Estimating groundwater recharge to the A-Unit of the Chad Formation's Upper aquifer system around Maiduguri, Borno State Nigeria using Water Table Fluctuation method

[1]Baba Musami Sheriff, [1]Ibrahim Baba Goni and [2]Jejung Lee
[1]University of Maiduguri, Borno State, Nigeria.
[2]University of Missouri, Kansas City, United State.
Corresponding email: mubasherr09@gmail.com

Abstract
Maiduguri the State capital of Borno, it is located between latitude 11°47' N and 11°49' N and longitude between 13°10' E and 13°12' E. It falls within the semi-arid region with low rainfall and non-existent perennial surface water except for the Alau Dam. Groundwater is the perennial source of water supply supplemented by treated water from the Alau Dam. Abstraction has increased considerably in Maiduguri because of population explosion, exacerbated by the insurgency. The A-Unit is a phreatic aquifer of the Upper Chad Formation aquifer system. This unit is the most exploited in Maiduguri on account of its low cost and thus the need to evaluate its renewal potentials for sustainable management. Water Table Fluctuation (WTF) model is used to estimate groundwater recharge to the A-Unit aquifer of the study area. Rainfall and groundwater level data for the study area were collected for three years from 2015 to 2017, in addition to lithologic log of the observation borehole. Groundwater recharge in the study area is via diffuse (through the unsaturated zone) and focus (laterally through the river channel) mechanisms. Total groundwater recharge obtained from the WTF method, representing both the diffuse and focus componentsis estimated at 15 – 20 mm/a with an average of 17 mm/a. This recharge rate is about 1.8% of the average annual rainfall of 965 mm for the period 2015 – 2017 in the Maiduguri station. When the 12 km^2size of the study area is considered, the amount of recharge is 204 x 10^3 m^3/a. This is in excess of the current local abstraction of about 150 x 10^3 m^3/a, with a net excess of 54 x 10^3 m^3/a. It thus appears that the shallow aquifer in the study area receives total recharge that can sustain present day abstraction levels. Although, caution need to be exercised and the system monitored continuously in view of the variability in rainfall events as a result of the present day climate change, especially in the sahel region.

Keywords: Groundwater, recharge, abstraction, water table fluctuations, Upper aquifer.

INTRODUCTION

Groundwater constitutes about 95% of the freshwater on our planet earth, making it fundamental to human life and economic development. Most of the Earth's liquid freshwater is found, not in lakes and rivers, but is stored underground in aquifers (Rao, 2016). This is therefore an essential resource that requires protection so that groundwater can continue to sustain the human race and the various ecosystems that depend on it(Rao, 2016). Groundwater is vulnerable and it is affected in ways that threaten both the quantity and the quality, and therefore, the need to understand the fundamentals that govern its sustainable utilization for proper management for the present and future generation.

In Maiduguri of Nigeria, water demand has dramatically increased over the last few decades, due to population growth. Population of Maiduguri for instance, has been estimated to be 300,000 people in 1980, which increases to about 1,112,400 in 2015(National Population Commission, 2015). However, the population has increased drastically due to migration of people caused by the insurgency. Not only has the demand for water supply increased due to population growth, but there has also been a change in the life style of the people occasioned by modernization, which exacerbate the demand for water supply. This has led to the inability of government to meet the water supply demands of the people in Maiduguri and environs. This situation has resulted in the advent and subsequent expansion of the low-cost manual drilling activities in this area from around the year 2002. To date, Maiduguri is estimated to have over 5000 manually drilled boreholes taping from the Upper aquifer. All these have put enormous pressure on the groundwater resource of especially the A-unit of the Upper aquifer system in Maiduguri, which calls for proper understanding and evaluation of its renewal potential.

