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ESTIMATING RUNOFF AND SOIL MOISTURE DEFICIT IN GUINEA SAVANNAH REGION OF NIGERIA USING WATER BALANCE METHOD

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ABSTRACT

The estimation of runoff and soil moisture deficit in Guinea Savannah region using semi arid model based on soil water balance technique (SAMBA) was carried out. The input to the SAMBA model are daily rainfall, daily evapotranspiration, type and date of planting of crop, and soil parameters. The estimated runoff was validated with field measurement taken in a 67.23 ha catchment in the study area. The annual rainfall for the year under study (2009) is 1356.2 mm, the estimated annual evapotranspiration, runoff and recharge are 638mm, 132.93mm, and 447.8mm respectively. Recharge was experienced 23 days after a significant depth of rainfall was recorded. For the crop growth in the catchment, the soil was cropped with a pepper and the growth monitored from the planting to the harvesting. The crop enjoyed so much moisture throughout the growing period as Total Available Water in the soil is greater than Soil Moisture Deficit (TAW>SMD). The model results show that the larger percentage of the total annual rainfall was lost to evaporation and recharge during the growing season. The low runoff and high recharge are attributed to soil characteristics of the area and moderate terrain of the study area.
Key words: Runoff, Soil moisture deficit, Recharge, Field capacity, Guinea savannah

1. INTRODUCTION

The relationship between the components of hydrology such as rainfall, infiltration, evapotranspiration, and subsequent runoff, coupled with the water holding capacity of the soil in form of soil moisture deficit, SMD, forms the basis of this study. This explains the roles the hydrologic cycle plays in ensuring the continuous availability of water for plant consumption. In this work, an hydrologic model is considered that gives the relationship between the various hydrological parameters and consequently the estimation of soil moisture deficit, runoff, and evapotranspiration. This model is a single layer soil water balance model that incorporates the physical processes, such as: rainfall, surface runoff, soil evaporation, crop transpiration, root growth, and soil water distribution following rain event. The model is termed SAMBA and it is semi arid model based on soil water balance technique.

Soil water balance technique accounts for all water entering and leaving the soil zone based on the quantification of the individual physical processes (the inputs and outputs), without representing all the physical soil physics and their interactions which describe the movement of water within the soil (Eilers et al., 2007). Thus, the approach is based on fewer physical processes and it is not subject to the uncertainties of the mechanisms of a full soil physics analysis. There are different types of soil water models. There are conventional single layer model as presented by Penman (1990); the CROPWAT model which was developed by the Food and Agriculture Organization of the United Nations (Smith, 1992); the Balance model (Grema and Hess, 1994), a two layer model which was developed to estimate daily soil water balance for cropped or un-cropped surface; and the four root layer model (FRLM) developed by the Institute of Hydrology, UK for the estimation of soil moisture

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deficits in sites under permanent grass cover (Ragab et al., 1997). (Grema and Hess, 1994) considered Maiduguri where a detailed field investigation was carried out for a complete rainy season and Nguru where daily rainfall and potential evaporation data are available for several decades. Though there is difference in the vegetation between these two locations and the study area, but the successes recorded in these two locations encouraged the application of this model to the Guinea Savannah region of Nigeria.

2. THE MODEL AND ITS COMPUTATIONAL METHOD

In the soil water balance model (Figure 1), the major components are: precipitation Pr, infiltration In, runoff RO, evaporation AE, and recharge R, soil zone, root zone, and transpiration from the leaves of the crop. With the inclusion of all these parameters in the model, the daily values of both the runoff and soil moisture deficit will be obtained. This is the basis of soil moisture balance method. Apart from the estimation of the said parameters, daily recharge estimation can also be obtained from the model. In this study, a temperature-based model for estimating evapotranspiration in Nigeria was adopted (Duru, 1984). Among the data needed are daily temperature and relative humidity. Specifically, soil water balance method is favoured for Guinea-Savannah region because of its physical credibility at a daily or less time scale, and its simplicity with less uncertainty in spatial variability in hydraulic soil properties. In addition, the technique is favoured because model parameters are few. As the number of parameters increases, the data required for parameter estimation increases.

