GROUNDWATER RECHARGE ESTIMATION AND TREND ANALYSIS USING HYDROLOGICAL AND SOIL MOISTURE BALANCE MODELS IN SEMI ARID REGION

A. R. Adesiji[1]*, O. D. Jimoh, P. A. Adeoye[2], I. O. Jimoh[1], O. A. Gbadebo[1], and M. Saidu[1]
[1]Department of Civil Engineering, Federal University of Technology, Minna
[2]Department of Agricultural and Bio-resources Engineering, Federal University of Technology, Minna
*Corresponding Author: ade.richard@futminna.edu.ng

ABSTRACT

Groundwater recharge estimation becomes very important, particularly in a cultivated land mass owing to the roles played by groundwater in the area of agricultural productivity. This paper presents the estimation and trend analysis of groundwater recharge in Kwadna basin using modified soil moisture balance model between the years 1996 and 2016. A single layer soil water balance model coupled with hydrological models was used in the recharge estimation while statistical techniques were used in groundwater recharge trend analysis. The meteorological data used in the models were obtained from Nigeria Meteorological Agency, Minna for the entire study period. Potential evapotranspiration (ETp) on daily basis was also estimated using Hargreaves evapotranspiration equation. Soil properties like moisture content at both field capacity and wilting point, near surface storage, soil moisture deficit, and crop properties like crop rooting depth and crop growth stages were obtained from the past studies and information gathered from the farmers in the study area. The results showed that annual groundwater recharge varied from 156 mm in 2004 to 731 mm in 2012 which correlated positively with rainfall. The soil moisture balance model results indicated sufficient soil moisture for crops' use during the period of June to September each year when SMD<TAW. The groundwater recharge trend analysis recorded an increasing trend with statistical significance in the two statistical tests used. Thus, the higher groundwater recharge and its increase in trend observed was attributed to higher rainfall depth recorded within the study period in the study area.

Keywords: Groundwater recharge; Soil moisture deficit; Evapotranspiration; Trend analysis

INTRODUCTION

Estimating groundwater recharge in a region with vast agricultural production where potential evapotranspiration often exceeds annual rainfall becomes very crucial owing to the rate at which the cultivated crops require water for their growth. In such a situation, the shortage of water in the root zone, in particular, has been responsible for low yield in agricultural production. This, in other words, means that to ensure increase in agricultural production in the region, replenishment of groundwater lost to evaporation and evapotranspiration through rainfall and irrigation becomes very significant. This replenishment is, therefore, termed groundwater recharge. According to Shukla and Jaber (2006), groundwater recharge occurs when a portion of the water falling on the ground surface percolates through the soil and reaches the water table. This recharge, spatially and temporally, is influenced by several factors, among which are meteorology, characteristics of soil and underlying geology, vegetal cover, depth to the groundwater level and frequency of groundwater recharge (Eni and Nicholas 2014; Adeleke et al. 2015).
Groundwater is replenished when rainfall percolates below the soil zone (Cao et al. 2016; Dash et al. 2016). And as previously reported, according to Awulachew *et al.* (2009), with adequate rainfall and minimum surface runoff, substantial percentage of rainfall known as effective rainfall would get to the root zones and become available soil moisture to the plants. Substantial part of the effective rainfall will also recharge the groundwater table thereby raising the water table depth and enhance adequate available soil moisture at the root zones (Rushton et al. 2006; de Siva and Rushton, 2007; Miguez-Macho and Fan, 2012). This is further buttressed by Eni and Nicholas (2014) which established rainfall as the most important source of groundwater in Nigeria. Dean et al., (2015) and De Silva and Rushton (2007) further submitted that groundwater recharge is highly variable as a result of erratic rainfall patterns. This, therefore, underscores the fact that for proper water management in any basin with large scale agricultural production, there is need for proper understanding of rainfall patterns and groundwater recharge rates of the region. As pointed out by De Silva and Rushton (2007), this information on rainfall patterns and groundwater recharge rates are required as inputs to regional groundwater models and predictions of climate change impacts.
With all these attributes of groundwater recharge, many methods have been developed in estimating the groundwater recharge and checking fluctuations in water table levels. The easiest of these methods is to directly measure the water table levels using monitoring wells. The effectiveness of this approach has been hampered due to huge costs involved and effort required in monitoring the groundwater behaviour over a long period of time. Due to limited data and the difficulty of the recharge process, precise estimates are often very difficult. As a result of this limited data on