The study area covers 12 Km^2 at the southwestern part of Maiduguri metropolitan council (Figure 1) within the Nigerian sector of the Chad basin. The physical features of the area are characterized by the Bama ridge, which diagonally cut across the study area from NW to SE. Adjacent to the ridge is the Ngadda river and with the exception of these, the area is generally flat. Although, it gently dips away from the Bama ridge and therefore, there is no significant surface runoff in the area, except, for sporadic and short-term flow following heavy precipitation. The loose nature of the superficial sediments also enhances vertical infiltration of the rain water.

Groundwater recharge in this region occurs through vertical infiltration of rain water and lateral inflow from rivers. Some studies estimating groundwater recharge in this region are by Edmunds *et al. (*2002) that obtained an estimated diffuse vertical recharge rate of 14-49 mm/a through the unsaturated zone for the Manga Grassland using chloride mass balance method. Goni *et al*. (2005), also obtained a rate of 20 mm/a of recharge to the phreatic aquifer of the Nigerian sector of the Chad Basin from unsaturated zone chloride profile using the spread sheet model. Goes (1999), estimates lateral groundwater recharge in the floodplain area between Hadejia and Nguru in the region at an average of 132 mm/a (ranging from 73-197 mm/a). The present study estimates groundwater recharge rate to the A-unit of Chad formation in Maiduguri using WTF method. This method is applied to the real-time groundwater data collected at the University of Maidguri station from 2015 to 2017.