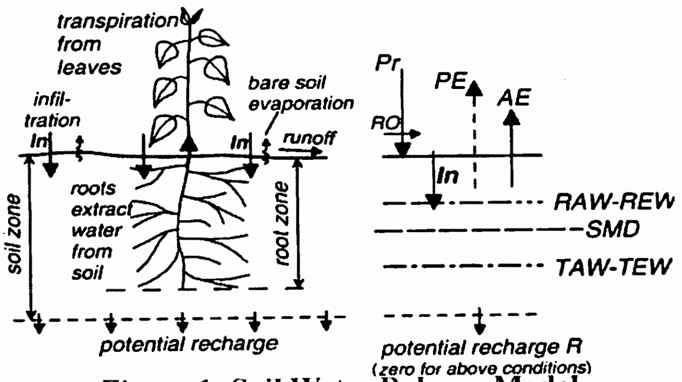

Figure 1: Soil Water Balance Model

In making use of the model, the steps below form the basis of the SAMBA model (Rushton *et al.*, 2006).

1. Get daily rainfall and reference evapotranspiration.(ET_o)
2. Use *SMD* at the driest season as initial soil moisture deficit - SMD (start up only)
3. Compute runoff coefficient, using the runoff matrix (assume)
4. Compute the Runoff = Rainfall * Runoff coefficient
5. Then, Available water for evaporation (AWE) is determined as follows:
   If SMDpr > 0 AWE = Rain – Runoff + *NSSpr
   If SMDpr ≤0 AWE = Rain – Runoff
6. Compute crop coefficient, Kc, using information on planting date and crop duration
7. Potential evapotranspiration = Kc * ETo
8. Determine root depth Zr based on growth stage
9. Total available water, TAW is determined as:
   TAW = max[(FC-WP)*1000*Zr, (FC-WP/2)*1000*Ze]
   Ze is the soil evaporative surface
10. Readily available water, RAW = TAW * ρ (a constant between 0.2 and 0.7 (Allen *et al.*, 1998).
11. Determine soil stress coefficient, ks as follows:

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If $SMDpr \geq TAW$, $ks = 0$

If $SMDpr \geq RAW$, $ks = \frac{TAW - SMDpr}{TAW - RAW}$

If $SMDpr \leq RAW$, $ks = 1$

12. Compute actual evapotranspiration, AE:

If $SMDpr < RAW$, $AE = PE$

Else If $AWE \geq PE$, $AE = PE$

If $SMDpr \geq TAW$, $AE = AWE$

Else $AE = AWE + ks(PE - AWE)$

13. Determine the near surface storage (NSS)

If $(AWE - AE) > SMDpr$, $NSS = 0$

Else, $NSS = \max((AWE - AE)*NSSfactor, 0)$

14. If $SMDpr \leq 0$, $SMD = AE - AWE + NSS$

Else $SMD = SMDpr + RECHpr + AE - AWE + NSS$

15. Compute recharge:

If $SMD < 0$, $Rech = -1 * SMD + NSS$

Else, $Rech = 0$

SMD denotes soil moisture deficit at the end of day t, while SMDpr denotes previous day SMD.
Rech denotes recharge at the end of day t, while Rechpr denotes previous day recharge
*NSS is near surface storage at the end of day t and NSSpr is the previous day NSS
NSSfactor is the storage fraction of near surface storage.

3. METHODOLOGY

3.1 The Study Area and Data Collection

The study area is the Gidan Kwano Inland Valley located between Latitudes *9°15' and 9° 45' N* and Longitudes 6°15' and 6°45' E. It forms the low land area of Garatu hilland extending to Yadna hill. The valley is located at the western end of Minna Township, and within the permanent site of Federal University of Technology, Minna, Niger State, in North Central Geo-political zone of Federal Republic of Nigeria. The catchment area of the case study is 671,778.17m^2 (67.23ha) with the perimeter of 3700m.

Hydrological data such as rainfall, evapotranspiration, temperature (both maximum and minimum), and actual evapotranspiration, AE were all collected from a meteorological agency (**NIMET**) and used in the model for the purpose of the runoff estimation. Discharge measurements were carried out with the aid of constructed weir mounted where the high runoff was expected. The measurements were carried out on four different days with reasonable amounts of rainfall for the years under study. The resulting runoff peaks were labeled Q_1, Q_2, Q_3 and Q_4 for respective measurements for the year under study.

