4.2 to 4.9 mm day^{-1}

3.3. Infiltration rate

Infiltration is calculated from obtained mean precipitation by subtracting the inception by vegetation (land cover) in the area. An interception factor of 0.08 was applied in this study using *Equation 2*. The infiltration was calculated as 0.92 of precipitation. The calculated infiltration for the area ranged from 0.6 mm d^{-1} to 1.3 mm d^{-1} which is also considered the UZF recharge in steady state. Therefore, the infiltration rate in the area showed that it was proportional to received precipitation thus it showed an increase in zones that received high rainfall and the opposite was also true as shown in Figure 15.

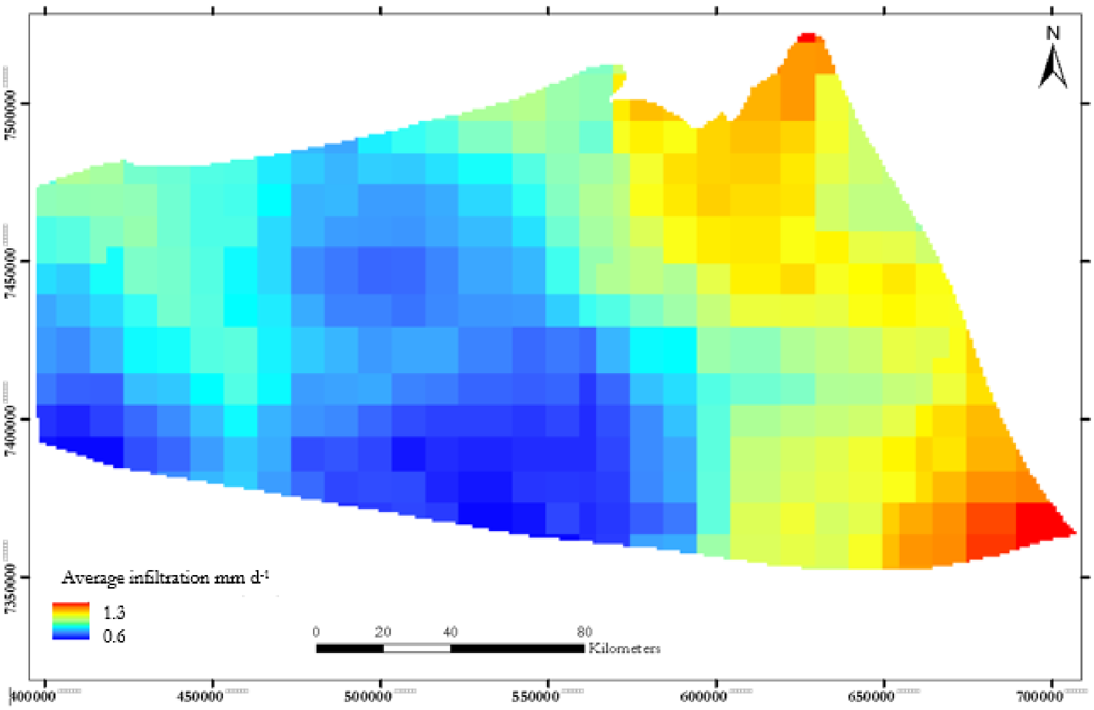

Figure 15. Mean daily infiltration for the period 1st October, 2012 -30th September, 2014.

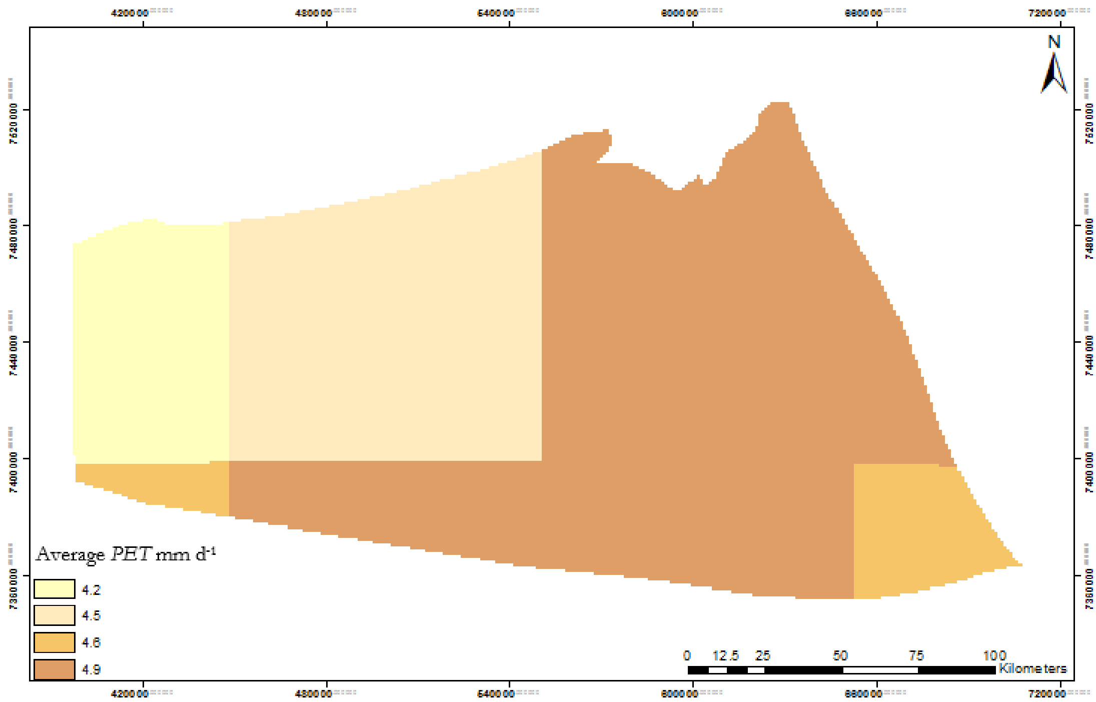

Figure 16. Mean daily *PET* estimated for the period 1st October, 2012 -30th September, 2014

3.4. Steady State model calibration

3.4.1. Calibration parameters under steady state

In steady state, calibration involved different parameters such as the horizontal and vertical hydraulic conductivities (HK & VK) for unconfined and confined aquifers. While for the confining beds namely Stormberg Basalt and Inter-Karoo Mudstone/Siltstone vertical conductivities (VCKB) was used. Model calibration results showed HK values ranging from 3.40 m day^{-1} to 7.65 m day^{-1} for the Kalahari Sand layer, while the Ntane Sandstone layer ranged from 0.1 m day^{-1} to 5.95 m day^{-1} and the Ecca Sandstone had a range of 0.1 m day^{-1} to 3.45 m day^{-1} as presented in figures 19-21. For the confining layers namely the Stormberg Basalt and Inter-Karoo Mudstone/Siltstone after calibration the VCKB ranged from 1.2 E-9 to 1.9E-7 for the second layer while the fourth layer ranged from 1.9E-8 to 1.1E-5 respectively.

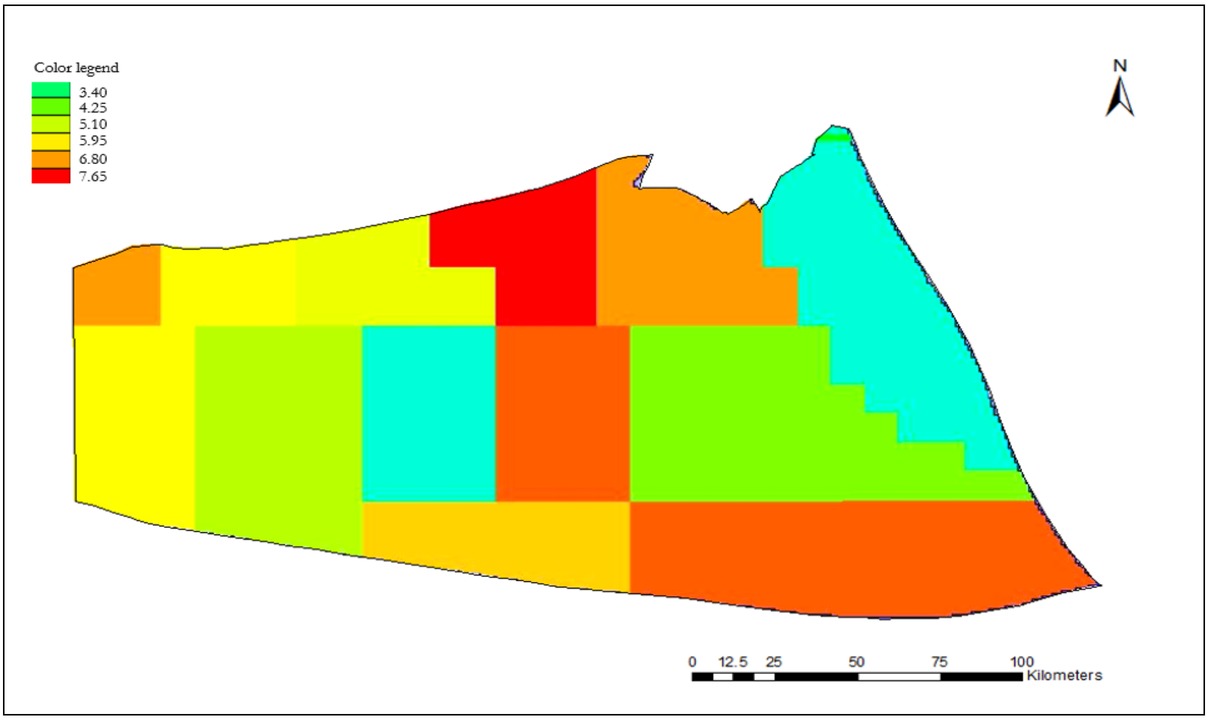

Figure 17. Calibrated horizontal hydraulic conductivities range 3.40-7.65 for the Kalahari Sand aquifer values in (m day^{-1}).