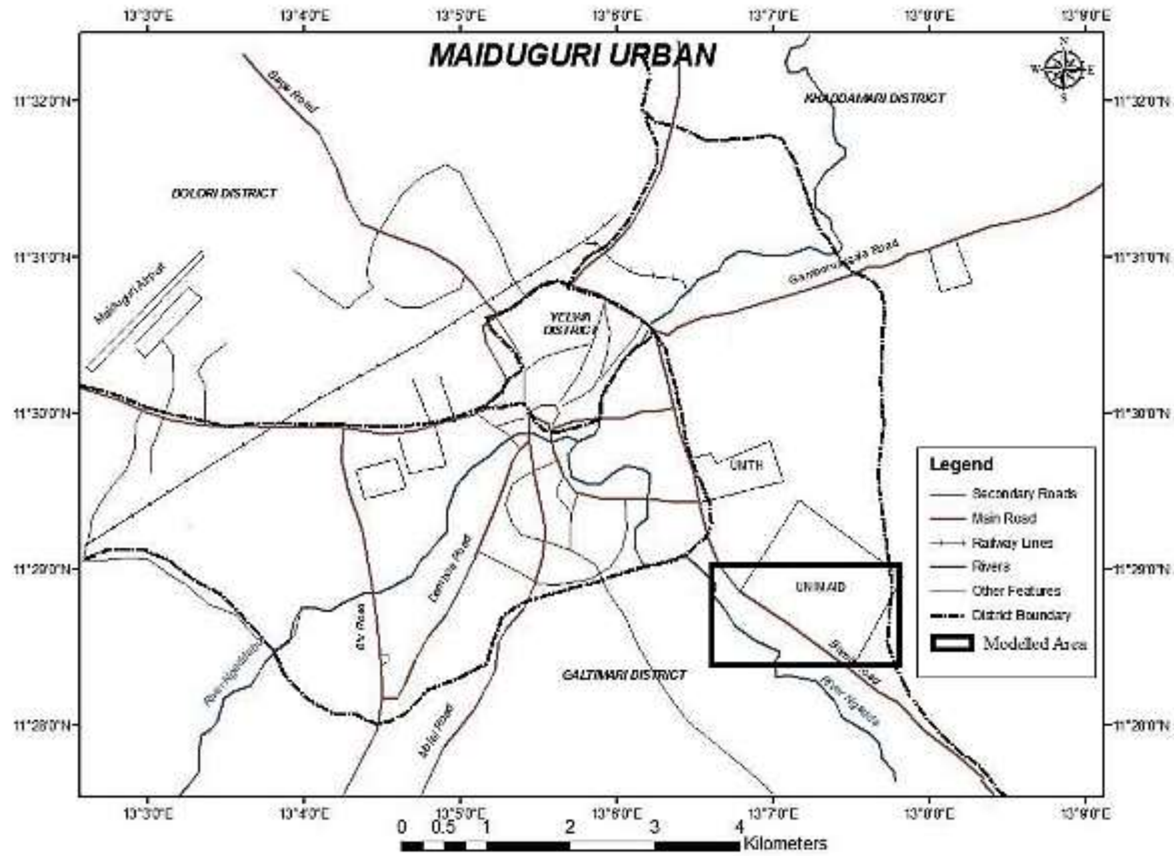

Figure1: Map of Maiduguri showing the Model area (After Mayomi and Jimme, 2014)

Site Description

Groundwater in the study area occurs in the Plio-Pleistocene Chad Formation and the overlying superficial deposits (Barber and Jones, 1960). It occurs under water table condition, in perched condition, in semi-confined and confined conditions (Barber and Jones, 1960). Three well-defined arenaceous horizons within the argillaceous Chad Formation constitute the aquifers; which are named Upper, Middle and Lower aquifers (Barber and Jones, 1960). The Upper aquifer in most of the study area is within the superficial deposits and extends across the entire outcrop of the Chad Formation. It is composed of alluvium and aeolian sands and gravel laid down on the surface.

Beacon Services Ltd. – Consulint Int. (1979) called the Upper aquifer a system, because of its three well definable units, which they termed the A, B and C units. A-unit is the water table aquifer largely within the superficial deposits; B-unit is artesian to leaky artesian while the C-unit is artesian with negligible leakage (Figure2). Occurrence of all the three units seems to be restricted to Maiduguri and its environment, perhaps because of location of Maiduguri in the ancient shoreline of mega Chad; of course, the deposits of these units have been associated with beach or deltas. The units exhibit extremely variable thickness. Most tube wells drilled recently especially those by the manual drilling are tapping the A-unit.

This unit is believed to be recharged annually from precipitation and possibly through seepage from the Ngadda river, although, rates are not known.

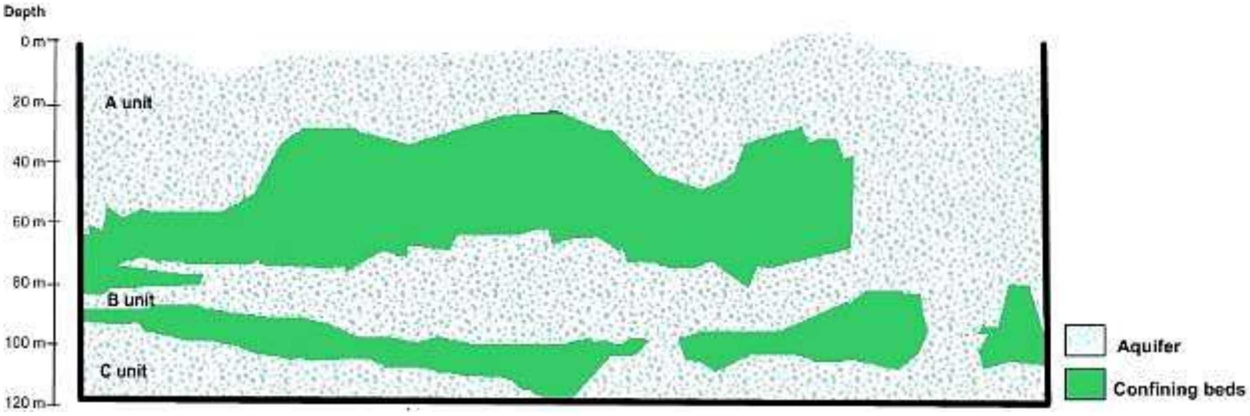

Figure2: Conceptual cross section of the Upper aquifer system (modified after Beacon Services Ltd, 1979)

