

ESTIMATING GROUNDWATER RECHARGE IN SEMI-ARID ENVIRONMENTS USING SOIL MOISTURE BALANCE

Murtala A. Gada and Ganiyu O. Salawu

Department of Geography, Usmanu Danfodiyo University, Sokoto
Nigerian Defence Academy, Kaduna

Corresponding Author's email: gada.abubakar@udusok.edu.ng



Abstract

Groundwater recharge estimation under different climatic conditions can be achieved using daily soil moisture balance. In semi-arid areas, crucial factors such as bare soil evaporation and crops transpiration are traditionally incorporated in the model. This paper estimated groundwater recharge in the Sokoto Basin, which is a semi-arid environment using the soil moisture balance approach. Meteorological data (rainfall and temperature), crop and soil data for years were obtained from and used in calculating soil moisture balance. Actual evapotranspiration was estimated based on the readily and total available water parameters which depend on soil properties and the effective roots depth, taking into account the near surface soil storage on days following heavy rainfall. Runoff on the other hand was estimated as a function of the daily rainfall intensity and the antecedent soil moisture condition. The findings revealed that recharge occurs during the peak rainy season through the period of main crop growth. Also, actual evapotranspiration accounts for the highest water budget, followed by runoff and then recharge, with about 70%, 20% and 10% respectively. Soil moisture balance model is thus a reliable approach for potential recharge estimation in semi-arid environments.

Keywords: Soil moisture; Water balance; Recharge; Crop development; Semi-arid

Introduction

Water is not a luxury but a necessity for humans due to a number of uses people put it to such as drinking, washing, food production, energy generation, transportation etc. Yet as critical as it is, most of the people in the developed and developing world alike know little about the resourcefulness of water and in general, take it for granted.

Estimating the quantity of water moving in and out of any hydrological system is a requirement for meaningful groundwater resource management. It is particularly more important in arid and semi-arid regions where groundwater supplies are in large demand for economic development. Sustainable groundwater management in these regions therefore requires estimate of the quantity of water moving into the deeper horizons of the soil as potential recharge. To achieve this, the physical processes governing water movement must be adequately represented using available field data. Potential recharge estimates into the aquifers are done with appropriate parameters representing a variety of physical hydrological and climatic conditions.

Different methods have been proposed and used to estimate groundwater recharge (Edmunds et al., 2002; Rushton et al., 2006; Yeh et al., 2007; Izuka et al., 2010). Some of these include the soil

water balance, the groundwater level fluctuation approach and the Darcian approach (Rushton et al., 2006, Lerner et al., 1990). Choosing the appropriate method is often difficult due to large uncertainties and errors associated with the various methods available. This necessitates a careful consideration of the range, reliability and spatio-temporal scales of any method to be chosen (Scanlon et al., 2002). Generally, however, the different methods are useful because they provide insights into the recharge processes, despite the fact that, they are in most cases not suitable for the estimation of routine recharge. Soil moisture balance approach which represents the real physical processes can be used for the estimation of routine recharge especially in semi-arid areas (Eilers et al., 2007).

Materials and Method

The study area

The study area (Sokoto Basin) is located at the extreme north-western part of Nigeria between latitudes $10^{\circ} 30''$ and $13^{\circ} 50''$ N and longitudes 4° and 7° E. The basin can be divided into three physiographic regions: the basement complex of the east and southern part, the Sokoto Plains of the north and center and the riverine lowlands of the Rima valley. The basement complex forms the old pre-Cambrian rocks of igneous origin that has undergone extensive metamorphism over time; the Sokoto Plains on the other hand form monotonous lowland derived from softer sedimentary rocks usually interrupted by isolated, flat topped hills or *mesas* (e.g. the Dange and Kalambaina escarpments near Sokoto); while the riverine lowlands are the *fadama* flood plains ranging between 2-7 kilometers wide in various places along major rivers and indicates different stages of erosional processes during early wetter conditions. The general elevation ranges between 250m above sea level where the River Rima enters the River Niger to 600m above sea level at the upper reaches of the south eastern tributaries (Gada and Eniolorunda, 2024).