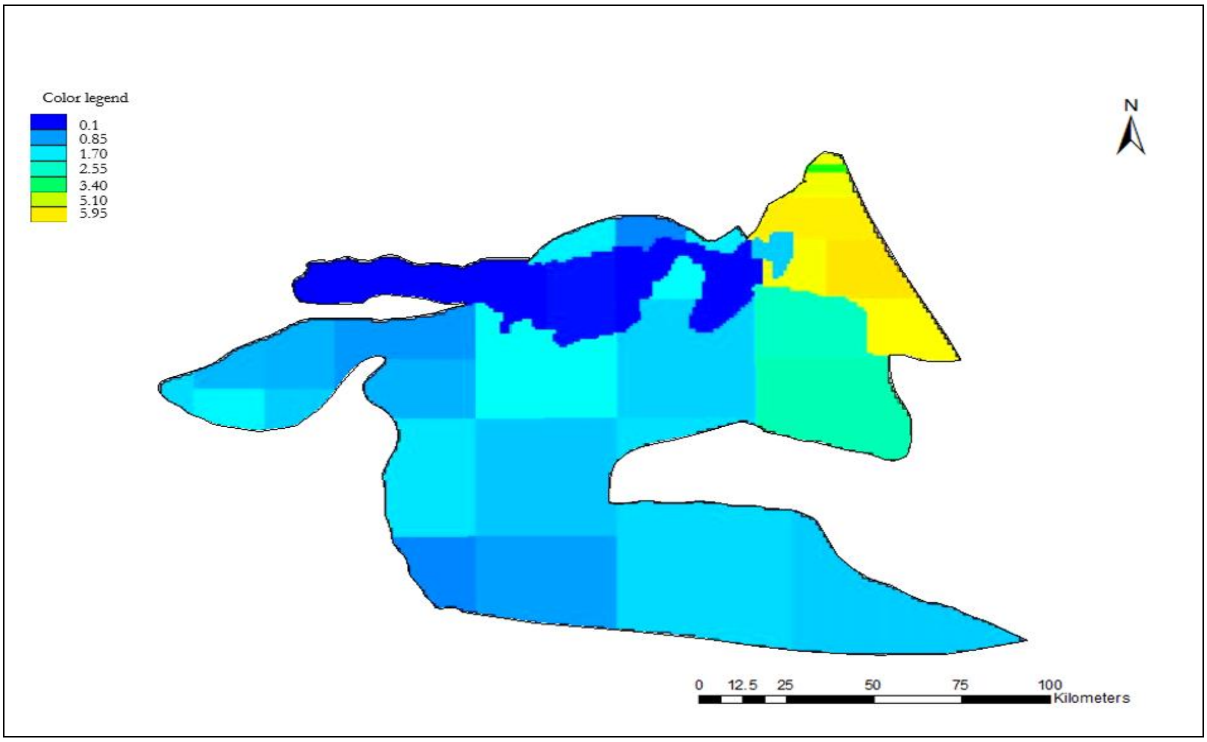

Figure 18. Calibrated horizontal hydraulic conductivities range 0.1-5.95 for the Ntane Sandstone aquifer values in (m day^{-1})

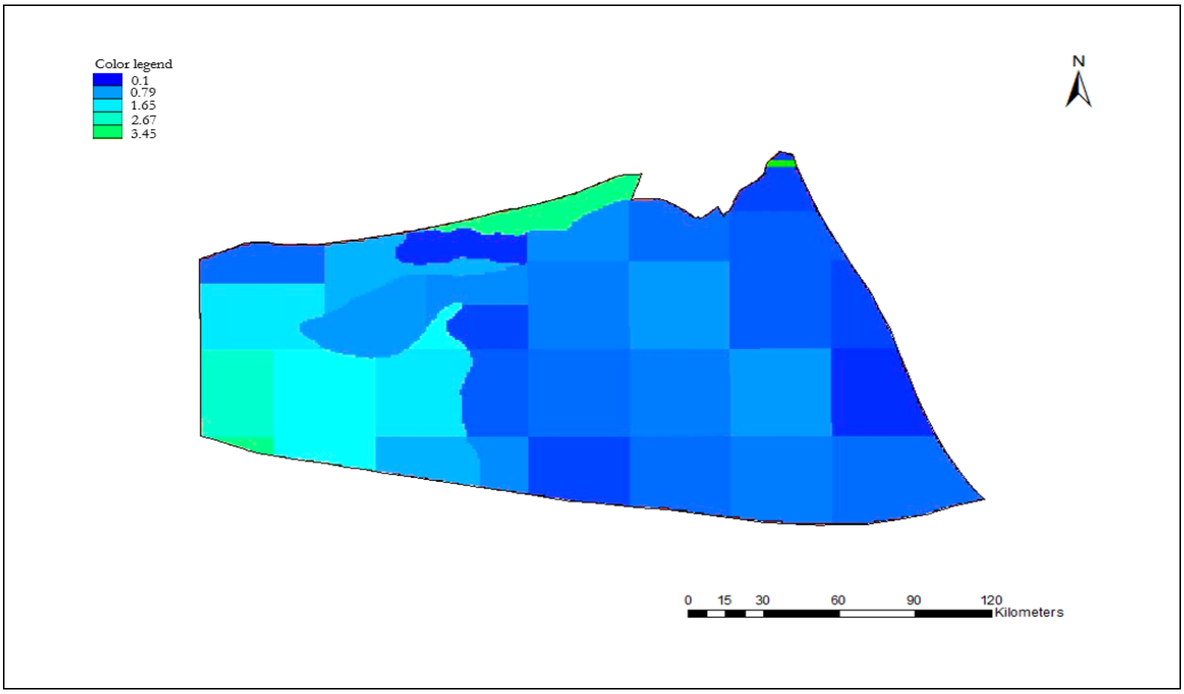

Figure 19. Calibrated horizontal hydraulic conductivities range 0.1-3.45 for the Ecca Sandstone aquifer values in (m day^{-1})

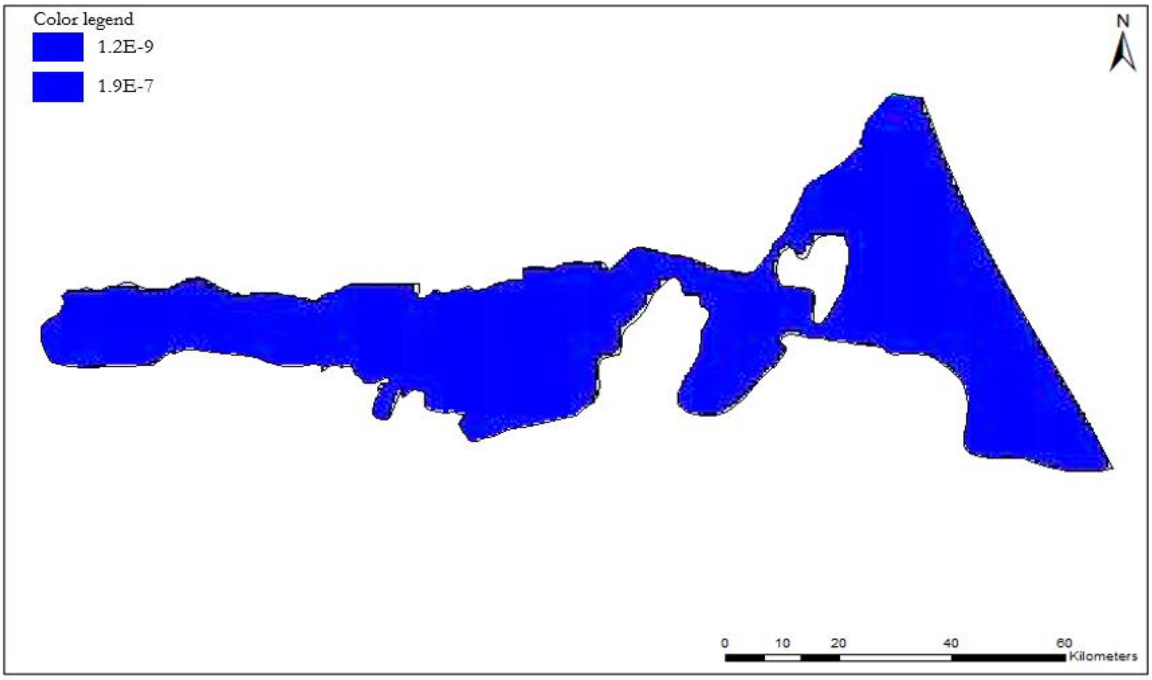

Figure 20. Calibrated vertical hydraulic conductivities (VCKB) range 1.2E-9-1.9E-7 for the Stormberg Basalt aquifer values in (m day^{-1})

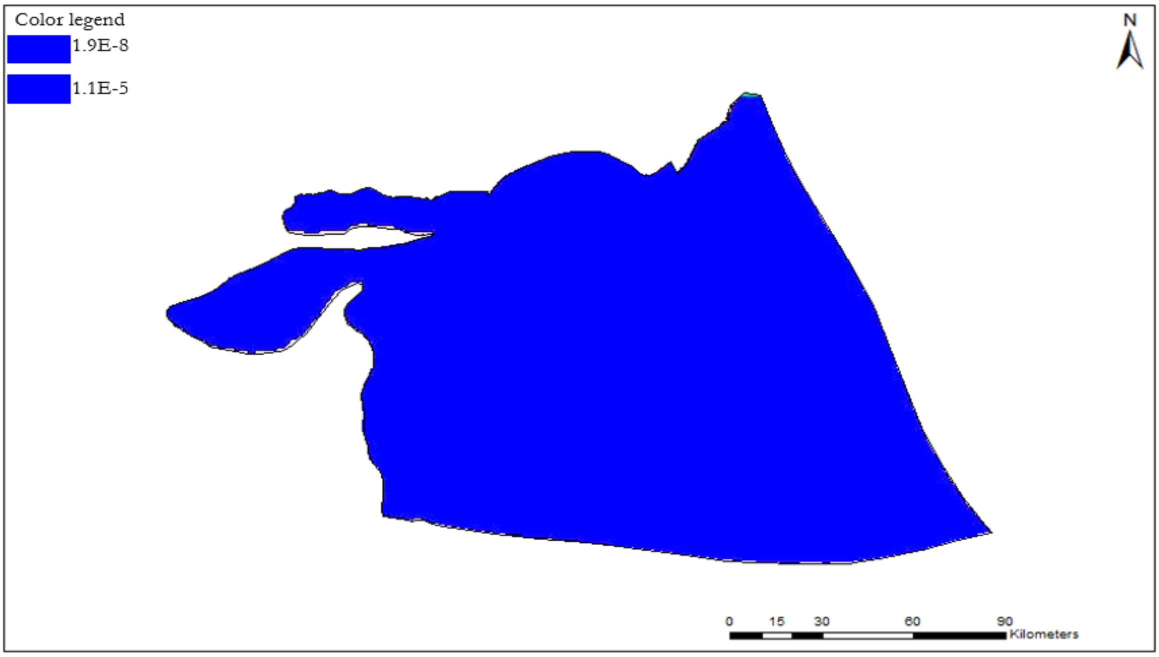

Figure 21. Calibrated vertical hydraulic conductivities (VCKB) range 1.9E-8-1.1E-5 for the Inter-Karoo Mudestone/Siltstone aquifer values in (m day^{-1})

3.4.2. Error assessment

For the steady state calibration the mean error (ME), mean absolute error (MAE) and root mean square error (RMSE) were calculated to ascertain the difference between measured hydraulic and simulated heads for the study area. The obtained values for the simulation ME -0.63, MAE 4.21 and RMSE 0.82 details are presented in Appendix 5

To further show the difference between observed and simulated heads a scatter plot in Figure 22 is shown. The scatter plot shows an acceptable model performance with a good correlation between the simulated and observed heads with a regression coefficient of (R^2) 98%.