groundwater recharge estimation for possible guide, there has been high degree of uncertainty among water resources engineers in the estimation of sustainable groundwater resources (de Silva and Rushton 2007). Alternative methods for groundwater recharge estimation in Nigeria have been presented by (Eni and Nicholas 2014; Fan et al., 2014; Adeleke et al. 2015; Cuthbert et al., 2016). These approaches, though, provide insights into the process leading to groundwater recharge, but estimating routine recharge on daily basis for a long period of time becomes difficult. Water table fluctuation (WTF) method has also been used for groundwater estimation with some levels of success recorded (Rushton *et al*. 2006). According to Rushton *et al*. (2006) and Fan et al., (2014), using the water table fluctuation method, the rise in water table during the recharge season is multiplied by the specific yield to obtain a groundwater recharge. Saghravani *et al* (2015) compared WTF method with Chloride Mass Balance (CMB) method for recharge estimation. They concluded that direct recharge estimation using WTF method gives a better recharge estimation due to its wider application for a large area compared to CMB method which is just for a point area application. They also concluded that groundwater recharge estimation is a function of soil properties as the coastal area with heavy presence of sandy soils yielded higher recharge.

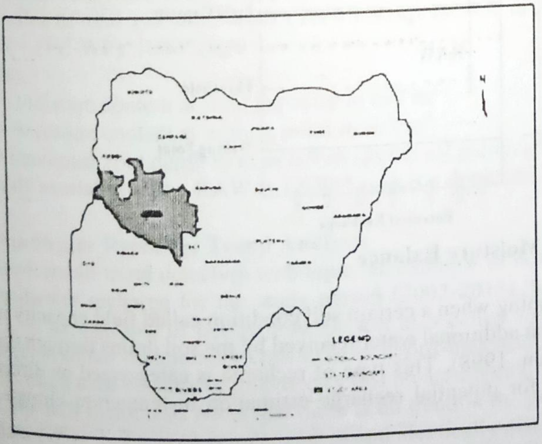
Groundwater recharge has also been correlated with rise in groundwater levels, according to Shamsudduha et al., (2009), which in other words means seasonal variation in water table levels as a result of variation in rainfall and intensive precipitation would have considerable effects on groundwater recharge (Mukherjee et al., 2007; Larsen et al., 2008; Norrman et al., 2008). This therefore calls for the need to check the trend in groundwater recharge to check the possible effects on crops and for the purpose of water resources management.

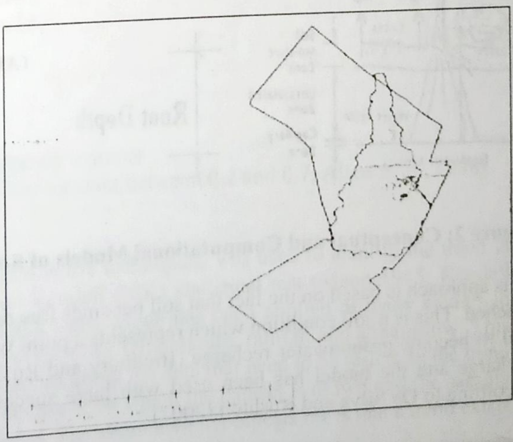
This study focused on groundwater recharge estimation in semi-arid region within a basin where the predominantly cultivated crops are peppers and corns which require adequate soil water availability for good yield. The study also appraised the trend in groundwater recharge within a period of fourteen years (2002 to 2015) using non-parametric method of trend analysis. Hydrological and soil moisture balance models which consider both the soil and crop properties were used for groundwater recharge estimation. The groundwater recharge was estimated in order to appraise the contribution of rainfall to the overall soil water need of the crops and to check the overall trend in groundwater recharge over some period of time. Consumptive use of soil water by the crops compared to the available soil moisture known as total available water (TAW) and readily available water (RAW) during the period of no recharge were also estimated on daily basis.

