Modelling Groundwater Recharge Estimation Using Modified Soil Moisture Balance Approach In Otukpo Basin, Nigeria

Adaudu, I. I.[1]; *Adesiji, A. R.[1]; Musa, J. J.[2]; Asogwa, E. O.[1], Mangey, J. A.[3]

[1] Department of Civil Engineering, Federal University of Technology, Minna, PMB 65, NIGERIA
[2]Department of Agricultural and Bioresources Engineering, Federal University of Technology, Minna, PMB 65, NIGERIA
[3]Water Resources and Environmental Engineering Department, Ahmadu Bello University, Zaria, NIGERIA
*Corresponding author email: ade.richard@futminna.edu.ng

ABSTRACT

In this paper, groundwater recharge in Otukpo basin is estimated using a modified daily soil moisture balance based on a single soil water store for a climate classified as tropical with distinct dry and wet seasons in the Middle Belt part of Nigeria. Soil properties like field capacity, permanent wilting point, readily available water, actual and potential evapotranspiration, soil moisture deficit were all estimated and deployed in the model which algorithm was developed using Python programming language, hence the name modified soil moisture balance model. Runoff is estimated using runoff matrix and runoff coefficients which depend on rainfall intensity and soil moisture deficits. A new component, near surface storage, is used to represent continuing evapotranspiration on days following heavy rainfall even though the soil moisture deficit is high. Groundwater recharge is estimated for cassava and yam which are commonly cultivated vegetable crops in the study area. Meteorological data for the periods of 2008 to 2018 were used in the model analysis. The model recorded annual groundwater recharge which varied from 38.119 mm in 2017 water year (just 3.6% of annual rainfall for the year) to 333.35 mm in 2009 water year which is 20.01% of annual rainfall for the year). The highest annual rainfall depth was also observed in the year 2009 as 1665.4 mm, with the lowest annual rainfall depth, 1062.4 mm also observed in the year 2017. The annual runoff ranged from 322.04 mm in the year 2015, a 32.16 % of annual rainfall for the year to 935.56 mm in the year 2008 a 58.17 % of annual rainfall for the year. The lowest actual evapotranspiration AE was also observed in 2017 as against the highest in 2012. The AE ranged from 583.84 mm in 2017 to 721.39 mm in 2012. The model gave a simplified method of groundwater recharge estimation as well as runoff depth coupled with rainfall-runoff relationship.

Keywords: *Soil and crop properties, groundwater recharge, soil moisture balance model, Otukpo basin*

.

1 INTRODUCTION

Recharge is the primary method through which water enters an aquifer. This process usually occurs in the Vadoze zone, below plant roots and is often expressed as a flux to the water table surface (Meyer, 2010). According to Flora (2000), Groundwater recharge also encompasses water moving away from the water table farther into the saturates zone. Recharge occurs both naturally through the water cycle and through anthropogenic processes in other words, artificial groundwater recharge where rain water and/or reclaimed water is rooted to the subsurface. Groundwater recharge happens when a part of precipitation on the ground surface infiltrates through the soil and the reaches the water table. Groundwater recharge can be known as water moving from the land surface to the unsaturated zone. When water reaches the water table, it can go out of the ground water to the surface water which is called discharge (Shukla and Jaber, 2006). The amount of recharge in humid region is usually high because the region receives large amount of rainfall, have favourable surface conditions for infiltration and a less susceptible to the influences of high temperatures and evapotranspiration (Reese and Risser, 2010). For example Azeez, (1972) reported that a substantial rate of groundwater recharge occurs in the regolith overburden in the basement complex of Southwestern Nigeria.

Groundwater has been identified as the primary source of water for domestic and agricultural water supplies throughout the tropics and much of sub-Saharan Africa (Doll *et al* .2012), Efforts to meet projected increase in freshwater demand over the next few decades across sub-Saharan Africa depend on the development of the groundwater resource which in many environments is the only perennial source of freshwater (MacDonald *et al.* 2012). Groundwater is the capital source of freshwater for nearly half of earth's population for irrigation and domestic water needs (Wendland et al., 2002). Groundwater is identified as a renewable water resource for supporting agricultural, industrial, environmental and municipal domestic water demands. According to Bogena (2005), the estimation of ground water recharge is the key to understanding the groundwater reservoir and forecasting its potential accessibility and sustainability even though other elements have to be taken into accounts for example, social, economic and hydrogeological considerations.

