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GIS-Based Prediction and Comparative Analysis of Potential Evapotranspiration using Selected Methods at Omi-Kampe Watershed, Nigeria

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Abstract

The study predicted potential evapo-transpiration (PET) of Omi Kampe watershed upstream in Kogi State, Nigeria using Soil and Water Assessment Tool (SWAT) based on Priestley Taylor, *Penman Monteith and Hargreaves methods. The model input data used were Digital Elevation Model, Soil map, Land use map and 30-year temporal weather data (January 1987- December 2016) for the simulation of the hydrological processes. The results showed that Penman Monteith and Hargreaves methods exhibited high correlation in the predicted values of PET while Priestley Taylor results for PET are least correlated with the other two methods and suspected to have under predicted PET values. On the other hand, all the three methods predicted the actual evapo-transpiration of the watershed with insignificant result variations. Outcome of this research could serve as a guide to water professionals and other stakeholders in selecting appropriate methods for evaluation of PET in the study area and sub region in Nigeria.*

Keywords: Hydrological Models, Nigeria, Potential Evapotranspiration, Simulation, SWAT, Watershed.

1.0 INTRODUCTION

Hydrological balance of an area involves majorly precipitation and total evaporation (Evapotranspiration or consumptive use) of water from water bodies, soils, snow, ice and vegetation [1, 2]. Although attempts had been made in the past to draw distinction between AET and consumptive use which are usually considered to convey the same meaning [2], AET is the combine effect of evaporation (loss of water to the atmosphere) from water bodies and soils and transpiration (loss of water to the atmosphere) through plants and leaves. Evapotranspiration which is considered as one of the water balance components of rainfall plays a very significant role mostly in hydrologic budgets, rainfall-runoff models, infiltration calculations and drought prediction models. On the other hand, Potential evapotranspiration (PET) can be defined as evapo-transpiration that will occur while there is an adequate moisture supply at all times. PET describes the maximum amount of evaporation which is possible when enough water is supplied [3].

There are numerous approaches of estimating AET and PET, depending on the purpose and type of data that is available. Some of these may be categorized into radiation, water budget, mass transfer, temperature, and combination methods [2]. These approaches differ largely in terms of complexity, required data and reliability. A comprehensive review of methods for estimating evapotranspiration has been carried out by [4]. It is to be noted that complex relationship between hydrometeorology and site peculiarity factors makes AET to be very difficult to measure. However, water balance modelling with the use of spatial information technology is recently adopted in estimating PET using catchment characteristics [5]. As a result of challenges encountered in measuring PET, it is very advisable to estimate it using established models and equations [6].

Though, there may be several established models and procedures for the estimation of PET and AET, each of the methods has its own advantages and shortcomings and suitability for estimating PET and AET in a particular region of the world. For example, [7] evaluated the performance of Priestley Taylor, Hargreaves and Penman-Monteith methods in Arid and Semi-Arid region of Iran and it was discovered that Hargreaves method was the best alternative in the estimation of both AET and PET when compared with other two methods used in the research. Also, [8] compared different methods of estimating

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Potential Evaporation in a regional area of India, the researchers concluded that Blaney-Criddle method of estimating PET proved to be reasonably correlated with the modeled data and with fewer data requirements and is closely followed by Hargreaves in the study area. Similar research was conducted by [9] on Reference ET in the Southeast of Fars province, Iran by making use of different methods and compared their performance. It was reported that a strong similarity exists between the Pan Evaporation and the Penman-Monteith methods.

However, research in this area is quite limited most especially for watershed in the arid and semi-arid regions of West Africa. Therefore, this study deals with the evaluation and comparative analysis of the performance of three methods of predicting PET and AET namely, Priestley Taylor, Hargreaves and Penman-Monteith embedded in Soil and Water Assessment Tool (SWAT) to identify the best alternative approach in terms of performance for the estimation of PET and AET in a watershed located in this sub-region.

2.0 MATERIALS AND METHODS

2.1 Description of Study Area

Omi-Kampe River watershed is in Yagba West local government area of Kogi State, Nigeria on Latitude 8.3145°N and Longitude 5.5197°E. It has an estimated area of 1,276 Km^2 and is in North-Central geo-political zone of Nigeria. The study area has a maximum and minimum temperature of 33.2 and 22.8°C respectively and is characterized by two seasons, dry and wet seasons [10]. The annual rainfall in the region ranges from 1016 mm to 1524 mm. The vegetation of the watershed consists of mixed guinea woodland and forest savannah. Human activities of the inhabitants of the study area include peasant farming, trading, and fishing. The elevation of the region ranges from 156m to 756m above sea level. The Map of Nigeria showing the location of the study area and connecting rivers is presented in Figure 1.