MATERIALS AND METHOD

Study area

The study area is Gidan Kwano Inland Valley located between Latitude 9° 5000^{I} and 9° 5625^{I} N and Longitude 6° 373^{I} and 6° 4375^{I} E (Figures 1 and 2). The valley is located at the western end of Minna, a North-Western town in Niger State, Nigeria within the permanent site of Federal University of Technology, Minna (Figure 1). The catchment area of the basin 30.79 km^2. The soil type on the study area was in a textural class of gravelly sand up to the depth of 80 - 90 cm. The area is characterized with low and erratic rainfall of between 1000 to 1200 mm as total annual rainfall with peaks in July and August.





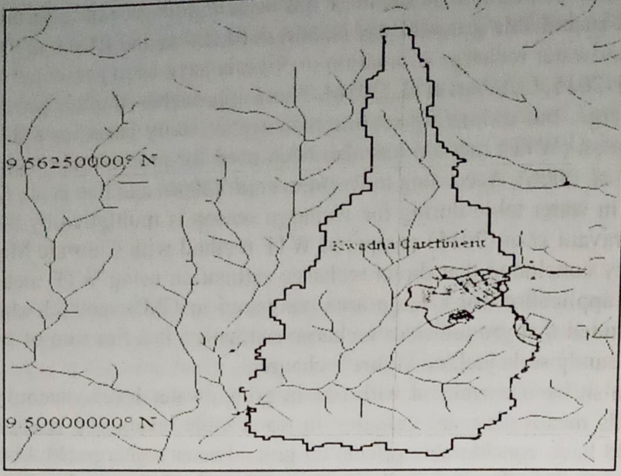


Figure 1: Location of Study Area (Kwadna basin)

The Model and its Computational Method

There are various models available for the estimation of groundwater potential recharge. There are conventional single layer model by Penman (1990), the CROPWAT model (Smith, 1992); the Balance model (Grema *et. al.* 1994), a two layer model developed to estimate daily soil water balance for cropped or un-cropped surface; and the four root layer model (FRLM) (Ragab et al., 1997). All the approaches listed above do not take into consideration routine recharge estimation. In order to achieve a routine recharge estimation and catchment-wide recharge estimates, a single layer modified soil water balance model with physical processes like rainfall, surface runoff, evapotranspiration, crop transpiration, root growth, soil water distribution following rain event and potential recharge is developed by Rushton (2003) and modified by De Silva and Rushton (2007). The conceptual and computational models of this approach are as shown in Figure 2.

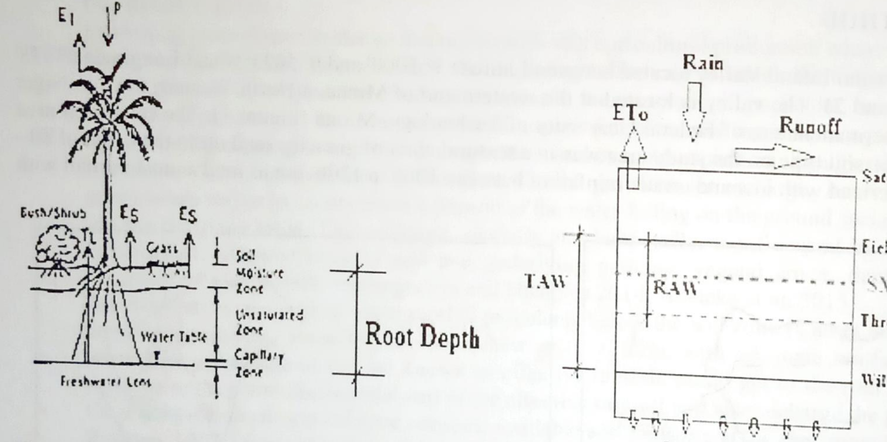


Figure 2: Conceptual and Computational Models of Soil Moisture Balance

This approach is based on the fact that soil becomes free draining when a certain soil condition called field capacity is reached. This is a soil condition which represents a point when additional water received by the soil drains through the soil to become groundwater recharge (Bradbury and Rushton, 1998). This type of recharge is categorized as direct recharge and the model has been used with huge success for potential recharge estimation in temperate climate, according to De Silva and Rushton (2007).