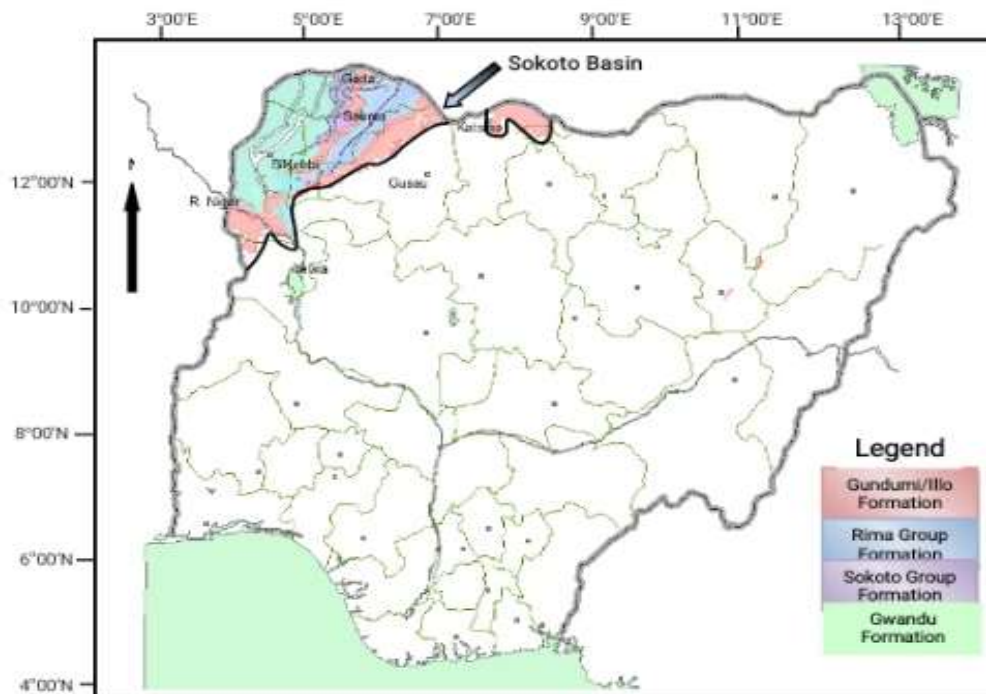


Figure 1: Map of Nigeria showing the Sokoto Basin

Geology

The Sokoto basin can be classified into two geological systems (Kogbe, 1979, Offodile, 2002); the basement complex rocks and the sedimentary rock formations overlying the basement rocks. The basement complex is a series of crystalline massif rocks outcropping to the east and south of the basin. It is pre-Cambrian in age consisting of granite gneisses, schist, phyllites and quartzites (Offodile, 2002). The basement rock is fractured and deeply weathered in many places especially to the western part of the basin. The sedimentary rock on the other hand consists of the cretaceous and tertiary formations which run from the northeast to southwest. The cretaceous deposits consist of the Gundumi/Ilo formations overlying the basement rocks. Gundumi formation is principally a lacustrine deposit of continental origin having a semi-consolidated clay material, sandy clay, fine to coarse-grained sand and some conglomerate at the base. The Ilo formation is the southern lateral equivalent of the Gundumi with unconsolidated alluvial sandstone of which three units were identified based on field study (Kogbe, 1979): (the upper grits, the pissolitic and nodular clays and the lower grits). The upper grits measured between 7-100 meters thick and consists of white friable pebbly bedded sandstones underlain by pissolitic member; the pissolitic clays measuring between 3-10 meters thick are however, fine-granular and chalky in nature and; the lower grits measuring about 130 meters thick with similar lithology as the upper grits.

The Gundumi/Ilo Formation is overlain by the Rima group deposits of marine origin consisting of Taloka, Dukamaje and Wurno formations in ascending order. Taloka formation consists of fine-grained sandstone with some films of intercalated carbonaceous mudstone; Dukamaje formation on the other hand consists of shale, mudstone and some gypsum beds; while Wurno formation is mainly semi-consolidated fine sand and silt (JICA, 1990).

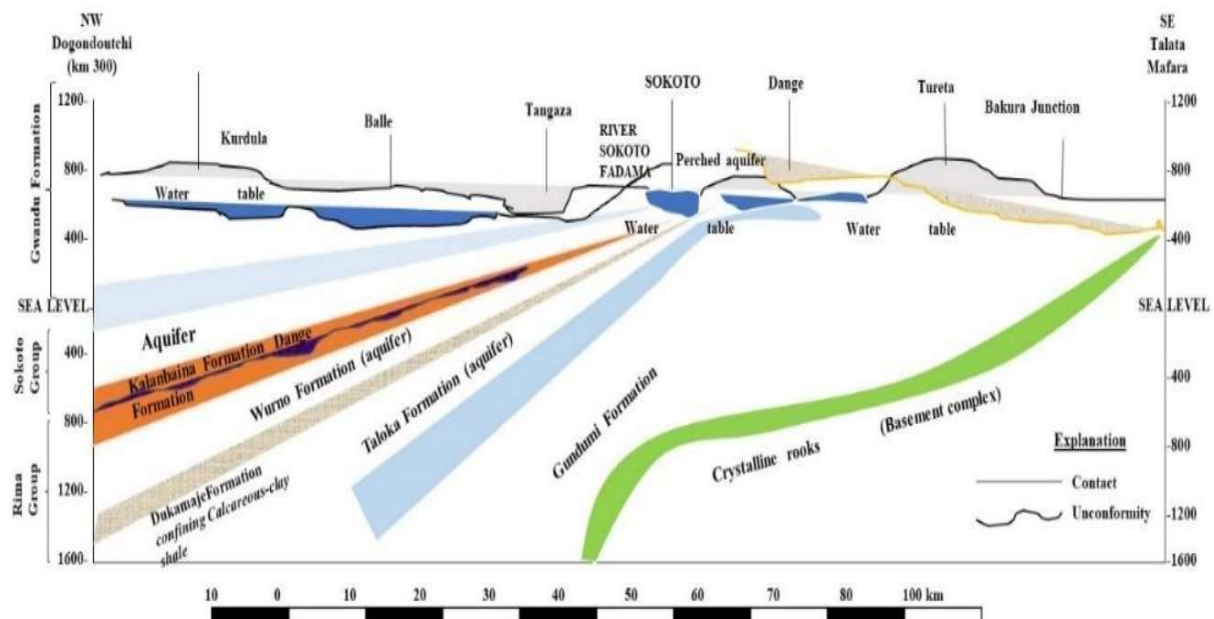


Figure 2: Geological Sequence of the Sokoto Basin
(Modified from Anderson and Ogilbee, 1973)

The Rima Group is overlain by the Sokoto group deposits that are also of marine or sub-marine origin consisting of the Dange, Kalambaina and Gamba formations in ascending order. The Dange formation is mainly of marine clayey shale, with the upper part containing phosphatic nodules and gypsum and the lower part mainly calcareous material and some limestone beds. The Kalambaina formation however consists of semi consolidated clayey limestone and marl. The Gamba formation on the other hand is very thin distinguishable layer of clay shale which is sometimes mistaken as the upper part of the Kalambaina formation.

The last deposit in the basin is the Gwandu formation overlying the Sokoto Group formations and contains sediments of mainly terrestrial origin made up of semi consolidated inter-bedded sandy-clay material with some limonite and lignite beds. Most of these deposits in the basin are covered on the surface by Quaternary sediments of Aeolian and fluvial origin along the flood plains of the major rivers.

Rainfall Distribution

Rainfall in Sokoto Basin like in most parts of the country is influenced by the movement of two contending air masses viz: dry continental air masses moving from north to south and moist maritime air masses moving from the south to the northern part of the country. The position of their convergence is called inter tropical discontinuity (ITD) and largely determines the advancement or decline of rainfall at a particular time of the year. The rainfall therefore generally decreases with increasing latitude away from the Atlantic Ocean (Philip et al., 2011); and the spatial variability was higher than the temporal variability even within the same locality (Olaniran, 2002; Philip et al., 2011).