The lithologic log of the observation borehole drilled in the study area is presented in Figure 3. The underlying geology at the site is characterized by beds of sands (fine to coarse), silts and clays (Figure 3). The geology of the area is strongly impacted by the Bama ridge, which is an ancient shoreline of the Mega Lake Chad. The superficial deposits are equally characterized by fine to coarse grained sands and gravels. These gravels and coarse sands define the aquiferous zones of the A-unit of the Chad Formation's Upper aquifer. The shallow groundwater resources in the study area are mostly derived from this unit and it represents the typical phreatic aquifer, mostly tapped by the populace on account of its low cost.

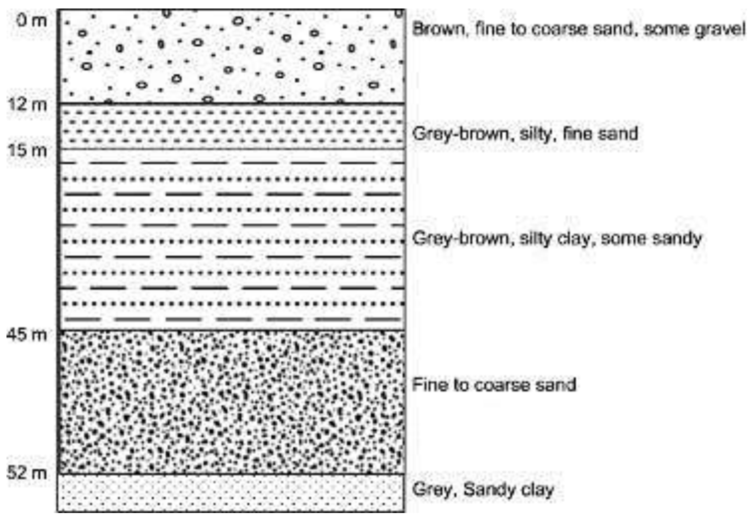

Figure 3: Log of a borehole at the University of Maiduguri Observation well (Latitude: 11.809817° and Longitude: 13.209583°).

DATA AND METHODOLOGY

Rainfall data for this study were collected from College of Agriculture meteorological station. The station records rainfall using a manual rain gauge and data are recorded on an event basis. The event records were cumulated over a month and then for the period required. In this study, data for the period of 2015 to 2017 were used.

An observation borehole (piezometer) was drilled to a depth of 54 m into the A-unit of the Chad Formation's Upper zone aquifer in the study area at the University of Maiduguri meteorological station site. Logging of the borehole was carried out during the drilling operation to obtain the lithologic succession of the site (Figure 3). Thereafter, automatic data loggers were installed to record the groundwater level data. The Hobo data logger was installed in the piezometer at the study area. This logger measures pressure in any of the units; kPa, Pa, mbar, mmHg, psi or Hg as selected and temperature in either in °C or °F.

Two pressure transducers were installed to measure air pressure and water pressure.The logger used for recording the air pressure (in kPa) and temperature (in °C) was installed at a depth of 4 m. The one that measures the pressure and temperature of groundwater was installed at a depth of 34 m. The difference in the pressure of the water and that of the air are then used to calculate the head. The static water level in this piezometer was at 31 m bgl at the time of installation. The data from these loggers were downloaded regularly to a computer using a coupler via a USB cable.

The Water Table Fluctuation (WTF) recharge calculation method

The water-table fluctuation method (WTF) assumes that change in groundwater level is controlled by the balance of recharge (R) to drainage (D). Recharge is therefore calculated based on the observed groundwater level fluctuation (Scanlon et al., 2002; Healy and Cook, 2002; Obuobie *et al.,* 2012; Jassas and Merkel 2014).