Groundwater recharge is a fundamental importance to meet the rapidly increasing agricultural, industrial and domestic water supply requirement within the Otukpo basin. This resource is almost the only key to economic development in the area and hence the estimation of groundwater is a necessity for the efficient and sustainable groundwater resource managements. Gehrels (1999) concluded that the method of estimating actual evapotranspiration and charges in soil water storage determines the accuracy of the water balance. However due to lack of basic understanding of the spatial and variability of hydrological processes, water management is becoming a major challenge. The groundwater recharge estimation and causes of groundwater level fluctuations in the Otukpo basin are not well understood due to limited knowledge of the soil water flow through the thick unsaturated zone and of the actual evapotranspiration from the area. Also, within the basin, the role of groundwater, with recharge estimation as a critical parameter for determining its sustainable use is becoming increasingly important in the emerging integrated water resource management. Therefore, a proper understanding of estimating recharge as a result of modeling is crucial to assessing groundwater availability efficiently. This study would provide a better understanding of groundwater recharge estimation in the Otukpo basin and would also provide detail of how much groundwater that is available for various uses such as agricultural, industrial, domestic and so on.

2 METHODOLOGY

2.1 DESCRIPTION OF STUDY AREA

The Otukpo basin is located in Benue State, North Central part of Nigeria. It is bordered geographically by latitudes 7o 12` 60.00`` N and Longitude 8o 08` 60.00``E. Climatically, the town belongs to the Kopper's Aw climate group and experiences, seasonal wet and dry seasons. The rain falls for seven months from April to October, while dry season sets in November and ends in March (Ologunorisa, 2006). Temperatures are constantly high averaging between 28o – 32oC and sometimes rising to 37^{o}C.

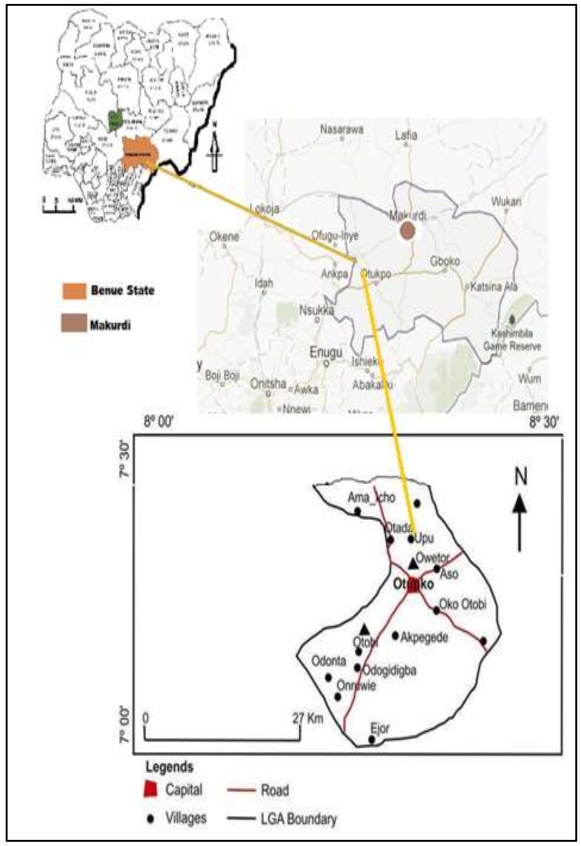

Figure 1: Map of Nigeria showing the study area (Otukpo Basin)

2.2 MODIFIED SOIL MOISTURE BALANCE

2.2.1 METHODS

A simplified daily soil moisture balance model is used which is based on the methodology described by Rushton (2003), which also lists the relevant algorithms; calculations can be performed using an Excel spreadsheet or any other program. But in this paper, Python was used in writing a programe for the execution of the algorithm. Other programmes that could still be used include languages like FORTRAN, BASIC, Java. Python is a generic, interpreted scripting language, supporting object-oriented programming which was first released in 1991.