4. RESULT AND DISCUSSION

4.1 Moisture Content and Rainfall Data

The trend of moisture content is shown in Figure 2 and this indicates an increasing trend in the measurement of moisture content up to the 25th week. The point of first rainfall which is precisely 4th April with the recorded depth of 57.9 mm is shown with the arrow in Fig. 2. Another point of interest is the point where the highest moisture content was recorded. This happened in September and the recorded moisture content noted. This point of highest moisture content also marked the field capacity, which is the point of total saturation of the soil mass, found to be 0.21 (21%) as shown by the arrow in Figure 2.

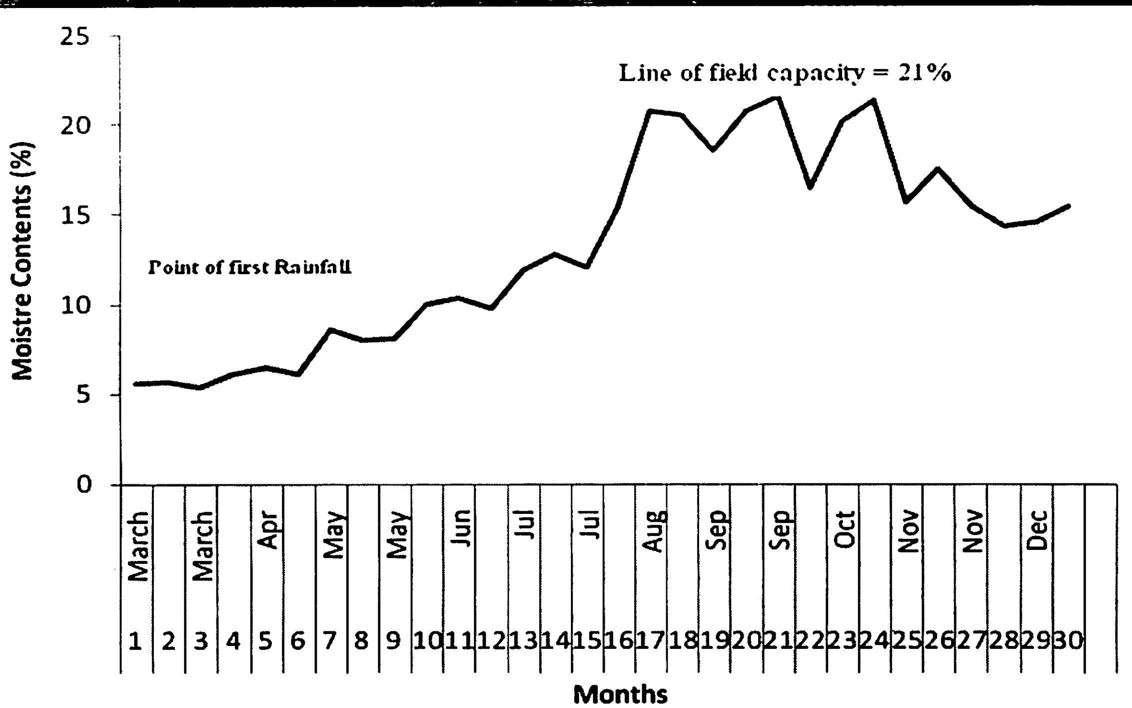

Figure 2: Moisture Content Trends of the Catchment

From Figure 2, low values of moisture content of a range 5.4 to 6.1 were obtained during the dry season close to the inception of rainy season. Expectedly there was an increase in the values due to the rainfall of magnitude 57.9 mm at the Julian day 94 of the study year. The relevance of this is that the more the infiltrated water into the soil mass the more the soil moisture content and the less the soil moisture deficit. Table 1 shows the existing runoff matrix for Minna (Jimoh, 1992), while Table 2 presents the adjustments made to the existing runoff matrix and adopted for use in the SAMBA model based on the existing soil characteristic in the study area. With the characteristics of the soil in the catchment coupled with the hydrological parameters of the region, the runoff matrix of the study area was developed and then employed in the model. The results obtained favourably conform to the results of the runoff obtained in the field measurement.

