GROUNDWATER RESOURCE ASSESSMENT USING MODELLING AND REMOTE SENSING: A CASE STUDY OF SESHEKE, ZAMBIA

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ABSTRACT

Groundwater is the major source of domestic water supply in rural Zambia. Sustainable utilization of these resources requires accurate knowledge of its quantity and quality. One the tools most used in assessing groundwater resources is the use of numerical groundwater models. The reliability of groundwater modelling is largely constrained by the quality of input data. Earth Observation data and groundwater modelling can help in quantifying the groundwater fluxes in an area where data is scarce. This paper discusses the assessment of groundwater resources in Sesheke using Geographical Information System (GIS), Remote Sensing (RS) and Groundwater modelling. The aquifer system was modelled using software Processing Modflow for Windows (PMWIN) as a pre and post processor for MODFLOW assuming steady state conditions. Only the upper aquifer was modelled under unconfined conditions represented by three numerical layers of varying thickness 130m to 364m. The grid cell size of the model was taken as 250 X 250m and 11,863 active cells were used to represent the entire study area which is 11,501Km^2. The model area and the elevation of the top layer were delineated using Shuttle Radar Topographical Mission (SRTM) Digital Elevation Model (DEM) and topographic maps. A combination of trial and error method and automatic method were used to calibrate the model using the observed hydraulic heads until the Root Mean Square Error (RMSE) reached 17m. From the sensitivity analysis hydraulic conductivity proved to be the most sensitive parameter of the model. From the pump testing analysis the average transmisivity was found to be 3.614m2/day and the hydraulic conductivity was in the range of 0.742 – 2.614m/day for the sandstone and 0.09-24m/day for the loose top Kalahari sands. From the Surface Energy Balance system (SEBS) the annual average actual Evapotranspiration (ET) was calculated as 745mm against the annual precipitation of 765mm. The estimated annual recharge from the groundwater model is 54.7mm in the north and 28mm in the southern part of the model. The model results suggest that the main recharge area is in the northern part of Sesheke which agrees well with hydraulic head survey conducted during the field work where high hydraulic heads in the north where comparable to the southern part of the District.

Key Words: *Groundwater Modelling, Geographical Information System, MODFLOW, Remote Sensing*

INTRODUCTION

Groundwater is one of the key natural resources of the world. Many cities and small towns depend on these resources for water supply mainly because of its abundance, stable quality and is also inexpensive to exploit unlike surface water which is unevenly distributed (Morris, et. al 2003). In Zambia there has been growing demand on the available water resources and groundwater use is increasing steadily. Today, some 9% of water usage is from groundwater and groundwater provides 28% of domestic water supply(Water Aid, 2001) but the accurate knowledge on the quantity and quality of this resource is lacking. In the Danida supported Rural Water Supply project (Component 1) (Danida 2005) drilling of over 400 boreholes into the Kalahari Sand Aquifer is planned in the Sesheke area and other parts of the Western Province. Sustainable use of these resources requires that the abstraction is limited to the amount that is recharging these aquifers otherwise groundwater mining would occur if the aquifers are over abstracted. Groundwater recharge can be defined in a broad sense as "an addition of water to a groundwater reservoir" (Sophocleous, 2004). In arid and semi-arid areas, assessment of groundwater recharge is one of the key challenges in determining the sustainable yield of aquifers as recharge rates are generally low in comparison with average annual rainfall or evapotranspiration, and thus difficult to determine precisely (Xu, 2003). Determination of groundwater recharge in arid and semi-arid areas is neither straightforward nor easy. This is a consequence of the time variability of precipitation in arid and semi-arid climates, and spatial variability in soil characteristics, topography, vegetation and land use. There are as many methods available for quantifying groundwater recharge as there are different sources and processes of recharge. Each of the methods has its own limitations in terms of applicability and reliability. Some of the promising among the many methods of recharge estimation is through GIS, RS and Groundwater modelling (Brodie, 1999). In this study the three methods are exploited to estimate the recharge of the Kalahari Sand Aquifers in the Sesheke area.

SITE DESCRIPTION

Sesheke District which is part of the Barotse Sub-Basin of the Zambezi River Basin is located in the south-western part of Zambia between Latitude 15°25' -17°39' South and Longitude 23°3'-25° 31'East and covers an area of about 29,893Km^2 (Figure 1). The topographic elevation ranges from 931m in the south to 1200m in the extreme North in Mulobezi area. The District is part of the great Central African Plateau (CAP) characterised by degraded plateau areas traversed by a network of rivers, streams and dambos of varying density and are largely confined to the area east of the Zambezi River (JICA/MEWD-D, 1995). The aggraded plateau is composed of semi consolidated or unconsolidated deep Kalahari sands. It is characterised by extensive, level to very gently undulating plains with generally widely spaced drainage lines and areas where a complexes of dunes and pans (some containing small lakes) predominate. Rainfall is extremely variable, falling between October and April. From the Tropical Rainfall Measuring Mission (TRMM) satellite data the mean annual rainfall declines South-Eastwards from 766 mm in Northwest to about 635 mm in South-East of the.

Temperatures are high from the second half of August until March. Cool temperatures prevail from May to the first half of August, with night-time temperatures approaching freezing in July. The average temperatures in July are between 4.4° C and 34.2° C in October. The annual pan evaporation is estimated at 2814mm and is high from August to November at 200 to 300mm per month and low from December to July at 100 to 200mm per month. Actual annual evapotranspiration is 616mm against an average of 657mm rainfall and 73 rainy days. The relative humidity is estimated at an average of 62.5%.

Average annual wind speed is 1.6m/s.(JICA/MEWD-D, 1995). The main type of soils in Sesheke are the Aerosols, which are somewhat excessively drained very deep, pale brown to yellow brown, loose to very friable sandy soils covering over 80% of the district. The second major soils are the Gleysols which are a complex of poorly drained very deep, dark greyish brown loose sandy soils with humic topsoil. The other soils are the Planosols, Histosols, and Fluvisols,.(JICA/MEWD-D, 1995).

REGIONAL HYDROLOGICAL AND HYDROGEOLOGICAL SETTING

Hydrology of the study area

Sesheke is situated in the Barotse sub-basin which is in the upper part of the Zambezi River Basin. The Zambezi is the fourth-longest river in Africa, and the largest flowing into the Indian Ocean from Africa. The area has a dendritic drainage pattern whose flow direction is controlled by the general geological fault lines direction NE-SW and NW-SE (Figure 2). The three sources of water in these rivers are: (i) rainfall and direct runoff and temporary (flash) flooding (ii) ponding and (iii) the slow release of seepage (base flow) water from the upland sands during the dry season. Most of the rivers in the area are ephemeral and only a few are perennial. The perennial rivers are the Zambezi, Kweemba, and the Njoko River whereas, Machile, Luazamba, Lusu, Luampungu, Sonso, and Luanja are ephemeral, they flow during the wet season and dry-up during the dry period.

