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Performance Evaluation of SWAT-based Model for the Prediction of Potential and Actual Evapotranspiration

Abdulkadir T. Sholagberu [1)]***, Farominiyi O. Okikiola*** [1)]***, Adelodun Bashir*** [2,3)]***, Aremu S. Adeniyi*** [1)]***,***
Iji O. Juliana [1)]***, Muhammad M. Muhammad*** [4)]***, Abdurrasheed S. Abdurrasheed*** [4,5)]*

1) Department of Water Resources & Environmental Engineering, University of Ilorin, PMB 1515, Ilorin, Nigeria.
2) Department of Agriculture & Biosystems Engineering, University of Ilorin, PMB 1515, Ilorin, Nigeria.
3) Department of Agricultural Civil Engineering, Kyungpook National University, Daegu 41566, Korea.
4) Department of Water Resources & Environmental Engineering, Ahmadu Bello University Zaria, Nigeria.
5) Department of Civil and Environmental Engineering, Universiti Teknologi Petronas, Seri Iskandar, Malaysia.
* Corresponding Author. E-Mail: abdulkadir.ts@unilorin.edu.ng

ABSTRACT

Hydrological models have become an important tool for the efficient management of water resources. However, selection of appropriate models for evapotranspiration (ET) computations in river basins remains challenging to watershed managers, especially in data-scarce regions. The performance of Soil and Water Assessment Tool (SWAT)-based model for the prediction of potential and actual evapotranspiration (PET and AET) of Ogun-Oshun river basin, Nigeria was investigated. Spatial and meteorological data was applied in setting up Map-window SWAT model. The three existing methods: Penman-Monteith, Priestly-Taylor (radiation-based) and Hargreaves (temperature-based), available in SWAT-were applied for the evaluation of PET and AET using soil, topographic, land-use and meteorological data as input parameters. The model results show a good correlation between the simulated and observed dataset as shown by Nasch-Sucliffe efficiency and coefficient of determination values. For the 30 year-simulation period, the predicted average PET values for Penman-Monteith, Priestley-Taylor and Hargreaves methods were 1791.516, 1684.597 and 1724.563 mm with corresponding standard deviation values of 89.322, 53.824 and 77.867 mm, respectively. The analysis indicated that Penman-Monteith and Hargreaves methods yielded almost the same results, while Priestly-Taylor method slightly differs, which establishes that it is not very suitable for arid/semi-arid regions. The study could be beneficial to watershed managers in addressing climate-related problems and for sustainable water resource management.

KEYWORDS: SWAT, Potential evapotranspiration, Actual evapotranspiration, Watershed.

INTRODUCTION

Climate change phenomenon has necessitated the efficient management of water resources as several regions around the world are currently faced with the growing concern of increasing atmospheric CO_2 and its adverse impacts on the hydrological cycle (Lemordant *et al.*, 2018). This has dictated further investigation on the response of river basins to possible climatic variability. To address the challenges of climate variability on the availability of water resources in watersheds, accurate evaluation of evapotranspiration (ET) is essential, as it plays a critical role in hydrological applications, rainfall–runoff models, drought prediction and monitoring, crop water management and maintaining water balance of the terrestrial ecosystem (Ahmad *et al.*, 2020; Dakhlaoui *et al.*, 2020). While there have been several proposed empirical methods for estimating potential evapotranspiration (PET), the local conditions are major hindrances preventing their applicability in all the watersheds (Jung *et al.*, 2016). Meanwhile, the water-budget calculation and spatially explicit models are among the most commonly used

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methods for estimating potential and actual evapotranspiration (PET and AET) (Abtew and Melesse, 2013). However, direct measurement of evapotranspiration is a complex process that requires expensive equipment to obtain accurate evapotranspiration data (Camp Van *et al.*, 2016; Ochoa-Sánchez *et al.*, 2019).