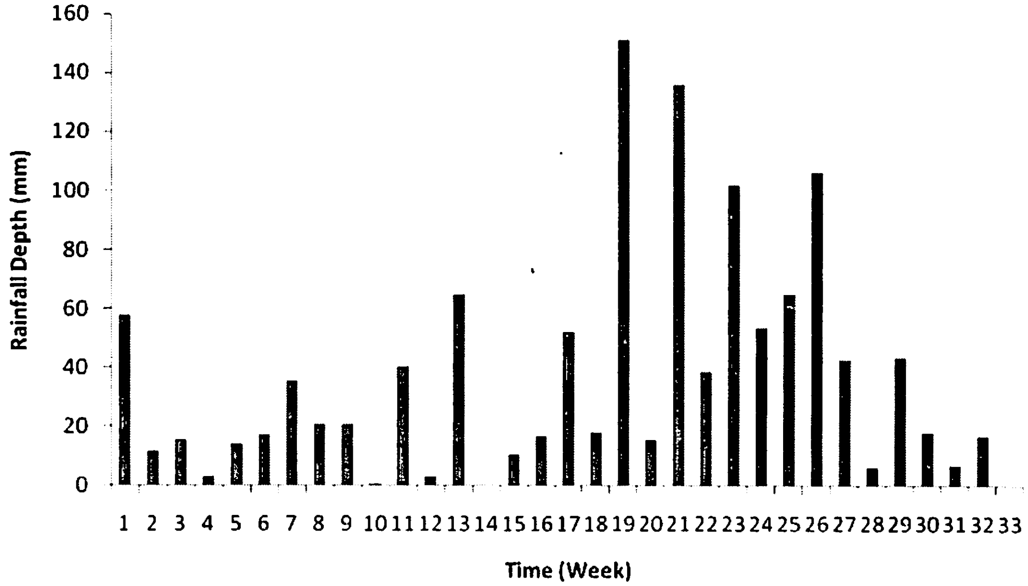

Figure 3: Weekly Records of Rainfall Depth for the Water Year (April-October, 2009)

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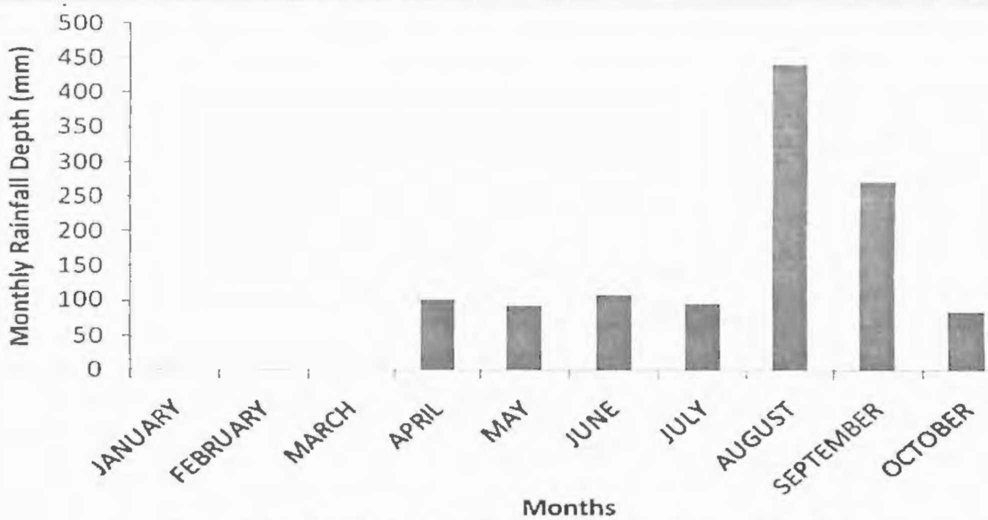

Figure 4: Monthly Rainfall Depth for Minna-2009.