The representation of crops and soils using this approach is based on FAO guidelines (Allen *et al.*, 1998). The estimation of potential recharge estimation using a modified soil moisture balance model (MSMB) is based on the fact that the soil becomes free draining when the moisture content of the soil exceeds a limiting value called the field capacity when excess water then drains through the soil to become potential recharge. Therefore, in order to determine when the soil reaches this critical condition, estimating soil moisture conditions on a daily basis throughout the water year becomes crucial. This is achieved by representing the appropriate properties of the soil, and also the ability of crops to take up moisture from the soil and to transpire to the atmosphere. The conceptual and computational models of this approach are as shown in Figure 2.

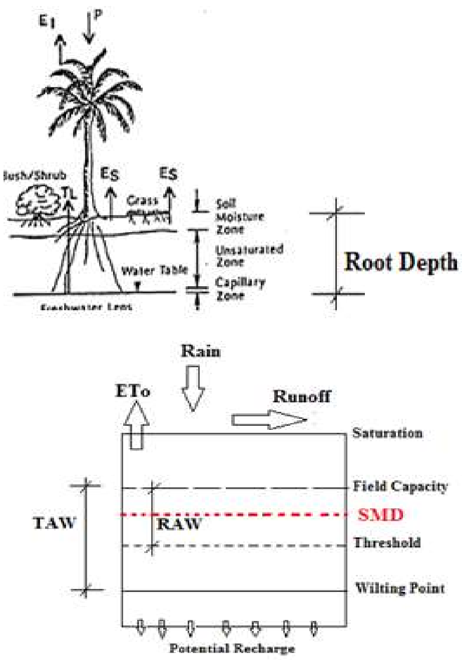

Figure 2: Conceptual and Computational Models of Soil Moisture Balance (Source: Adesiji *et al*., 2020)

Predominantly, the land use in the upland area of the study area is permanent grass with few trees; there are also vegetable plots around the areas where the soil samples for the laboratory analysis were collected. Input parameters for the soil moisture balance are highlighted in Table 1. The parameters are deduced from Allen *et al.* (1998), Rushton (2003) and from farmers' information on planting and harvesting dates in the study areas. Soil in the uplands of the study area is well drained sandy clay loam, which, according to the laboratory results, was observed to have a water content at field capacity of 0.55 m^3/m^3 and a water content at wilting point of 0.23 m^3/m^3. The coefficient for near surface storage for grass is selected to be FRACSTOR = 0.70 based on studies in locations with similar soils. The crop parameters highlighted in Table 3 are selected based on the predominant crops in the study area.

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

Parameters/Year of cultivation	
CROP PARAMETERS:	
Maximum root depth (m)	0.50
*Depletion factor	0.70
Kc (initial)	0.15
Kc (development)	0.70
Kc (mild stage)	1.00
Kc (late)	1.00
SOIL PARAMETERS:	
Bulk density (gcm^{-3})	0.302
VMC @ Saturation (m^3 m^{-3}) θ_{sat}	0.55
VMC @ Field capacity (m^3 m^{-3}) [θ_{sat} x $\frac{\gamma_b}{\gamma_w}$]	0.55
VMC @ Wilting Point (m^3 m^{-3}) **[FC/2.4]**	0.23
Maximum TAW (mm)**[FC-WP]/900%**	35.5
Maximum RAW (mm) **[TAW*0.7]**	24.9
Soil Moisture Deficit (mm)	58.3
*NSS Factor	0.70

Actual evapotranspiration and potential recharge are calculated from daily rainfall data and the daily Penman-Monteith reference evapotranspiration of grass, ETo. Rainfall was recorded in the study area with a tipping bucket raingauge. The CROPWAT model (Smith, 1992) was used to calculate the FAO adapted Penman-Monteith reference evapotranspiration for the study period. The crop potential evapotranspiration PE is calculated from ETo by multiplication with the crop coefficient *K*c. Crop coefficients for various crops are listed in Allen *et al.* (1998). The *K*c values vary during the crop period from initial stage, development stage, maturity and ripening stages; however, for grass, *K*c remains constant at 1.00. Values of *K*c for eggplant are listed in Table 3.