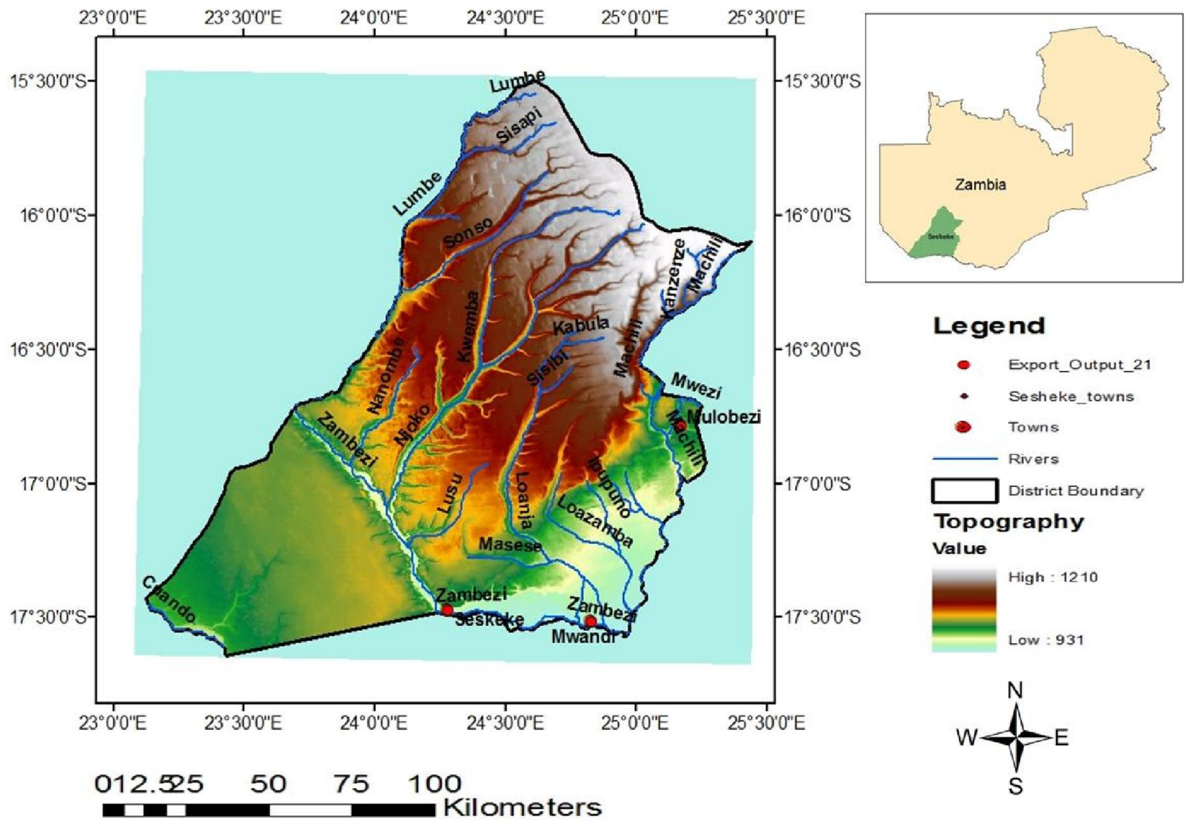


Figure 1: Map of the study area Sesheke District

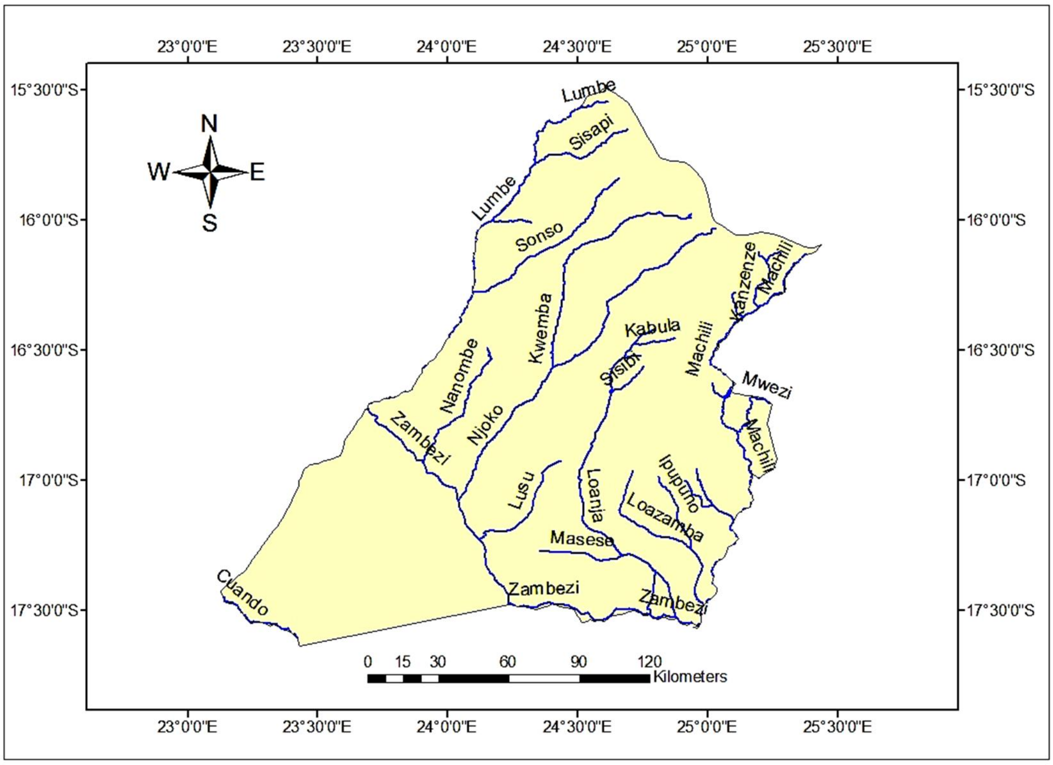


Figure 2: Drainage map of Sesheke District Zambia.

Geology and stratigraphy framework of the study area

Sesheke District is underlain by the Mesozoic Supergroup Machile Mudstone, Tertiary Kalahari loose sands and Quaternary consolidated sand layers (duricrusts) and clay layers. These layers have been named the Cenozoic Super and they are divided in two formations; namely the Zambezi Formation of the lower part and the Barotse Formation of the upper part. The so called Kalahari Sandstone is a member of the Zambezi formation(Money, 1972). The Sesheke District is characterised by an extensive and deep covering of Kalahari sands of Tertiary age, which extend westwards into Angola and southwards into Botswana. They are described by Trapnell and Clothier (1937) as pure and coarse grained, with few signs of profile characteristics. In the marginal areas to the south and the north-eastern parts of Sesheke District the sands thin out and contain higher proportions of clay derived from the underlying Karoo beds in the subsoil (Figure 3). The sands are highly permeable and, except in the transitional sands of the east, extremely deficient in nutrients. Rainwater is absorbed in the sands and slowly released through seepage into drainage lines, and pans (Concern-Worldwide-Zambia, 2007).