Table 1: Runoff Matrix for Minna
Soil Moisture Deficit (SMD) values

Rain (mm/d)	0	15	30	45	60
0	0.000	0.000	0.000	0.000	0.000
5	0.048	0.038	0.029	0.019	0.009
15	0.144	0.115	0.086	0.056	0.027
30	0.288	0.230	0.171	0.113	0.054
45	0.432	0.344	0.257	0.169	0.081
60	0.576	0.459	0.342	0.225	0.108
75	0.720	0.574	0.428	0.281	0.135
>75	0.720	0.574	0.428	0.281	0.135

Table 2: Adjusted Runoff Matrix for Minna
Soil Moisture Deficit (SMD) Values

Rain (mm/d)	0	15	30	45	60
0	0.000	0.000	0.000	0.000	0.000
5	0.012	0.009	0.006	0.005	0.0022
15	0.040	0.028	0.021	0.013	0.0065
30	0.069	0.055	0.041	0.027	0.013
45	0.10	0.08	0.062	0.041	0.019
60	0.576	0.459	0.342	0.225	0.108
75	0.720	0.574	0.428	0.281	0.135
>75	0.720	0.574	0.428	0.281	0.135

Table 2 is the adjusted runoff matrix for Minna which is as a result of this study. The measurement of rainfall and the soil moisture deficit in the study area coupled with the obtained runoff coefficient in Table 3 give rise to the adjusted runoff matrix in Table 2.

Table 3: Adjustment of Runoff for the Four Discharge Measurements

Date	Rainfall (mm)	SMD (mm)	Runoff (Measured) (mm/d)	Runoff (Model) mm/day	Remarks	Runoff Coefficient
28/07/09	28.6	79.8	2.0	2.86		0.1
18/08/09	25.5	-17.8	1.2	5.1	24% <	0.1
17/09/09	24.4	-13.9	1.0	4.88	21%<	0.04
21/09/09	66.3	-39.4	20.5	19.89		0.3

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4.2 Model Performance

The performance of the model is enhanced with the comparison of the results of the runoff obtained from the model and that obtained from the field measurements. The focus is in the percentage difference in the values of surface runoff obtained from the previous study and this present study.

4.3 Variations in SMD and Crop Growth

Figure 5 shows how crop growth change with time. The figure refers to a single crop grown during the rainy season. Before the crop is sown, in June, 2009, bare soil evaporation is the only process occurring. After sowing, the roots extend and draw water from the soil storage, transpiring it to the atmosphere. After harvest bare soil conditions apply once again. Three significant soil zone conditions are presented in the lower half of Figure 5. The seed sown on June 17, 2009 is monitored throughout its growth period and the schematic growth is as shown in Figure 5. The same Figure 5 (i) shows the early period before the rainfall is recorded when the crop has not been sown. The soil was overgrown with shrubs where we had bare soil in some areas, and due to the fact that no crop was planted yet, the assumption was that partial evaporation is expected. At this period, the soil moisture deficit is greater than total evaporable water, i.e. *SMD>TEW*, as shown in Figure 5..The second stage represents a stage when the occasional rainfall is being experienced. At this stage, the water being made use of by the crop is that due to near Surface Storage, NSS, which is as a result of the occasional rainfall being stored at the root zone of the crop from the previous stage. Hence, *SMD>RAW*, where RAW is Readily Available Water. Fig. 5(iii) illustrates a situation where the rainfall is at the peak, and *SMD*, the lowest, which invariably symbolizes the occurrence of recharge i.e. *SMD<RAW*, unlike stage (ii) when *SMD>RAW*.