For the successful application of MSMB model, the structure below was used and followed with the input of the hydrological components;

(i) Daily rainfall and reference evapotranspiration.(ET_o)

(ii) Use *SMD* at the driest season as initial soil moisture deficit - SMD

(iii) Compute runoff coefficient, using the runoff matrix

(iv) Compute the Runoff = Rainfall * Runoff coefficient

Obtain Runoff Coefficients through 'trial and error' approach

(v) Determine Available water for evaporation (AWE)

If SMDpr < 0, AWE = Rainfall – Runoff

AWE(Jan 3rd) = 47 - 19.74 = 27.3mm, This is when $SMD_{prev} < 0$

(vi) Compute crop coefficient *Kc* using information on planting date and crop duration
(vii) Potential evapotranspiration (PE) = *Kc* * ETo [*Kc* = 1.0 for mature oil palm]
(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
(xi) Determine soil stress coefficient, *Ks* as follows:'

'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
NSS factor is the storage fraction of near surface storage.
NSS = (AWE – AE)x 0.45, where 0.70 is a NSS constant (Rushton et al. 2003)
SS (Jan 3rd) = (27.3 5.1)x 0.45 = 9.99 = 10 mm
Groundwater Recharge = [SMD_{pre} – 1] + NSS
Recharge only occurs when the SMD ≤ 0

3 RESULTS AND DISCUSSION

3.1 INTERPRETATION OF SOIL MOISTURE BALANCE MODEL OUTPUT PARAMETERS

The modified soil moisture balance components 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: Otukpo basin between 2008, 2009, 2017 and 2018 are presented in Figures 3 to 6 respectively. The most important among the parameters in the figures are the relationships between groundwater recharge, soil moisture deficit (SMD), reference evapotranspiration (ETo), total available water (TAW), readily available water (RAW) and surface runoff. In the figure, the shaded parts represent the periods of higher soil moisture deficits (SMD), where SMD > RAW. The moistures that are held up in the root zones are readily available for crops use. They are termed readily available water (RAW). It is defined as the amount of water readily available for crop for extraction from its root zone (Steduto, 2012) and depends on soil types, depth and distribution of roots within the soil mass (Carr, 2011).

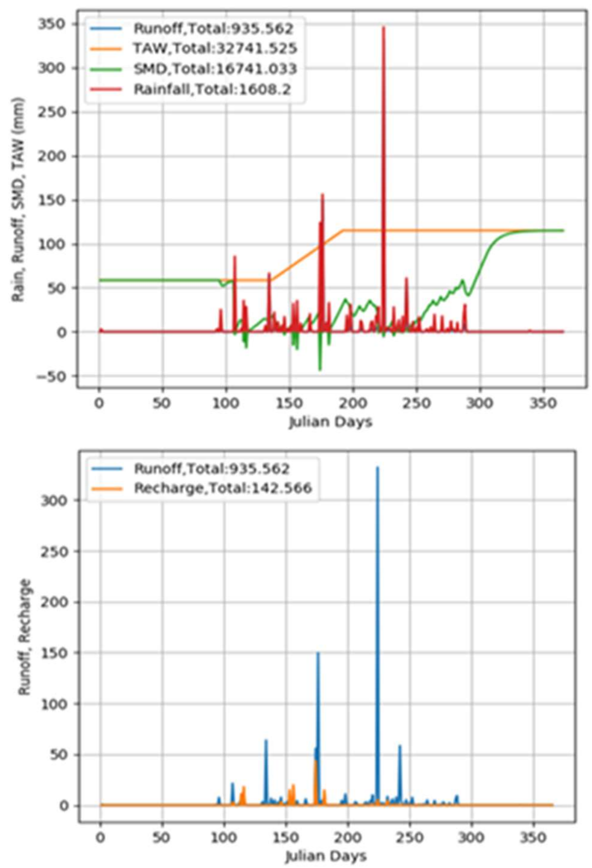

Figure 3: Modified Soil moisture balance components for Otukpo basin (2008)

The total rainfall computed using the MSBM for the year 2008 was 1608.2 mm as presented in Figure 4. The Total Available Water computed using the model for the year 2008, was 32741.525mm and a total Runoff of 898.362mm.