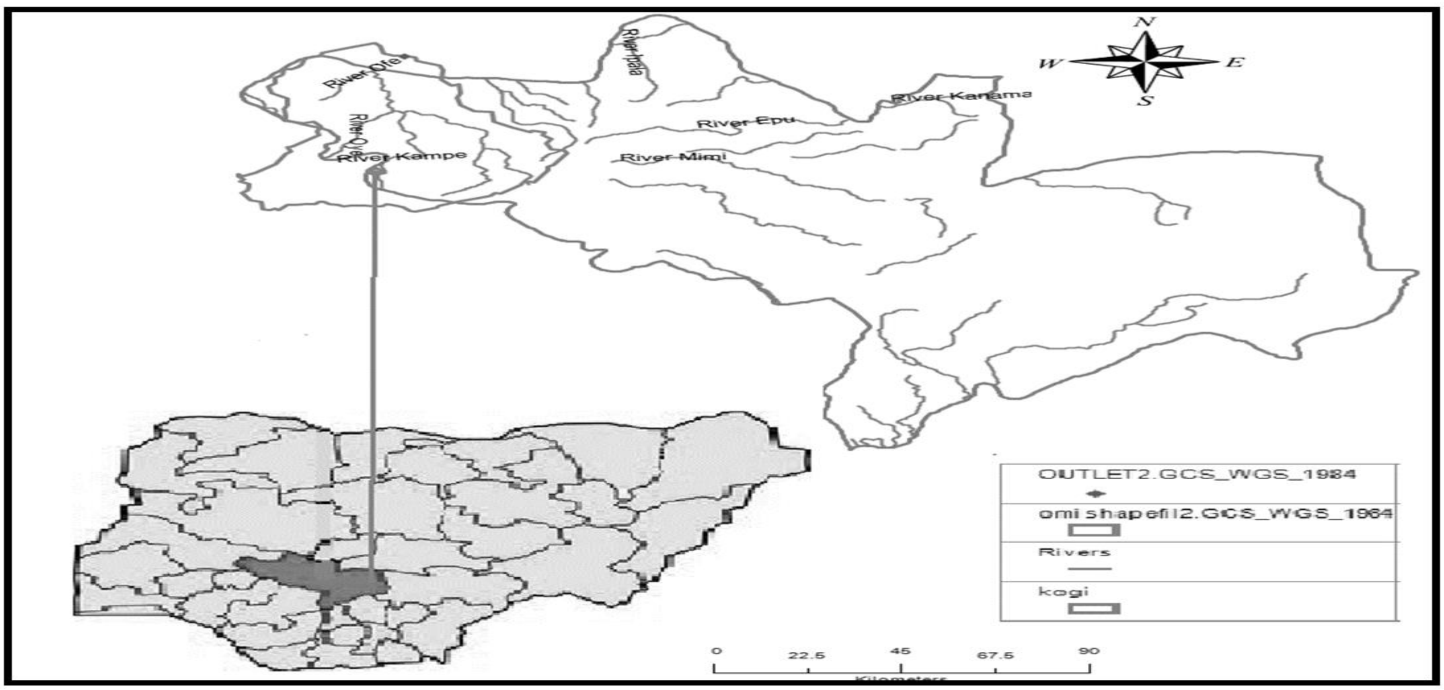


Figure 1: Map of Nigeria showing the location of the study area and connecting rivers

2.2 Model Selection and Description

The hydrological model selected for this research is the Soil and Water Assessment Tool (SWAT). Full description of the model capabilities and mode of operation can be found in [11]. SWAT was originally developed by the United States Department of Agriculture (USDA) to predict the impact of land management practices on water, sediment and agricultural chemical yields in large ungauged basins. The SWAT model is a catchment-scale continuous time model that operates on a daily time step with up to monthly/annual output frequency. The model was selected based on its availability and efficacy in prediction of different hydrological processes as reported in many literature [12-16].

2.3 Modelling Input Data

As reported by [17], there are more than 50 PET methods or models used by researchers around the world. However, in this work, the three most commonly used models based on Priestley-Taylor, Penman Monteith and Hargreaves methods were adopted for the modelling and the results compared. MapWindowGIS integrated with SWAT was used for the hydrological modeling and the prediction of AET and PET in each of the subbasins of the watershed. The MapWindow GIS works in layers and the environment provides the tools and interface for watershed delineation, shape file editing, inputs parameterization, model running, calibration and simulation of results. Model inputs required to run SWAT include the Digital Elevation Model (DEM), land use map, soil map and weather data [18].

2.3.1 Digital elevation model (DEM)

The Digital Elevation Model was extracted from the Shuttle Radar Topography Mission (SRTM) obtained online from [19]. The DEM is of 30m x 30m resolution and the GIS component of the model was used in the pre-processing and geo-referencing of the data to the format suitable for SWAT. Figure 2 shows the DEM of the study area.

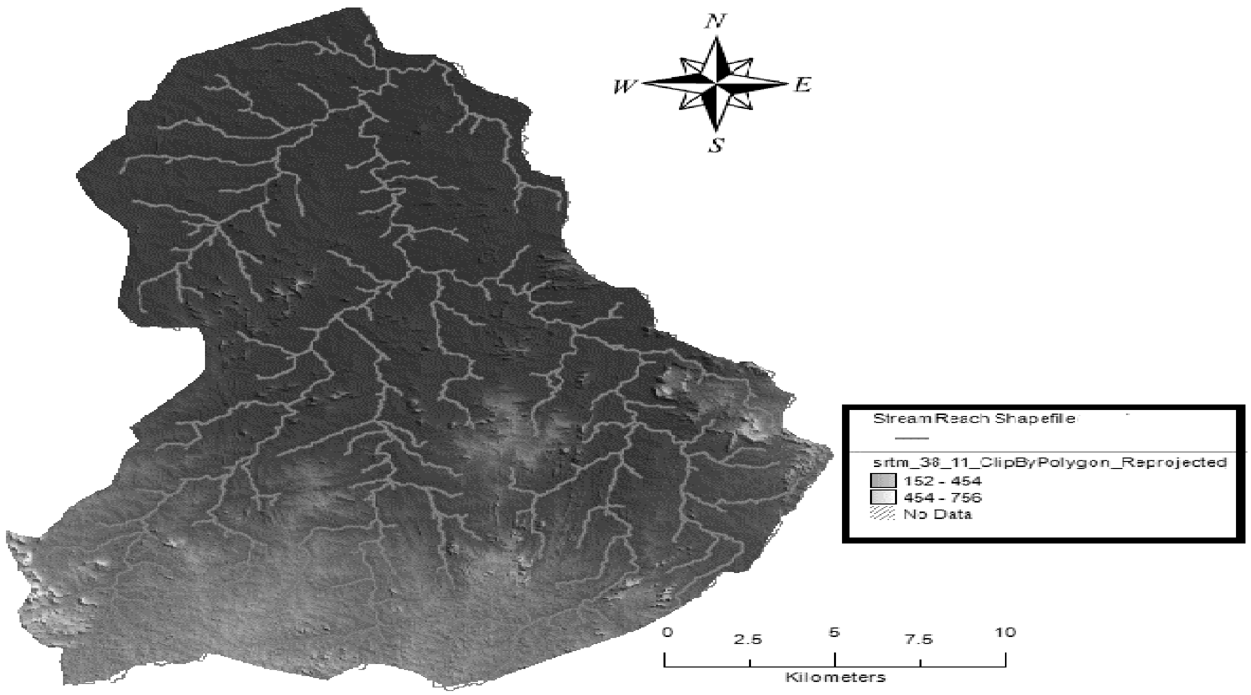


Figure 2: Digital Elevation Model of the study area

2.3.2 Land use and soil data

Land use map of the study area was obtained from Global Land Cover Characterization (GLCC) database. The description of each of the land use, area (hectare) and the percentage coverage is presented in Table 1. Based on this information, it can be inferred that the watershed is significantly covered by savannah type of forest. Soil data for the study was extracted from harmonized digital soil map of the world as described in [20]. Table 2 summarizes the types and approximate percentage area coverage of different type of soil at Omi-Kampe watershed. Figure 3 presents the land use map of the study area.