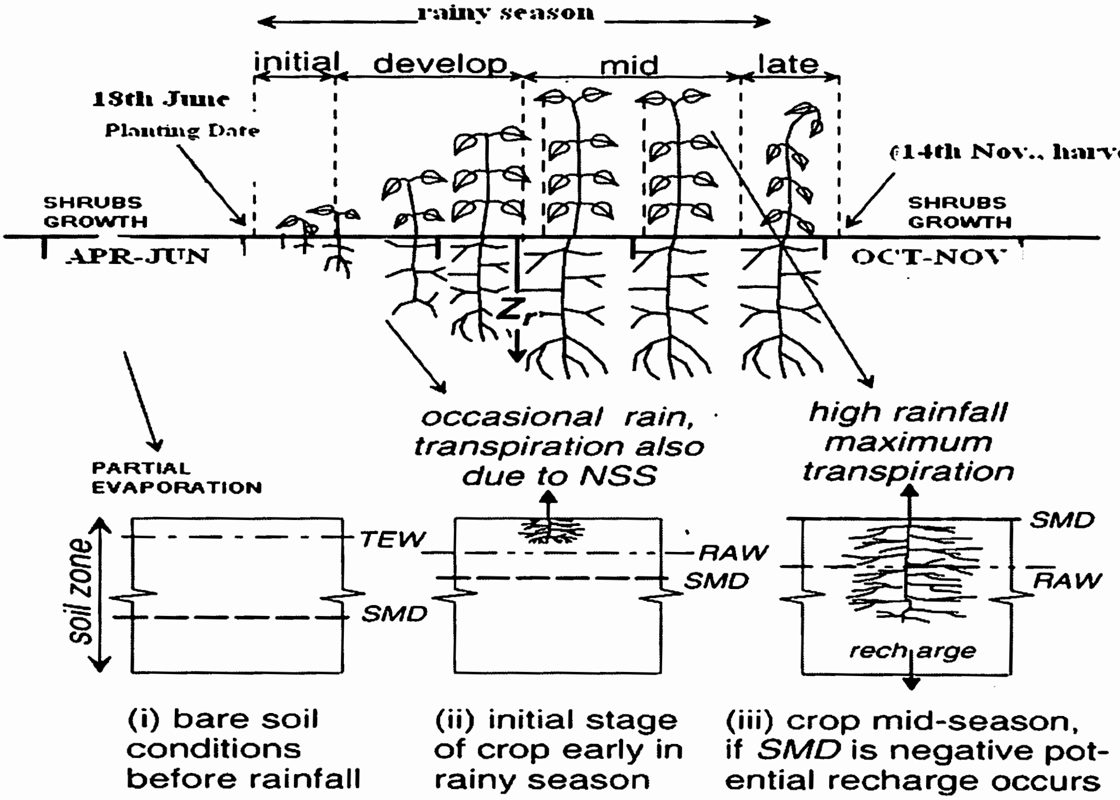

Figure 5: Growth of Pepper Crop and Soil Water Balance Conditions on Three Occasions (Rushton et al., 2006)

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In Figure 6, actual evapotranspiration, AE is compared to potential evapotranspiration PE. Before the planting stage (precisely the first 93 days of the year) the Actual Evaporation, AE was zero. During this period, the soil maintains the SMD value of 49.8 mm, as shown in the model. This implies that the soil was at a point where 49.8 mm depth of moisture was all that was needed to achieve field capacity. From 159th day of the year through 169th day (planting date), and at the start of the mid stage till a day before the harvest (317th day of the year), AE = PE. During the bare soil stage, before planting, AE is often less than PE (0-93 days). On many occasions, after harvest, AE is zero, precisely from mid November till December. This occurs because during the bare soil stage the depth from which evaporation can occur is less than the SMD. It is also evident from the graph that throughout the whole crop year the potential evaporation varies from 2.5 to 4.3 mm/day.

4.4 Variation of SMD, TAW, RAW, PE, AE, and Rainfall depth

The field capacity and permanent wilting point of the soil are 0.21m^3/m^3 and 0.03m^3/m^3 respectively. The linear root growth increases from approximately 8 days after planting to a maximum root depth of 1.2 m at maturity. The readily available functions REW and RAW are calculated using a depletion factor p equal to 0.6 (Rockstrom et al., 1998). Variations of these parameter values with time are plotted in Figure 7. The Figure shows the rainfall distribution, Total Available Water, TAW and Readily Available Water, RAW, Potential Evaporation, PE, and Actual Evaporation, AE which applied during the dry season.