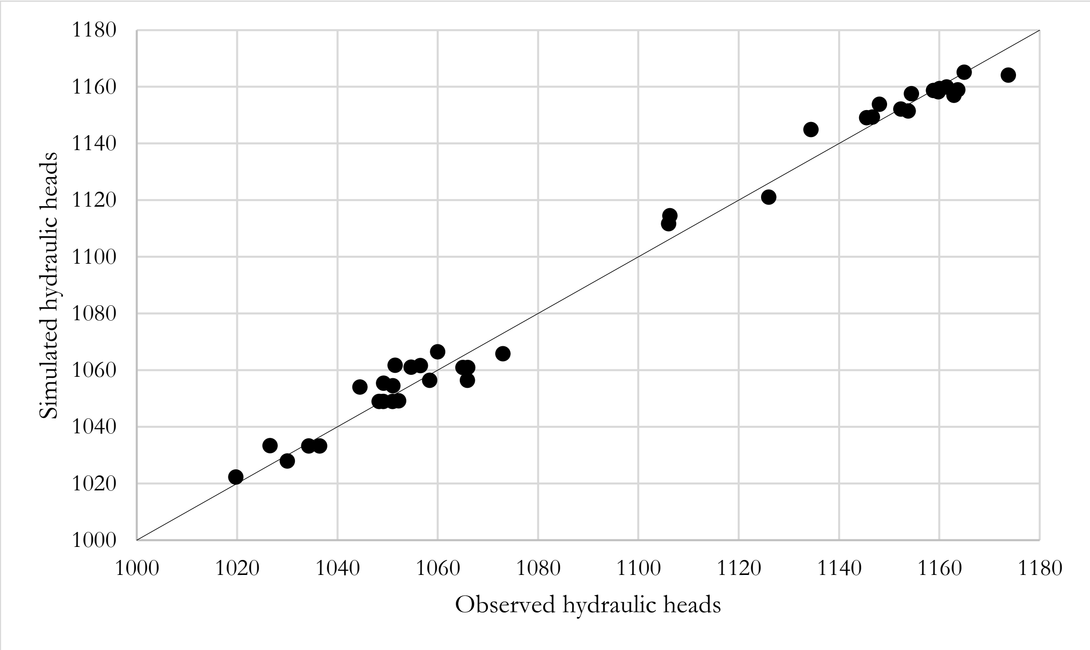

Figure 22. Scatter plot of observed and simulated heads for steady state calibration

3.4.3. Hydraulic heads

After model calibration the general distribution of the heads in all the three simulated aquifers show the groundwater flow in the study area is from west and discharged in the eastern side. The general head distribution shows that the highest hydraulic heads are in the western parts of the area. The simulated head distribution for the average period 1st October, 2012 to 30st September, 2014 show that the heads in the Kalahari Sandstone are higher than those in the Ntane Sandstone and Ecca Sandstone as presented in Figures 21 and 23.

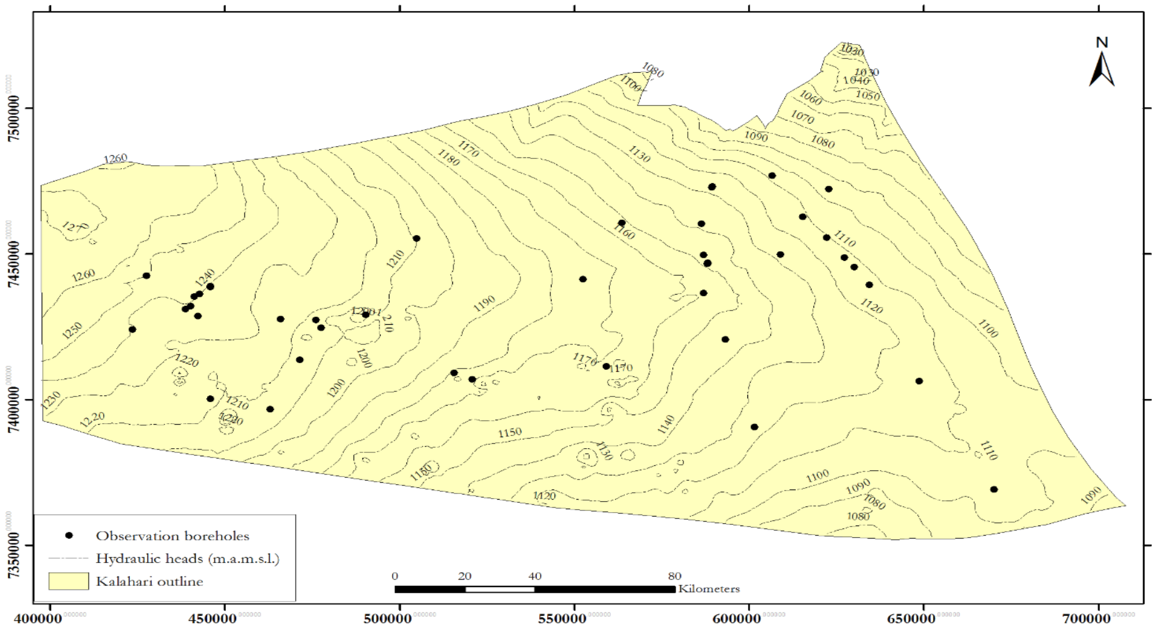

Figure 23. Head distribution in the Kalahari Sand aquifer after steady state calibration

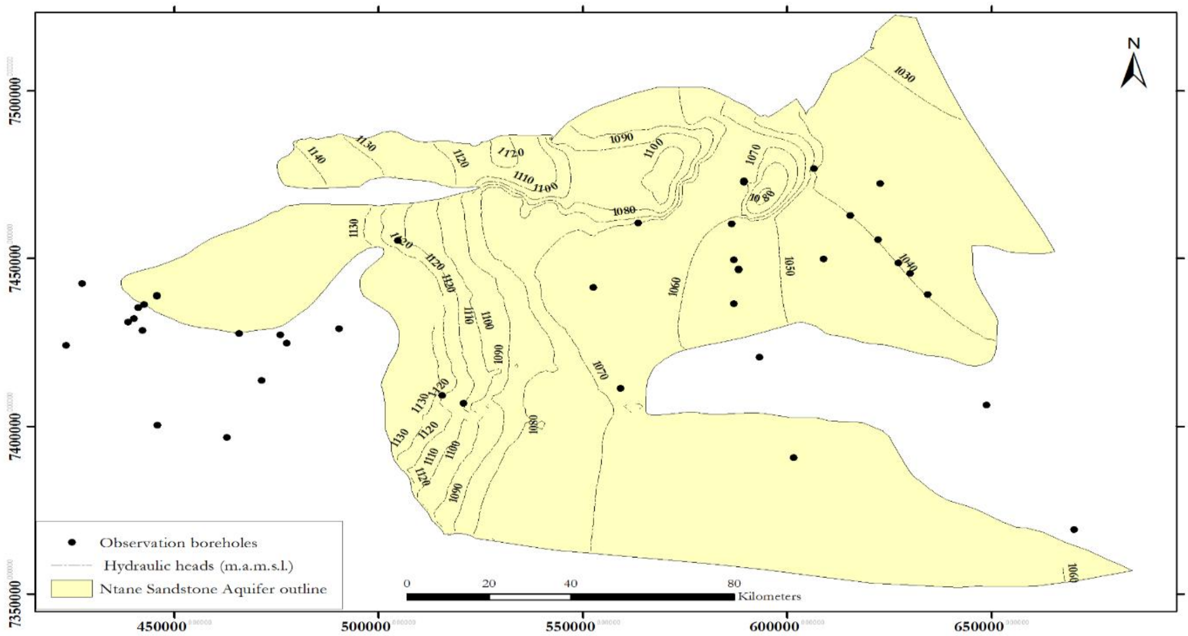

Figure 24 Head distribution in the Ntane Sandstone aquifer after steady state calibration

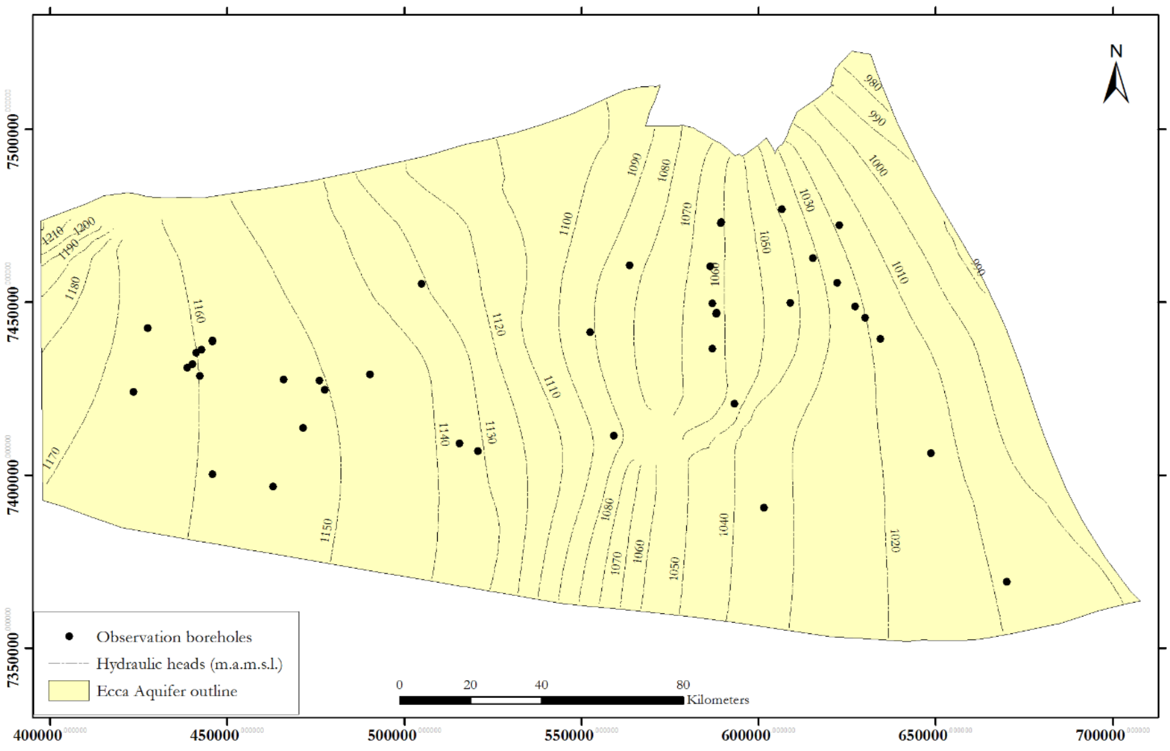

Figure 25. Head distribution in the Ecca Sandstone aquifer after steady state calibration

3.4.4. Sensitivity analysis of parameters

A sensitivity analyses was conducted on the different parameters with aim of groundwater assessment. The results of the effect of changing calibrated parameters on the heads Figure 26 and UZF parameters and GHB conductance Figure 27. The model with regards to calibration parameters shows that it is was sensitive to increase and decrease of both HK and VCKB while the VK was less sensitive. Comparing the two more sensitive calibration parameters the VCKB was the most sensitive. This shows that there is connection of the confining layers (aquitards) and the aquifers. This possibility in the study can be caused by the presence of faults thus, allows flow of water between the aquitards and the aquifers in the study area which is different from the study by Kisendi, (2016) who also applied an integrated model for the area and showed that the HK was more sensitive.

The UZF parameters also showed that they were less sensitive to both their increase and decrease to the model. While the GHB conductance was more sensitive to changes both when increased and decreased. Therefore, great care was taken when applying the changes to GHB conductance. This helps prove that there is flow of water from the west to the east were it is discharged and justifies the adopted conceptual model and the boundary conditions for this study area.

