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Modelling Runoff Estimation In Bida Basin Using Improved Soil Moisture Balance Model

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ABSTRACT

In this paper, an improved soil moisture balance model was used in estimating surface runoff in Bida basin. The model is a single layer soil moisture balance that estimates daily surface runoff using daily rainfall, some hydrological parameters coupled with both soil and crop parameters. The model estimates were validated with discharge measurements using field measurement of direct runoff using weir. This was used in calculating the runoff coefficients of the basin with the aid of soil moisture deficit and rainfall depths. Five (5) years, ranging from 2015 to 2019 were used as study years of which daily rainfall depths and daily minimum and maximum temperature data were used in the model validation. From the results obtained, the annual runoff from the basin for 2015 water year is 507.85 mm, which is 39.3 % of the annual rainfall. For 2016 water year, the annual runoff from the basin is 501.64 mm, which represents 34.05 % of the annual rainfall of 1473.2 mm. The first recorded significant runoff was observed between 125th and 175th days in all study years (when SMD = 0) while the highest value was recorded at 180th day.as 47 mm. 2018 study years recorded the highest annual rainfall depth as 1615.2 mm, while the year 2019 study year recorded the highest annual runoff value as 580.76 mm, which is observed as 41.30 % of annual rainfall. The highest values of runoff depth recorded in the years 2018 and 2019 study years could be attributed to the lower value of SMD during those years as against the higher values recorded in the years 2015 to 2017. Once the hydrological parameters (crop and soil properties) involved like TAW, RAW, SMD, PE, ETo and especially runoff coefficients can be selected carefully; a reliable estimation of hydrological outputs like runoff, recharge and rainfall-runoff relationship can be achieved with high precision.

Keywords: *runoff; improved soil moisture balance; soil properties; crop properties; Bida basin*

1 INTRODUCTION

Runoff can be defined as the quantity of water discharged in surface streams which does not just include the waters that travel over the land surface and through channels to reach a stream but also interflow (Hallema et al., 2016). This represents the water that infiltrates the soil surface and travels by means of gravity toward a point and eventually empties into common outlet such as the outflow of a reservoir. A basin can be defined as an area of land that drains all the streams and rainfall to a common outlet such as the outflow of a reservoir, mouth of a bay, or any point along a stream channel. A basin otherwise known as watershed can also be referred to as a precipitation collector which contributes runoff to a common point that represents the exit from the watershed. However, watershed runoff has become a major concern due to its impact on environmental, agricultural, and flood potential. For any watershed, runoff volume and peak flow directly rely on characteristics of watershed (Patil et al., 2008; Zhang et al., 2013) which include watershed vegetal cover, saturation level of the basin, shape of the watershed, size of the watershed and so on.

The relationship between the runoff and the watershed surface on which it travels is very crucial to what happens to the basin from hydrological point of view. As it is earlier pointed out, amount of runoff in a basin has a relationship with rainfall intensity (Miao et al., 2020), vegetation of the basin (Espinoza et al., 2016), size of the basin (Yu et al., 2020) and the infiltration capacity of the basin (Miyata et al., 2019). Any rain that falls on the saturated basin must run off over the surface once the soil moisture deficit has been satisfied and the field capacity reached (Wells et al., 2017). Within a basin, the excess water remains on the surface and flows down slope as runoff. Many recorded flood events in basins have been due to saturation of the soil mass in the basin. In times of prolonged heavy rainfall, large areas of a gently sloping landscape may become saturated, and much of the rain that follows runs off rapidly to streams (Sharma et al., 1986) and eventually results to flooding, depending on the rainfall intensity and duration. The hydrologic behaviours of watershed play an important role in water resources planning and management (Shin et al., 2002). Many recurrent flood events recorded so far in many river basins in Nigeria were due to lack of watershed management planning in spite of the consequent devastating effects on human lives and properties (Ekeu-wei, 2018). Watershed management is a very important aspect of hydrology as it is necessary to predict or simulate flood and very crucial for early flood forecasting (Ming et al., 2020). The watershed management planning starts with the knowledge of amount of runoff expected in the watershed at a particular rainfall depth. With the precise estimation of runoff quantity in a particular basin from a rainfall event, proper watershed management will help in drastically reducing flood events.

Many methods have been adopted in estimating surface runoff from catchments. Hydrological models like rainfall-runoff models, process based methods like Green and Ampt method and empirical equations like rational and Curve Number methods have all been used with great success in runoff estimation. Apart from hydrological model, all other methods highlighted recorded great success in a very small catchment. In addition, hydrological modelling do not just estimate continuous surface runoff, but also helps in the knowledge of catchment performances and modelling impacts of climate and land use changes on surface water balance (Li et al., 2012; Zhao et al., 2012. Therefore, in this study runoff estimation is modelled using improved soil moisture balance method in Bida basin with the sole aim of achieving runoff estimation from a not-too complex hydrological model.