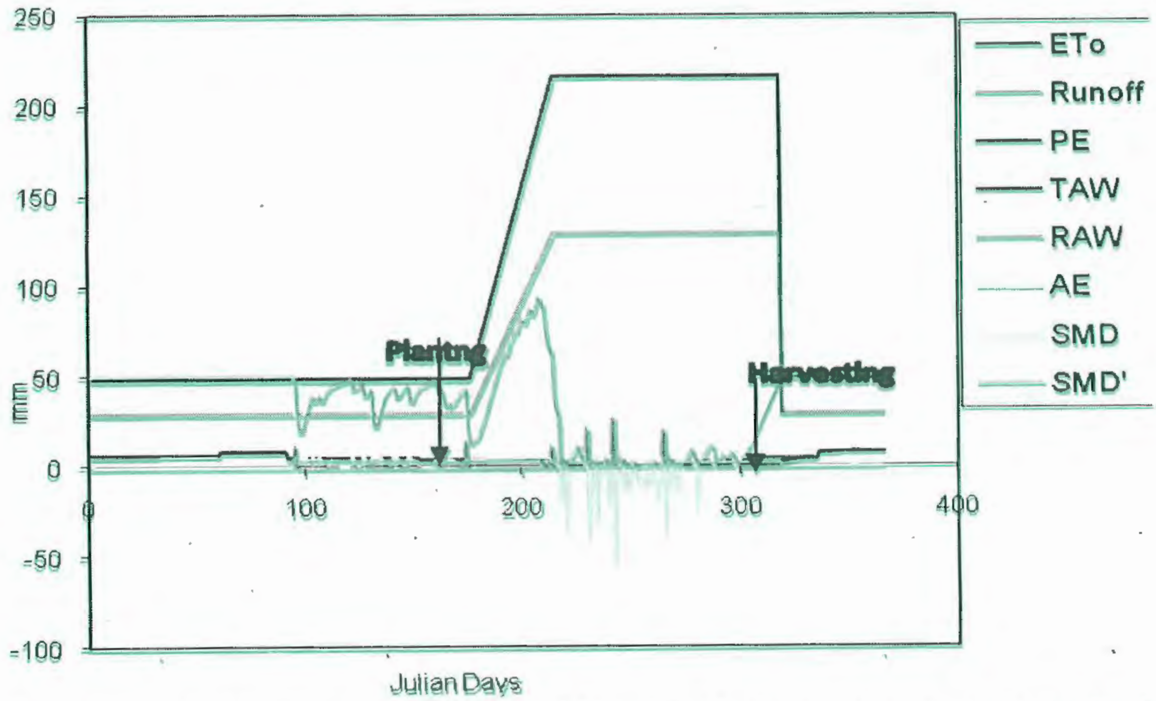

Figure 7: Graphical Representation of Model Showing Variation of SMD, TAW, RAW, PE, AE, and Rainfall Depth.

From Figure 7, below are the facts that are derivable.

1. Once SMD<RAW, evapotranspiration occurs at the potential rate, even on days with no rainfall. This happened 47 days during the study period and mostly during the planting season.

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2. The soil moisture deficit, SMD, becomes zero on 5th August (Julian day 217); this was the first day when recharge occurred. This simply means on this day the soil was saturated, any excess water infiltrating into the soil drained through the saturated soil to recharge the ground water.

Two days after the harvest the SMD starts increasing and the SMD<TAW, and with critical look on the model, evaporation only occurs on days with rain. Readily Available Water is the water the crops depend on for survival and is a function of soil properties as different soils have different water holding capacities. From early April to early November, it is seen that TAW>SMD. This holds for the whole year as there is no single day where the SMD>TAW. Figure 8 further stresses the fact that TAW>SMD which means the crops had sufficient moisture throughout the growing period for the year under study.