Reference evapotranspiration ETo

With the available maximum, minimum and mean temperature data with radiation, *Ra*, the Hargreaves method of evapotranspiration estimation was used in this study. The available daily maximum, minimum and mean temperature data for the study period with the obtained daily evapotranspiration values are presented in Appendix D.3. According to Droogers and Allen (2002), Hargreaves *ETo* equation is presented in [1]

$$ETo = 0.0023(T_{mean} + 17.8)\ (T_{max} - T_{min})^{0.5}\ Ra \qquad [1]$$

Where *ETo* represents the daily reference evapotranspiration (mm/day),

T_{max} and T_{min} = Maximum and minimum daily temperatures respectively (°C)

T_{mean} = Mean Temperature (°C)

Ra = Extraterrestrial radiation as 16.4 MJm^2/day

Soil moisture deficit

Initial soil moisture deficit ($SMD_{initial}$) which represents the soil moisture deficit at the beginning of the study was estimated as 49.8 mm using the method described in Adesiji (2012). The initial SMD was a function of moisture content at field capacity and wilting point which were estimated as 0.21 m^3/m^3 and 0.03 m^3/m^3 respectively (Adesiji, 2012).

Soil moisture deficit at the driest period (Initial SMD) is thus represented by the formula:

$$SMD_{initial} = [\theta_{fc} - \theta_{pwp}]\ Z_r \qquad [2]$$

Where;

$\theta_{fc} = 0.21\ m^3/m^3$

$\theta_{pwp} = 0.03\ m^3/m^3$

Z_r = Maximum root depth (1.2 mm for peppers).

$$SMD' = SMD_{prev} + AE - AWE + NSS \qquad [3]$$

Where;

SMD' = Present day SMD measured in mm

SMD_{prev} = Previous day SMD measured in mm

AE = Actual evapotranspiration measured in mm/day

AWE = Available water for evaporation measured in mm/day

AWE = Rainfall – Runoff + NSS, if SMD > 0

Where;

NSS = Near surface storage measured in mm

But, If SMDprev < 0, AWE = Rain – Runoff

NSS factor is the storage fraction of near surface storage represented by 0.45 by Rushton (2003).

Total available water and readily available water (TAW & RAW)

The value of total available water (TAW) is represented in eqn. [4].

$$TAW = (FC-WP)*1000*Zr, \qquad [4]$$

Where;

FC = Moisture content at field capacity in $m^3/\ m^3$

WP= Moisture content at wilting point in $m^3/\ m^3$

Zr = maximum root depth in m as 0.9 m (as the oil palms are already mature)

Readily available water, RAW = TAW * ρ (ρ is a depletion factor constant between 0.2 and 0.7, Allen et al., 1998).

Groundwater Recharge Trend Analysis

Mann-Kendall trend detection technique, an example of non-parametric techniques, was used to identify the trend in groundwater recharge for the study period (2002-2015). Mann-Kendall (MK) statistical test (Mann 1945; Kendall 1975) is an example of non-parametric test also called Kendall's *t*-test which has been applied in many studies to identify whether monotonic trends exist in hydro-meteorological data like temperature, rainfall and streamflow. This test is often used because of its property that no assumption is needed about the data that need to be tested. In the trend test, the null hypothesis *Ho* is that there is no trend in the population from which the dataset is drawn and the sample of data $\{xj, j = 1, 2, \ldots, n\}$ is independent and identically distributed. The alternative hypothesis *H*1 is that a trend exists in the dataset. The test statistic, Kendall's *S*, is defined as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j-k+1}^{n} Sign(x_j - x_k) \qquad [5]$$

where x_j and x_k are the sequential data values,
n is the length of the dataset, and

$$Sign(x) = \begin{cases} 1 & if \quad x > 0 \\ 0 & if \quad x = o \\ -1 & if \quad x < 0 \end{cases} \qquad [6]$$

Under the null hypothesis, the statistic S is approximately normally distributed when $n \geq 8$ with zero mean and the variance is given as follows:

$$Var\ (S) = \frac{n(n-1)(2n+5) - \sum_{t}^{n} t(t-1)(2t+5)}{18} \qquad [7]$$

where t is the extent of any given tie and denotes the summation over all ties. The standardized test statistic Z is computed by

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}} & for \quad S > 0 \\ 0 & for \quad S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}} & for \quad S < 0 \end{cases} \qquad [8]$$

The equation follows a standard normal distribution. For a two sided test for trends analysis, *Ho* should be accepted if $|Z| \leq 1.645$ at the 0.10 level of significance. A positive Z value indicates an upward trend, whereas a negative one indicates a downward trend. In other words, the hypothesis that there is no trend is rejected when the Z value computed in eqn. [8] is greater in absolute value than the critical value $Z\alpha$, at a chosen level of significance α, say 0.01 or 0.05. For the ease of using Mann-Kendall statistical test, TREND VI.0.2 was used in this study for groundwater recharge trend detection. The data set for the recharge is from 2002 to 2015.