Hydrogeology of the study area

The Sesheke area is flat characterised by uniform geological conditions at the surface. The sediments of the Kalahari Sequence and more recent deposits overlie the entire area and are believed to be of an Aeolian origin. Outcrops of underlying rocks are scarce. The hydrogeology in Sesheke District can be divided into two major lithological groups: (i) the Kalahari Sands; and (ii) Alluvial. These are inter-granular aquifer covering about 90% of the District. The alluvial aquifers are found mainly along the margins of main river channels or in old channels as the river changed its course along the years. The Kalahari sands aquifers form good aquifers because of very high porosity in the range of 25-30% , permeability and high yielding with great potential for large scale use.

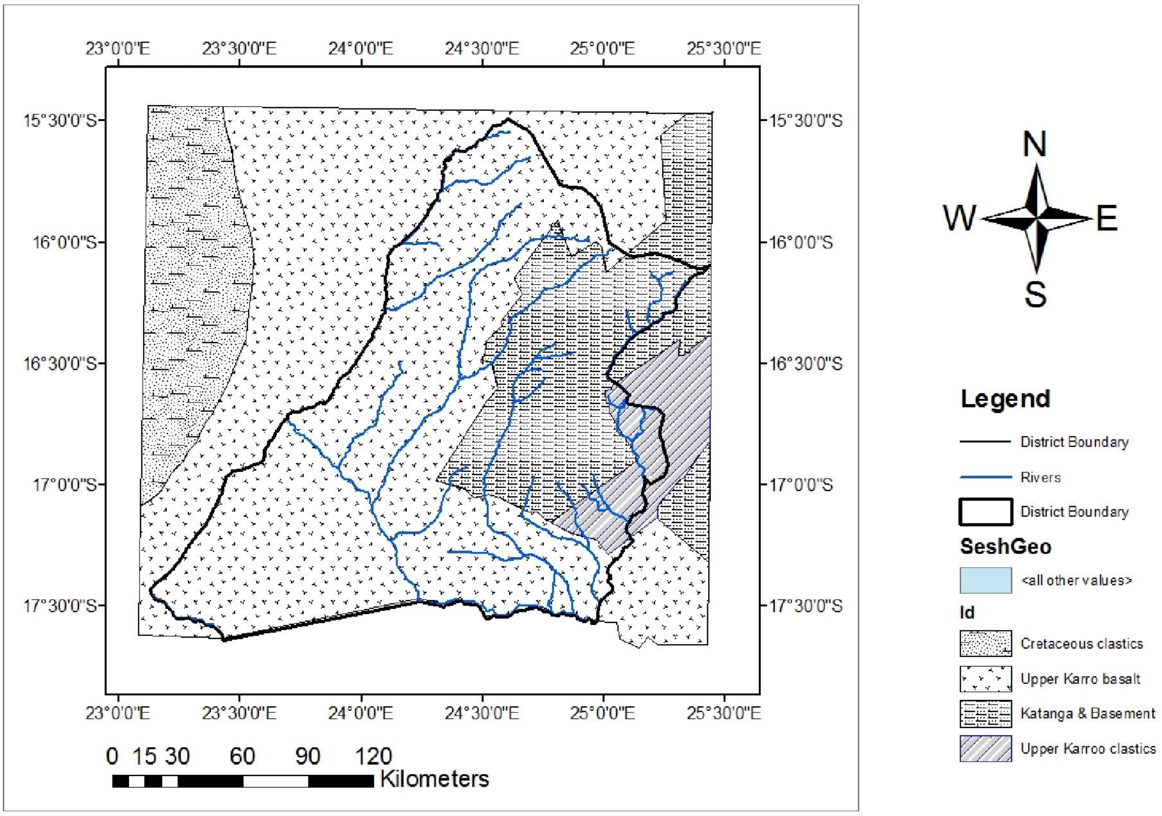


Figure 3: Geological Map of Sesheke District after Money 1972

MATERIALS AND METHODS

The study was carried out to assess the groundwater resources of the Sesheke District. The methodology used in this study was an integrated approach using Remote Sensing, Geographical information, and modelling integrating them with the traditional Hydrogeological analysis like pump testing and base flow analysis. The methods used are base flow analysis, water balance using remote sensing and GIS, pump testing analysis and lastly the output above was used in developing a numerical groundwater model.

Recharge Estimation using the Seasonal recession method (MEYBOOM METHOD)

According to Meyboom (1964), estimates of groundwater recharge can be calculated from stream flow analysis. Analysis of the stream flow hydrograph, specifically separating base flow from quick flow is one of the ways of estimating groundwater recharge. The method uses stream hydrograph data over two or more consecutive years (Meyboom, 1961) and the base flow is assumed to be entirely groundwater discharged from the unconfined aquifer. An annual recession is interpreted as the long-term decline during the dry season following the phase of rising stream flow during the wet season. The total potential groundwater discharge (V_{tp}) to the stream during this complete recession phase is derived as:

$$V_{tp} = \frac{Q_o t_1}{2.3026} \qquad (1)$$

Where V_{tp} (L^3) is the total potential groundwater discharge, Q_o (L^3T^{-1}) is the base flow at the start of the recession, and t is recession index (T), the time that it takes for the baseflow to drop from Q_o to $0.1\,Q_o$. The underlying assumptions of this method are that the Catchment area has no dams or other method of stream flow regulation and that snowmelt contribution to runoff is negligible for regions with snow fall. The amount of potential base flow, V_t remaining at some time, *t,* after the initiation of a base flow may be estimated by:

$$V_t = \frac{V_{tp}}{10^{\left(t/t_1\right)}} \qquad (2)$$

The difference between the remaining potential groundwater discharge at the end of a given base flow recession and the total potential groundwater discharge at the beginning of the next recession represents the recharge that has taken place between these two recessions. The Meyboom method is an idealized analysis assuming that all groundwater discharge is by means of base flow to streams. In reality however, there are consumptive uses of groundwater in the basin i.e. evapotranspiration and abstraction for irrigation or other uses and these uses need to be accounted for during the analysis.

Groundwater Balance estimation using remote Sensing and Geographical Information System

Estimation of Actual Evapotranspiration

Evapotranspiration is one of the largest fluxes in the groundwater balance and therefore accurate estimation is very vital. The average annual actual evapotranspiration was estimated from the MODIS images (Parodi 2009) using Surface energy Balance (SEBS) algorithms in ILWIS (Su, 2000). A total of 24 MODIS images from 2000 to 2008 were analysed for the determination of bio geophysical parameter. It should be noted here that in some years it was difficult to get a cloud free image for analysis.