In the WTF, Equation (1) was used to derive a time series of groundwater recharge. The relationship between recharge and rainfall was then analysed using water table depth. The water table depth was then fitted to the observed recharge-rainfall relationships in the Forward model, which was also used to test the time lags between rainfall and groundwater response (Valerie-Kotconi*et al.,*2018). The choice of time-step in the model is based on the recession rate, which is used to estimate recharge rate in the Inverse model. The resulting recharge estimates will vary with the chosen time-step due to the finite-difference inherent in Equation (1). Finite difference is simply derived as approximation of the differential equation calculated in discrete order.

$$R_t = \frac{S_y\left(h_t - h_{(t-\Delta t)}\right)}{\Delta t} + D_t + S_y S_t \qquad \dots 1$$

Where R_t is the recharge rate,
D_t is the rate of net drainage,
S_t is the drawdown rate,
S_y is the specific yield (at correct scale), and
$\Delta t$is the time step.

S_y is the specific yield and Δh represents the change in groundwater level through time Δt

[T]. To solve Equation (1), S_y estimates was obtained from previous studies which is measured using pumping test data, whereas D_t is estimated based on observed recessions in groundwater levels during dry seasons that is for long periods of low or zero rainfall (Cuthbert, 2016). Recharge R_t was first calculated at a daily time step by linearly interpolating the observed change in groundwater level Δh; monthly and yearly recharge were calculated by summing daily recharge. Relationships between rainfall and recharge were assessed on monthly events which also fits into the specific yield of the study area. To assess the influence of daily rainfall on recharge, relationships between rainfall and recharge were systematically assessed by applying a threshold of cumulative rainfall of 140 mm to generate recharge. The time-lags between rainfall events and response of the groundwater recharge (ranging from 0 to 90 days) were then obtained from the model developed.

RESULTS AND DISCUSSION

The groundwater level data (m AD) at the University of Maiduguri weather station site for the period of 2015-2017 and those of rainfall data for the same period were plotted in Figure 4. This was used to obtain the observed recession rate in groundwater levels for period when no rainfall has occurred over multiple weeks.

The data from the University of Maiduguri meteorological station's observation well show that hydraulic head starts to rise as rainfall intensifies around July and reaching its peak in August. The hydraulic head tends to decline as the dry season sets in around December and reach its lowest level in June for the study period (2015 – 2017). The fluctuations in the hydraulic head of this aquifer reflects seasonal trends, although, it could also be influenced by increased abstraction as a result of population expulsion and consequent demand for potable water.

Based on this, the exponential model of recession is applied as in Equation 2.

$$D_t = \frac{H_{(t-\Delta t)}}{C} \qquad \ldots 2$$

where, D_t is the rate of net drainage,
H is the hydraulic head,
$\Delta t$is the time step,
C is constant chosen to best replicate the observed hydrograph behaviour.

These were used as input data to the Forward model of the study area. The model was adjusted continuously until a best fit is achieved, which simulates the hydraulic head of the area as shown in Figure4. Both the measured and the modelled hydraulic head distributions (Figure4) over the period of study reflect the seasonal variability of the area. The Forward model results gave the specific yield and recession rates for the study area as 0.12 and 0.50 mm/month respectively. These values (yield and recession rates) were then used in the inverse model to estimate the groundwater recharge of the study area.