2.3.3 Weather data

Temporal weather data required to run the model was obtained from Nigerian Metrological Agency (NIMET), in Nigeria and include daily rainfall, temperature (maximum and minimum), solar radiation and humidity. These data cover a period of 30 years (January 1987 to December 2016) and were processed and imported into the Microsoft access database of the model.

2.4 Model setup, Simulation and Visualization of AET and PET

Setting up the SWAT interfaced with GIS involves several stages and was described in [14]. Watershed delineation was carried out using the GIS component of the model. The watershed was delineated and discretized into 91 sub-watersheds and 130 Hydrologic Response Unit (HRU), each with unique combination of land use, slope, and soil.

Also, the estimation of surface runoff and channel water routing were achieved using the curve number and variable methods respectively. The prediction of potential evapotranspiration and AET were carried out using the three available methods embedded in SWAT, i.e., Priestley-Taylor, Penman-Monteith and Hargreaves. The model is also capable of reading the daily PET values if the user prefers to apply a different potential evaporation method.

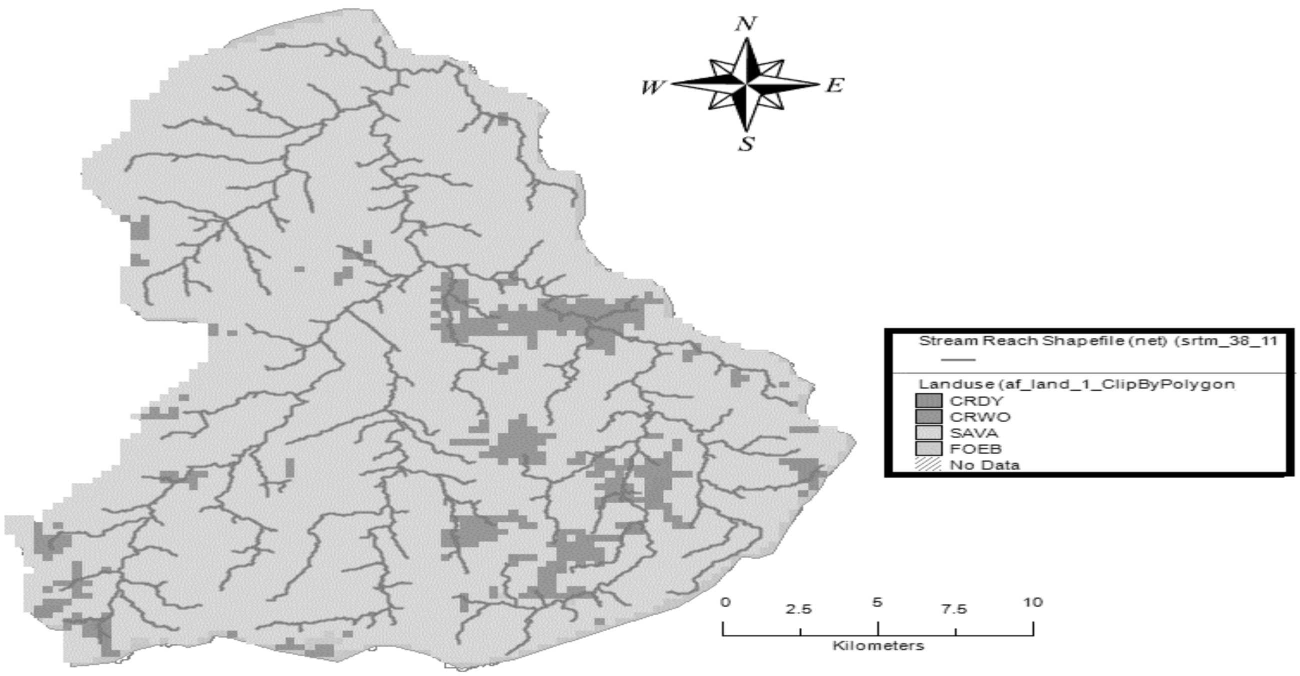


Figure 3: Land use map of the study area

Table 1: Land use and land cover types and % area coverage of the watershed

S/N	SWAT Code	Description	Area (Ha)	% of Watershed
1	CRDY	Dryland Cropland and Pasture	5307.28	1.21
2	CRWO	Cropland/Woodland Mosaic	33393.75	7.59
3	SAVA	Savannah	399410.77	90.72
4	FOEB	Evergreen Broadleaf Forest	869.38	0.20
Total			438981.18	99.71

Table 2: Soil map types and % area coverage of the watershed

SWAT Code	TEXTURE	Area (Ha)	% of Watershed
Lf63-2a-1489	Sandy_clay_loam	128101.75	29.10
Lf64-1490	Sandy_clay_loam	190168.29	43.19
Lf60-2b-1484	Sandy_clay_loam	115806.55	26.30
Lf61-2a-1486	Sandy_clay_loam	4904.60	1.11
Total		438981.18	99.71

The three PET methods embedded in SWAT varies in the amount of data requirement for their estimation. The Penman-Monteith requires solar ration, air temperature, relative humidity, and wind speed while Priestley Taylor method made use of solar radiation, air temperature and relative humidity. The Hargreaves method requires air temperature only.

The Penman-Monteith equation was developed to account for energy needed to sustain evapotranspiration and is written as follows:

$$\lambda E = \frac{\Delta.(H_{net} - G) + \rho_{air}.C_p.[e_z^0 - e_z]/r_a}{\Delta + \gamma.(1 + r_c/r_a)} \quad (1)$$

Where;
λE = Latent heat flux density $(MJ/m^2/d)$
E = Depth rate evaporation (mm/d)
Δ= Slope of the saturation vapour pressure-temperature curve de/dT (kPa/ ◦C)
H_{net} = Net radiation $(MJ/m^2/d)$
G = Heat flux density to the ground $(MJ/m^2/d)$
ρ_{air} = Air density (kg/m^3)
C_p = Specific heat at constant pressure (MJ/kg/ ◦C),
e_z^0 = Saturation vapour pressure of air at height z (kPa),
e_z = Water vapour pressure of air at height z (kPa),
γ = Psychrometric constant (kPa/ ◦C),
r_c = Plant canopy resistance (s/m), and
r_a = Diffusion resistance of the air layer (aerodynamic resistance) (s/m).