Precipitation

The spatial distribution of precipitation was estimated from cloud temperature and height derived from various satellites. An example of the application of such algorithms is the estimation of precipitation by Tropical Rainfall Measuring Mission (TRMM). TRMM-based precipitation estimates is available to the research community via anonymous ftp. The estimates are provided on a global 0.25 ° x 0.25 ° grid over the latitude band 50 ° N-S within about seven hours of observation time. Three products are provided: A TRMM-calibrated merger of all available TMI, AMSR-E, SSM/I, and AMSU-B precipitation estimates (three-hourly accumulations); a geosynchronous infrared estimate which is calibrated by the merged-microwave data (hourly estimates); and a combination of the first two fields (three-hourly accumulations). The data is available under ftp://trmmopen.gsfc.nasa.gov/pub/merged. In this study, the precipitation data from the TRMM stations 3B42 between 1998 and 2008 was used and this was compared with the data from the Sesheke the only meteological ground station that records rainfall in the area

Runoff

Runoff was read from Famine Early Warning Systems Network (FEWS NET),which utilizes Meteosat V satellite data, Global Telecommunication System (GTS) rain gauge reports, and microwave data from SSM/I and AMSU for the computation of runoff. Runoff Estimates for the study area was ready from NOAA/CPC (Climate Prediction Centre) website and the data for the whole of the study area are available for download from the website (http://www.cpc.noaa.gov/products/fews/data .html). A comparison with the runoff calculated with some empirical formula was carried out.

Recharge

The recharge was estimated using a water balance method. According Haijing et. al (2007) for a long term analysis over a period of one year the system was assumed as a steady state and recharge was calculated as follows;

$$\mathbf{R = P - ET - Q} \quad (3)$$

Where

R = recharge rate (mm)
P = precipitation rate (mm)
ET = actual evapotranspiration rate (mm)
Q = surface runoff (mm/yr)

An assumption of no recharge in the cool dry and hot dry season in semi-arid region is considered. For values of evapotranspiration larger than precipitation, they were taken as discharge areas.

Aquifer characterization using pump testing analysis

Pumping test is a critical task where very important information and data are collected regarding the overall aquifer hydraulic properties of the study area. Pump testing analysis was carried out to determine aquifer hydraulic properties like hydraulic conductivity, transmisivity which also helped in the understanding of the general groundwater flow. Due to the absence of an observation borehole during the pump testing exercise, the single well analysis was done using the Cooper-Jacob method (Kruseman et al., 1994). The pump testing data used in the analysis was collected during the JICA (2003) and DANIDA (2010/2011) rural water supply supported drilling programme.

Groundwater level survey,

The groundwater table survey measurements were conducted with the static carrier phase GPS to try to ascertain the general groundwater flow and the hydraulic gradient in the study area. Based on Darcy's Law hydrometric analysis the investigation of the hydraulic gradient between aquifer and surface water feature and the hydraulic conductivity of the intervening aquifer material were analysed.

Groundwater Flow Modeling,

The groundwater flow in the unconsolidated Kalahari Sand deposits of Sesheke was simulated using the U.S Geological Survey (USGS) modular three-dimensional finite difference groundwater flow model, MODFLOW CODE 2005 (McDonald & Harbaugh, 2005). The numerical modelling was performed using the interface of PMWIN Processing MODFLOW for Windows version 8.0 (Chiang and Kinlezbach 2001) as a code for environments for data input and output management. The system in Sesheke was conceptualized as a three layer unconfined aquifer incorporating unconsolidated Aeolian Sand underlain by highly weathered sandstone and the fractured basalts based on the borehole drilling completion reports and also the geological model by Chongo 2010. The model area was developed consisting of 254 rows and 325 columns with a pixel resolution of 250m. The modelled area has an extent of 325000 Easting and 254000 Northing covering an area of 11,501 km^2. The natural features (.i.e. rivers) were used as the groundwater model boundary which include the grid cells of the Zambezi River in the South West, Njoko River in the North West direction and Machile on the eastern side, were considered as constant head cells boundaries. The top elevation was derived from the SRTM DEM of 90m resolution which was resampled to 250m resolutions. The bottom elevation was determined by subtracting the model thickness from the top elevation. From the borehole completion reports and the geological model by Chongo 2010 the aquifer geometry was estimated to have an average thickness of 300m. . The SRTM DEM was processed to define the model area, top elevation of the model area and also the initial hydraulic heads. The corrected values of SRTM topographic height along the rivers were taken as the fixed head. The primary sinks are groundwater outflow and evapotranspiration. Recharge in the model area originates from the precipitation and was conceptualized as diffuse over the whole model area which was estimated using base flow analysis and remote sensing assumed as representing the long term average annual recharge. Evapotranspiration is the water loses through the plants and also from the groundwater when the water table is near to the surface. In the analysis the evapotranspiration was incorporated in the calculation of the recharge, therefore there was no phreatic Evapotranspiration surface input in the Model (Figure 4.b). The initial values of hydraulic conductivity were estimated from the pumping test analysis. The effective porosity was estimated using laboratory method from the collected soil samples.

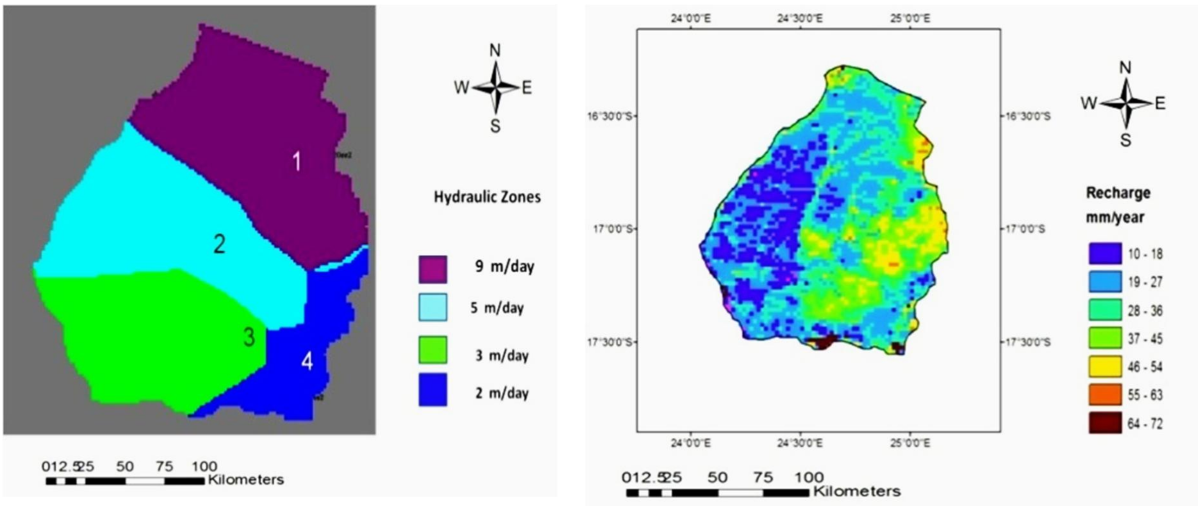
The calibration of a model was performed both manually as well as automatically. The model was calibrated using both trial and error, and automatically using the PEST programme. Assumptions made included: (1) no flow in the northern boundary between Kwemba, Njoko and Machile Rivers (2) the aquifer properties within each model cell were homogeneous and isotropic. (3) Unconfined three layer aquifer system and, (4) the impact of the abstraction wells is negligible since there are no major abstractions in the area.