The concept of evapotranspiration is widely used to indicate the climate-driven water demand governed by available surface water and atmospheric conditions (Dakhlaoui *et al.*, 2020). Evapotranspiration represents the combined loss of water through transpiration process in plants *via* their vascular system and evaporation from the soil and open water surfaces. The rate at which evaporation occurs largely depends on the availability of energy and water, among other factors, at the evaporating surfaces to aid the diffusion of water vapor into the atmosphere (Allen *et al.*, 1998, Abtew and Melesse, 2013). While the soil water availability could limit evapotranspiration considering other environmental conditions, the maximum evapotranspiration rate that occurs when there are sufficient water sources for both plants and soil is termed PET (Anabalón & Sharma, 2017). However, due to an unavoidable limiting effect of soil moisture on transpiration, especially in arid regions, the real water loss to the atmosphere is referred to as AET (Prudhomme & Williamson, 2013). The knowledge of PET and AET is often required in the scheduling of irrigation after estimating the crops' water requirements and landscape plants to achieve efficient water use, reduce waste and pollution. Both PET and AET represent important concepts of traditional evapotranspiration used in hydrology (Anabalón & Sharma, 2017).

The literature survey revealed some models that can be used to estimate evapotranspiration indirectly using meteorological data. The FAO Penman-Monteith model has been widely accepted as a standard approach for estimating reference evapotranspiration from meteorological records (Allen *et al.*, 1998; McMahon *et al.*, 2013). However, the acquisition of reliable and continuous meteorological data is one major issue for hydrological modeling in developing countries and tropical regions (Odusanya *et al.*, 2019). As a result, meteorological data is simulated using different hydrological models with the aid of global earth observations (Lopez *et al.*, 2017). In most studies, the three basic techniques predominately used to estimate PET are Penman-Monteith, Priestly-Taylor (radiation-based) and Hargreaves (temperature-based) (Aouissi *et al.*, 2016). The Penman-Monteith is considered a universal standard method, but it requires continuous daily climatic data, such as solar radiation, wind speed, relative humidity and maximum and minimum temperatures essentially influencing evapotranspiration rate, noting that such data is rarely available in some data-scarce regions making other methods like Priestly-Taylor and Hargreaves that required fewer data indispensable (Arnold *et al.*, 1998; Aouissi *et al.*, 2016; Banda *et al.*, 2018; Djaman *et al.*, 2019). Moreover, temperature and relative humidity were reported to be the essential variables required for PET estimation (Prudhomme & Williamson, 2013). Thus, there is a need for a better understanding of the available models for sustainable water resource management for a particular place of interest.

The application of Geographic Information System (GIS) coupled with remote sensing technology has been continuously explored as an alternative for spatiotemporal estimation of the water budget and its detailed predictions to ensure efficient and effective management of river basins. These technologies are often integrated with some hydrological models, such as Soil and Water Assessment Tool (SWAT), among others, for easy application on a large scale for spatiotemporal analysis of river basins (Arnold *et al.*, 1998). The existence of advanced technology and the availability of cost-effective to free data have encouraged the users for the integration of spatial data, GIS and hydrologic modeling (Odusanya *et al.*, 2019; Lopez *et al.*, 2017, Sholagberu *et al.*, 2019).

SWAT belongs to the group of deterministic and distributed hydrological models embedded with the three techniques: Penman-Monteith, Priestly-Taylor and Hargreaves, for PET estimation. SWAT is a physically-based semi-distributed model that can perform daily, monthly and annual calculations of hydrological balance parameters within the watershed (Neitsch *et al.*, 2011; Abbas and Mohammad, 2012). It is a continuous-time model that operates on a daily time step at the basin scale. In estimating PET from real meteorological data, temperature (minimum and maximum) and precipitation were used as input, often derived from local meteorological stations (Aouissi *et al.*, 2016). Considering the lack of reliable to non-existent ground observed climatic data required for accurate daily estimation of PET and AET in many parts of Nigeria (Xie *et al.*, 2010; Odusanya *et al.*, 2018), an assessment of other alternative methods requiring less climatic data is invaluable to estimate PET and AET that would ensure efficient water resource management for agricultural, hydrological and environmental purposes.