RESULTS AND DISCUSSION

Recharge estimation

Figures 2 - 7 show the relationships between the soil moisture balance components for some selected years. Prominent among the components are rainfall, runoff, available water (TAW and RAW), soil moisture deficit, SMD and the groundwater recharge. In the presented cases annual groundwater recharge estimates ranged from 156 mm (13.9 % of annual rainfall) in 2004 to 731 mm (47.4 % of annual rainfall) in 2012. This expectedly correlated with annual rainfall pattern which recorded the highest rainfall depth in 2012 as 1543 mm. Surface runoff of 129 mm was recorded in 2014 while 169 mm was recorded in 2012. The groundwater recharge was recorded between the months of May and August in all the years. Table 1 shows the rainfall pattern, runoff, reference evapotranspiration, groundwater recharge and specific days the recharge was first recorded in the years under study.

Table 1: Annual values of measured hydrological parameters

Year	Annual Rainfall (mm)	Runoff mm	ETo mm	First Recharge Date	Recharge Mm
2002	1159	109	1696	June 19	455
2003	1048	106	2095	June 1	158
2004	1120	129	2117	June 1	156
2005	1088	151	2095	July 19	362
2006	1423	162	2048	May 21	389
2007	1382	145	2059	July 19	363
2008	1251	142	2066	May 26	334
2009	1297	197	2107	Aug. 17	296
2010	1223	123	2107	July 29	182
2011	1056	169	2189	Aug. 4	427

2012	1543	189	2095	May 30	731
2013	1140	169	2095	Aug. 4	427
2014	1232	139	2095	May 1	433
2015	1076	169	2095	Aug. 4	427

Soil moisture availability for Crop water use

From Figures 2 -7, total available water (TAW) and readily available water (RAW) are clearly defined and these two parameters, with soil moisture deficit (SMD), determined the availability of soil moisture for crop use. From a careful examination of Figures 2 - 7, it is apparent that between late June and Mid-September TAW and RAW reached peak levels which means there will be soil moisture availability for crop use, especially at the root zone (De Silva and Rushton, 2007). In other words, when SMD<RAW, there is sufficient soil moisture available for crop use and the actual evaporation (AE) occurs at the potential rate i.e. AE becomes the potential evaporation (PE). This is consistent with Bradbury and Rushton (1998). Consequently, the crop is likely to survive with this moisture availability with rainfall pattern kept constant. Excessive crop water use, which is also referred to as evapotranspiration (ETo), would lower both TAW, RAW, groundwater recharge and by extension, the surface runoff. This would mean there would be rise in SMD, which, if continued, would amount to excessive water stress within the root zone.