2 METHODOLOGY

2.1 DESCRIPTION OF STUDY AREA

The study area is Bida basin, with catchment area of 39 km2, and a perimeter of 23.8 km, located in Bida, Niger state. Bida lies on the geographical co-ordinate of 90 36’ 50” N (Latitude) and 6033’24” E (Longitude) (Figure 1). It is in the north central geopolitical zone of Nigeria. It is a guinea savannah zone according to its class by vegetation as evidence with shrubs and scattered vegetation characterizing the area. The climate of the study area is characterized by high temperature and excessive humidity. Rainfall ranges between 1000mm to 1200mm annually with rainy season commencing from April and ending in October. Temperatures are relatively high throughout the year hovering between 27 0C and 35 0C. It is underlain by basement complex rocks comprising of gneisses and schists (Amadi et al., 2011).

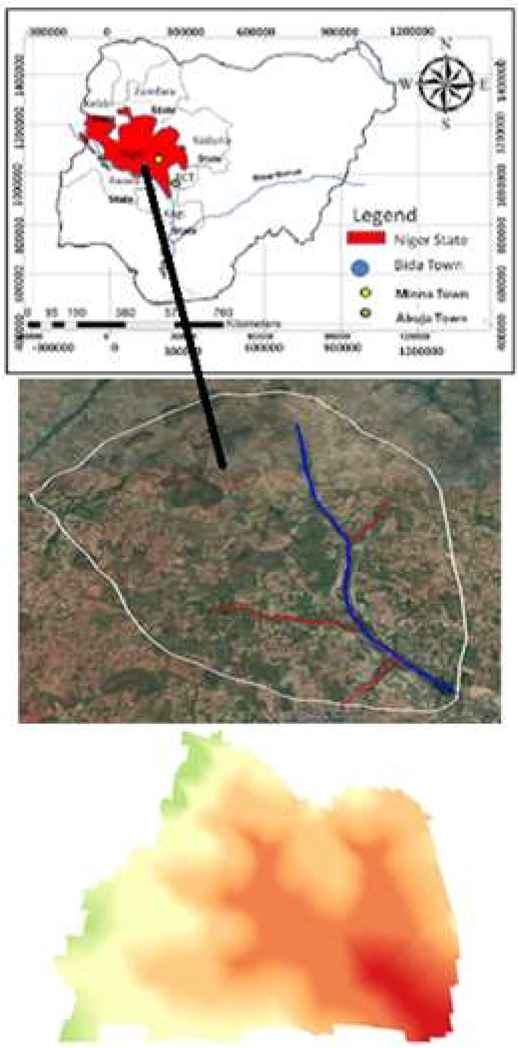

Figure 1: A) Map of Nigeria with Study Area Location, Catchment Area in 3D, & The Extent of The Catchment

2.2 FIELD EXPERIMENT AND DATA COLLECTION

Meteorological data for the study area covering the study years 2015 to 2019, which include rainfall data, terrestrial radiation, temperature data (both maximum and minimum), were obtained from Nigerian Meteorological agency, Abuja (NIMET). Soil data for the study area were obtained from the laboratory having obtained the soil samples from the study area. The soil data obtained are; field capacity, permanent wilting point, near surface storage (NSS), bulk and dry density of soil, water holding capacity and depletion factor. Crop data such as crop depth and crop coefficients were obtained from FAO website. Computer programming language, Python was used in writing a programme for the execution of the algorithm. Python is a generic, interpreted scripting language, supporting object oriented programming which was first released in 1991.

For the discharge measurement in the catchment, a metal weir was installed at the outlet of the catchment and firmly braced at the downstream to withstand the built-up pressure from the impounded water (Figure 2). The weir was buried into the soil at about 0.7 m and clay materials were used to brace the metal weir by pressing to avoid water seeping through underneath and leaking through sideways. Records of water level above the weir crest were recorded. Measurements were taken for three consecutive days with appreciable rainfall. The weir discharge formula in equation 1 based on Larry (1993) was used to convert the recorded water level to discharge;

$$Q = 0.0184 (b-0.2H) H^{3/2} \quad 1.$$

Where Q = Discharge in cm^3/s
B = crest width (cm)
H = head (difference between the crest and the water surface)

Figure 2: Weir Installation and runoff measurement

3 RESULTS AND DISCUSSION

The results of both laboratory and filed experiments are as presented and discussed below. Tables 1 and 2 present the soil and crop parameters for the study area. The dominant crops in the study area is yam and palm trees with the properties highlighted in Table 1. Table 2 presents the soil parameters for the study area.