RESULTS AND DISCUSSION

Recharge assessment from remote sensing

Precipitation

From the long-term mean annual values of the point measurements of Precipitation (P) from TRMM 3B42 between (1998-2008), a rainfall pattern surface was generated using the ESRI ArcGIS version 9.3 environments using ordinary kriging (Figure 5). An analysis of the average annual monthly rainfall from 1998-2008 showed that the region receives highest rainfall in the months of December, January and February (Figure 6). It is assumed that it is during these months that recharge in the area takes place. From Figure 5 the rainfall varies spatially from North-East to South-West with the north receiving average annual rainfall of 780mm and the south 682mm. The average annual rainfall was calculated as 765mm.



(A) **(B)**

Figure 4: (A) Map of Hydraulic conductivity zones (B) Derived recharge Map for the model area within the Sesheke District.

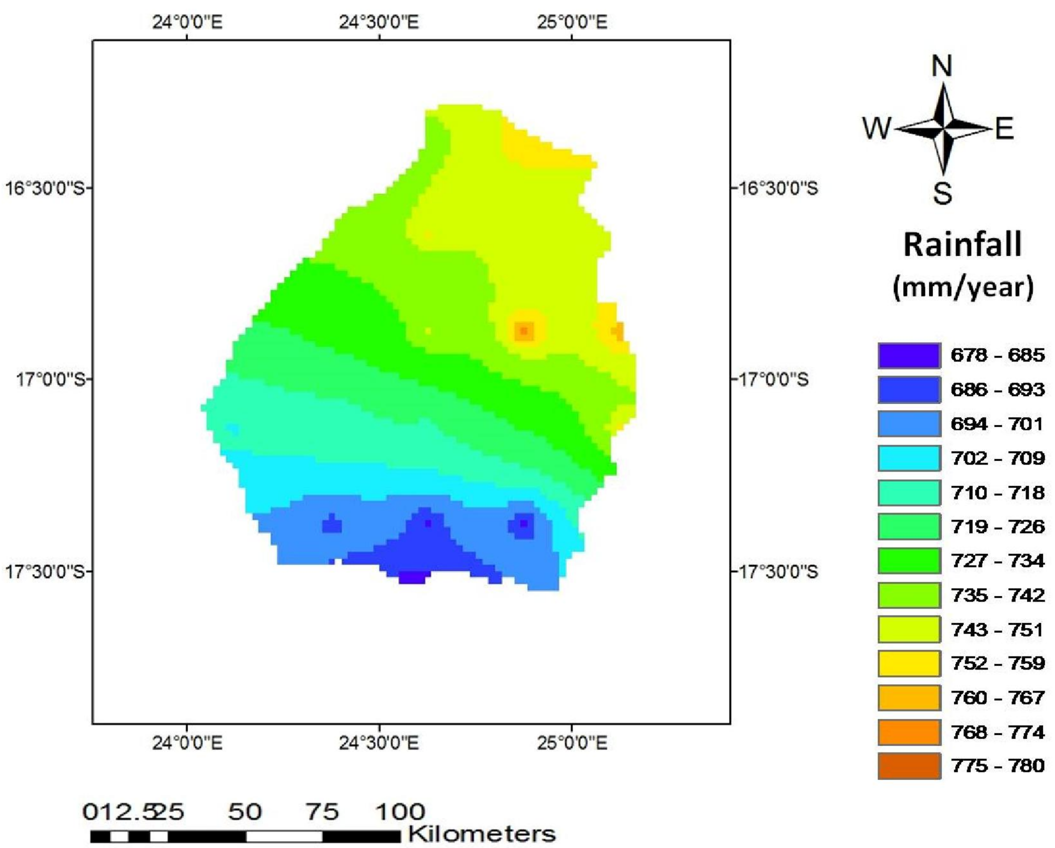


Figure 5: Average annual Rainfall Map of the Model area within Sesheke District

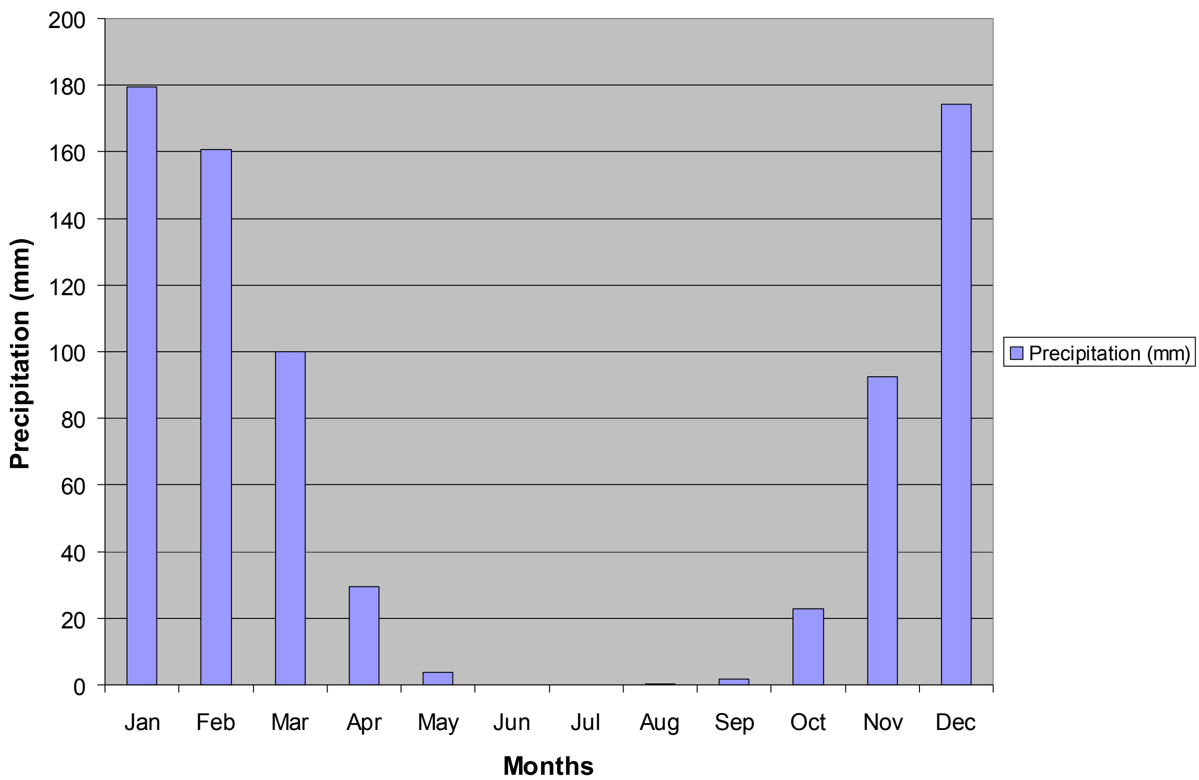
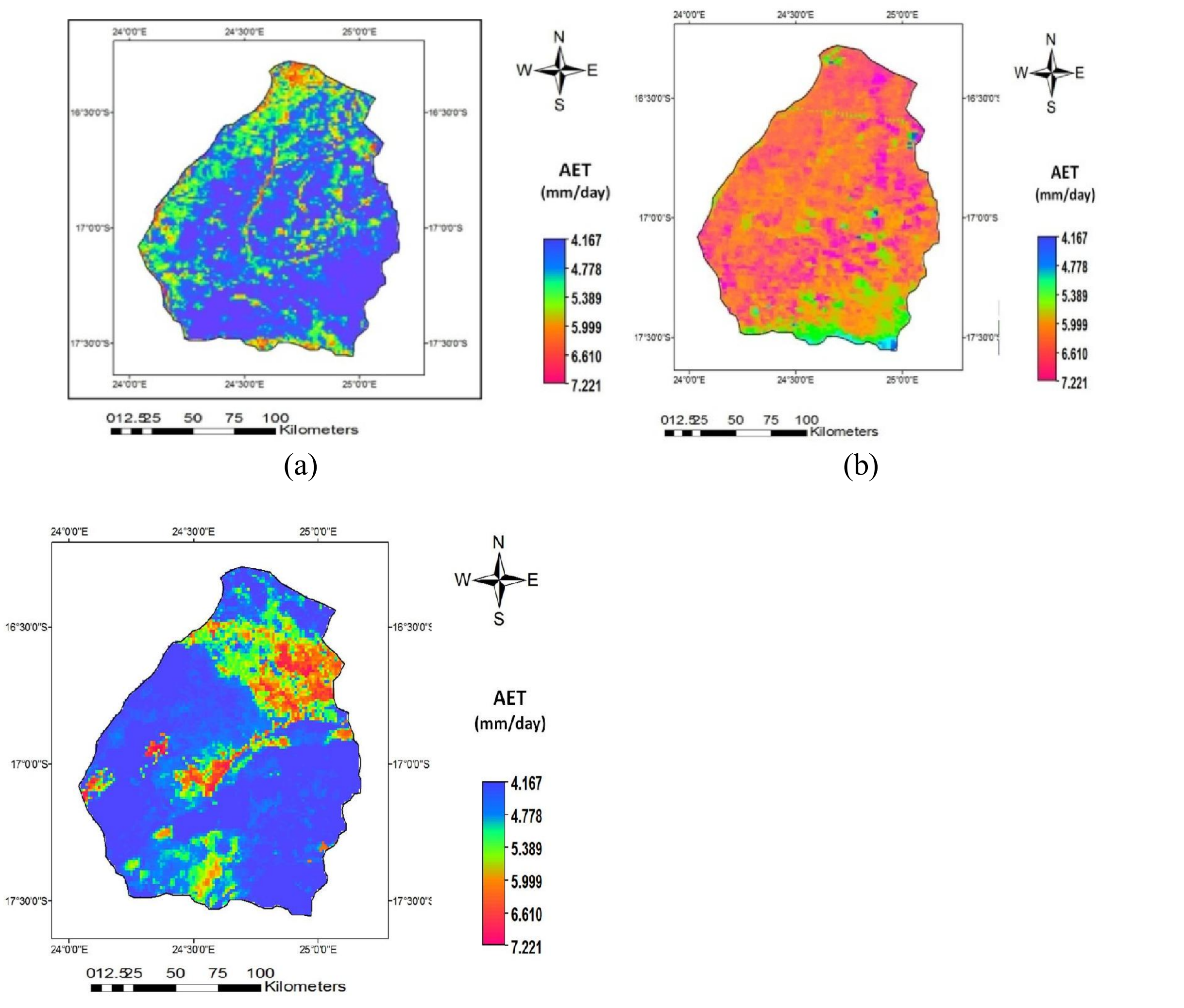