In Sokoto basin of north western Nigeria, complete long-term data on climate parameters are usually scarce due to inadequacy of weather observation stations. Airports to some extent seems to be the only reliable source of data in the region and the records obtain from the Airports needs to be checked carefully due to frequent errors associated with recording and measurement. The daily rainfall data was obtained from the Nigeria Meteorological Agency (NIMET) for Sokoto and Gusau stations. There is high variability in the annual rainfall received at different stations in the region but the rainfall amount is generally low to moderate range. The annual rainfall in Sokoto station for the 39 years period (1971-2010) ranged from 373 to 1183 mm with a mean of 621 mm/year. For the 39 years record obtained, only five years annual rainfall totals exceeded 800mm and were considered as the wet years, while nine years with annual totals below 550mm were considered as dry years . Similarly, about 25 years which received total rainfall between 550 to 600 mm were considered as normal years. For Gusau station however, the annual rainfall totals for the same period varied significantly from 618 to 1504 mm, with the mean annuals of 878 mm. The high spatial variation shows that rainfall decreases towards the northern part of the basin frontier with Niger republic as shown by annual rainfall totals for Sokoto station (Figure 3a) and increases southward at Gusau station (Figure 3b).

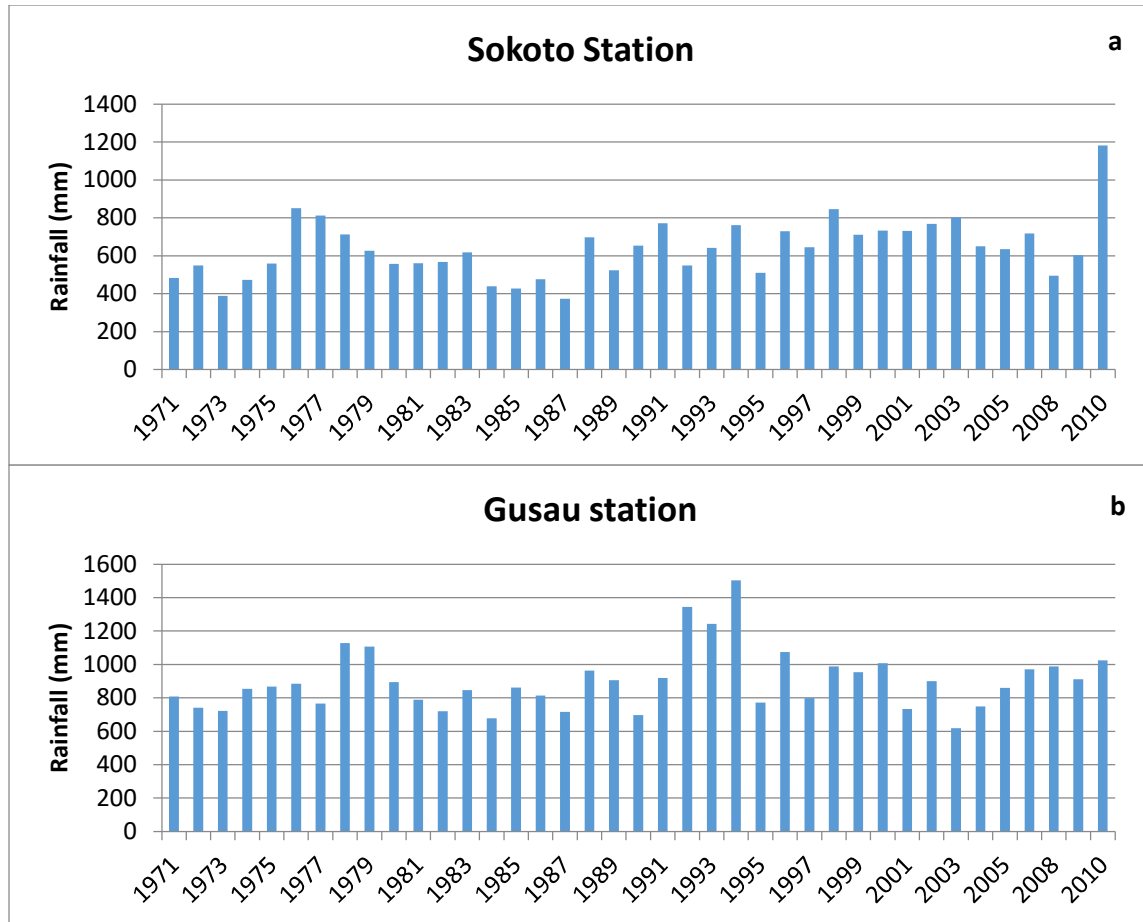


Figure 3 (a & b): Total Annual Rainfalls

Soil Moisture Balance Model

The soil water balance approach chosen for this research is based on daily moisture balance calculations of the soil with coefficients introduced to represent both runoff and reduced evapotranspiration under limited moisture condition. After rainfall (P) some of the water infiltrates (I_n), some water runs off (R_o) and some water are ponded in depressions [*To be represented in the model possibly by allowing a negative SMD*]. Some part of the infiltrated water is extracted by the roots and transpired (T) by the plants and where there are no roots the water may be drawn to the bare soil surface and evaporate (E). While some water under certain conditions passes vertically downward from the soil bottom and reaches the groundwater table as recharge ($Rech$).

Processes in the water balance

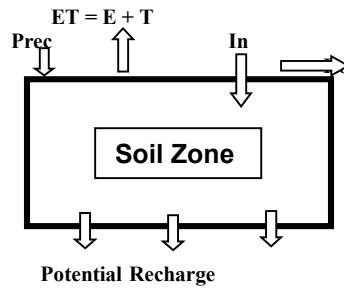


Figure 4: Recharge Processes

The soil water balance approach requires the estimation of water stress (K_s) on a daily water balance computation for the root zone. The water content of the root zone can be expressed as the water content of a representative volume of soil that fluctuates showing the depletion. The adding and subtracting of losses and gains becomes straightforward as the various parameters of the soil water budget are usually expressed in terms of water depth. Depletion is decreased when water is added to the soil zone through rainfall, irrigation and capillary rise of groundwater towards the root zone, while, soil evaporation, crop transpiration and percolation losses remove water from the root zone and increase the depletion (Figure 5) (Eilers, 2007).