The form of Hargreaves equation adopted in SWAT was arrived at after several improvements in the original equation and was published in 1985. This is as written in equation 2: [11, 21]

$$\lambda E_0 = 0.0023.H_0.(T_{mx} - T_{mn})^{0.5}.(\overline{T}_{av} + 17.8) \qquad (2)$$

Where;
E_0 =PET (mm/d),
H_0 = Extra-terrestrial radiation (MJ/m2/d1),
T_{mx} = Maximum air temperature for given day (◦C),
T_{mn} = Minimum air temperature for given day (◦C), and
$\overline{T}_{av}$ =Mean air temperature for a given day (◦C)

In Priestley Taylor Equation, the aerodynamic component was removed, and the energy component was multiplied by a coefficient. The general form of the equation is as written in equation 3:

$$\lambda E_0 = \propto_{pet}.\frac{\Delta}{\Delta + \gamma}.(H_{net} - G) \qquad (3)$$

The model was run for a period of 30 years, that is, from 01 January 1987 to 31 December 2016 for each of the selected methods of predicting AET and PET. Visualization of output was achieved after running all the simulations using either static or animation option. In this study, Output results were domiciled in the subbasins and selection of variables in relation to the study were added as output parameters while visualization was carried using static option of the model output.

2.5 Model Calibration and Validation

Due to lack of observed stream flow data for Omi River in the study area, it was quite difficult to calibrate and validate the model for the studied watershed. However, the predicted results of hydrological modeling using SWAT has been previously calibrated and validated in a similar watershed in North-Central Nigeria. The two watersheds are similar in terms of slope, shape, drainage density as well as land cover and were located in the same geopolitical zone of Nigeria. Details of the previous validation and calibration results can be obtained in [22]. The performance evaluation of the model in the area showed a good correlation between the simulated and observed stream flow data.

3.0 RESULTS AND DISCUSSION

3.1 Prediction of Potential Evapotranspiration (PET)

The spatial distributions of the results of PET using the selected methods are as shown in Figure 4. The average predicted value of potential evapotranspiration (PET) using Penman Monteith method was 2036.68 mm (5.58mm/day). Also, maximum value of PET obtained was in 2003 with a value of 2301.75 mm (6.31mm/day) at sub-basin 1 with catchment area of 0.19 km^2 while the minimum value was predicted as 1828.53 mm(5.01mm/day) in 1998 at sub-basin 53 with catchment area of 30.02 km^2. The average predicted value for PET using Hargreaves method was 2055.719 mm (5.63mm/day). The maximum predicted value of 2213.05 mm (6.06mm/day) was obtained in the year 2003 at sub-basin 49 with catchment area of 35.1 km^2 while the minimum value of 1876.95mm (5.14mm/day) was predicted in 1998 at sub-basin 91 with catchment area of 91.63 km^2. The result obtained in this study compared well with the research conducted by [23] where the highest value of 6.43mm/day, 7.58mm/day, and 8.63mm/day were obtained respectively for Penman Monteith, Blaney Criddle, and Hargreaves within Kaduna Central District, Nigeria.

In the case of Priestley Taylor method, the average predicted value of 1699.478 mm was obtained for the PET of the watershed using. Also, subbasin 53 with catchment area of 30.02 km^2 has the maximum predicted value of 1827.38 mm in 2015 while subbasin 1 with catchment area of 0.19 km^2 has minimum predicted value of 1601.63 mm in 1995. Quantitative summary of the predicted results obtained from the 30 years simulation is presented in Table 3 while Figures 4 and 5 show temporal variation and spatial variation respectively for the three methods. Also, Table 4 presents the summary of the results obtained for PET and AET values for Penman-Monteith, Priestley Taylor and Hargreaves.

Table 3: Quantitative Summary Statistics for Potential Evapotranspiration

Variable	Observations	Observed with missing data	Observed without missing data	Minimum	Maximum	Mean	Std. deviation
Penman	30	0	30	1828.529	2301.745	2036.680	124.666
Priestley	30	0	30	1601.633	1827.376	1699.478	63.147
Hargreaves	30	0	30	1876.953	2213.048	2049.760	100.433