Figure 6: Average monthly rainfall in Sesheke District

Actual Evapotranspiration

The Actual Evapotranspiration (AET) for three seasons namely the hot-dry season (September to October) (Figure 7(a)), cool-dry (May to August) in (Figure 7(b)) and wet hot season (December to March) in Figure 7(c) were calculated using the SEBs algorithms in ILWIS. The results show that the estimation of Actual Evapotranspiration from cloud free MODIS images overestimates the AET, because the status quo of having a cloud free environment is not maintained throughout of each of the seasons as someday have cloudy cover and which affects the energy balances for that day. The other reason is that according to Mamo, (2010) SEBS algorithms overestimates AET in the morning and underestimate it in the afternoon due to the underestimation of land surface temperature in the morning and overestimation in the afternoon, this study used images mainly captured in the morning in the analysis. The other fact is that of not having clouds free images for all the days of the period under review. The average annual AET calculated was 1245mm which is very high compared to the annual rainfall received in the area.



(a) (b)

(c)

Figure 7: Actual ET map for the hot-dry season (September to October), b). Cool-dry season (May to August,) c) hot-wet season (November to March)

Runoff

The average runoff value of 30mm/month during the wet season was used in the calculations, though the value seems to be on a high side as the Kalahari sands are highly permeable.

Recharge

The recharge map (Figure 8) was calculated by subtracting the annual average ET map (Figure 7 and the annual average runoff map from the precipitation map (Eqn .(3)). From the recharge map Figure 8, recharge is more in the central and eastern side of the study area and less in the western part. Recharge ranges from 10-72mm with the following spatial variation: 32-45mm in east and central part and only 18-27mm in the western part. A comparison of the monthly average annual precipitation and evapotranspiration shows that the evapotranspiration is higher than the precipitation and only during the wet season does the precipitation exceed the evapotranspiration. It is during the wet season that recharge is assumed to take place and therefore, the wet season was the one used for the analysis of recharge. Average recharge was calculated to be 54.5mm representing about 7.2% of the annual precipitation