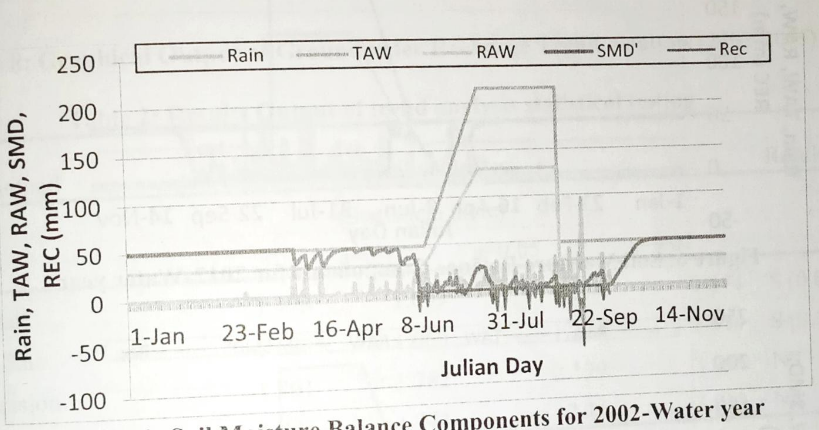


Figure 3: Soil Moisture Balance Components for 2002-Water year

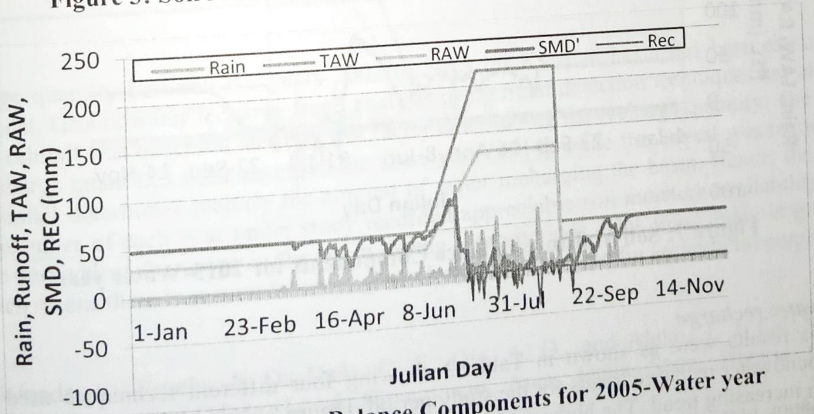


Figure 4: Soil Moisture Balance Components for 2005-Water year

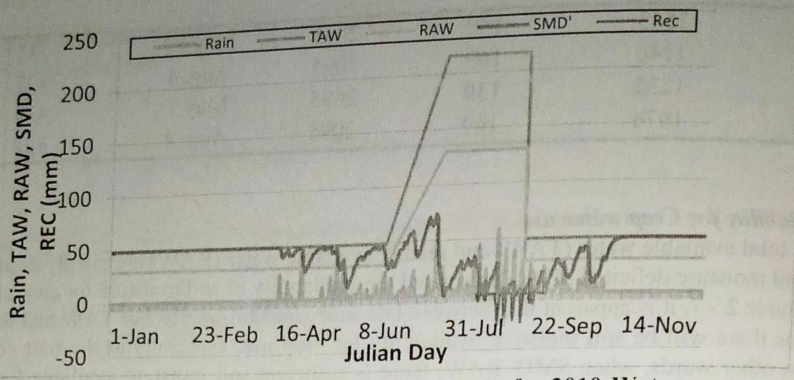


Figure 5: Soil Moisture Balance Components for 2010-Water year

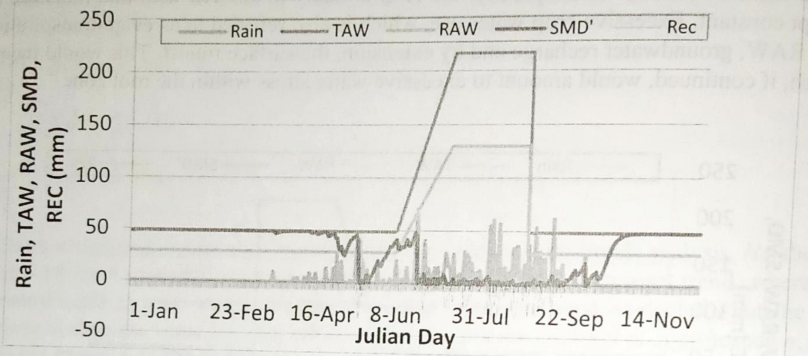


Figure 6: Soil Moisture Balance Components for 2012-Water year

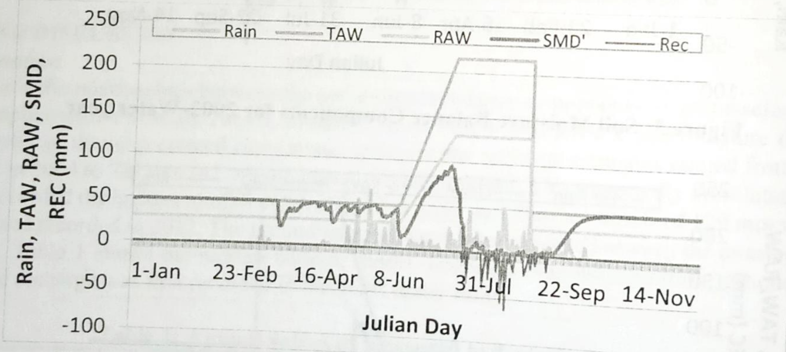


Figure 7: Soil Moisture Balance Components for 2015-Water year

Trend in groundwater recharge

The trend analysis results were as shown in Table 2 showing four different techniques used in checking any significance in groundwater recharge trends for the study period. Figure 8 showed the graphical representation of the trend analysis with increasing trend. The highest recharge (731 mm) was recorded in the year 2012 with the lowest in 2004 as 156 mm. From Table 2, critical values are compared with test statistics to check the statistical significance of the trend. From the four techniques used in the analysis, Mann-Kendall method and Spearman's Rho showed that there is statistical significance in groundwater recharge trend at significance levels of 0.05 and 0.01 respectively. The other statistical tests used: Linear Regression and Student's t-tests showed no statistical significance in groundwater recharge trend.