TABLE 1: CROP PARAMETERS FOR THE SOIL MOISTURE BALANCE FOR STUDY AREA

Crop Parameters	Values
Maximum root depth (m)	0.9
*Depletion factor	0.70
Kc (initial)	0.90
Kc (development)	1.00
Kc (mild stage)	1.00
Kc (late)	1.00

TABLE 2: SOIL PARAMETERS FOR THE SOIL MOISTURE BALANCE FOR STUDY AREA

Soil Parameters	Values
Bulk Density	
VMC @ Field capacity (m^3 m^{-3}) [$\boldsymbol{\theta_{sat}}$ **x** $\frac{\gamma_b}{\gamma_w}$]	0.254
VMC @ Wilting Point (m^3 m^{-3}) **[FC/2.4]**	0.12
Maximum TAW (mm)**[FC-WP]/900**	84
Maximum RAW (mm) **[TAW*0.7]**	59
Soil Moisture Deficit (mm)	60.9
*NSS Factor	0.70

For the successful application of improved soil moisture balance model, the following parameters were used as inputs in the hydrological model;

(i) Daily rainfall and reference evapotranspiration.(ET_o)
(ii) Soil moisture deficit *SMD* obtained from the laboratory analysis
(iii) Runoff coefficient, using the runoff matrix which was obtained by trial and error from hydrograph analysis
(iv) Runoff values which were calculated using;
Rainfall * Runoff coefficient
(v) Available water for evaporation (AWE)
(vi) Crop coefficient *Kc* using information on planting date and crop duration
(vii) Potential evapotranspiration (PE) = *Kc* * ETo [*Kc* = 1.0 for mature oil palms]
(viii) Actual evaporation (AE) = PE, When SMD < TAW * *Zr*
Where *Zr* represents maximum root depth in *m* and *Zr* = 0.9 m (as the oil palms are already mature)
(ix) Total available water, TAW is determined as:
TAW = [(FC-WP)*1000*Zr
(x) Readily available water, RAW = TAW * ρ (ρ is a depletion factor constant between 0.2 and 0.7, Allen *et al*., 1998). Here 0.7 is used for peatland soil.

The soil moisture balance components which include rainfall, runoff, near surface storage, potential and actual evapotranspiration, total available water (TAW), readily available water (RAW), soil moisture deficit (SMD) and potential recharge for the study area are the outputs of the improved soil moisture balance model obtained through the use of computer programming. The relationships between the rainfall, TAW, SMD and the runoff are presented in Figures 3 & 4.

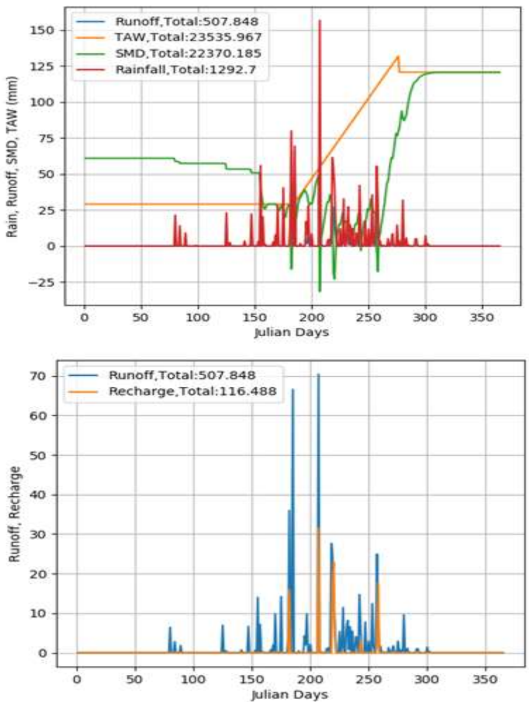

Figure 3: Improved Soil moisture balance components Rainfall-Runoff 2015 Values for Bida basin

For 2015 water year as shown in Figure 3, the annual runoff from the basin is 507.85 mm, which is 39.3 % of the annual rainfall. During days with low or zero rainfall, the actual evapotranspiration is less than the potential only when SMD > RAW. From the figure, between 0-175 Julian days, SMD was observed to be greater than TAW, which explained why there was no significant runoff in the catchment. The first recorded significant runoff was observed at 152th day while the highest value was recorded at 180th day.as 67 mm. As a result of significant rainfall recorded and the consequent runoff, TAW was observed to be greater than SMD between 182th to 300th day. It was during this period the highest runoff vales were recorded.