Confidence interval (%): 95; Tolerance: 0.0001

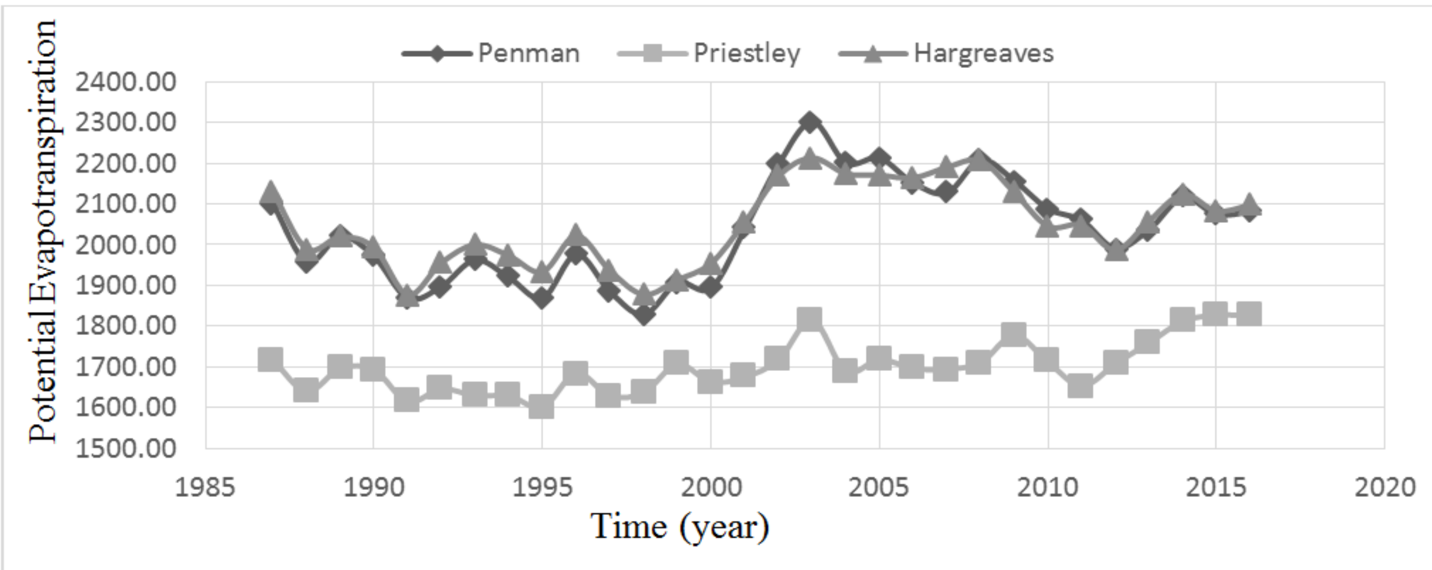
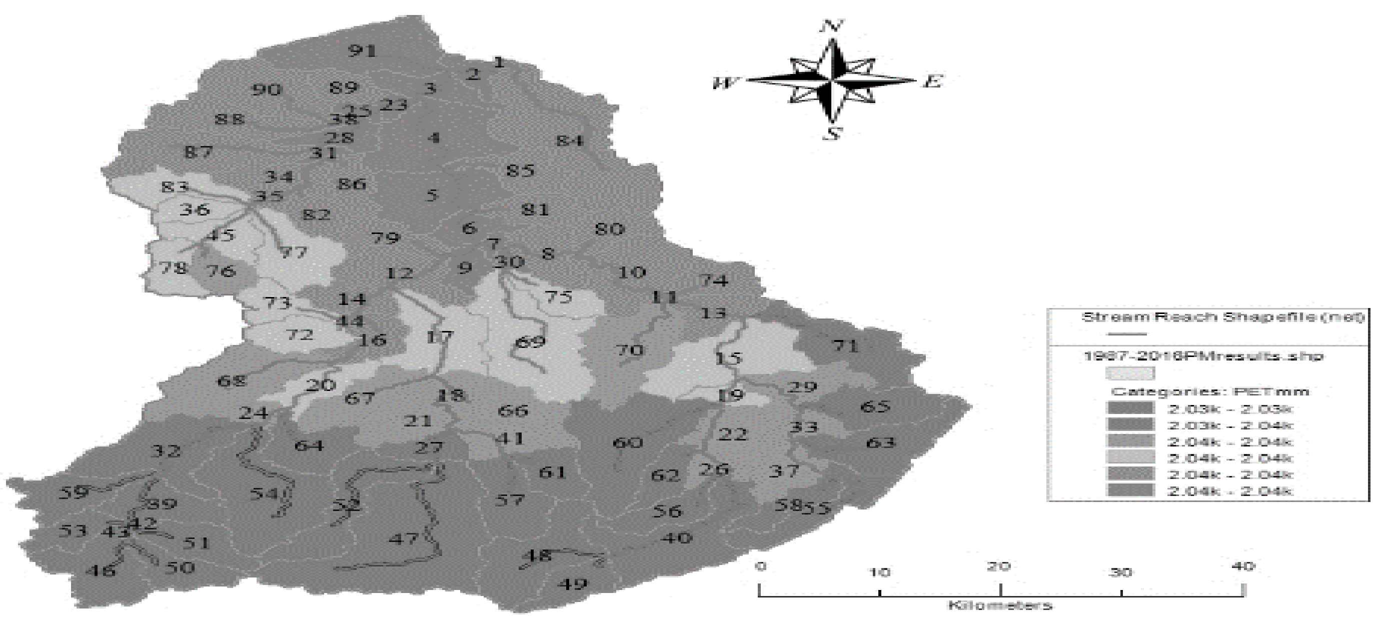


Figure 4: Temporal Variation of predicted annual mean of potential evapotranspiration



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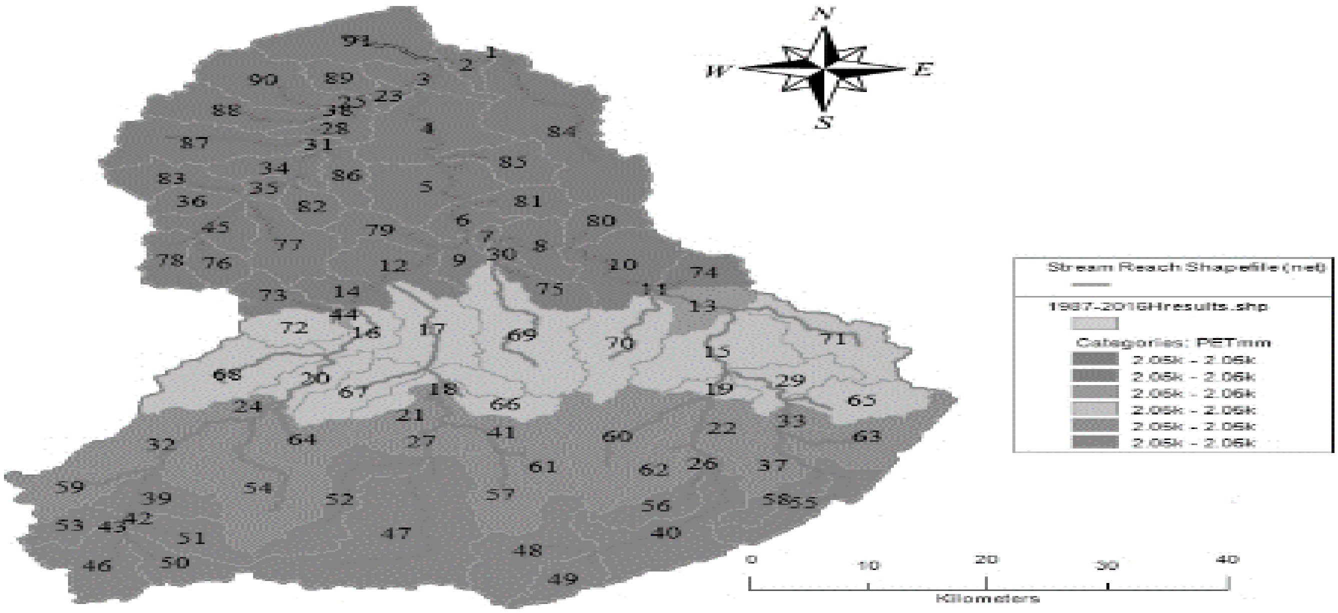