The daily water balance, expressed in terms of depletion at the end of the day is:

$$SMD' = SMD'_{-1} - I_i - CR_i + ET_{c,i} + DP_i$$

$$I = P - Ro$$

Where

SMD' root zone depletion at the end of day i [mm],

SMD'_{-1} water content in the root zone at the end of the previous day, $i-1$ [mm],

P_i precipitation on day i [mm],

Ro_i runoff from the soil surface on day i [mm],

I_i net infiltration depth into the soil on day i [mm],

CR_i capillary rise from the groundwater table on day i [mm],

$ET_{c,i}$ crop evapotranspiration on day i [mm],

DP_i water loss out of the root zone by deep percolation on day i [mm].

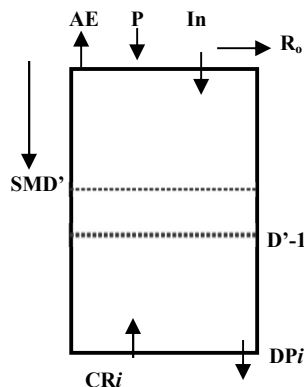


Figure 5: Soil Moisture Balance Distribution in ideal Field condition

Soil Moisture Deficit (*SMD*) is the amount of water required to bring the moisture content of the soil back to field capacity. The amount of water a soil can hold against gravity is referred to as soil field capacity. In a given volume of soil, field capacity (*fc*) is the amount of water you can put on the soil plant without it leaking out of the bottom of the soil. Too much of the water will give you a negative *SMD* (the soil bottom leaks), too little water will give you a positive *SMD* (the soil plant needs watering) while, just enough water and the *SMD* = 0 (Carter et al., 2002).

The water content in the root zone gradually decreases and the root zone depletion increases as a result of percolation and evapotranspiration until it reaches its minimum value (q_{wp}) in the absence of any rainfall event. At that point no water is available for evapotranspiration in the root zone, and the root zone depletion has reached its maximum value (Grema and Hess, 1994).

Water in the root zone is assumed to be stored until field capacity is reached and any addition of water after a heavy rain or irrigation might cause the water content to temporally exceed *field capacity*. The total amount of water above field capacity is assumed to be lost to deep percolation, after deducting *ET* for that day. Therefore at field capacity it is assumed that after a heavy rain or irrigation the minimum value for the depletion in the root zone $D_{r,i}$ is zero.

Data input requirements

a. Rainfall:

The nature of rainfall in Sokoto basin has already been discussed earlier. Rainfall is a critical parameter because all other processes in the water balance model depend on the input of rainfall. High spatial variability of rainfall in the basin as discussed previously tends to have a significant variability on the rates of groundwater recharge from one location to another throughout the basin considering the fact that the aquifers have their recharge outcrop areas distributed over different rainfall regions of the basin.

b. Evapotranspiration, K_c and bare soil evaporation

The empirical equations usually applied to calculate *ET* in arid and semiarid regions include the Penman-Monteith, Turc, Thornthwaites, Blaney-Criddle and Bouchet. Because of data limitation for the study area, Blaney-Criddle method was used to calculate the *ET* used in this model. This is one of the methods recommended in the FAO Irrigation and Drainage Paper No. 24 'Crop water requirements' for the calculation of ET_o water requirement to accommodate users with different data availability (Provide full citation of the paper). The Blaney-Criddle method was recommended for periods of one month or longer.

Based on FAO method, determination of evapotranspiration from a cropped surface under optimum moisture condition *PE* was carried out by relating evapotranspiration from a reference surface ET_o to a particular crop by utilizing the crop coefficients K_c .

$$PE = K_c * ET_o$$

The K_c integrates the main features distinguishing a typical crop from the reference surface. Crop growing period is divided into four stages (initial stage, crop development stage, mid-season stage and late-season stage) to see the effect of changing crop characteristics on crop coefficients over the growing season. The determination of K_c and length of stage depend on the type of crop and the condition of growth.

The model also calculates bare soil evaporation by integrating a coefficient K_{cbs} in order to relate the reference evapotranspiration ET_o to potential bare soil evaporation at a reduced rate before crop planting and after harvest. It assumes that K_{cini} has the same numerical value as K_{cbs} because

soil evaporation is the dominant factor at that stage. The bare soil evaporation before planting and after harvest was calculated as the total amount of water that can be depleted by evaporation (TEW) from a particular depth of a surface soil layer (Z_e)

$$TEW = 1000 (\theta_{fc} - 0.5 \theta_{wp}) Z_e$$

Where TEW is total evaporable water, Z_e is depth of surface soil layer subject to drying (adopted as 0.25 m), fc is the field capacity and wp is the wilting point.

Conditions for reduced evapotranspiration and evaporation

As the soil moisture deficit increases, evapotranspiration and evaporation may occur at a reduced rate. It is assumed that evapotranspiration occur when the soil moisture deficit (SMD) is greater than the readily available water (RAW) (Figure 6). The possible conditions for estimating actual evapotranspiration (AE) in the model can be represented by the following equations integrating water stress coefficient (K_s) as a decay function of the soil moisture deficit:

- i. $AE = PE$ when $SMD < RAW$ or $In \geq PE$
- ii. $AE = In + K_s (PE - In)$ when $TAW \geq SMD \geq RAW$ and $In < PE$
- iii. $AE = In$ when $SMD \geq TAW$ and $In < PE$