In figure 4 which represents the hydrological components of improved soil moisture balance model for 2016 water year, the annual runoff from the basin is 501.64 mm, which represents 34.05 % of the annual rainfall of 1473.2 mm. Between 0-130 Julian days, SMD was observed to be greater than TAW, which means there will hardly be available soil moisture for the crops. This also explained why there was no significant runoff in the catchment during this period as the soil has not yet reached field capacity. The first recorded significant runoff was observed at 125th day (when SMD = 0) while the highest value was recorded at 180th day.as 47 mm. As a result of significant rainfall recorded and the consequent runoff, TAW was observed to be greater than SMD between 182th to 300th day. The constant SMD up to 118th day was attributed to lack of rainfall. The onset of significant amount of rainfall at 118th day caused the reduction in SMD values to as low as 18 mm at 150th day.

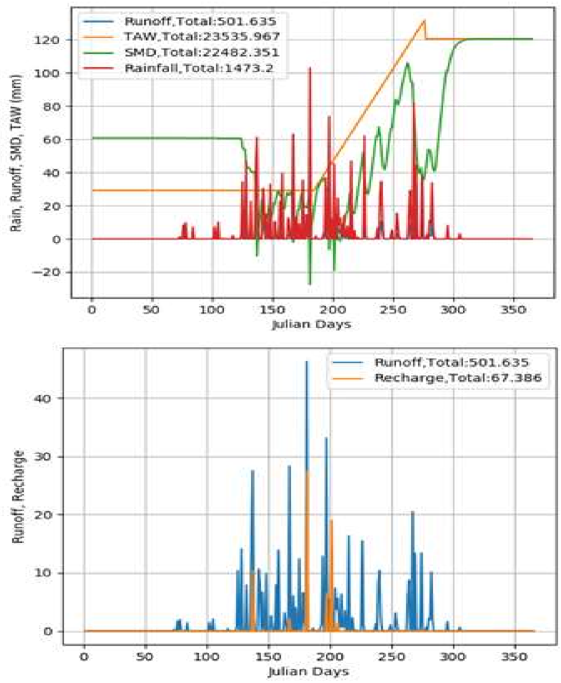

Figure 4: Improved Soil moisture balance components Rainfall-Runoff 2016 Values for Bida basin

The hydrological components for the rest of the study years were presented in Table 3. 2018 study years recorded the highest annual rainfall depth as 1615.2 mm, while the year 2019 study year recorded the highest annual runoff value as 580.76 mm, which is observed as 41.30 % of annual rainfall. The highest values of runoff depth recorded in the years 2018 and 2019 study years could be attributed to the lower value of SMD (Song and Wang 2019) during the both years as against the higher values recorded in the years 2015 to 2017.

TABLE 3: ANNUAL VALUES OF IMPROVED SMB MODEL COMPONENTS

Year	Rainfall (mm)	Annual Runoff (mm)	% of Rainfall	SMD (mm)	TAW (mm)
2015	1292.7	507.848	39.29	22370.19	23535.97
2016	1473.2	501.64	34.05	22482.35	23535.97
2017	1088.3	351.97	32.34	22396.52	23535.97
2018	1615.2	561.04	34.74	21172.79	23474.55
2019	1406.3	580.76	41.30	21282.98	23474.55

4.0 CONCLUSION

Surface runoff has been estimated in a semi-arid region of Bida basin, in Bida, Niger State, Nigeria using an improved soil moisture balance model based on a single soil water store. Soil and crop properties are simulated in the model using crop coefficients and total and readily available water. Runoff coefficients are based on the current soil moisture deficit and the magnitude of the daily rainfall. The results obtained from the field measurements and that obtained from the model have shown that the model is able to give an accurate estimate of the hydrological parameters. Though this paper focused on the estimation of surface runoff for a study area with a tropical climate having distinct dry seasons, the improved soil moisture balance model adopted has been proven to be applicable to areas with different climatic conditions. Once the hydrological parameters (crop and soil properties) involved like TAW, RAW, SMD, PE, ETo and especially runoff coefficients can be selected carefully; a reliable estimation of hydrological outputs like runoff, recharge and rainfall-runoff relationship can be achieved with high precision. Appropriate runoff coefficients must be carefully selected as this is significant, especially if there are days with intense rainfall (De-Silva et al., 2007). The improved soil moisture balance model has also been found to be effective in estimating irrigation water requirement.

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