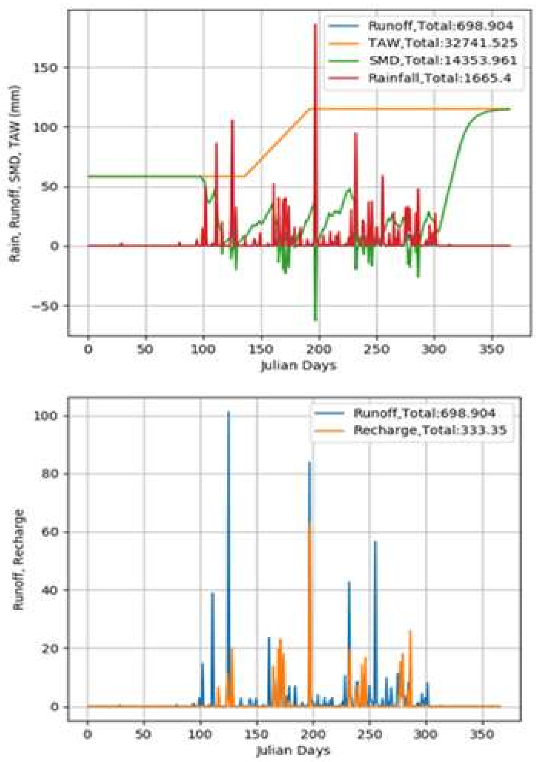

Figure 4: Modified Soil moisture balance components for Otukpo basin (2009)

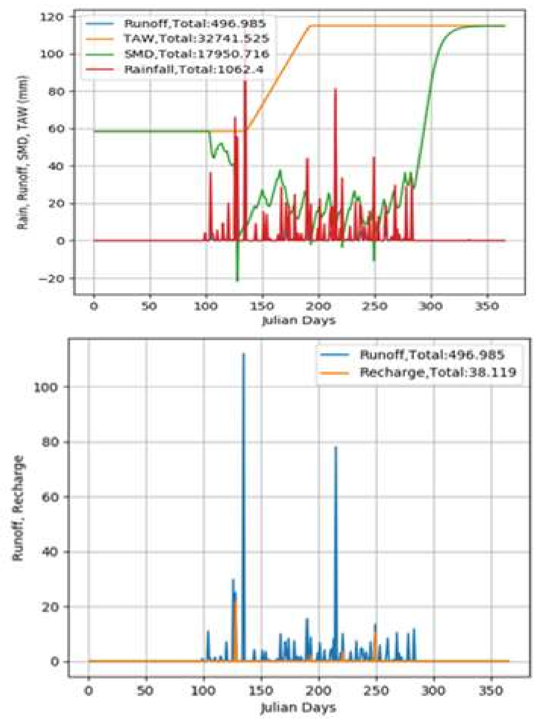

Figure 6: Modified Soil moisture balance components for Otukpo basin (2017)

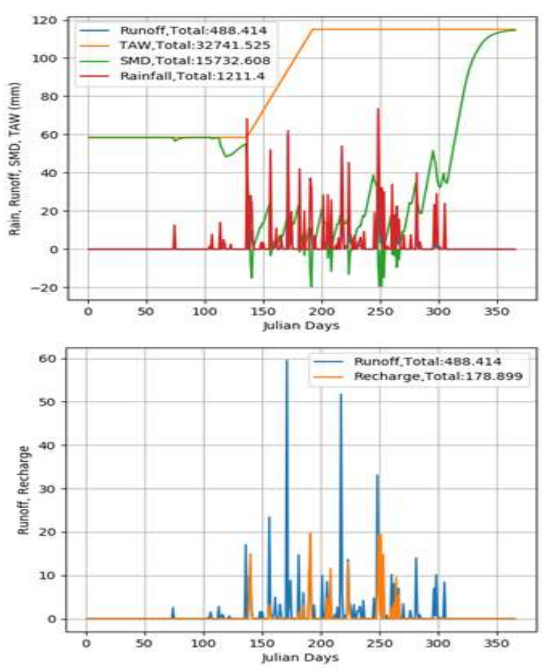

Figure 5: Modified Soil moisture balance components for Otukpo basin (2010)