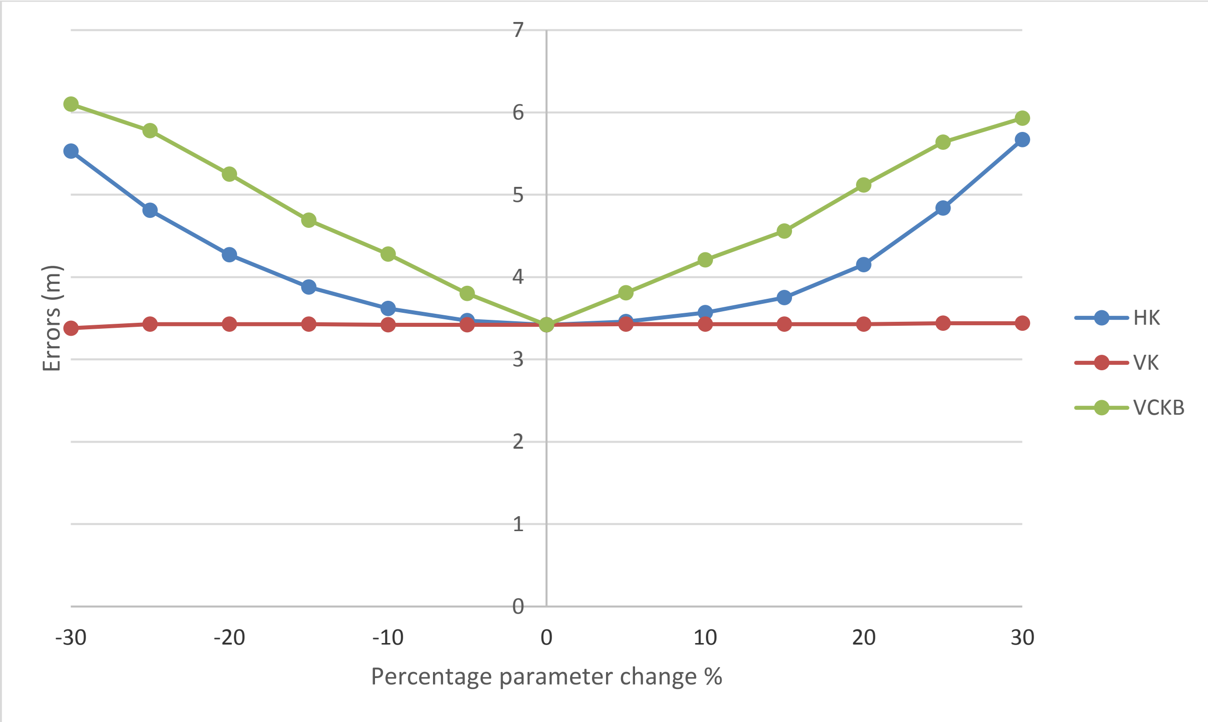

Figure 26. Effect of changing calibrated parameters on piezometric heads

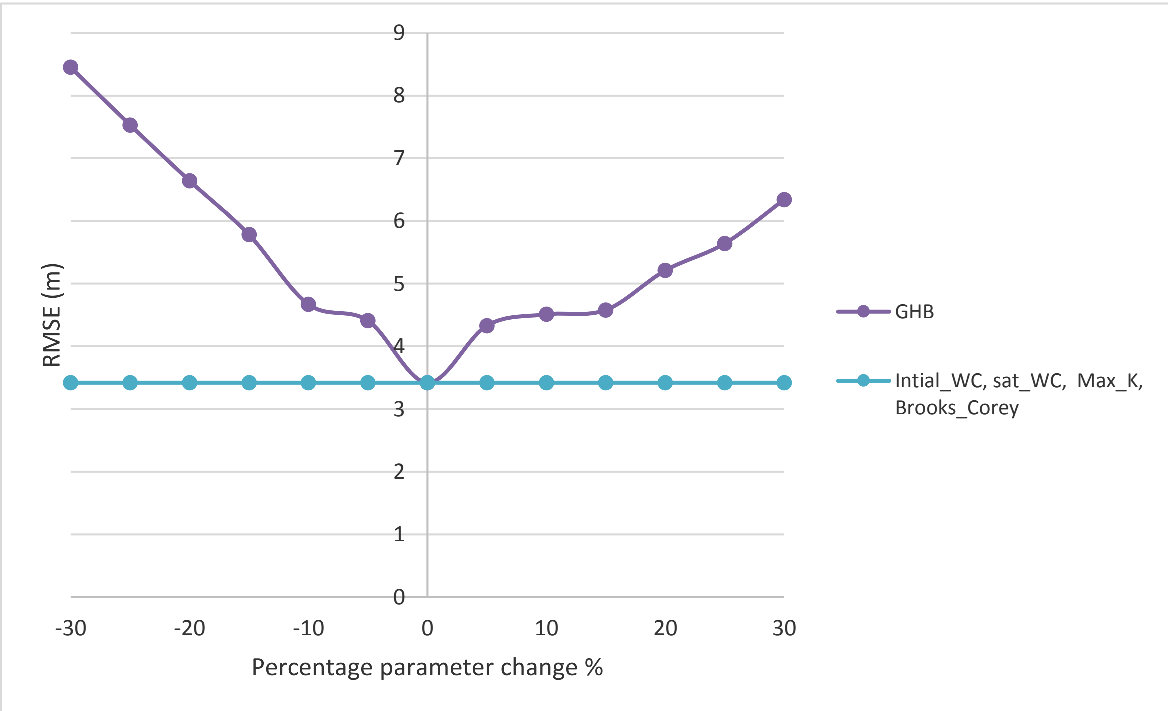

Figure 27 Effect of changing UZF parameters and GHB conductance on piezometric heads

3.4.5. Annual net recharge

After successful calibration of the model in steady state an annual net recharge for the study area was obtained. The model using the zone budget processor was able to calculate components of water budgets for the individual simulated aquifer layers namely for the Kalahari Sand aquifer, Ntane Sandstone and Ecca Sandstone aquifers and also a composite water budget for the entire area. The obtained volumetric flow water budget for the area in steady state for the composite water budget is presented in Table 3 and also in a graphical form in Figure 28. For the composite water budget it consists a sum of the total inflows and outflows to the model.

Based on the surface area the volumetric water budget was converted to fluxes in mm yr^{-1}. The obtained values for the gross recharge components to the model was 0. 28 mm yr^{-1} contributed by the UZF component after subtracting interception while ET_{ss} was 0.27 mm yr^{-1} which leaves only a few to contribute as recharge for the area. In this case the ET_{ss} refers to a combination of two component's namely groundwater *ET* (ET_{gw}) and unsaturated zone *ET* (ET_{u}) which are combined in the UZF package. Also calculations for the net recharge for the area which is the difference between the gross UZF recharge and the ET_{ss} was calculated. For this study the calculated net recharge was small with a value of 0.01 mm y^{-1} represented using the Equation 4.

$$R_n = R_{UZF} - EXF_{gw} - ET_{ss} \qquad \textit{Equation 4}$$

Where R_{UZF} - 0.28 mm yr^{-1}; EXF_{gw} -0.00 mm yr^{-1} and ET_{ss} -0.27 mm yr^{-1}

This helped to arrive at a conclusion that with the calibrated steady state model for the area the net recharge was 0.01 mm yr^{-1} which is very minimal as suggested by other studies conducted in the LNKB

Table 2. Volumetric water budget for composite water budget (m^3 day^{-1})

FLOW BUDGET COMPONENT	FLOW (m^3 d^{-1})	
	IN	OUT
QL_{in}/QL_{out}	7921.17	7947.08
UZF ET_g	0.00	31340742.00
UZF R_g	31341792.00	0.00
Exf_{gw}	0.00	0.00
QV_{in}/QV_{out}		
Total	31349714.00	31348690.00
IN-OUT	1024	
Percent Discrepancy	0.00 %	

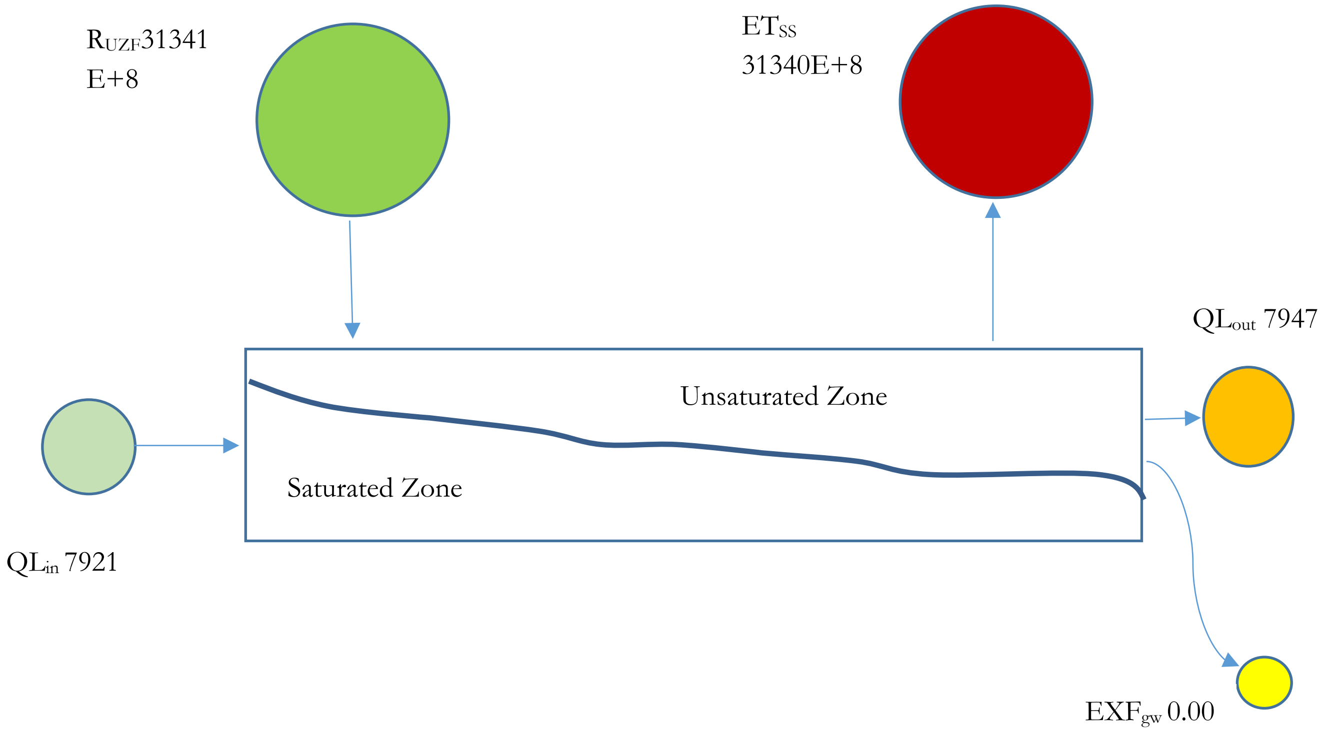

Figure 28. Schematization of the composite water budget (m³ d⁻¹)

The calculation of the water budget for the individual aquifers was also calculated using the zone budget processor as illustrated in table 4 and also in Figure 29. The individual budgets are based on what are the inflows and outflows in a single layer

Table 3. Volumetric water budget for individual layers ($m^3\ day^{-1}$)

FLOW BUDGET COMPONENT	KALAHARI ($m^3\ d^{-1}$)		NTANE ($m^3\ d^{-1}$)		ECCA ($m^3\ d^{-1}$)	
	IN	OUT	IN	OUT	IN	OUT
QL_{in}/QL_{out}	3435.6	0.00	91.449	4080.5	4332.6	3794.9
UZF ET_g	0.00	0.31341E+08	0.00	0.00	0.00	0.00
UZF R_g	0.31341E+08	0.00	0.00	0.00	0.00	0.00
Exf_{gw}	0.00	0.00	0.00	0.00	0.00	0.00
QV_{in}/QV_{out}	0.00	3461.	5150.66	1161.75	523.91	1061.5
Total	0.31344E+08	0.31344E+08	5242.1	5242.2	4856.5	4856.4
IN-OUT	-42.218		-0.85826E-01		0.85513E-01	
Percent Discrepancy	0.00		0.00		0.00	