Where K_s is calculated using the SMD for the previous day

$$K_s = \frac{TAW - SMD'}{TAW - R}$$

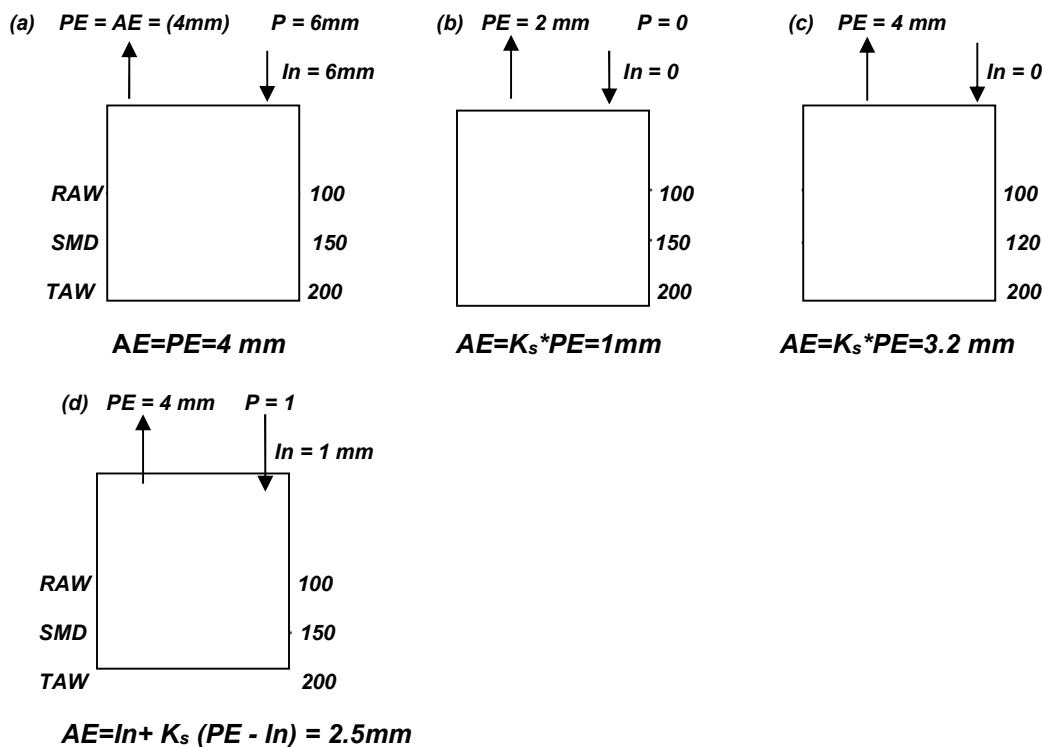


Figure 6: Calculating actual evapotranspiration under different moisture condition

In the illustration (figure 6) for example, in a situation where plant is looking for 4 mm of rain, the infiltration of 1 mm would be transpired easily and the plant is still looking for 3 mm. That is going to come from the deeper roots (reduced rate of K_s).

But $K_s = 0.5$ (therefore $0.5 * 3 = 1.5$ mm from the deeper roots)

$$AE = In + K_s (PE - In)$$

$$AE = 1 + 0.5 (4 - 1) = 2.5 \text{ mm}$$

c. Rooting depth

The maximum root depth of representative crop (Millet) is taken as 1.2 m at maturity. This represents the highest depth that can be attained by the plant roots at any point after maturity.

d. Field capacity and wilting point

In the model, parameters such as the field capacity and permanent wilting point were adopted from FAO, 56 values and used (Table 1). The field capacity (θ_{fc}) is defined as the amount of water that a given volume of soil can hold against gravity and permanent wilting point (θ_{wp}) is also defined as the moisture content below which the plant roots cannot be able to extract any moisture.

Table 1: Field Capacity and Wilting Points of Representative Soil Types

Soil type	θ_{fc}	θ_{wp}	$(\theta_{fc} - \theta_{wp})$
Sand	0.07 – 0.17	0.02 – 0.07	0.05 – 0.11
Loamy sand	0.11 – 0.19	0.03 – 0.10	0.06 – 0.12
Sandy loam	0.18 – 0.28	0.06 – 0.16	0.11 – 0.15
Loam	0.20 – 0.30	0.07 – 0.17	0.13 – 0.18
Silt loam	0.22 – 0.36	0.09 – 0.21	0.13 – 0.19
Silt	0.28 – 0.36	0.12 – 0.22	0.16 – 0.20
Silt clay loam	0.30 – 0.37	0.17 – 0.24	0.13 – 0.18
Silty clay	0.30 – 0.42	0.17 – 0.29	0.13 – 0.19
Clay	0.32 – 0.40	0.20 – 0.24	0.12 – 0.20

Adopted from Torres et al., 2021

The condition of soil field capacity and wilting point depends on the hydraulic conductivity (K) of soil. During and after rainfall when the soil is wet the hydraulic conductivity became high and rate of water movement into the upper layers of the soil is more rapid, but as the soil become drier the movement gradually decreases. As the soil became increasingly wet the hydraulic conductivity became high enough to allow more transmission of water to deeper layers of the soil. At this point drainage occurs rapidly as the water is held at low suction. At low water contents therefore clayey soil having a finer texture than sandy soil can have higher unsaturated hydraulic conductivity and consequently longer water movement than sand.

e. Total Available Water (TAW), Readily Available Water (RAW) and Soil Moisture Deficit (SMD)

Other parameters such as the *TAW* and total evaporable water (*TEW*) for values of field capacity and permanent wilting point were estimated based on the values suggested by FAO publication 56 (provide full citation). The *RAW* and readily evaporable water (*REW*), (determined using a depletion factor p as 0.6), were all adopted from Eilers (2002).

Runoff

It is assumed that runoff estimation depends on rainfall intensity and the antecedent soil moisture condition of a given area. In the model, 20 mm/day-1 was chosen as the minimum rainfall intensity threshold value required for runoff to begin in semiarid areas (Table 2). This was after considering a range of values given by various researchers in semiarid areas e.g. Owonubi et al., 1991, (20mm/hr-1 in North east Nigeria), Peugeot et al, 1997 (18mm/hr-1 in Niger), Audu, 1999 (16mm/day in the northeast Nigeria) and Eilers, 2002 (20mm/day-1 in northeast Nigeria). Based on the understanding that runoff can be initiated even when soil did not reach field capacity in semiarid environment, the estimation of runoff in the model was correlated to the rainfall intensity and the condition of soil moisture deficit at the start of the day through a matrix of coefficient (r_c) representing the complex physical processes involved between soil surface, rainfall and infiltration capacity limits. This relationship is based on the assumptions that runoff is significant when the soil became wet and rainfall intensity is high; high rainfall values have enough intensities to cause runoff and low rainfall values have little or no runoff (Gada, 2014). The matrix coefficient can be modified to represent series of factors such as the soil type, slope, tillage and crusting. The method allows for parameterization and validation of the coefficients and the inclusion of further intervals of rainfall intensity and soil moisture deficit.