Earls and Dixon (2018) applied SWAT model to estimate and assess the accuracy of PET using different meteorological input data (simulated *vs.* real data) and the three commonly adopted PET methods; namely, Penman–Monteith, Priestley-Taylor and Hargreaves. The study highlighted no significant differences in the predicted PET of modeled and real meteorological data for a given PET calculation method. However, there may be significant differences among the three methods. Furthermore, studies have shown that AET and PET are controlled by several hydrometeorological parameters, such as wind, soil moisture, temperature, relative humidity, … etc. in warmer and drier seasons (Xu and Singh, 2005). Thus, this study aimed to investigate the performances of Penman-Monteith, Priestly-Taylor and Hargreaves methods in estimating PET and AET for the Ogun-Oshun river basin, southwest Nigeria.

MATERIALS AND METHODS

Description of the Study Area

Oyan river dam located on latitude 7°15’N and longitude 3°16’E in Abeokuta north local government area was commissioned in 1983. This dam is run by Ogun-Osun river basin development authority with irrigation and energy generation potential, but it basically supplies raw water to Lagos and Ogun states. The average elevation of the lake is about 43.3m above sea level on the confluence of Oyan and Ofiki rivers (Ofoezie *et al.*, 1991). The total catchment area is approximately 9,000km² within the southern climatic belt of Nigeria. The lake covers an area of 40 km^2. The dam was designed to provide 525 million litres and 175 million litres of raw water daily to the water corporations in Lagos and Abeokuta, respectively.

Modeling Input Data

The map-window SWAT platform is enabled for preprocessing and delineation of watershed into sub-watersheds based on their topographical characteristics. Some other processing on the platform includes shapefile editing, input parameterization, model running and calibration. Input parameters required to run SWAT models are digital elevation model (DEM), digital soil map, land-use map and weather data, as presented in Table 1. In setting up a model using map-window SWAT, GIS process, analyzing all the maps and delineating the watershed and stream networks are carried out, while SWAT generates all the files required to run the model (George & Leon, 2007; Abbas and Mohammad, 2012).

Table 1. Model input parameters for SWAT modeling

Data type	Description	Resolution	Source/Remark
Topography	Digital elevation model	30 x 30 m	USGS, Shuttle radar topography mission
Land-use map	Land-use classification	1 km and 24 classes	FAO, Global land cover classification
Soil map	Soil type and texture	0-30cm and 30- 100 cm depth	FAO, Harmonized digital soil map of the world
Weather	Daily precipitation, maximum and minimum temperatures, relative humidity, wind and solar radiation	Daily	Sourced from Nigeria Meteorological Agency (NiMET)

Digital Elevation Model

A 30×30m pixel DEM was obtained from the shuttle radar topography mission (SRTM) archive. The extracted DEM for the study area (Figure 1) was used to delineate the catchment and to provide topographical parameters, such as overland slope, stream networks and slope length for each sub-basin. During SWAT modeling, the catchment was delineated and discretized into fifteen sub-catchments and nineteen hydrological response units (HRU). Each of the sub-catchments has a distinct mixture of land-use, slope and soil information. This makes it possible to study the differences in evapotranspiration and other hydrological characteristics for different land cover, soil and slope units within the catchment area.