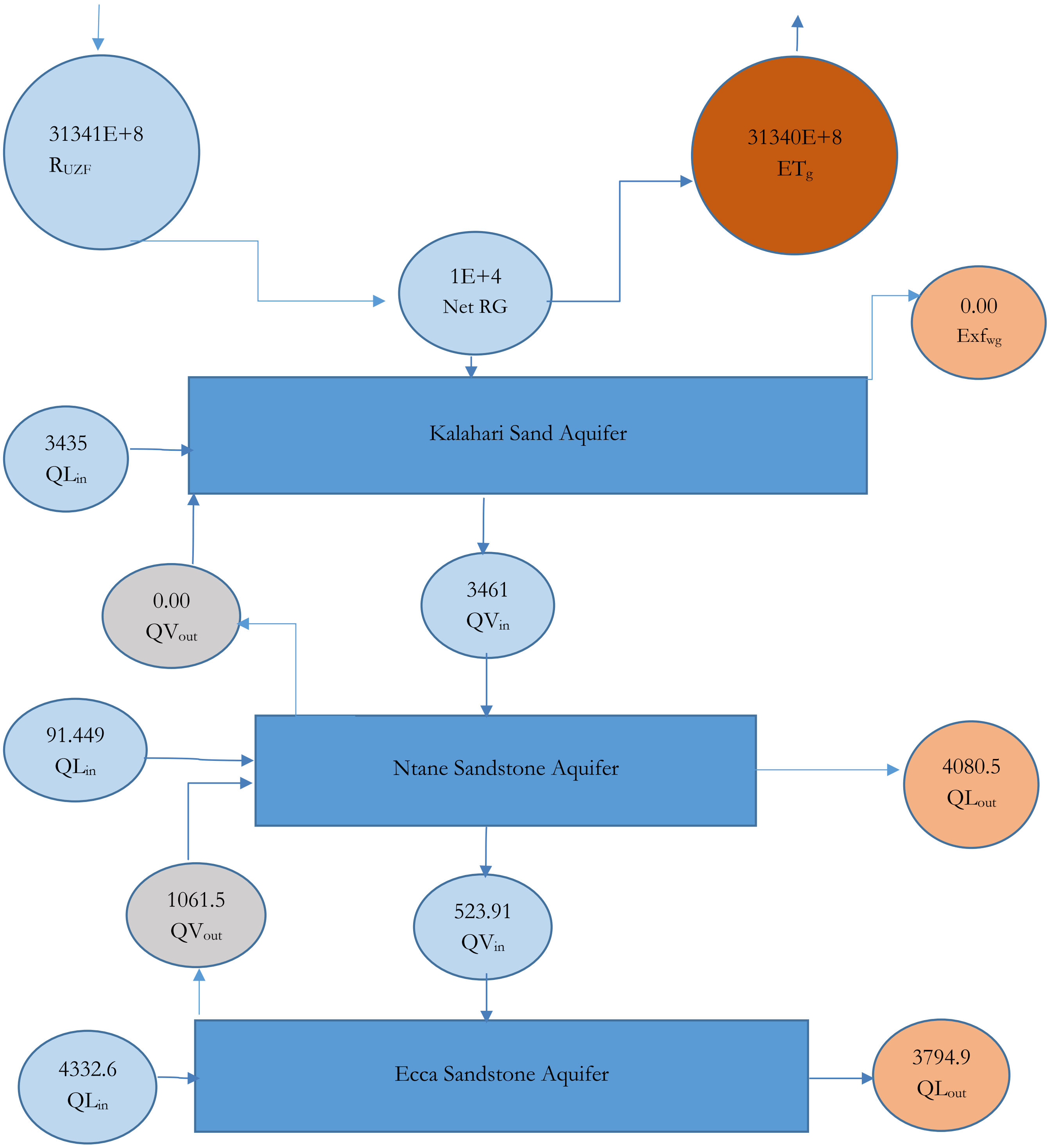

Figure 29. Schematization of water budget (m^3 d^{-1}) for each saturated layer after steady state calibration

3.4.6. Spatial variability of groundwater fluxes

The calculation of groundwater fluxes such as groundwater recharge (R_{UZF}) and subsurface (ET_{ss}) which is the combination of saturated (ET_{gw}) and unsaturated zone (ET_u) are not calculated in the units of length per time (LT^{-1}) in MODFLOW-NWT under ModelMuse but rather calculates them in volumetric units (L^3T^{-1}). Therefore, a conversion of units from volumetric units (m^3day^{-1}) to units of length per time (mm day^{-1}) was conducted for each pixel and a spatial representation per pixel was obtained. This was done by dividing the calculated water budget components in (L^3T^{-1}) with the cell area which was obtained from grid mesh which gave the fluxes spatial distribution in mm d^{-1}. The spatial distribution of R_{UZF} (Figure 15) for the all area for the average period 1st October, 2012 to 30th September, 2014 shows that LNKB receives spatially low recharge expect the NE and SW parts. This can be attributed to the low variable and erratic rainfall rates which eventually leads to low infiltration rates after factoring interception which was a constant factor in this study of 0.08. The spatial R_{UZF} varied with highest pixels having 1.3 mm d^{-1} and lower ones with 0.6 mm d^{-1}.

For subsurface ET_{ss} also the average of the period 1st October, 2012 to 30th September, 2014 was obtained from the model and the calculation was done based on the pixel contribution. Generally for the subsurface ET_{ss} it can be mentioned as illustrated from Figure 30 that the distribution is equally spatially variable. The ET_{ss} varied from 0 mm d^{-1} to highest pixel having values of 4.4 mm d^{-1}. This small differences in fluxes between R_{UZF} and ET_{ss} in the LNKB results in a minimal net recharge in the LNKB (Figure 31).

This study found something interesting that actually although the LNKB has no major connecting water bodies there are seasonal water ponds which has an influence on the fluxes in the study area. From both the spatial distribution of ET_{SS} and net recharge it was discovered that there are pockets of high fluxes as presented in Figures 30 and 31. The reason why we are having such trend of fluxes was discovered after investigating further using the DEM and topography maps of Botswana which proved that the fluxes are more pronounced where there are seasonal water ponds as illustrated after zooming in part of the DEM and spatial distribution of ET_{SS} Figure 32a & b.

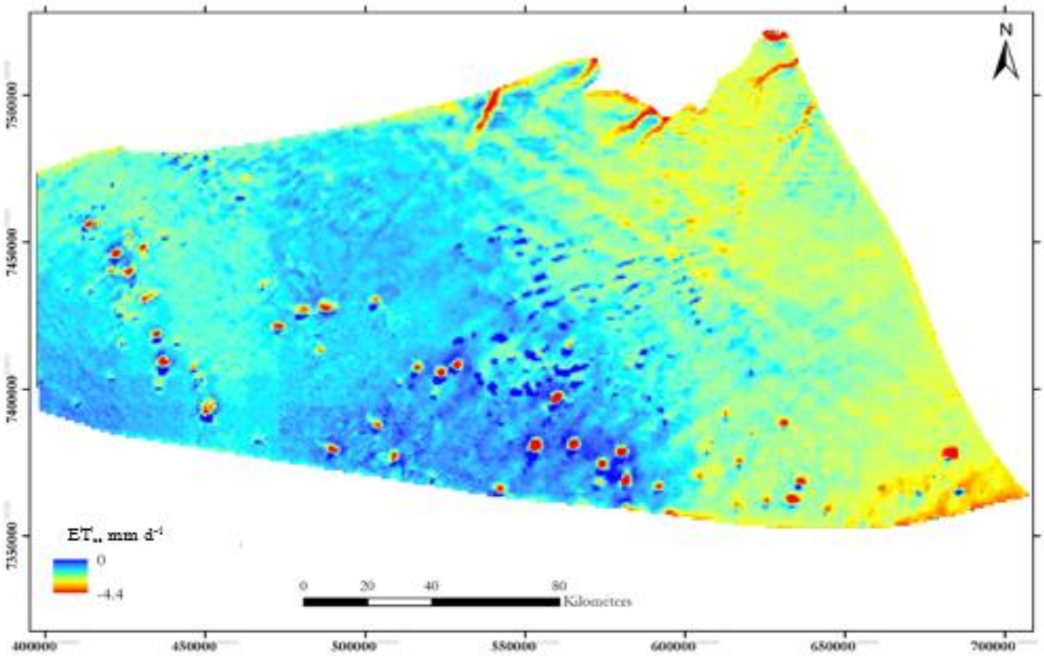

Figure 30 Unsaturated zone spatial distribution of ET_{SS} in mm d^{-1} for the period 1st Oct 2012 to 30th Sept 2014.

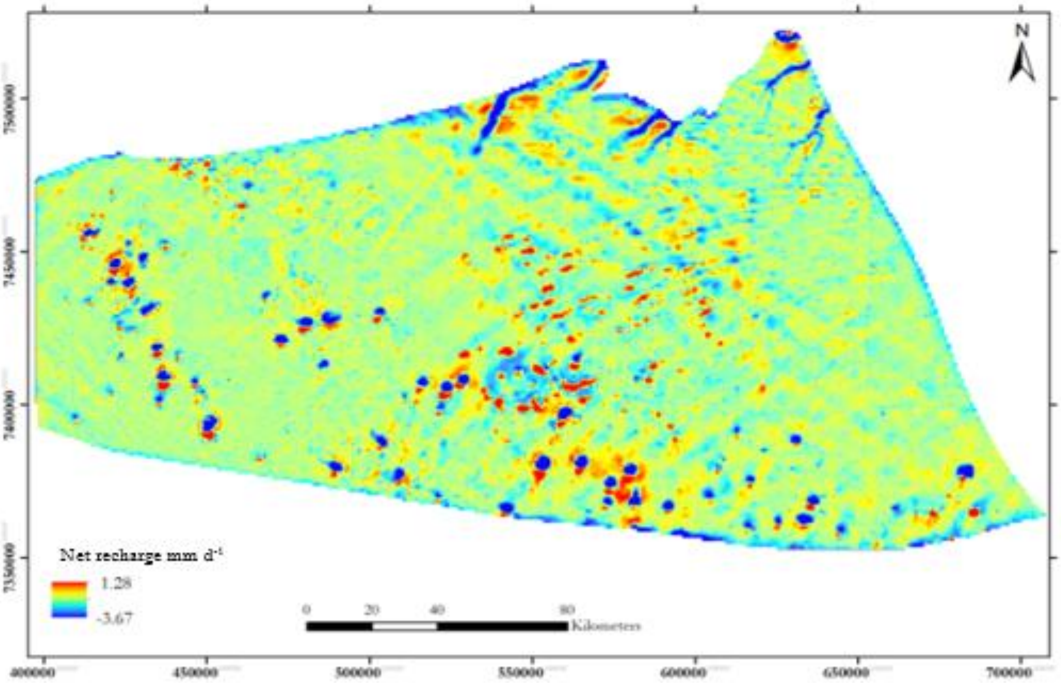

Figure 31. Unsaturated zone spatial distribution of Net recharge in mm d^{-1} in for the period 1st Oct 2012 to 30th Sept 2014.