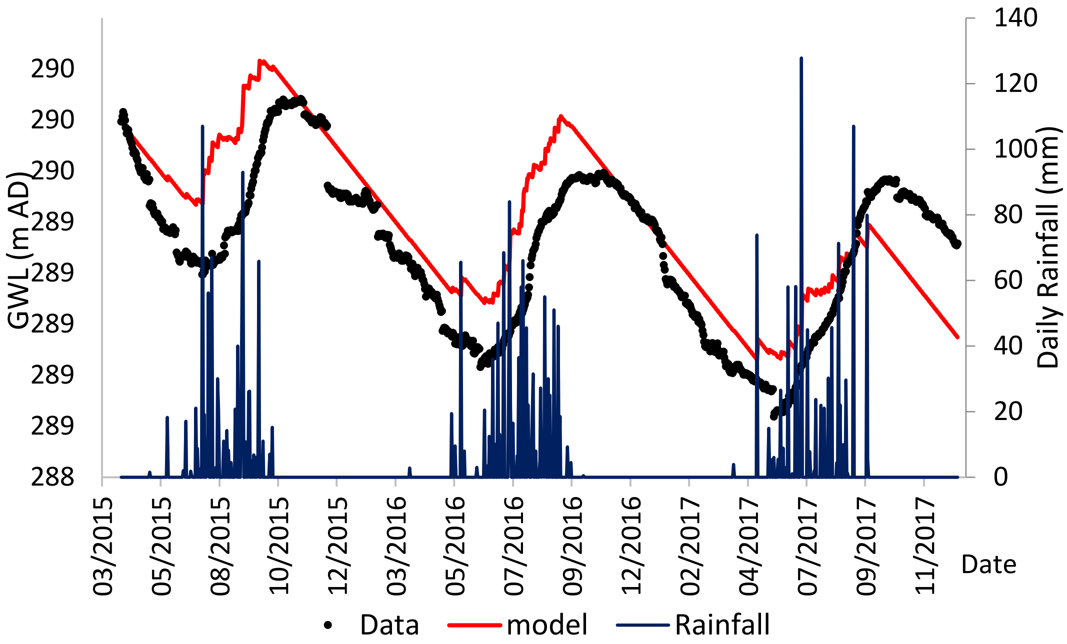

Figure4: Response of rainfall to groundwater of the study area.

The analysis of the rainfall and groundwater data from the Forward model (Figure4) was used to estimate the threshold of cumulative rainfall amount that will lead to groundwater level response. In the study area, these thresholds for the years 2015, 2016 and 2017 are 181.9 mm, 148.2 mm and 136.2 mm respectively. From the Inverse model, however, an average of 100 mm cumulative rainfall amount was obtained as the threshold for groundwater level response in the study area, which is slightly lower than the values obtained from the Forward Model. This can be explained by the fact that in the Forward model, rainfall amount for the period in which there is delay in groundwater level response is added, while the Inverse model, it tend to consider only cumulative rainfall amount that lead to the beginning of response in the groundwater level. The threshold values obtained in this study is similar to the 140 and 250 mm obtained by Valerie-Kotchoni *et al.* (2018) for the seasonally humid Benin Republic. Annual groundwater level fluctuates to a maximum of 1.1 m in the study area over the three-year period. The lag time in groundwater level response to rainfall event is estimated at 100 – 140 days in the study area.

The output from the Inverse model of the study area is shown in Figure 5, which is obtained by using the same input parameters as those used in the Forward model. In estimating the groundwater recharge, the months of July to October were used as representative of the wet season, when significant recharge occurs. The Inverse model estimates the rate of groundwater recharge as a function of rainfall and therefore, in Figure 5, the trend line shows that groundwater recharge is directly proportional to increasing rainfall event.