Thus, runoff in the model was calculated using the following equation:

$$R_o = P \times r_c$$

Where R_o is runoff, P is precipitation (mm/day) and r_c is the runoff coefficient (from the matrix).

Table 2: Coefficients for runoff determination

Soil Moisture Deficit at start of day (mm)	Rainfall intensity (mm/d)								
	Sand			Clay			Loam		
	0-20	20-50	>50	0-20	20-50	>50	0-20	20-50	>50
0-20	0.10	0.20	0.30	0.20	0.30	0.50	0.15	0.25	0.40
20-50	0.05	0.15	0.25	0.15	0.25	0.35	0.10	0.20	0.30
>50	0.00	0.10	0.20	0.10	0.20	0.30	0.05	0.15	0.25

Adopted and modified from Eiler's, (2002)

In Sokoto basin the occurrence of stormy and high intense rainfall events usually result in rapid runoff despite the presence of cover for the sandy soils in many locations. This is because the soil has weak structure with high tendency to form surface crusting (Sambroek and Zonneveld, 1971).

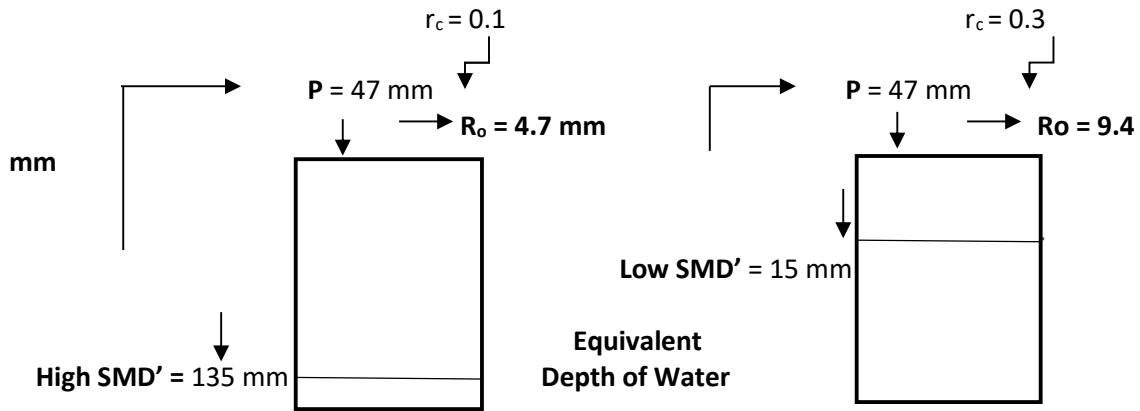


Figure 5: Runoff calculation on Sandy soil in the sedimentary area of the basin

Runoff coefficients in the basement complex areas of the basin are generally higher than the sedimentary areas due to the geology, soil, and vegetation characteristics (Figure 6).

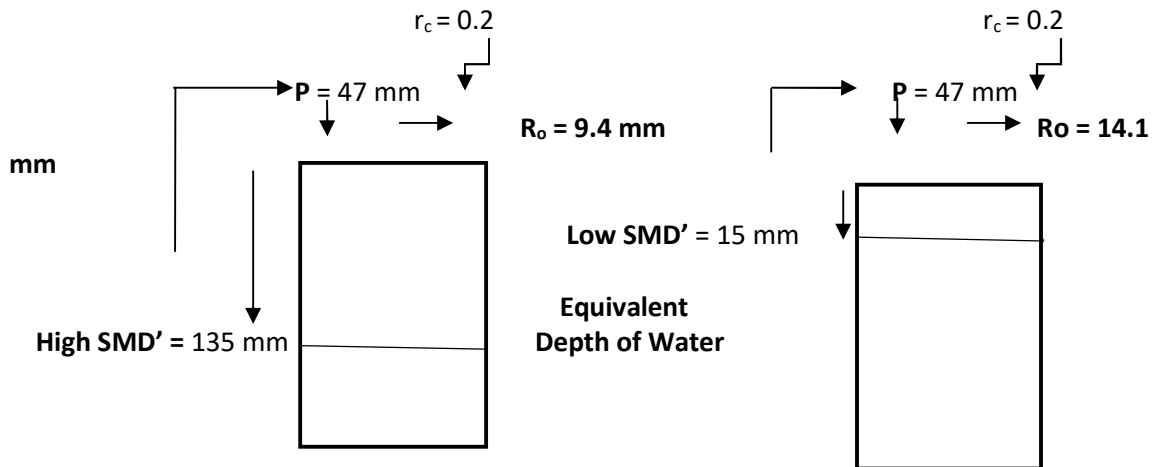


Figure 6: Runoff calculation on Clay soil in the sedimentary area of the basin

i. Infiltration

In the model the daily rainfall was assumed to be distributed over the day and therefore the amount of water infiltrating into the soil at the start of the day was considered as a fraction of precipitation minus surface runoff as expressed by the equation:

$$In = P - R_o$$

Where In is infiltration, P is precipitation and R_o is runoff.

ii. Near surface storage

The soil water balance model also integrates the concept of near surface storage (NSS) where significant amount of infiltrated water is assumed to be kept near the soil surface after a heavy rainfall event, while the remaining amount reduces the soil moisture deficit. The near surface water storage would be used to reduce the SMD or for evapotranspiration in the following days in the absence of any significant rainfall. A value of 0.45, 0.55 and 0.75 were used in the model to represent the proportion of water that is retained as near surface storage in a sandy, loamy and clay soils respectively based on the soil texture. This is to ensure that adequate water retained as near surface storage in less permeable soils is higher than the in the permeable soils as is the case in semiarid areas. The NSS is calculated using a storage retention fraction (*FRACSTOR*) which represents equal amount of water received near surface store (*SURFSTOR*) on the first day that will be available the following day (Figure 7).

$$FRACSTOR * (In - PE)$$

The same value of *FRACSTOR* would be used to calculate the fraction of water that remains in the shallow zone in the following days, while the fraction that goes into deeper soil zone to reduce the *SMD* is also estimated.