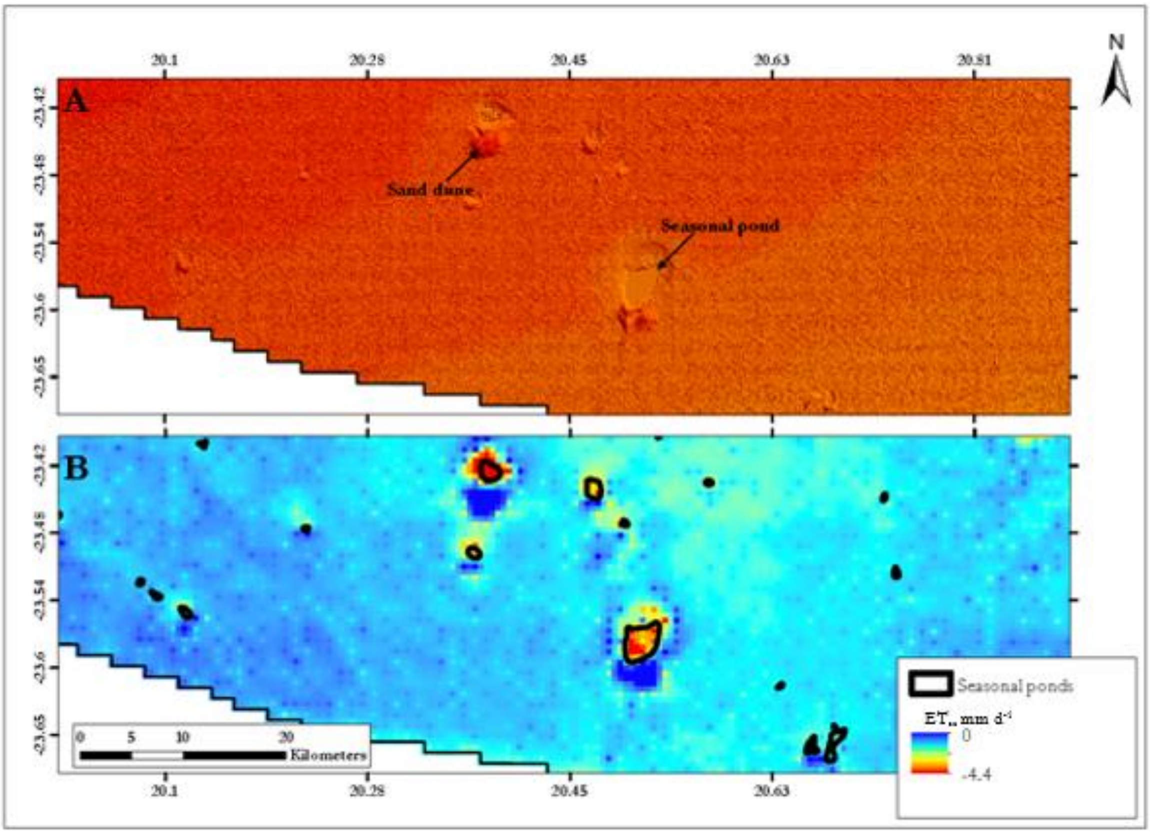

Figure 32. Influence of seasonal water ponds on the GW fluxes in the unsaturated zone of the LNKB a comparison of DEM and ET_{ss}

3.5. Comparison with other studies

3.5.1. Horizontal hydraulic conductivity

The hydraulic conductivities (HK) considered were for the three simulated layers namely the Kalahari Sand aquifer, Ntane Sandstone aquifer and the Ecca Sandstone aquifer. The Kalahari Sand aquifer was simulated as the first aquifer since the UZF package allows for integrating the unsaturated zone. The hydraulic conductivities for Kalahari Sand aquifer ranged from 3.40 m d^{-1} to 7.65 m d^{-1} which is slightly different to the finding of Kisendi, (2016) who also used an integrated model and found values ranging from 0.4 to 8.5m d^{-1}. While other studies such WRC, (2006) and (Rahube, 2003) in the LNKB used standalone models which did not factor in the Kalahari Sand so no comparison was done.
The Ntane Sandstone for this study HK ranged from 0.1 m d^{-1} to 5.95 m d^{-1} which were different with the finding of Rahube, (2003) who found the range to be from 0.08 m d^{-1} to 1.8 m d^{-1} and Kisendi, (2016) who found the range to be from 0.4 m d^{-1} to 1.65 m d^{-1}. While for the Ecca Sandstone the range was from 0.1m d^{-1} to 3.45 m d^{-1} which was also different from both Kisendi, (2016) and Rahube, (2003) who found it to range from 0.4 m d^{-1} to 1.7 m d^{-1} and from 0.01 m d^{-1} to 0.13 m d^{-1} respectively.
For the vertical hydraulic conductivities also independent zones were applied and found to range from 0.34 m d^{-1} to 0.765 m d^{-1} for the Kalahari Sand which is different to the finding of Kisendi, (2016) who found it to range from 0.1 m d^{-1} to 0.8 m d^{-1} while the Ntane Sandstone ranged from 0.01 m d^{-1} to 0.595 m d^{-1} and the Ecca Sandstone ranged from 0.01 m d^{-1} to 0.345 m d^{-1} which are different compared to previous studies which found 0.01 m d^{-1} to 0.08 m d-1 for Ntane and 0.01 m d^{-1} to 0.05 for Ecca respectively (Kisendi, 2016).

The other two layers namely Stromberg Basalt and the Inter-Karoo Mudstone/Siltstone were also given zones and simulated as aquitards which had VCKB values ranging from 1.1E-7 m d^{-1} to 5.5E-8 m d^{-1} and 1.1E-5 m d^{-1} to 6.8E-7 m d^{-1} respectively. They were found to be sensitive during model calibration which shows interaction with the aquifers. While Kisendi, (2016) who also simulated the two aquitards applied different VCKB values of 2E-7 m d^{-1} for Stormberg Basalt and 1.2E-7 m d^{-1} to 5E-9 m d^{-1} for Inter-Karoo Mudstone/Siltstone and found that the model was not sensitive to changes in VK and VCKB which is slightly different from the finding in this study which showed sensitivity to changes of VK and VCKB.

3.5.2. Net recharge

The net recharge for this study was found to be 0.01 mm yr^{-1}. Although this study has slightly different values compared to other studies such as Kisendi, (2016) who found the recharge to be about 0.03 mm yr^{-1} and Rahube, (2003) who found the minimum recharge in the to be 1.46 mm yr^{-1} they all concluded that the LNKB receives low rate of groundwater recharge. Also this is suggested by de Vries et al., (2000) that the groundwater recharge for the Kalahari can be as low as <1 mm yr-^{1}.

The low groundwater water recharge received in the area can be attributed to presence of a very thick unsaturated zone of more than 70 meter in some places and also the high temperatures enhancing ET_{ss} and erratic precipitation that easily infiltrates into the sand but also easily evaporates from the unsaturated zone leaving very few if any to percolate downward to become recharge.

3.5.3. Water balance

The obtained water balance components for the basin were compared with other previous studies particularly that of Rahube, (2003) and the most recent one conducted by (Kisendi, 2016). For the Ntane Sandstone both studies conducted by Rahube, (2003) and Kisendi, (2016) suggested that the Ntane Sandstone received higher average recharge of about 0.18 mm yr^{-1} and 0.08 mm yr^{-1}. While the volumetric aerial recharge in the Ntane Sandstone according to this study was 3461 m^3 d^{-1} which slightly similar to that of Kalahari Sandstone thus, also gives an average recharge of 0.04 mm yr^{-1}. For the Ecca Sandstone Kisendi, (2016) estimated the average recharge to be 0.07 mm yr^{-1} while Rahube, (2003) suggested it to be 4.2 x 1^{-6} mm yr^{-1}. Also this study found the average recharge for the Ecca Sandstone to be less in a magnitude of 0.005 mm yr^{-1}.

For the study all the three aquifers recorded volumetric lateral flow since general head boundary was applied both on the western and eastern side of the model. For the Ecca Sandstone aquifer a general head was applied since in the western part of the study it is exposed on the surface allowing inflow. The Ecca Sandstone recorded a lateral flow of 4332.6 m^3 d^{-1} which can attributed to it being in contact with the Kalahari Sandstone thus allowing inflow and an outflow of 3794.9 m^3 d^{-1}. While Rahube, (2003) suggested a volumetric inflow of 1878 m^3 d^{-1} since he also applied a general head boundary on the western side and an outflow of 1336 m^3 d^{-1} but Kisendi, (2016) recorded lateral flow of 4994.37 m^3 d^{-1} and outflow of 1220 m^3 d^{-1} although he did assign no flow boundary. This might have been an error with the model.

In terms of the Ntane Sandstone it recorded lateral inflow of 91.45 m^3 d^{-1} and an outflow of 4080.5 m^3 d^{-1} while previous studies by Kisendi, (2016) and Rahube, (2003) suggest slightly higher outflow of 8184 m^3 d^{-1} and 4270 m^3 d^{-1} respectively. Since they applied no flow boundary for the Ntane Sandstone no inflow was expected although Kisendi, (2016) recorded an inflow of 6.57 m^3 d^{-1} which can be attributed to an error with the model.

The study also shows that there is vertical groundwater exchange both upwards and downwards between all the aquifers. It shows the downward vertical flow of 3461 m^3 d^{-1} from Kalahari Sand aquifer to Ntane Sandstone aquifer and 523.91 m^3 d^{-1} from Natne Sandstone aquifer to Ecca Sandstone aquifer while the upwards vertical flow exchange shows 1061.5 m^3 d^{-1} from Ecca Sandstone aquifer to Ntane Sandstone aquifer and 0.00 m^3 d^{-1} Ntane Sandstone aquifer to Kalahari Sand aquifer. While previous study by Kisendi, (2016) also show vertical flow exchange both upwards and downwards with 5345 m^3 d^{-1} from Ntane Sandstone aquifer to Ecca Sandstone aquifer and 4126 m^3 d^{-1} from Ecca Sandstone aquifer to Ntane Sandstone aquifer. Which shows a significant difference with this study recording a net vertical flow towards the Ecca Sandstone aquifer of 2938 m^3 d^{-1} while Kisendi, (2016) recorded a net vertical flow to the Ecca Sandstone aquifer of 1219 m^3 d^{-1}

3.6. Limitation of study

Most of the available borehole data had gaps thus lack of continuous measurements which limited simulation to only three years with piezometers which had better measurements. The other technical limitation under steady state was that it was difficult to quantify and report of the individual contribution of ET from the saturated zone (ET_g) and unsaturated zone (ET_u) since that package which was used the UZF package calculates the ET as a combination which makes it difficult to appreciate what is been contributed by the specific zones.

4. CONCLUSION AND RECOMMENDATION

4.1. Conclusion

This study's main purpose was using an integrated model which incorporates both unsaturated and saturated zone to help evaluate the groundwater resources of the LNKB. To ensure that, a reliable conceptual model for the area had to be formulated by understanding and investigating the physical features of the LNKB such as geometry, lithology and the entire hydrological regime of the area. Therefore, to help build such a model a 3D lithostratigraphic model was built and later converted into hydrostratigraphic model using available borehole log data in Rockworks. This resulted in five hydrostratigraphic units that were applied to the model namely the Kalahari Sandstone aquifer, Stormberg Basalt aquitard, Ntane Sandstone aquifer, Inter-Karoo Mudstone/Siltstone aquitard and Ecca Sandstone aquifer.

Rockworks helped develop well defined model layers and a holistic view of the LNKB, it helped to arrive at selecting the external boundaries for the study area. MODFLOW-NWT in Model Muse was used to simulate and integrated model for the study area together with UZF1 package which makes it possible to integrate the unsaturated zone. For this study satellite products namely precipitation and *PET* already biased corrected from FEWNET were processed and applied to the model. The infiltration applied as inputs of the UZF package, was calculated by subtracting interception from precipitation while the interception was assumed 8% of precipitation. The selected simulation period was from 1st October, 2012 to 30th September, 2014 and an average for both input parameters to the model was applied and calibrated under steady state using trial and error. Error assessment was also performed between measured and simulated heads using ME, MAE and RMSE. After steady state calibration the result in terms of ME, MAE and RMSE were 0.65, 5.27 and 4.32 respectively. Further, ensuring the performance of the model was accurate a correlation analysis between simulated and observed heads was performed which indicated a good model performance correlation of 98%.