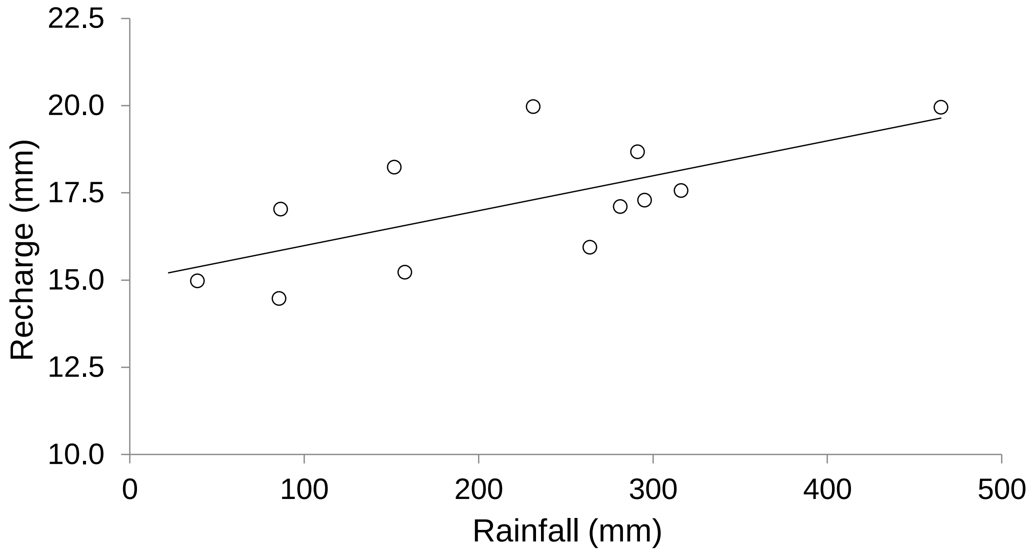

Figure 5: Relationship between recharge and rainfall over the study period.

The total recharge togroundwaterfrom the WTF method is estimated to range between 15 – 20 mm/a with an average of 17 mm/a (Figure5).There is river Ngadda to the west of the study area, which is hydrologically connected to the shallow aquifer and therefore, focus recharge is envisaged. The total average recharge of 17 mm/arepresents the diffuse and focus recharge. This rate is about 1.8% of the average annual rainfall of 965 mm for the period 2015 – 2017 in the Maiduguri station. The amount of the groundwater recharge obtained in this study is similar to the rate of 14-49 mm/a by Edmunds *et al.,* (2002) and the 20 mm/a by Goni *et.*al., (2005) for the region from Cl mass balance studies. Similarly, Goni (2002) recharge rates of 15 to 50 mm/a were derived for the Manga Grassland using the unsaturated zone chloride profiles, which represents between 4 and 12% of rainfall of the area over the past three decades. Also, in the southwest of Niger with similar semi-arid landform, present day recharge rates of between 20-50 mm a^{-1} have been reported (Favreau *et al.,* 2002).

Overall, the WTF method estimates average groundwater recharge to the shallow aquifer of the study area at 17 mm a^{-1}, which amounts to 204 x 10^3 m^3/a for the 12 km²size of the study area. This is quite in excess of the current local abstraction of 149.650 x 10^3 m^3/a (Sheriff, 2018). When compared to the total amount of recharge to the study area of 204 x 10^3 m^3/a, a net excess of 54.35 x 10^3 m^3/a is obtained (Sheriff, 2018). It thus appears that the shallow aquifer receives total recharge that can sustain present day abstraction levels of the area. However, caution must be exercised and the system monitored continuously in view of the variability in rainfall events as a result of the present-day climate change, especially in the sahel region.

CONCLUSION

The superficial and underlying geology of the study area is characterized by fine to coarse grain sands and gravels. These lithologies favour vertical diffuse recharge through the unsaturated zone. The Ngadda river at the western part of the study area, also favours lateral focus recharge to the groundwater. The WTF method tends to estimate total groundwater recharge from both mechanisms (diffuse and focus) and obtained a range of 15 – 20 mm/a with an average of 17 mm/a.This amounts to about 204 x 10^3 m^3/a for the 12 km^2size of the study area. Total groundwater abstraction rate of 149.650 x 10^3 m^3/a has been obtained for the study area, giving a net excess of 54.35 x 10^3 m^3/a recharge over abstraction. The shallow aquifer in the study area thus receives total recharge that can sustain present day abstraction levels. Although, caution need to be exercised and the system monitored continuously in view of the variability in rainfall events as a result of the present day climate change, especially in the sahel region. This is because rainfall amount is an important factor in recharge and the 17 mm/a recharge estimated for the study area is about 1.8% of the average annual rainfall of 965 mm for the period 2015 – 2017 in the Maiduguri station.

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