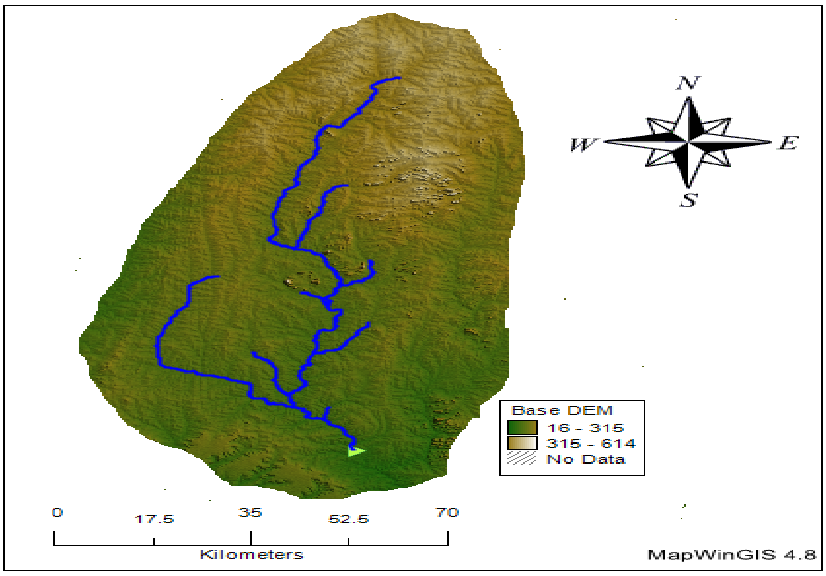

Figure (1): Digital elevation model & stream network

Land-use Map

The land-use map used for the SWAT modeling was obtained from Global Land Cover Characterization (GLCC) database. This was used to evaluate the vegetation and other parameters of interest for the catchment under investigation. The GLCC has a spatial resolution of 1km and 24 classes (GLCC, 2012) of land-use representation. Figure 2 shows the spatial distribution of land use of the study area.

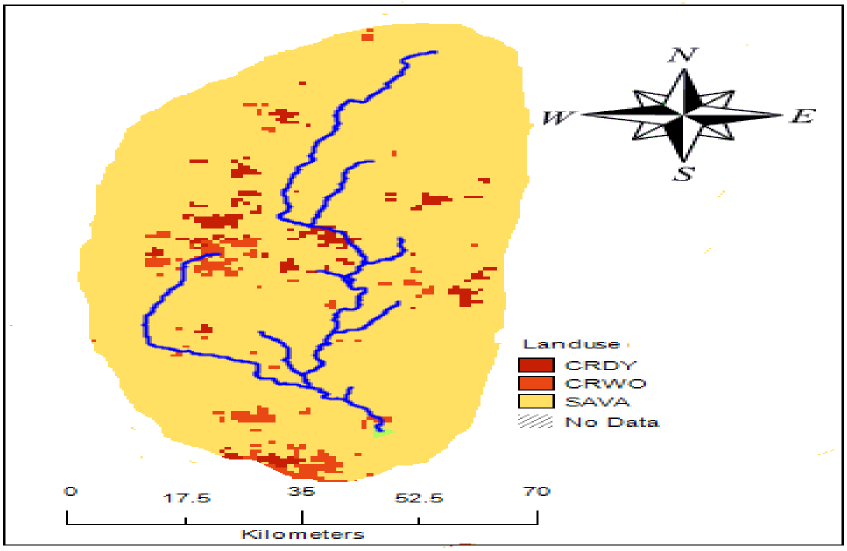

Figure (2): Catchment's land-use map

Soil Map

The digital soil map for the catchment area was obtained from harmonized digital soil map of the world (HWSD vl.1) produced by United Nations Food and Agriculture Organization (FAO) (Nachtergaele *et al.*, 2012). The digitalized soil map provides data for 16000 different soil mapping units containing two layers (0-30cm and 30-100cm depth). The soil map of the catchment area (Figure 3) was extracted for use in the SWAT model as one of the input parameters.