The sensitivity analysis was performed after steady state calibration to assess to which model parameters hydraulic heads were more sensitive the most. The analysis revealed that the model was more sensitive to vertical hydraulic conductivities VK and VCKB while it was less sensitive to changes made to horizontal hydraulic conductivities (HK) especially for the Kalahari Sand aquifer. The model also showed sensitivity to changes made to the GHB conductance either when the values were increased or reduced.

The other aspect for the study was that water budget was calculated based on the inflows and outflows to the model. Some of the main components that this study focused on were overall groundwater recharge and overall groundwater ET_{SS} which were 0.28 mm yr^{-1} and 0.27 mm yr^{-1} and gave a net recharge for the LNKB of 0.01 mm yr^{-1}. The other aspects to the water budget are the lateral inflow and outflow and these are calculated based on what each aquifer discharges as outflow as the contribution of each aquifer. The Kalahari shows no lateral outflow which shows that most of the flow is in vertical order while The Ntane Sandstone shows outflow of about 825.30 m^3 d^{-1} and the Ecca Sandstone shows slightly higher value of 4134 m^3 d^{-1}. This high can confirm that most of the infiltration ends up in the Ecca Sandstone aquifer. The groundwater fluxes were also calculated and presented the spatial variability contributed per pixel. The groundwater recharge ranged from the highest pixels having 1.3 mm d^{-1} and lower ones with 0.6 mm d^{-1}.While the ET_{ss} varied from 0 mm d^{-1} to highest pixel having values of 4.4 mm d^{-1} which explains the low rate of recharge in the area. This study also found out that the presence of seasonal water ponds in the area has influence of the spatial distribution of the groundwater fluxes (net recharge and ET_{ss}).

4.2. Recommendation

Future studies in LKNB should focus at understanding the amount of water that is taken up by the deep rooted plants and also the contribution in terms of ET_{ss} from the different zones namely the unsaturated and the saturated zones. Since most studies have focused on understanding the recharge and concluded that there is low recharge in the area as brought out in this study with only a net recharge of 0.01 mm/yr^{-1}

In order to fully understand the resource in the area in terms of the groundwater water storage, specific storage and yield of the different aquifers a transient model needs to be undertaken. This will then help bring out of the contribution of each aquifer and which to have knowledge of which ones are more productive

Since this study found that the presence of water ponds has an influence of the groundwater fluxes there is need to further investigate the contribution that is coming from the seasonal ponds.

Although the model recorded positives there are also areas that still need to be improved such as improving the correlation between simulated and observed heads which was a challenge in the study due to the fact that most the monitoring wells were in the fifth layer which proved to be a problem to attain a perfect calibration.

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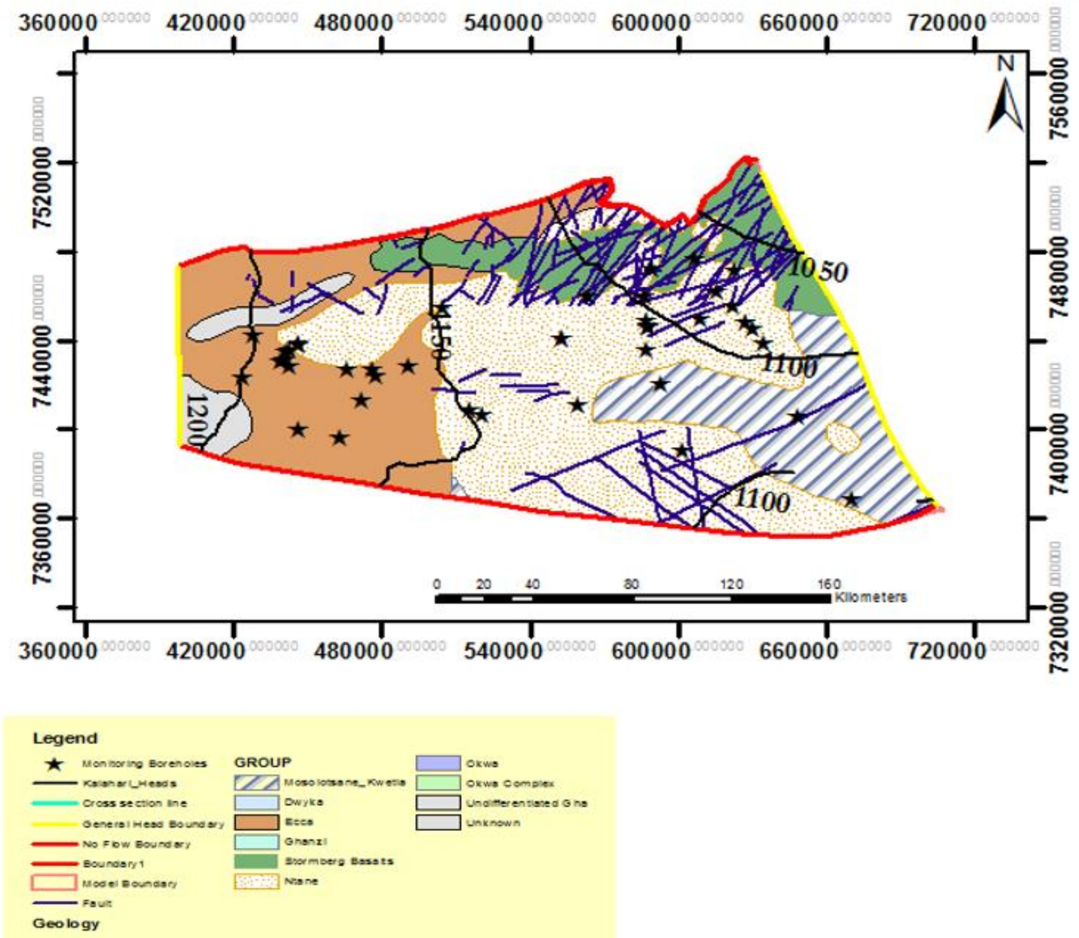
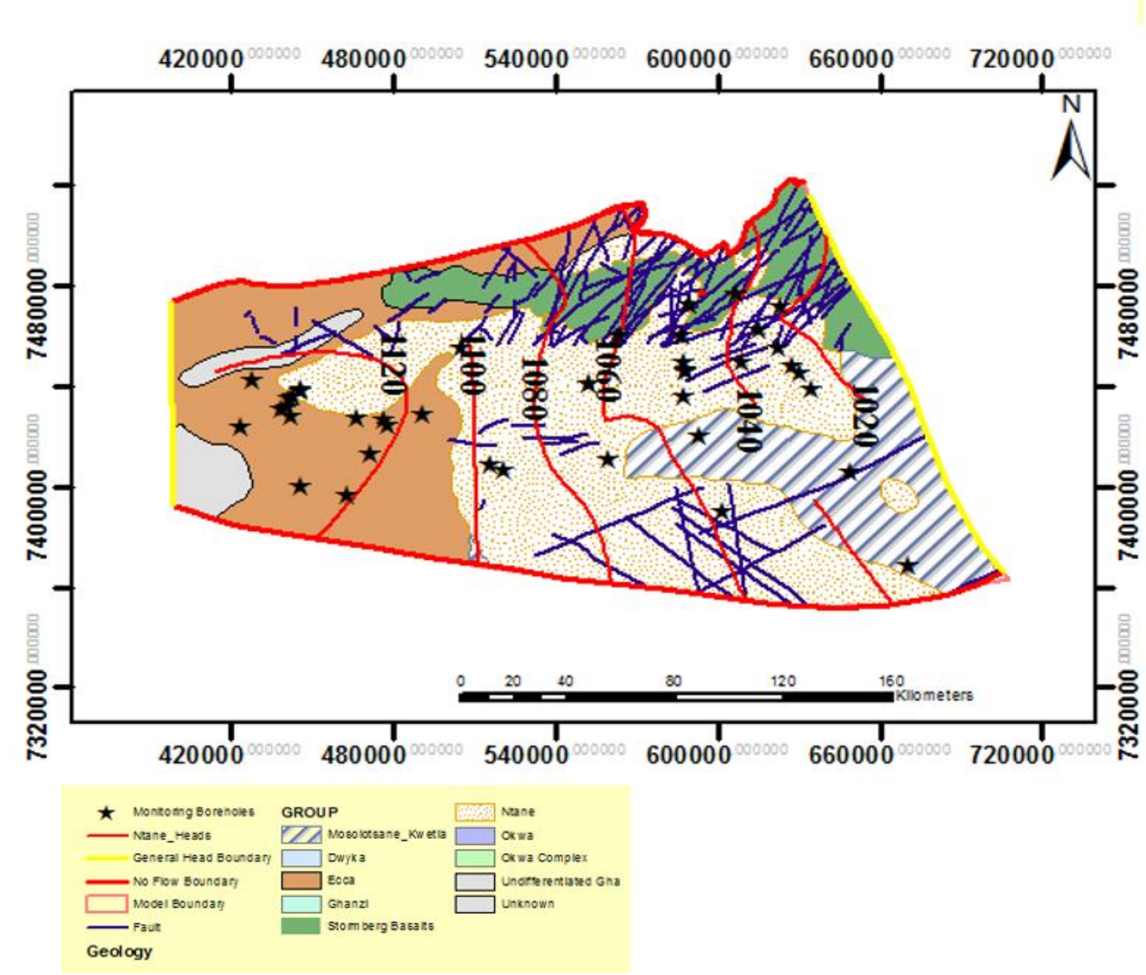
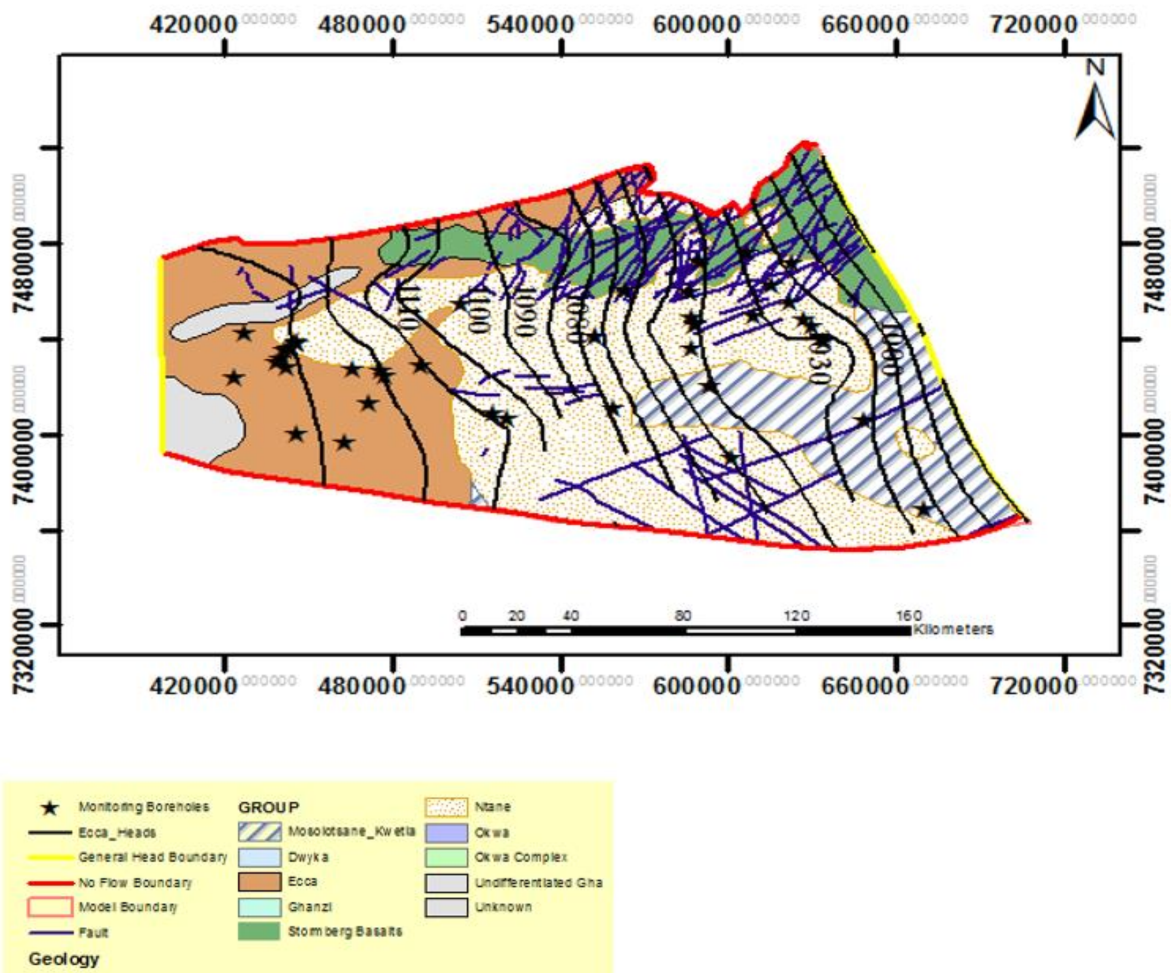
APPENDIX 1. JUSTIFICATION FOR BOUNDARY CONDITIONS (ECCA AQUIFER POTENTIOMETRIC MAP)