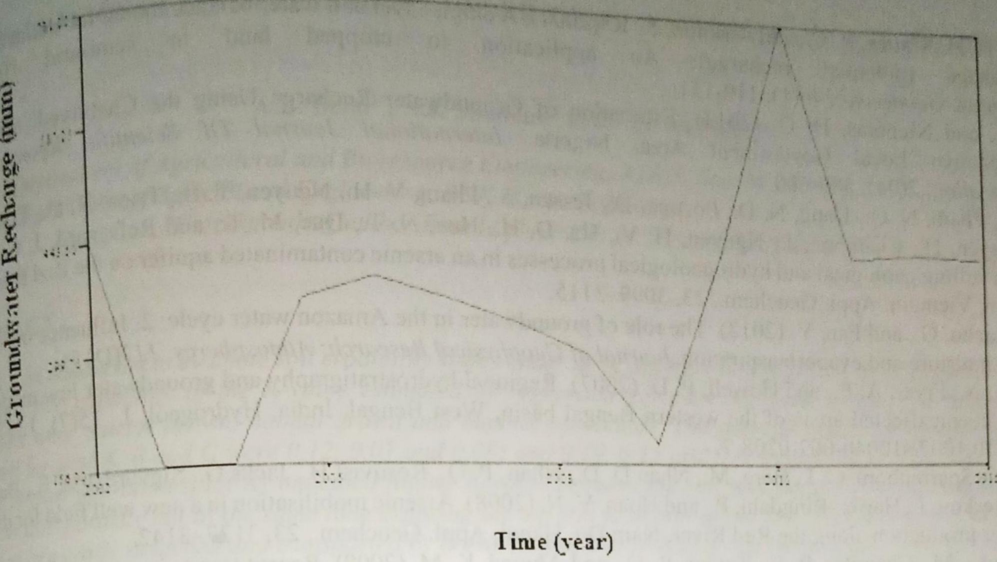


Figure 8: Graphical Output of Groundwater Recharge Trend Analysis (2002-2015)

Table 2: Results Output of trend analysis statistical testing

Statistical Method	Test statistic	Critical values (Statistical table) a=0.1	a=0.05	a=0.01	Result
Mann-Kendall	1.478	1.069	1.274	1.674	S (0.05)
Spearman's Rho	1.688	1.069	1.274	1.674	S (0.01)
Linear regression	1.761	1.782	2.179	3.055	NS
Student's t	-1.275	1.771	2.16	3.012	NS

CONCLUSION

Groundwater recharge quantity between the years 2002 to 2015 for Kwadna basin has been estimated using soil moisture balance model. Groundwater recharge trend analysis using trend detection techniques has also been carried out. From the study, rainfall was observed as the major factor determining the recharge quantity. The highest rainfall and groundwater recharge quantities were recorded the same year (2014) while the lowest was recorded in the year 2004. This shows rainfall determines majorly the amount of water recharging the basin. Hence, the farming period between May to September of each year under study recorded appreciable soil moisture availability (SMD<RAW) which explained the survival of the crops in the basin during these periods. This trend analysis generally gave an increasing trend which means there is accumulation of groundwater in the region for agricultural purposes in the basin.

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