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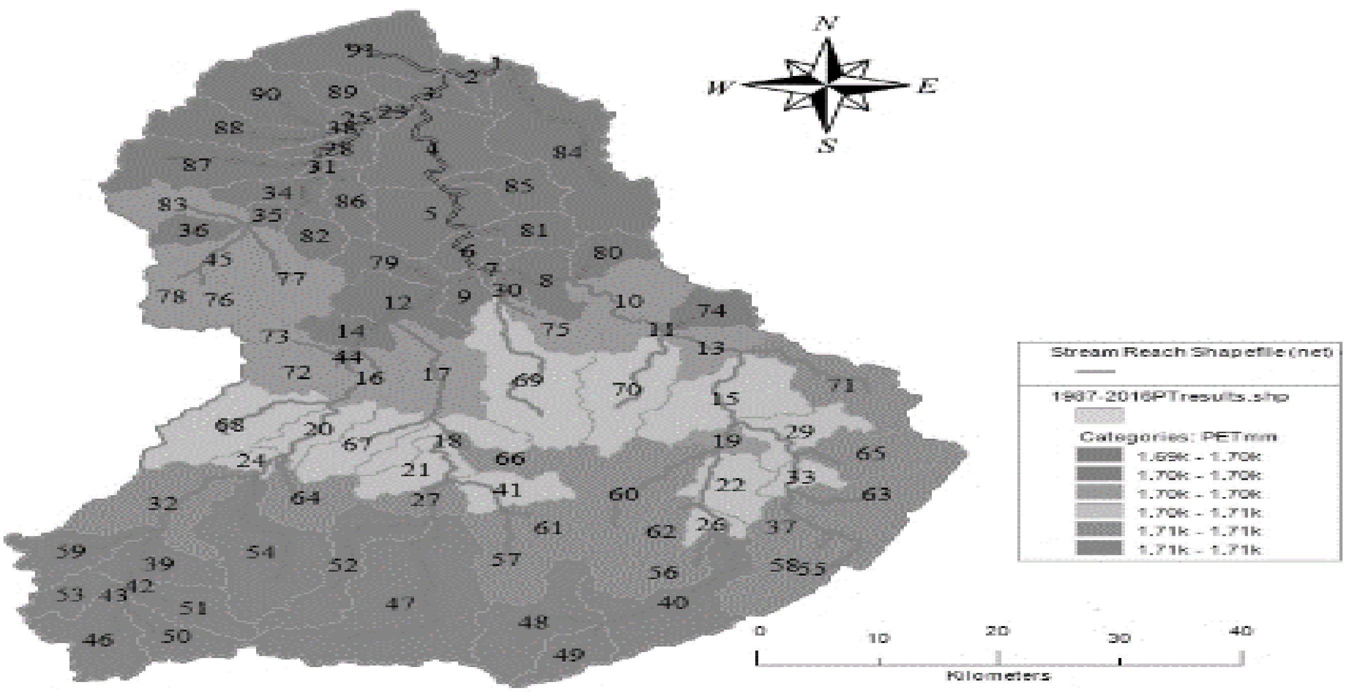


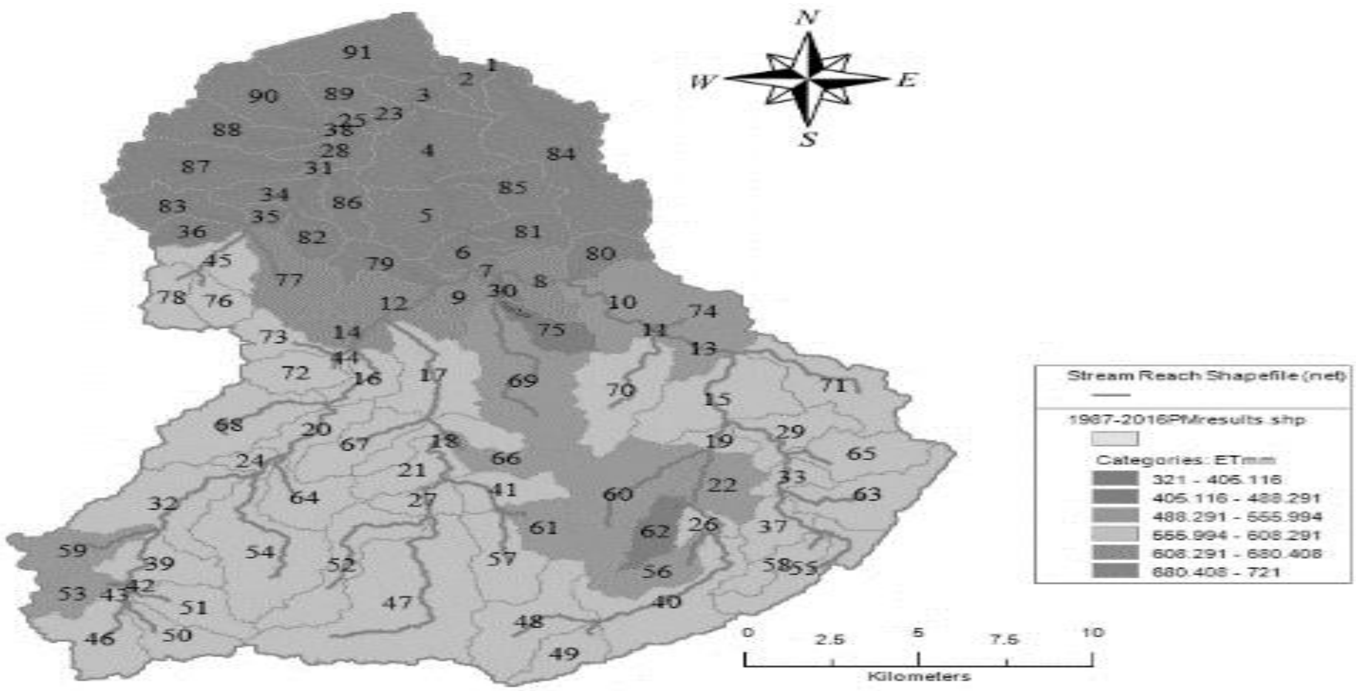
(c)

Figure 5: Spatial variation of predicted annual means of potential evapo-transpiration contributed by each sub-basin using (a) Penman-Monteith (b) Priestley Taylor (c) Hargreaves methods.