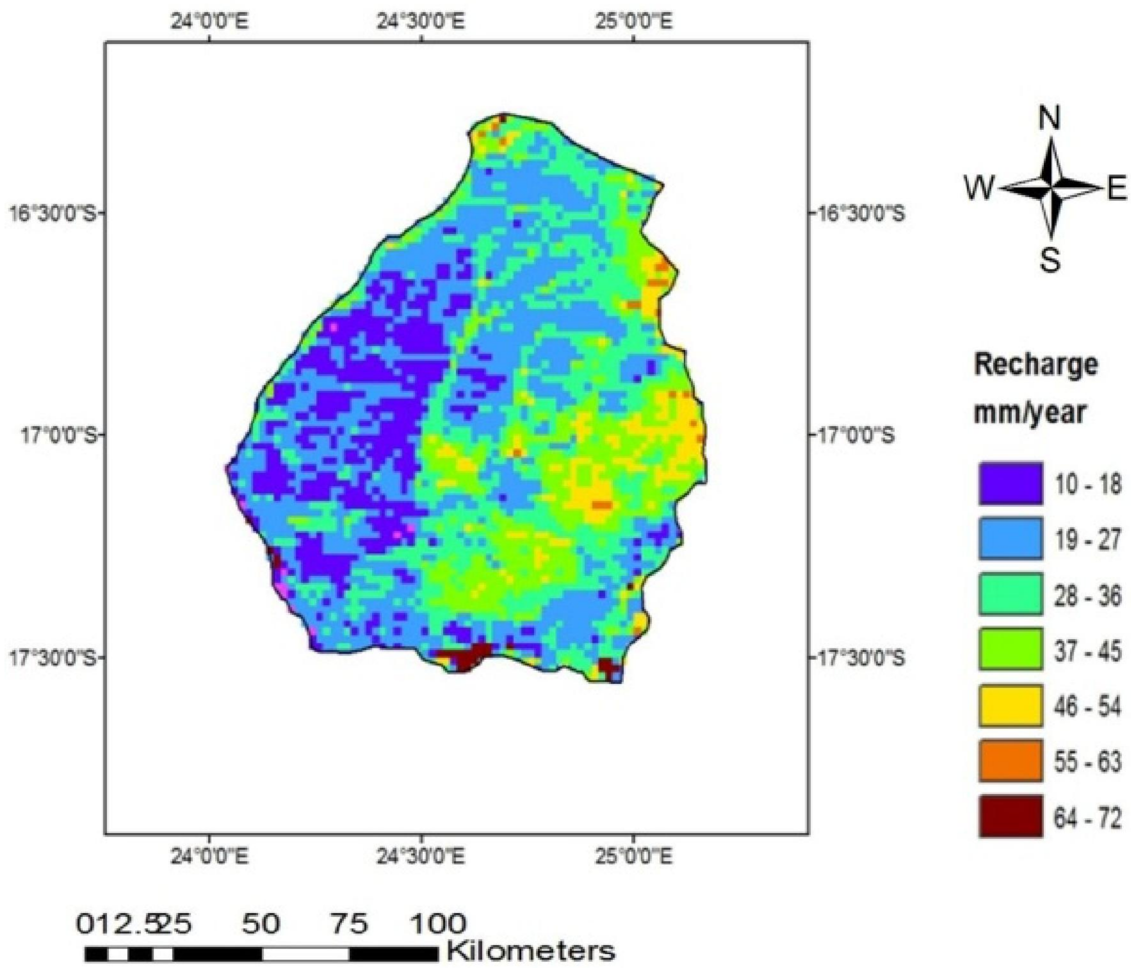


Figure: 8: Average annual Recharge Map of the Model area within Sesheke District

Hydrogeological Evaluation

From a total number of over 200 boreholes in the study area only 26 wells (Figure 9) have had relatively complete pumping testing data and these were the ones used in the analysis of the aquifer characterisation. The single well analysis of the constant discharge test was done using the Cooper Jacob straight line method(Fetter, 2001). Generally all the analytical methods assumed the aquifer is homogenous and isotropic, the groundwater flow is horizontal and the Darcy Law is valid, discharge at constant rate, fully penetrating well of very small diameter and the geological formations are horizontal and have infinite horizontal extent(Kruseman and Ridder, 1994). The main aquifer in the study area is the unconfined highly weathered Sandstone with fractured and weathered basalts in a few places. The three main geological layers are fine loose, sand underlain by Sandstone which in turn is underlain by Karoo Basalt. From the pumping test results apart from the two extreme values at Masses and Kamenyani the average transmisivity in the area is $3.614m^2$/day for the Sandstone and the average hydraulic conductivity is 1.64m/day. From the laboratory experiments the average porosity of the loose sand was calculated as 35% and the saturated hydraulic conductivity 12m/day.

Topographical Groundwater table Surveying

From topographical groundwater table survey analysis, groundwater flow in the basin generally complies with the topographical land surface (Figure 10) and also follows the pattern of the drainage system. The results indicate a North East to south west groundwater flow direction and on the southern it changes to South-East direction. The hydraulic gradient of the water table is approximately; 0.0014 along a North East to South West slope as the water table decreases from 1100m a.m.s.l to 930m a.m.s.l. locally the gradient is a little steeper along the North to South direction. The high hydraulic heads in the north suggest that recharge takes place mainly in the north.

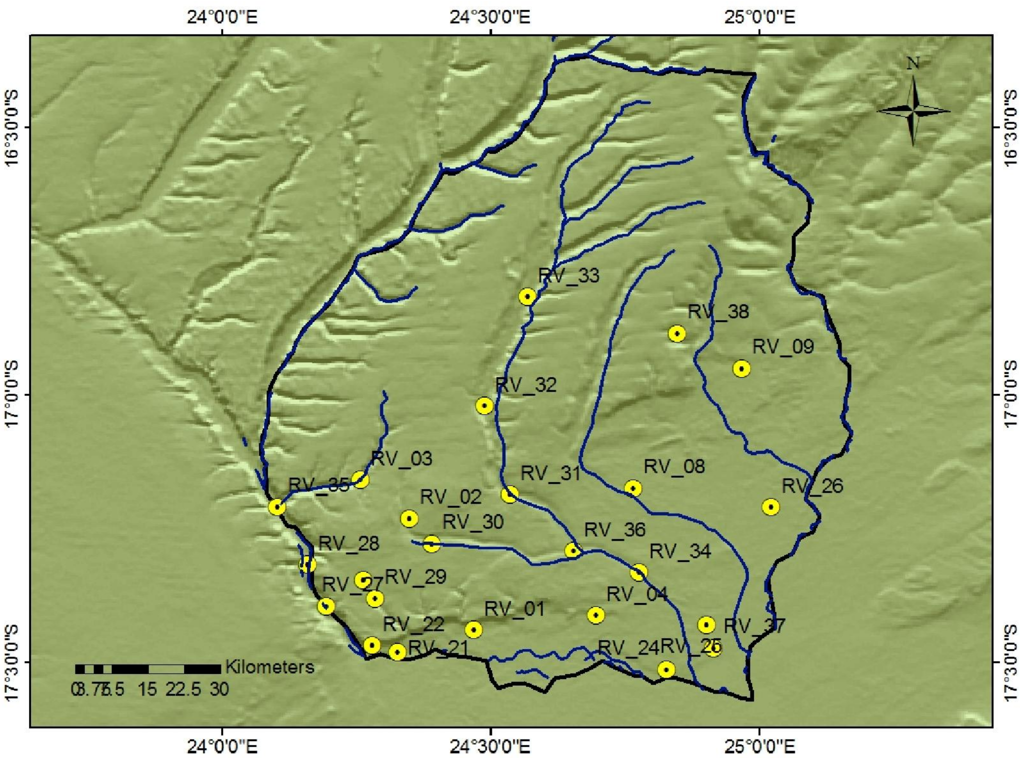


Figure 9: Location of Boreholes with analysed pumping tests

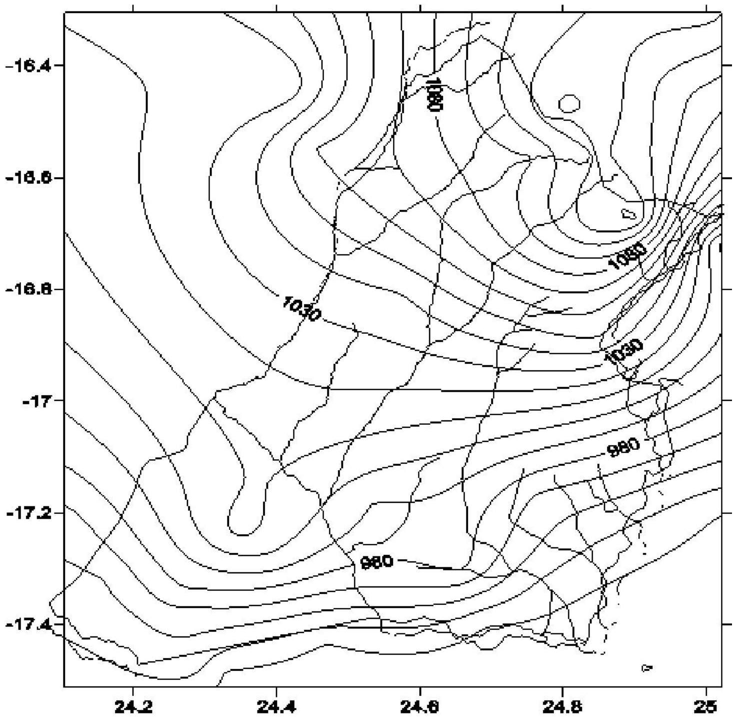


Figure 10: Map of Sesheke showing the measured hydraulic gradient indicating slightly steeper gradient in the North-west to South East direction.