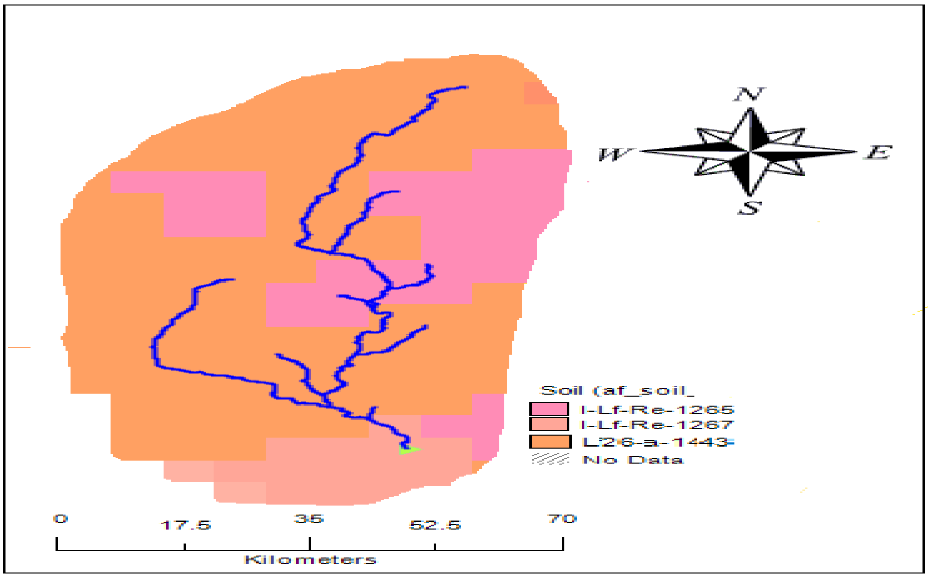

Figure (3): Soil map of the study area

Weather Data

The weather records, such as rainfall, temperature (maximum and minimum), solar radiation and humidity are some of the factors driving hydrological balance within the catchment. Weather data was obtained from the Nigerian Meteorological Agency (NiMET), Lagos, Nigeria and employed in AET and PET simulations using the SWAT model. For the insufficient required weather data for the simulation, a weather generator embedded in the SWAT model was employed to generate more data for successful simulation.

Model Setup

Delineation of catchment into sub-catchments, definition of soil, land-use and weather data are the most crucial steps involved in SWAT modeling. The first step is the catchment delineation followed by inputting the land-use and soil information for the creation of HRUs in sub-catchments. The setup of SWAT model begins by projecting all the spatial datasets to have same projection (i.e., UTM Zone 31N northern hemisphere of the WGS84 for the catchment under consideration). Furthermore, the setup also involves defining simulation periods (start and finish dates) and the selection of weather sources from SWAT database. The weather data obtained was simulated for a period of 30 years using SWAT model in MapWindow. In addition, selection of methods for the estimation of surface runoff (curve number or Green and Ampt method), channel water routing (variable of Muskingum method) and potential evapotranspiration (Hargreaves, Priestley-Taylor, Penman-Monteith) are available. In this simulation, runoff curve number was employed to estimate surface runoff from precipitation data.

PET Model Simulation Scenarios

The criterion for the selection of simulation options was based on the type of data obtained and experiences from previous studies (Ndomba & Griensven, 2011). Surface runoff was estimated using Soil Conservation Services - Curve Number (SCS-CN) method from daily precipitation records using default parameters provided in SWAT. These parameters were defined based on land-use and soil data in the study area. In order to account for the differences in soil, land-use, topography, weather information, amongst others, the catchment was first divided into sub-catchments and further into hydrologic response unit – HRUs (Gassman *et al.*, 2007). Missing weather records were filled using the built-in weather generator. In order to evaluate the performance of PET techniques available in SWAT model, simulations were carried out using the three methods. The potential evapotranspiration was computed using all three available methods in SWAT (i.e., Hargreaves, Priestley-Taylors and Penman-Monteith) based on observed daily temperature data. The Hargreaves method was used as it requires only temperature data contrary to more extensive data requirements for other methods like Priestley-Taylor and Penman-Monteith. The compound runoff from each sub-watershed was routed through the river network to the main watershed outlet by using Muskingum method. A first-order Markov chain skewed normal was used to determine rainfall distribution. Descriptive tools, such as percentages, means, standard deviations… etc., were used to analyze the results obtained. Subsequently, the model was validated and calibrated using statistical measures; Nasch-Sucliffe Efficiency (NSE) and coefficient of determination (R^2) criteria for reliability of the results (Adeogun *et al.*, 2014; Adeogun *et al.,* 2015). The XLSTAT program that performs all descriptive tools was used for the analysis, as well as repeated ANOVA to compare the three methods under discussion.