3.2 Prediction of Actual Evapo-Transpiration (AET)

The spatial maps for the results of annual mean values of AET in the watershed is as shown in Figure 6. Penman-Monteith method has an average value of 640.29 mm while both Priestley Taylor and Hargreaves method predicted 639.17 mm and 669.80 mm respectively. Also, the maximum and minimum values respectively predicted by Priestley Taylor method are 742.94 mm in 1994 and 382.48 mm in 2003. On the other hand, Hargreaves method predicted 791.44mm (1994) and 390.66mm (2003) while Penman-Monteith methods predicted 760.55mm (1994) and 387.29mm (2003) as maximum and minimum values respectively. It was also discovered that the maximum and minimum values of the AET using all the methods occurred in sub-basin 83 and 11 respectively. The model results were in tandem when compared with the results of the predicted AET as obtained by [24] which uses three potential evapotranspiration (PET) equations (Hargreaves, Priestley-Taylor and Penman-Monteith) for the simulation of AET. The minimum AET obtained by the researchers was estimated as 738mm in 2001 at a watershed in Abeokuta South western Nigeria. The maximum predicted value of 91mm was obtained in1989 at the same watershed.

Tables 4 shows the quantitative summary of the statistics of results while the detailed simulated results for the average PET and AET can be obtained from Table 5. Temporal variation of the results is as shown in Figure 7.



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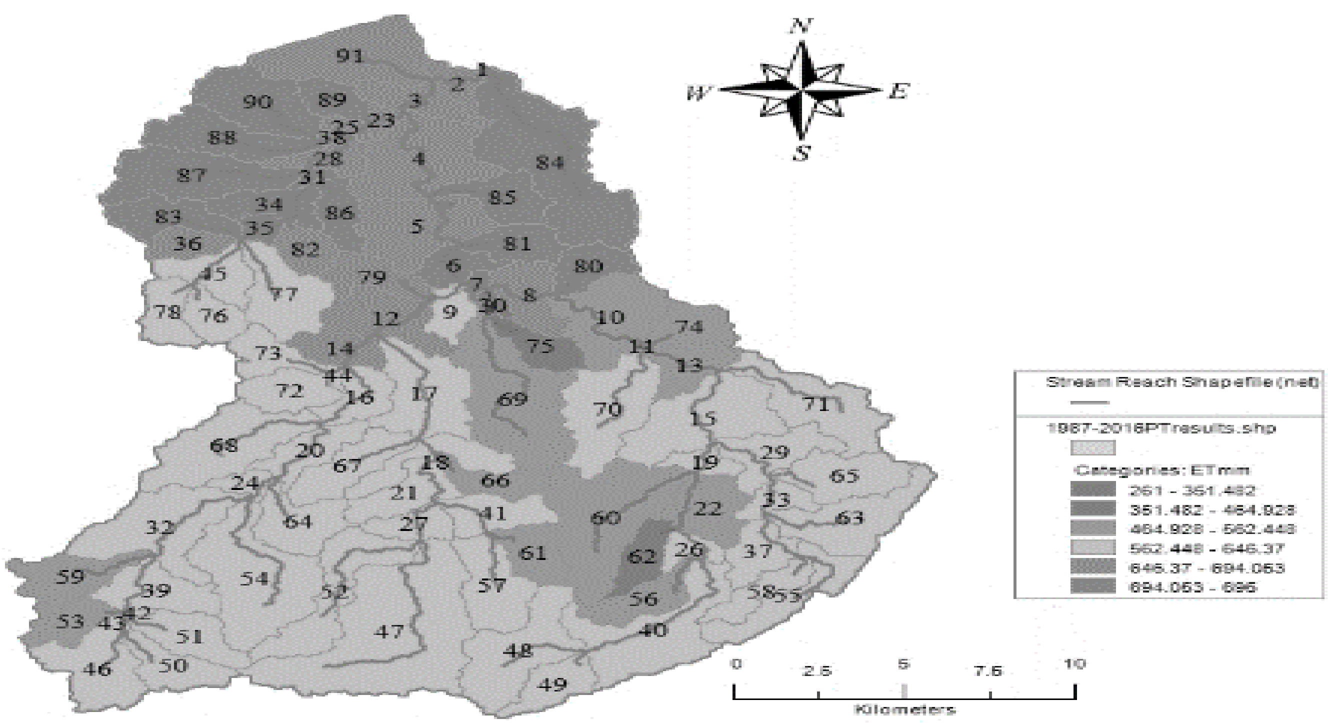

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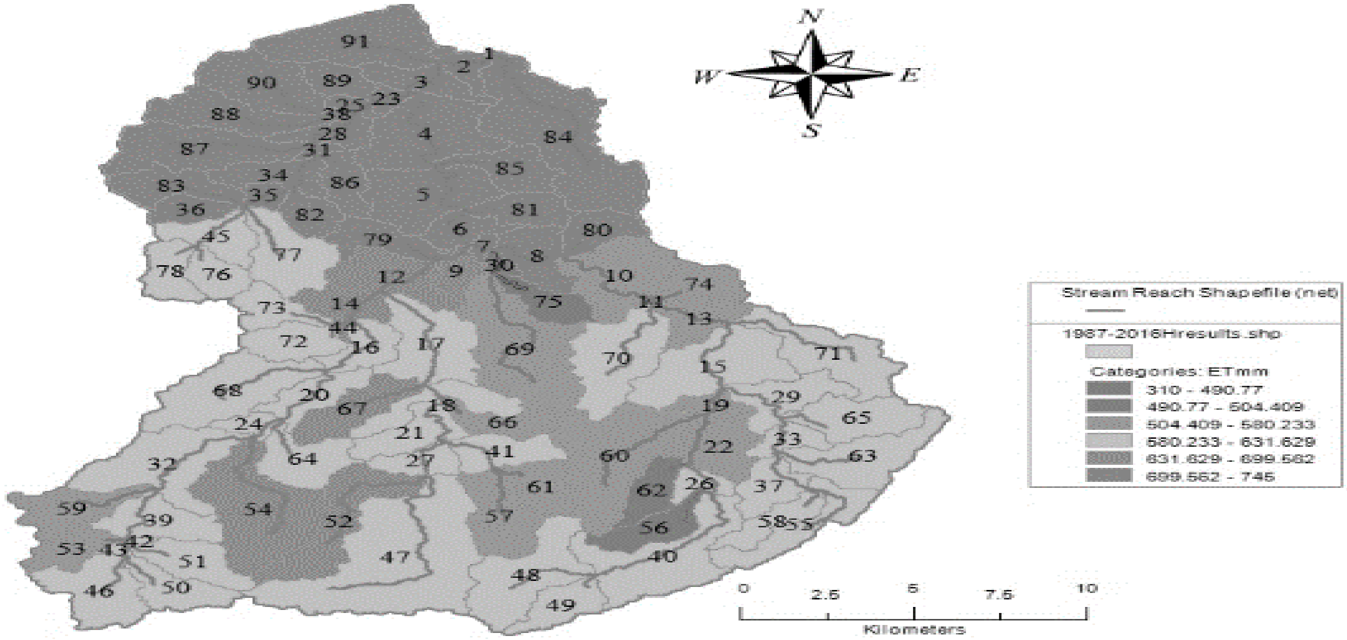