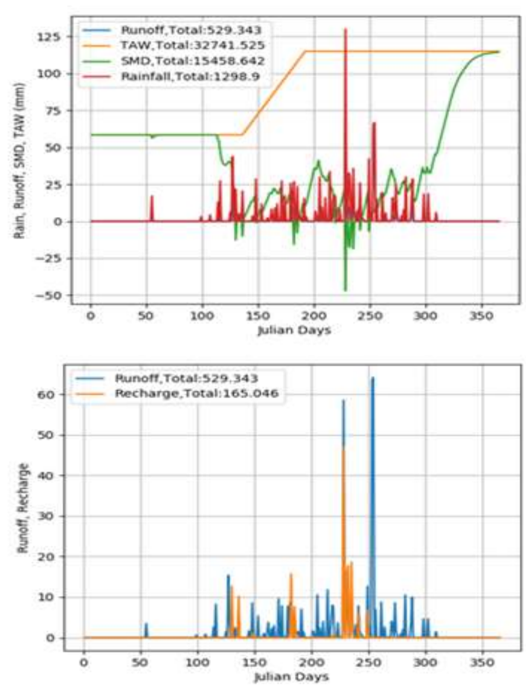

Figure 7: Modified Soil moisture balance components for Otukpo basin (2018)

In all the years under study, from 2008 to 2018, the recharge occurs during April and May when the SMD fell below zero with daily potential recharge ranging from 0.605 in June 2008 to 63.05 mm in July in 2009. The highest potential recharge occurs during mid-July in all the years under study when the SMD falls below zero for 17 days. The total annual recharge for all the years under study are presented in Table 2.

The model recorded annual groundwater recharge which varied from 38.119 mm in 2017 water year to 333.35 mm in 2009 water years. The highest annual rainfall depth was also observed in the year 2009 as 1665.4 mm, with the lowest annual rainfall depth also observed in the year 2017. The annual runoff ranged from 322.04 mm in the year 2015 to 935.56 mm in the year 2008. The lowest actual evapotranspiration AE was also observed in 2017 as against the highest in 2012. The AE ranged from 583.84 mm in 2017 to 721.39 mm in 2012. This shows a significant correlation between rainfall and actual evapotranspiration AE.
MSMB components for the study years are all presented in Table 1.

TABLE 2: ANNUAL VALUES OF MODIFIED SOIL MOISTURE BALANCE COMPONENTS FOR THE STUDY PERIODS

Year	Rainfall (mm)	Runoff (mm)	Recharge (mm)	AE (mm/year)
2008	1608.2	935.56	142.57	586.61
2009	1665.4	698.904	333.35	689.45
2010	1211.4	488.414	178.899	600.34
2011	1449.2	785.705	90.924	628.95
2012	1493.9	640.34	188.269	721.39
2013	1287.9	541.544	137.852	664.78
2014	1248.7	497.64	154.579	652.50
2015	1001.3	322.04	91.699	644.04
2016	1379.9	598.44	190.44	647.56
2017	1062.4	496.985	38.12	583.84
2018	1298.9	529.34	165.05	660.59

From Figure 8, ETo of 5.66 mm/day was earlier recorded from the 1st to the 59th Julian day for the 2008 study year and this was common to all other study periods. There was an increase to 6.07mm/day from the 60th to 90th Julian day. The highest ETo of 6.57mm/day was recorded from the 335th to 365th Julian day. 4.14 mm/day was recorded as the lowest value of ETo recorded from 213th to 243th. Potential Evapotranspiration (PE) was highest with a value of 6.07 mm/day from 60th to 61st Julian day and the lowest value of PE was 0.786mm/day on the 112th Julian day. Actual Evapotranspiration AE at the earlier Julian day was recorded as 0 mm/day.