RESULTS AND DISCUSSION

The correlation between the observed and simulated datasets yielded 0.69 and 0.72, respectively, for calibration and validation using NSE and approximately 0.76 for both calibration and validation when R^2 was used. These values of NSE and R^2 indicated a good model performance in simulating PET and AET for the watershed under consideration. The land-use and land-cover information for the upstream watershed of Oyan is presented in Table 2. The results showed that the study area is predominantly occupied by savannah land-use with about 94% of the watershed. Table 3 shows that the watershed is majorly filled up with sandy clay loam soil occupying about 75% of the total watershed area.

Table 2. Land-use and land-cover types and % coverage area in the watershed

S/N	SWAT Code	Description	Area (Ha)	% of Watershed
1	CRDY	Dry land cropland and pasture	14790.78	3.36
2	CRWO	Cropland/woodland mosaic	11768.16	2.67
3	SAVA	Savannah	413593.74	93.97
Total			440152.68	100

Table 3. Soil types and % coverage area in the watershed

S/N	SWAT Code	Texture	Area (Ha)	% of Watershed
1	Lf26-a-1443	Sandy-Clay-Loam	330901.89	75.18
2	I-Lf-Re-1265	Sandy-Loam	98677.13	22.42
3	I-Lf-Re-1267	Loam	10573.67	2.40
	Total		440152.69	100

Statistical Analysis for the Predicted Potential Evapotranspiration

A quantitative analysis of the simulated dataset obtained from the 30-year simulation period using the SWAT model was carried out and the results are presented in Table 4. Figure 4 shows the representation of predicted annual means of potential evapotranspiration (PET), illustrating the relationship among Penman-Monteith, Priestley-Taylor and Hargreaves methods. It was observed that Hargreaves method produced a higher prediction value in the year 1988 and continued with a close proximity to Penman-

Monteith method. The predictions from the three methods are closer to one another with similar patterns. However, Priestly-Taylor method predicted the least prediction until 2014 through 2017 when it predicted almost the same as the other two methods.

Table 4. Simulated average values of PET and ET for the three methods

	Penman-Monteith		**Priestley-Taylor**		**Hargreaves**	
Year	**PET (mm)**	**ET (mm)**	**PET (mm)**	**ET (mm)**	**PET (mm)**	**ET (mm)**
1988	1819.28	735.82	1759.08	689.74	2021.88	737.60
1989	1631.13	862.56	1684.71	860.59	1778.84	866.42
1990	1724.05	798.56	1682.11	777.98	1821.30	803.99
1991	1647.76	840.48	1713.76	852.56	1724.54	843.71
1992	1581.50	906.19	1664.17	904.64	1650.71	903.49
1993	1644.41	839.74	1718.68	843.03	1756.82	836.25
1994	1680.73	815.78	1717.15	824.80	1791.60	830.67
1995	1543.43	857.94	1578.21	845.48	1705.11	882.33
1996	1579.97	770.67	1618.83	765.22	1771.03	788.78
1997	1689.04	885.29	1714.67	876.09	1792.85	885.18
1998	1644.84	870.76	1672.33	853.73	1756.64	873.25
1999	1617.82	908.78	1721.28	916.43	1703.31	894.61
2000	1588.10	906.16	1680.62	916.54	1657.20	894.73
2001	1610.51	888.05	1703.78	896.02	1707.84	866.00
2002	1759.56	776.81	1729.71	755.05	1897.97	798.90
2003	1738.61	797.82	1758.36	819.21	1808.59	815.61
2004	1906.67	599.40	1839.30	600.19	2027.01	606.79
2005	1773.59	631.27	1733.64	633.23	1905.47	664.51
2006	1754.51	707.93	1735.45	721.00	1854.53	717.75
2007	1770.40	786.23	1770.53	796.32	1850.73	807.76
2008	1731.47	850.20	1758.47	862.75	1841.57	868.61
2009	1697.03	702.18	1674.72	710.73	1833.60	722.47
2010	1699.04	767.75	1761.82	797.82	1788.94	792.02
2011	1702.93	756.21	1739.87	779.43	1798.16	772.60
2012	1692.94	766.23	1718.38	790.89	1818.45	789.32
2013	1668.38	876.07	1752.66	887.18	1752.06	880.40
2014	1710.87	834.00	1806.59	865.91	1750.02	831.18
2015	1660.70	817.69	1791.83	862.37	1751.52	831.91
2016	1620.88	877.16	1766.57	918.30	1703.65	888.55
2017	1647.76	870.85	1769.62	908.75	1723.57	883.21