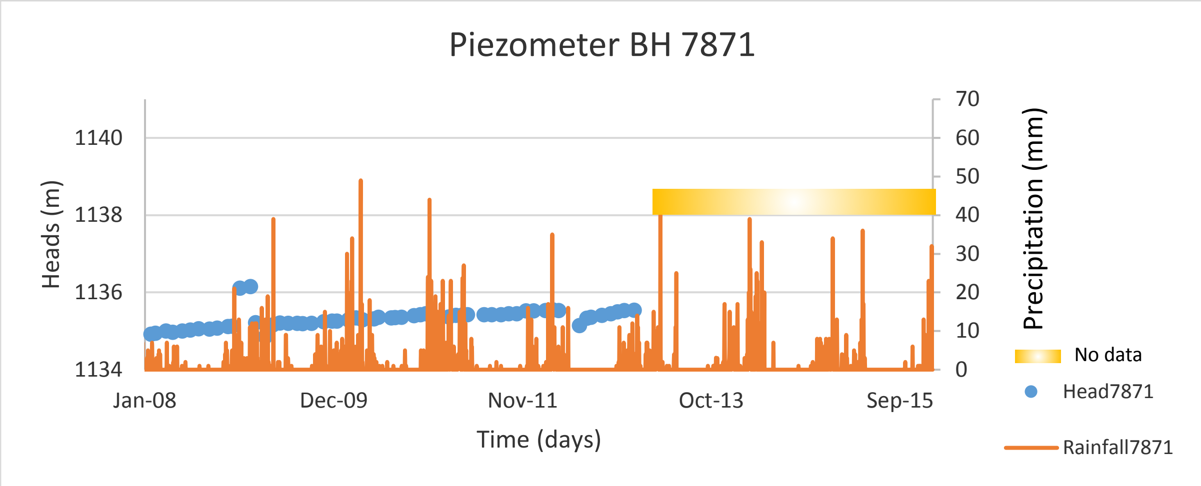
APPENDIX 2. JUSTIFICATION FOR BOUNDARY CONDITIONS (KALAHARI AQUIFER POTENTIOMETRIC MAP)

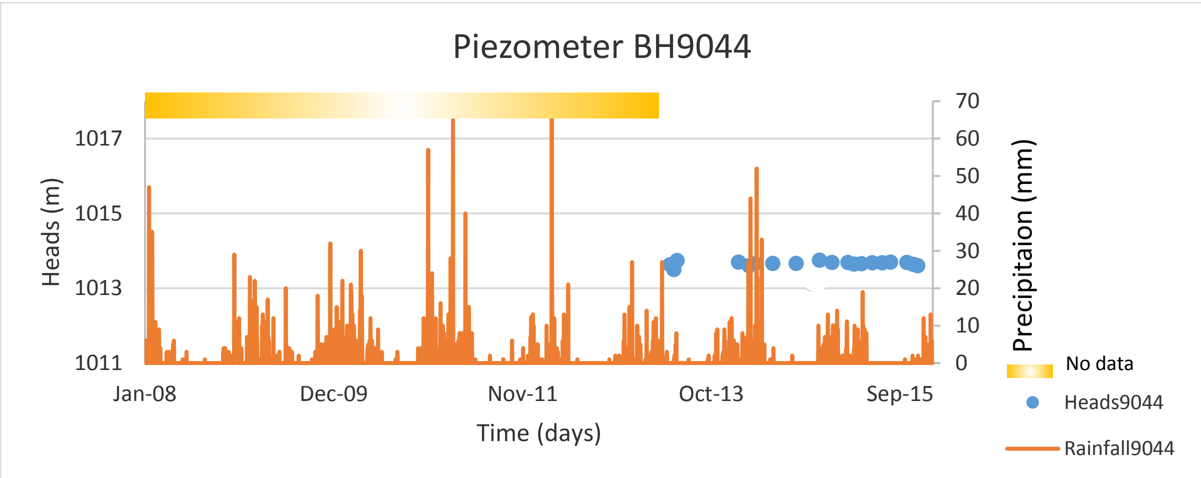


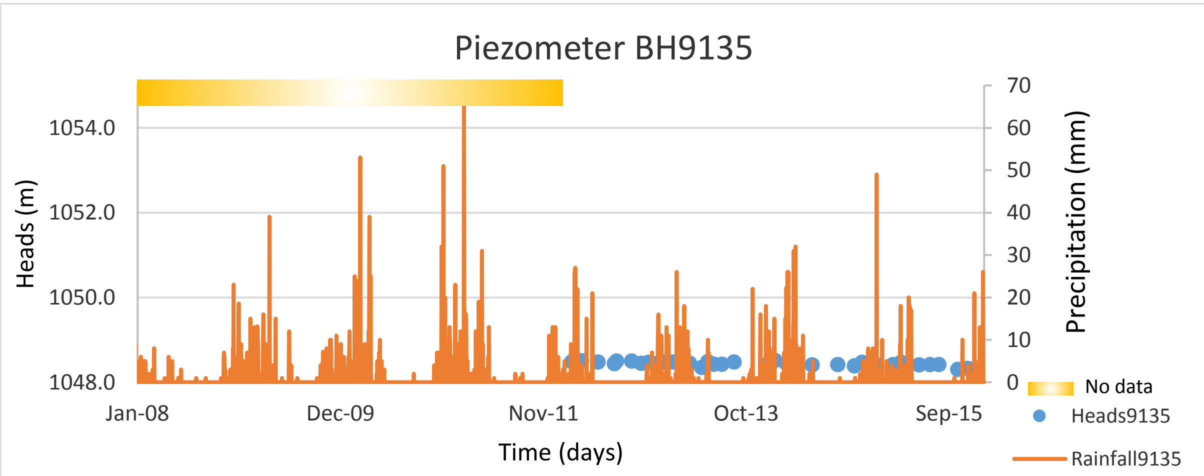
APPENDIX 3. JUSTIFICATION FOR BOUNDARY CONDITIONS (NTANE AQUIFER POTENTIOMETRIC MAP)



APPENDIX 4. MORE EXAMPLES ANALYSED HYDRAULIC HEADS AGAINST DAILY SATALLITE RAINFALL







APPENDIX 5. MONITORING BOREHOLES USED IN THE STUDY

Borehole	**Aquifer**	**O (m)**	**S (m)**	**O -S (m)**	**$(O-S)^2$ (m2)**	**$\lvert O-S \rvert$ (m)**
BH9153	Ecca	1056.53	1061.64	-5.11	26.08	5.11
BH9239	Ecca	1054.71	1061.04	-6.33	40.04	6.33
BH9291	Ecca	1051.05	1054.5	-3.45	11.9	3.45
BH9297	Ecca	1065.93	1056.36	9.57	91.68	9.57
BH2211	Ecca	1065.02	1060.9	4.12	17.01	4.12
BH7171	Ecca	1026.6	1033.33	-6.73	45.23	6.73
BH7320	Ecca	1019.75	1022.3	-2.55	6.48	2.55
BH9135	Ecca	1051.51	1061.69	-10.18	103.64	10.18
BH671	Ecca	1051	1048.93	2.07	4.28	2.07
BH6186	Ecca	1073	1065.78	7.22	52.09	7.22
BH6756	Ecca	1106	1111.65	-5.65	31.92	5.65
BH6757	Ecca	1126	1121.08	4.92	24.21	4.92
BH7172	Ecca	1030	1027.86	2.14	4.56	2.14
BH7540	Ecca	1049.14	1048.96	0.18	0.03	0.18
BH9044	Ecca	1048.35	1048.98	-0.63	0.39	0.63
BH9045	Ecca	1106.26	1114.49	-8.23	67.81	8.23
BH1066	Ecca	1066	1060.9	5.1	26.04	5.1
BH9237	Ecca	1044.5	1054.03	-9.53	90.77	9.53
BH9238	Ecca	1060	1066.47	-6.47	41.89	6.47
BH9239	Ecca	1052.2	1049.19	3.01	9.03	3.01
BH9240	Ecca	1034.3	1033.18	1.12	1.24	1.12
BH8346	Ntane	1173.75	1164.15	9.6	92.08	9.6
BH929	Ntane	1049.24	1055.42	-6.18	38.14	6.18
BH10201	Ntane	1153.82	1151.44	2.38	5.67	2.38
BH10215	Ntane	1164.97	1165.14	-0.17	0.03	0.17
BH10216	Ntane	1154.41	1157.6	-3.19	10.16	3.19
BH10218	Ntane	1148.07	1153.8	-5.73	32.89	5.73
BH10221	Ntane	1152.3	1152.16	0.14	0.02	0.14
BH10222	Ntane	1146.62	1149.3	-2.68	7.17	2.68
BH10225	Ntane	1036.45	1033.18	3.27	10.7	3.27
BH10226	Ntane	1058.39	1056.38	2.01	4.04	2.01
BH10229	Ntane	1145.5	1149.08	-3.58	12.78	3.58
BH10314	Ntane	1134.4	1144.9	-10.5	110.26	10.5
BH10402	Ntane	1163.7	1158.86	4.84	23.41	4.84
BH10404	Ntane	1162.91	1156.94	5.97	35.66	5.97
BH10405	Ntane	1159.81	1158.23	1.58	2.51	1.58
BH10407	Ntane	1160.03	1159.33	0.7	0.49	0.7
BH10410	Ntane	1158.83	1158.67	0.16	0.03	0.16
BH10411	Ntane	1161.44	1159.9	1.54	2.37	1.54
			SUM	**-25.23**	**1084.7**	**168.5**
					ME (m)	**-0.63**
					MAE (m)	**4.21**
					RMSE (m)	**0.82**