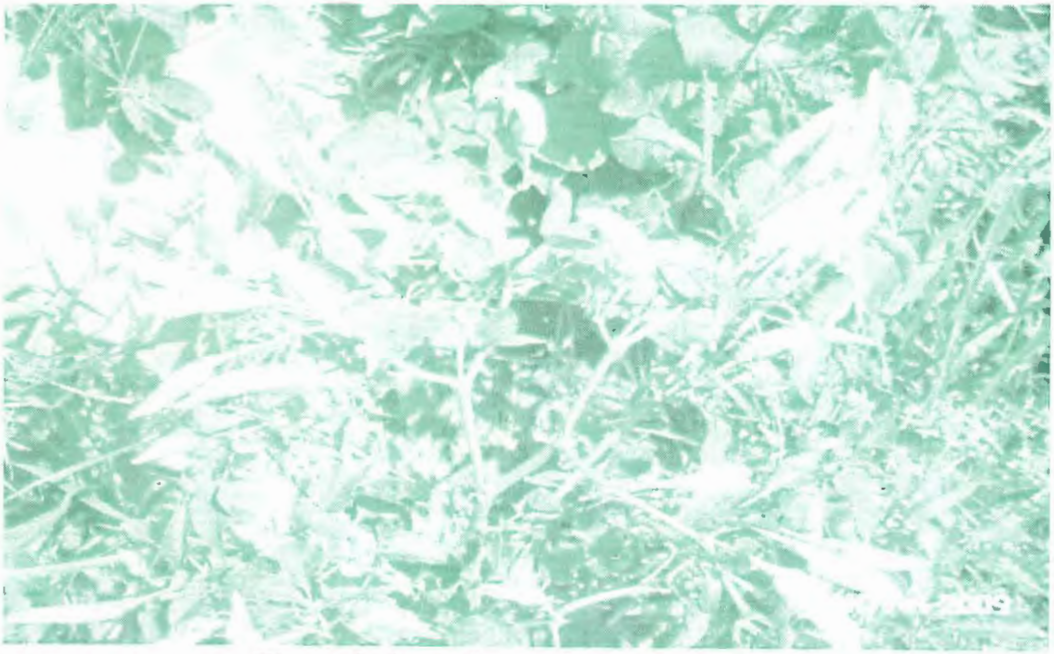

Figure 8: Crop Grown in the Study Area

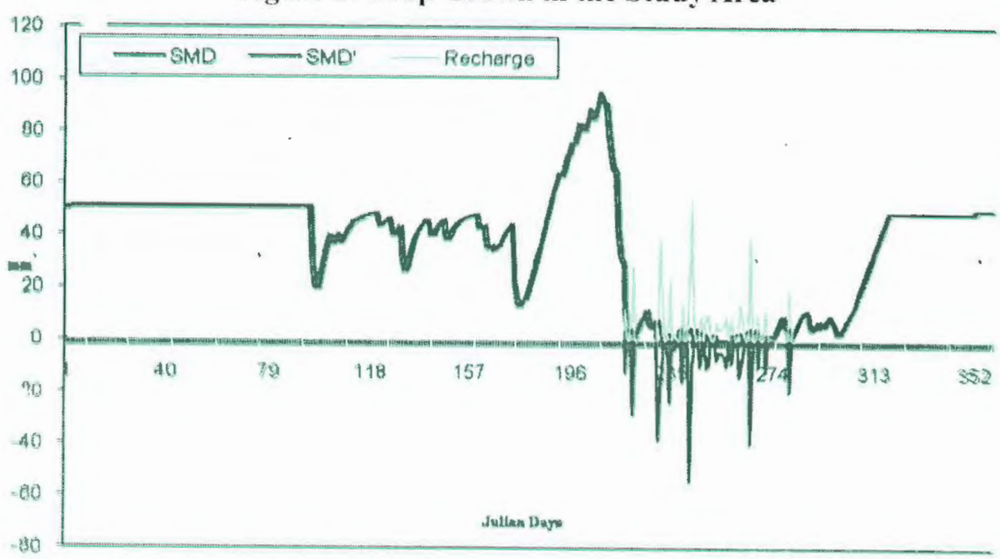

Figure 9: Annual Variation in Soil Moisture Deficit (SMD) and Recharge

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From Figure 9, the soil moisture deficit (SMD) becomes zero on 5th August (217th Julian day; this is the first day when recharge occurs. This simply means on this day the soil has reached the field capacity, i.e. saturated. and any excess water infiltrating into the soil drains through the saturated soil to recharge the ground water. Recharge occurs on 104 further days. This is a remarkable recharge estimate in a year as this means abundant water will have been trapped underground as ground water.

5. CONCLUSIONS

The meteorological and field measurement data were collected, analysed and used in the model. The following conclusions follow from the study:

1. Annual runoff for the year 2009 was 167.7mm, which is 14.5% of the total annual rainfall of 1356.2 mm.
2. For 2009, maximum runoff occurred on 1st September (244th day), coinciding with high rainfall in 29th August through 1st September.
3. Low rainfall-runoff rate observed explains the nature of the soil in the catchment which allows for much water infiltrating into the soil mass there by recharging the groundwater and reducing the soil moisture deficit, *SMD*
4. The model has so far only been used under rain-fed cropping conditions, but irrigated crops can also be included by setting the daily rainfall equal to the actual rainfall plus the depth of irrigation.

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