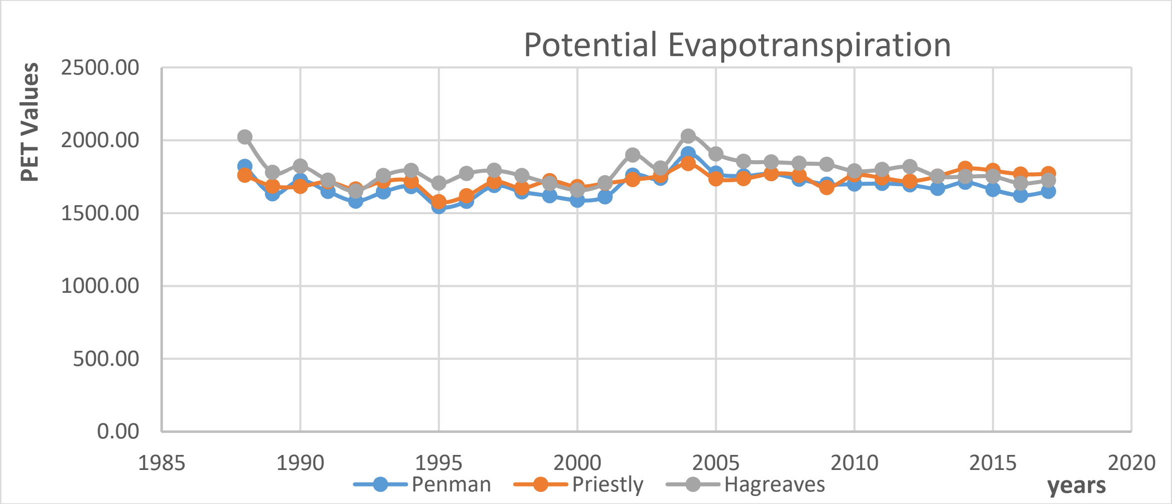

Figure (4): Predicted annual means of potential evapotranspiration

Analysis of Covariance for the Simulated Average Values

Table 5 shows the statistical summary for all the methods evaluated in this study. It was deduced that the standard deviation values for Penman-Monteith and Hargreaves methods have relatively little differences, contrary to Priestly-Taylor method. Analysis of the results showed that the Penman-Monteith, Priestly-Taylor and Hargreaves models produced average PET values of 1724.56, 1684.60 and 1791.52 mm, respectively. The variance in the obtained average values was consistent with the study of Earls and Dixon (2018).

Table 5. Quantitative summary for potential evapotranspiration

Variable	Minimum	Maximum	Mean	Standard deviation
Penman-Monteith	1543.430	1906.670	1724.563	77.867
Priestly-Taylor	1578.206	1839.300	1684.597	89.322
Hargreaves	1650.708	2027.007	1791.516	53.824

Confidence interval is 95% and tolerance is 0.0001.