Groundwater model

The groundwater was modelled in the steady state and the following is a summary of the modelling results. Looking at the regional scale of the model the Root Mean Square (RMS) is still very large at 17.05m is reasonable. The contour map of the simulated heads is shown in Figure 11.

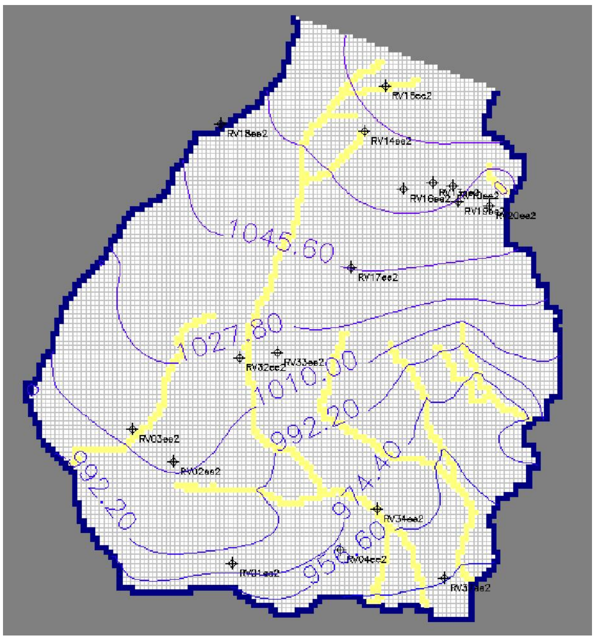


Figure 11: Contour map of the simulated hydraulic heads for the model area within Sesheke District

Groundwater Budget

The groundwater budget was calculated from the calibrated model based on the water budget tool in MODFLOW. In the summary below the inflows is the recharge and the outflow is the drains evapotranspiration was included in the recharge calculation. The estimated summary of the water budget is show in Figure 12.

Calibration results

A comparison of the measured heads and the simulated results (Figure 13 (a)) shows some similarities. The difference might be attributed to the coarse resolution of the model due the larger area that had to be modelled. A scatter plot of the simulated versus the observed head is another way of measuring the accuracy of the calibration (Figure 13 b) The scatter plots are visually examined to check whether the points show deviations, the more they are closer to the straightline the more accurate the calibration is. From the scatter plot in Figure 13(b). show a correlation of 0.78 and the of RMSE of 17m.

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 1

CUMULATIVE VOLUMES	L**3	RATES FOR THIS TIME STEP	L**3/T
IN:		IN:	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	155255392.0000	CONSTANT HEAD =	425357.2500
DRAINS =	0.0000	DRAINS =	0.0000
RECHARGE =	294383392.0000	RECHARGE =	806529.8125
TOTAL IN =	449638784.0000	TOTAL IN =	1231887.0000
OUT:		OUT:	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	186544800.0000	CONSTANT HEAD =	511081.6562
DRAINS =	263092960.0000	DRAINS =	720802.6250
RECHARGE =	0.0000	RECHARGE =	0.0000
TOTAL OUT =	449637760.0000	TOTAL OUT =	1231884.2500
IN - OUT =	1024.0000	IN - OUT =	2.7500
PERCENT DISCREPANCY =	0.00	PERCENT DISCREPANCY =	0.00

Figure 12: Volumetric water budget for the entire model domain within the Sesheke District

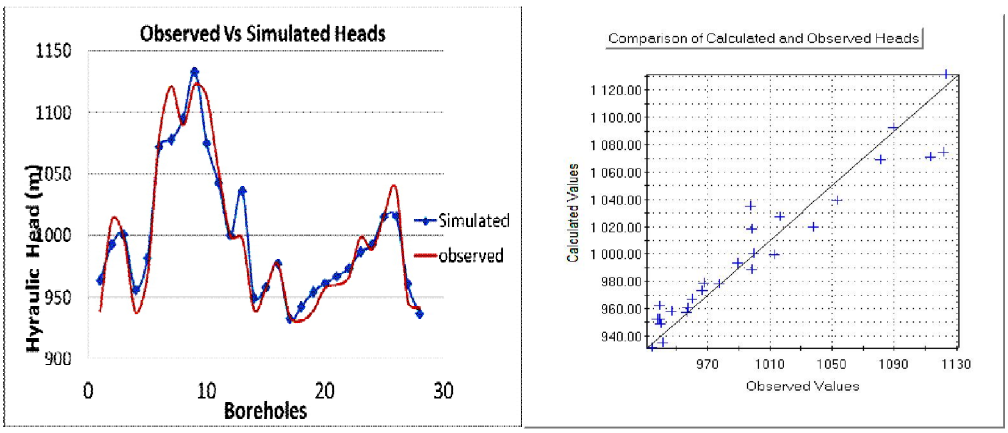


Figure 13:a) Simulated head Versus Observed Head and b) a Scatter plot of simulated head versus the observed heads of the modelled area with the Sesheke District

CONCLUSION

In conclusion the main recharge areas for the groundwater system in Sesheke District are the Kamanga, Luamuloba and Nawinda wards, and these waters are mainly discharged through the rivers and streams. The groundwater flow generally complies with the topographic trends although; the slope of the topography is slightly more North West to South East direction. The difference is attributed to the drainage pattern in the study area. The general geological faults lines trending in NE-SW and NW-SE directions in the area is the main factor controlling the flow direction of the rivers and streams in the area. The estimated annual average recharge in the area based on SEBS analysis is 35.2mm that is 5.4% of the average annual rainfall received in the area (657mm/year). The recharge mechanism is by direct infiltration of the rainwater through the blanketing unconsolidated Kalahari Sands covering the whole area. The estimated ET from SEBS algorithm is too high and this is because of the conditions under which the algorithms were designed as well as input parameters of which some were estimated as there were no station to measure atmospheric correction input parameters such as net radiation. The estimated annual recharge from the model is 54.7mm in the north and 28mm in the southern part of the model. The model results suggest that the main recharge area is in the northern part of Sesheke which agrees well with hydraulic head survey conducted during the field work where high hydraulic heads in the north where comparable to the southern part of the District.

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