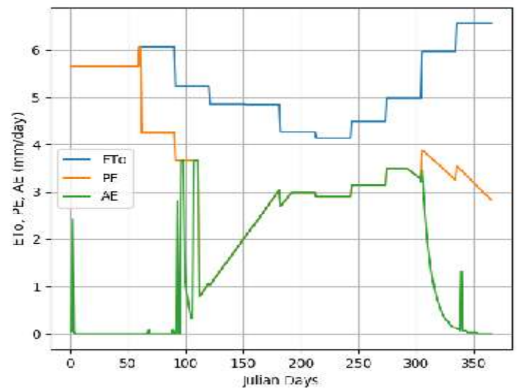

Figure 8: Relationship between ETo, PE and PE for 2008

4. CONCLUSIONS

Potential recharge has been estimated for a climate that belongs to the Kopper's Aw climate group and defined as "tropical with distinct dry seasons" using a daily Modified Soil Moisture Balance Model based on a single soil water store. Reliable estimates can only be obtained if all the physically important processes are represented satisfactorily. Soil and crop properties are determined and 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. Field records of runoff are required so that, by a trial-and-error procedure of adjusting the runoff coefficients, improved simulation of the runoff can be achieved. Near surface storage should be included in the model to represent the

REFERENCES

Adesiji, A.R.‚ Nik Daud, N.N, Asogwa, E. O., Mangey, J. A., Musa, H.H., Adaudu, I.I. (2020). Irrigation and Crop Water Requirement Estimation for Oil Palms Using Soil Moisture Balance Model In Peninsular Malaysia. Journal of Agricultural and Food Engineering. DOI: http://doi.org/10.37865/jafe.2020.0018

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. (1998) *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy.

Azeez, L.O. (1972). Rural Water Supply in the Basement Complex of Western State, Nigeria. IASH Bulletin, 17(1): 97-110.

Bogena, H., Kunkel, R., Schöbel, T., Schrey, H. P., & Wendland, F. (2005). Distributed modeling of groundwater recharge at the macroscale. *Ecological modelling*, *187*(1), 15-26.

Carr, G., Potter, R. B., & Nortcliff, S. (2011). Water reuse for irrigation in Jordan: Perceptions of water quality among farmers. *Agricultural Water Management*, *98*(5), 847-854.

Döll, P., Hoffmann-Dobrev, H., Portmann, F. T., Siebert, S., Eicker, A., Rodell, M., ... & Scanlon, B. R. (2012). Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics*, *59*, 143-156.

Gehrels, H., (1999). Groundwater level fluctuations. Separation of natural from anthropogenic influences and determination of groundwater recharge in the Veluwe area, The Netherlands. PhDthesis, Vrije Universiteit Amsterdam, 267 p

MacDonald, A. M., Bonsor, H. C., Dochartaigh, B. É. Ó., & Taylor, R. G. (2012). Quantitative maps of groundwater resources in Africa. *Environmental Research Letters*, *7*(2), 024009.

Ologunorisa, T. E., & Tersoo, T. (2006). The changing rainfall pattern and its implication for flood frequency in Makurdi, Northern Nigeria. *Journal of Applied Sciences and Environmental Management*, *10*(3), 97-102.

Reese, S. O., & Risser, D. W. (2010). *Summary of groundwater-recharge estimates for Pennsylvania* (No. 70). Pennsylvania Geological Survey.

Rushton, K. R. (2003). Groundwater hydrology. *Conceptual and Computational Models, Wiley*.

Shukla, S., & Jaber, F. H. (2006). Groundwater recharge from agricultural areas in the Flatwoods Region of South Florida. *University of Florida. IFAS Fact Sheet ABE370 EDIS Web Site at http://edis. ifas. ufl. edu*.

Smith, M. (1992) *CROPWAT: A Computer Program for Irrigation Planning and Management*. FAO Irrigation and Drainage Paper 46, FAO, Rome, Italy.

Steduto, P., Hsiao, T. C., Fereres, E., & Raes, D. (2012). *Crop yield response to water* (Vol. 1028). Rome: Food and Agriculture Organization of the United Nations.

Wendland, F., Bach, M., Behrendt, H., & Kunkel, R. (2002). Integrated modelling of groundwater-borne nitrate intakes into the river Elbe basin (German part). In *Proceedings of the 9th International Specialized Conference on River Basin Management, Edinburgh, Scotland*.