Statistical Analysis for AET

Figure 5 shows the predicted annual means of actual evapotranspiration, illustrating the prediction pattern of Penman-Monteith, Priestley-Taylor and Hargreaves methods. The quantitative summary of the outputs of the SWAT model is presented in Table 6. It has been stated formally that AET is estimated from PET. However, water loss from the catchment area does not always precede the potential, since it is dependent on PET. The predicted values in Figure 6 are lesser than the PET values, which supports the study of Bergstrom (1992) in that the vegetation is unable to abstract water from the soil when ET value is lesser than PET value. The Penman-Monteith, Priestly-Taylor and Hargreaves models produced average AET values of 810.15, 817.73 and 819.28 mm, respectively.

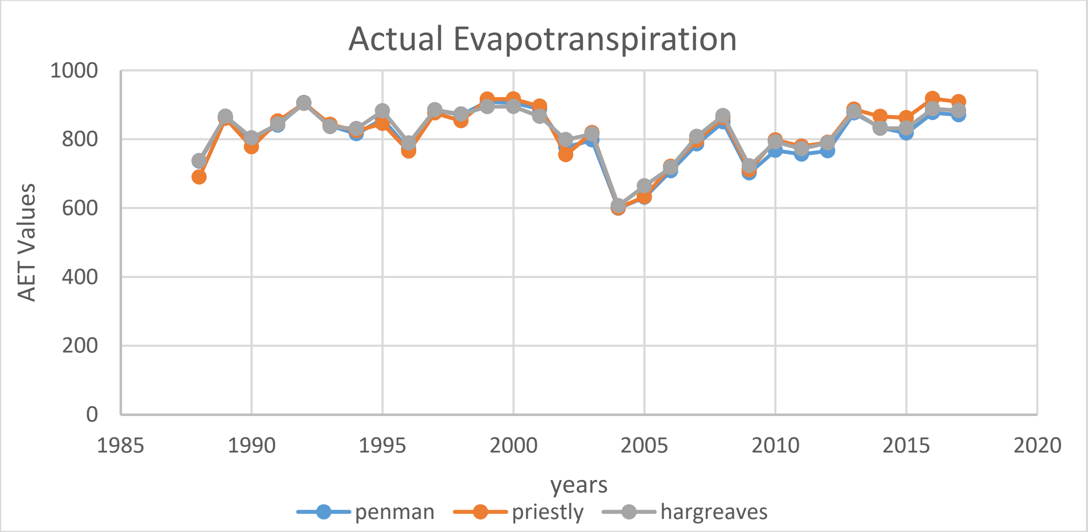

Figure (5): Predicted annual means of evapotranspiration

Table 6. Quantitative statistics for AET

Variable	**Observations**	**Minimum**	**Maximum**	**Mean**	**Standard deviation**
Penman	30	599.40	908.78	810.15	78.64
Priestly	30	600.19	918.30	817.73	83.42
Hagreaves	30	606.79	903.48	819.28	72.27

Confidence interval is 95% and tolerance is 0.0001.

CONCLUSION

The direct measurement of ET is expensive, difficult and time-consuming. SWAT method used in this study is embedded in the Hargreaves as a temperature-based method, Priestley-Taylor as a radiation-based method and Penman-Monteith as a combined method for modeling ET and PET. Water budget calculations and spatially explicit models -among other methods- are the most commonly used for the estimation of PET and AET. However, selection of appropriate models for ET computations in river basins remains challenging to watershed managers. The study investigated the performance of SWAT-based techniques for the prediction of PET and AET of Ogun-Oshun river basin, in Ogun state, Nigeria. The study revealed that the three validated models were able to simulate PET and AET in a very similar pattern, but with different parameter responses. It was observed that Penman-Monteith and Hargreaves methods have the least correlation in the input parameters with similar results for PET and AET. This is in agreement with the previously reported studies in data-challenged regions. However, Priestley-Taylor underestimated the PET and AET for the study area. Also, the analyses indicated that Penman-Monteith and Hargreaves methods yielded almost the same results, while Priestly-Taylor method slightly differs, which establishes that it is not very suitable for arid/semi-arid regions. The study could be beneficial to watershed managers in addressing climate-related problems and for sustainable water resource management in river basins.

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