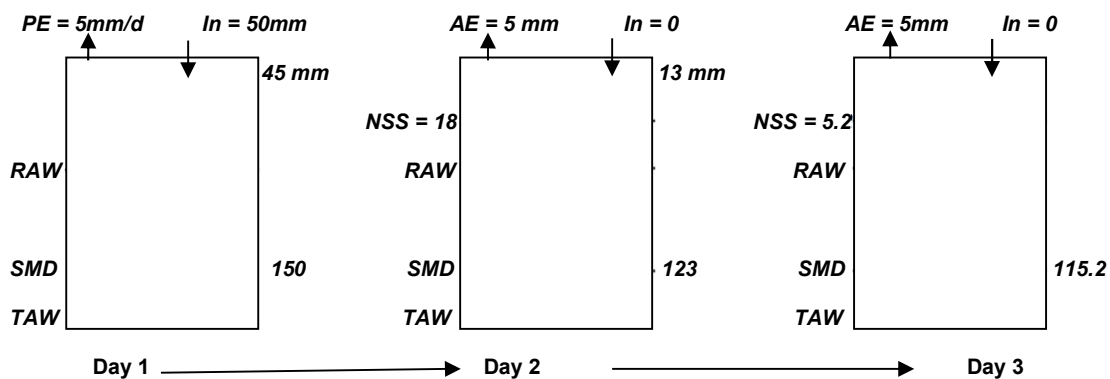


Figure 7: Near Surface Storage Estimation

b. Occurrence of potential recharge

Recharge occur only when the soil is at field capacity (i.e. when the *SMD* = 0), and excess water drains through the bottom of the soil at this stage because the soil is assumed to be free draining. *SMD* at the end of the day is therefore set to zero and any negative value is regarded as positive recharge (Fig. 8).

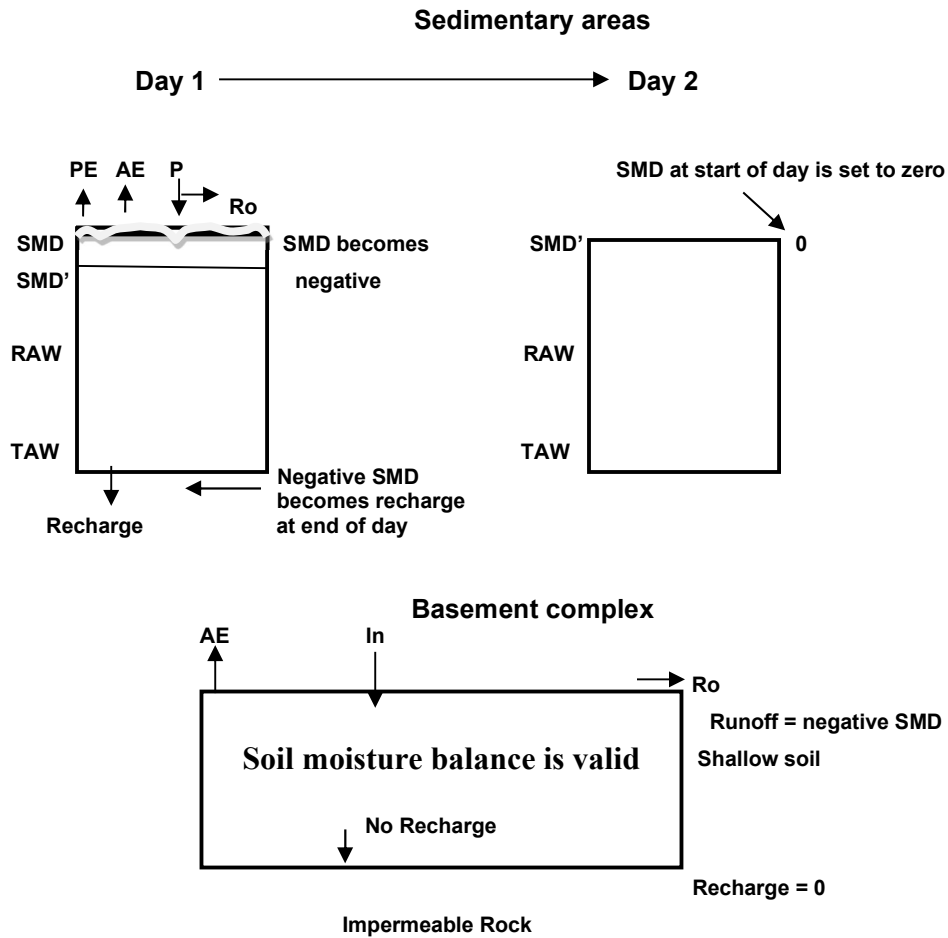


Figure 8: Recharge in the sedimentary and basement complex areas

Results And Discussion

Model Inputs and outputs for a representative year

An analysis of the components of the soil water balance model was done for a representative year (2006) based on series of inputs and outputs as represented in figure 9 below:

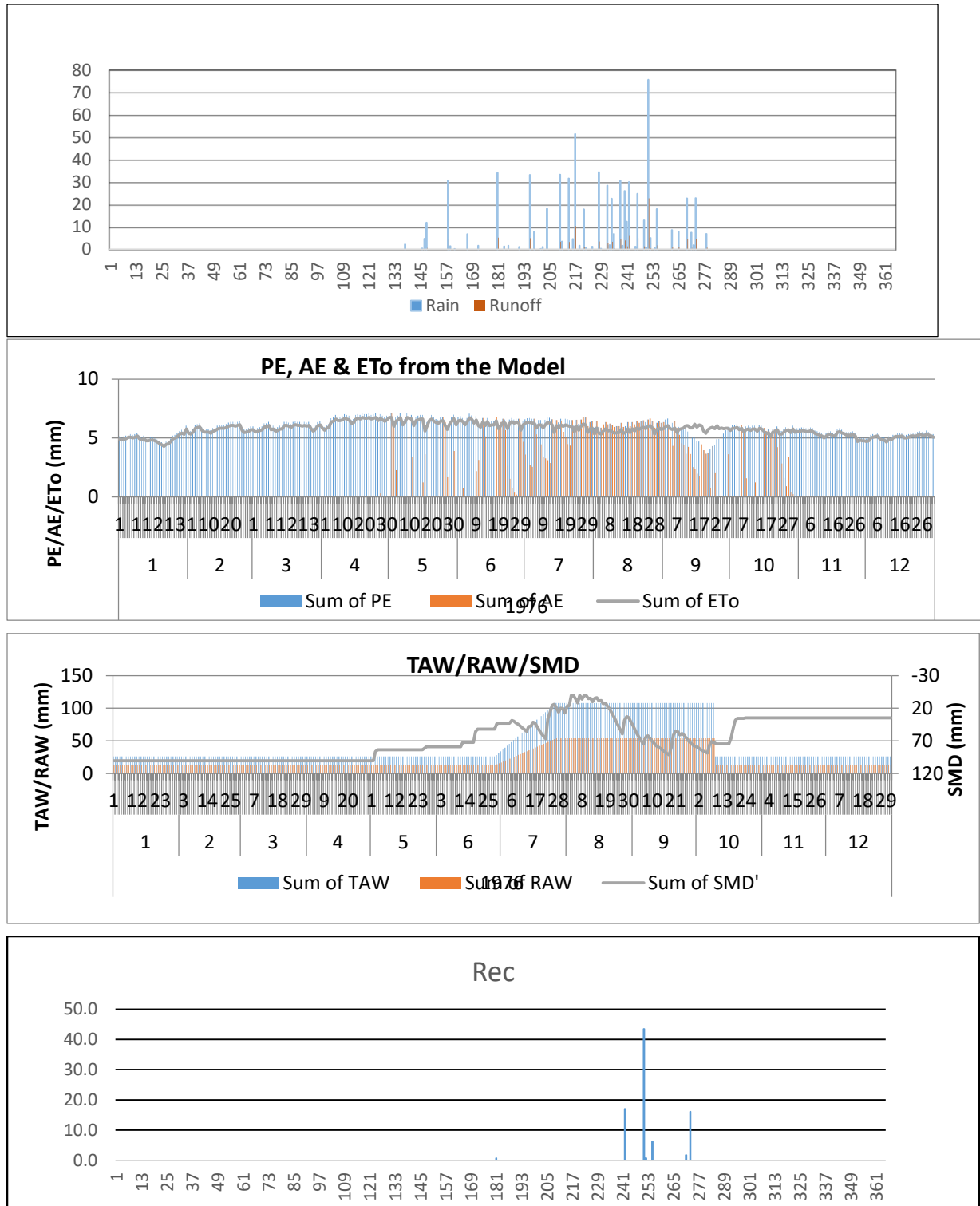


Figure 9: Recharge processes from the model for Sokoto station (2006)

i. Rainfall

In figure 9, the year 2006 was chosen because it is considered as an average wet year showing a fair distribution of rainfall starting from May and ending in October. The annual total rainfall for

this year was 717 mm higher than the long term annual average of 420 mm and having about nine rainfall events over 30 mm.

ii. Potential and actual evapotranspiration

The estimated *PE* and *AE* for the year 2006 is also shown in figure 9. The reference evapotranspiration *ET_o* represents the atmospheric demand and varies between 4 to 6.5 mm daily. This represent the highest water loss for actual and potential rates respectively. The AET occur at potential rate whenever rainfall occur in a day and at reduced rate in the subsequent days without rainfall.

Total Available Water (*TAW*), Readily Available Water (*RAW*) and Soil Moisture Deficit (*SMD*)

Figure 9 equally shows that AE occur whenever the TAW and RAW are within the evaporable layer of the soil and within the reach of plant roots. The *SMD* start to decrease at the start of rainy season and subsequent crop development. The *SMD* changes in response to evapotranspiration demand and water availability in the soil. When heavy rainfall is received sometimes the soil reaches field capacity. The *SMD* remains almost uniform during the dry season until the return of another rainy season based on the assumption that the soil is kept bare after cropping season thus, making the root extraction and deep drainage below the soil zone insignificant.

iii. Runoff

The total runoff for 2006 is 114 mm (13.4% of total annual rainfall) (Fig. 9). Runoff doesn't occur usually during the early onset of rainy season due to the high soil moisture deficit, but became more significant as the deficit decreases following series of heavy rainfall events.

iv. Recharge

Despite the high amount of rainfall received, the year 2006 is one of the less significant years with regard to groundwater recharge in the area. The total annual recharge for that year is 72 mm (about 8.5% of the total annual rainfall) (see Fig. 9). The highest rainfall amount received for that year was on September 8 (75.8 mm) and about 43.5mm of that amount goes to recharge on that day because the low *SMD* for that day. Recharge also occurs in early September and early October despite daily lower rainfall received; this is attributed to the associated wetter soil condition of the previous days prior to the peak recharge day.

Conclusion

The paper investigated groundwater recharge estimation using soil moisture balance approach in semi-arid environment. It was found that the occurrence of recharge is not only due to rainfall occurrence but also the condition of soil moisture. That recharge usually occur during the peak rainy season when the *SMD* is low (from August – October). That the annual recharge represents only between 10 – 15 % of the total annual rainfall depending on the season and distribution of rainfall. In addition, evapotranspiration account for the highest water loss during the day and is dependent on RAW. That the annual water loss through evapotranspiration accounts for about 60-70% of the annual rainfall. That runoff generate is also significant when the *SMD* is low. The paper concludes that the soil moisture balance approach is a vital tool for groundwater recharge estimation in arid and semi-arid environments. It is therefore recommended that similar approach be used in other climatic regions using appropriate parameters to represent real physical condition obtained there.

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