(c)

Figure 6: Spatial variation predicted annual means of evapotranspiration contributed by each sub-basins using (a) Penman-Monteith (b) Priestley Taylor and (c) Hargreaves methods

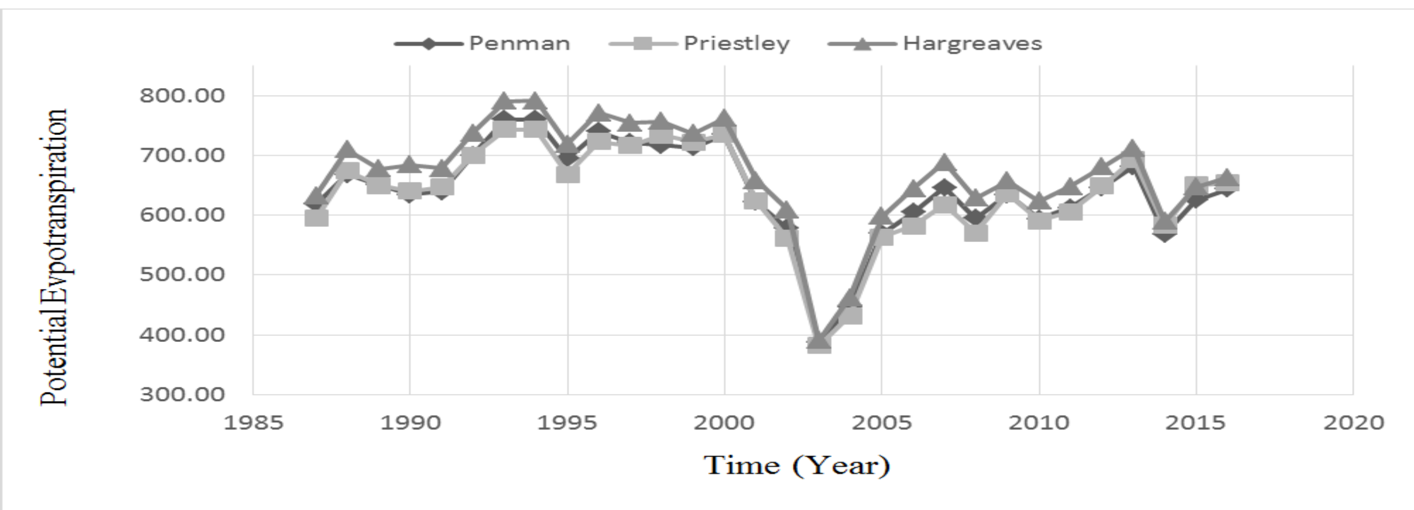

Figure 7: Temporal variation of predicted annual means of evapotranspiration

Table 4: Quantitative Summary of Statistics for Evapotranspiration

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Penman	30	0	30	387.294	760.545	640.291	82.590
Priestley	30	0	30	382.485	742.936	636.174	84.404
Hargreaves	30	0	30	390.662	791.409	670.093	87.439

Confidence interval (%): 95; Tolerance: 0.0001

Table 5: Detailed simulated results for the average PET and AET for Penman-Monteith, Priestley Taylor and Hargreaves Method

	Penman Monteith		**Priestley Taylor**		**Hargreaves**	
Year	PET(mm)	AET(mm)	PET(mm)	AET(mm)	PET(mm)	AET(mm)
1987	2099.46	618.41	1716.65	594.7	2128.61	632.59
1988	1958.11	668.48	1639.88	673.85	1989.82	709.24
1989	2020.71	650.2	1696.95	649.44	2019.66	677.49
1990	1971.29	634.3	1692.59	640.19	1992.93	684.02
1991	1868.83	639.35	1615.2	646.84	1876.95	678.58
1992	1898.04	700.32	1646.67	700.65	1956.25	737.46
1993	1962.81	760.45	1629.37	742.94	2000.06	790.39
1994	1919.92	760.55	1629.37	742.94	1973.11	791.41
1995	1869.34	694.29	1601.63	668.43	1933.65	718.64
1996	1976.6	740.24	1685.23	723.36	2022.64	771.21
1997	1885.04	721.76	1628.73	716.02	1936.64	754.17
1998	1828.53	717.46	1637.42	734.36	1878.14	756.89
1999	1906.15	713.06	1706.64	721.83	1913.71	736.79
2000	1893.32	734.67	1663.26	735.06	1954.74	762.1
2001	2038.45	621.5	1675.48	623.09	2055.74	657.73
2002	2196.91	578.09	1717.53	561.33	2169.38	608.72
2003	2301.75	387.29	1815.17	382.48	2213.05	390.66
2004	2200.76	447.04	1689.64	432.26	2174.54	462.69
2005	2212.67	569.19	1718.65	563.17	2170.68	598.34
2006	2151.66	604.63	1696.35	581.78	2164.36	644.68
2007	2127.19	646.45	1694.86	617.75	2190.19	688.82
2008	2208.1	594.67	1710.74	570.67	2206.05	628.43
2009	2157.35	634.7	1777.92	636.49	2128.45	657.28
2010	2088.03	594.03	1711.76	590.76	2045.3	623.41
2011	2060.04	612.34	1653.63	605.67	2048.03	648.11
2012	1991.27	646.55	1708.04	648.45	1987.01	680.63
2013	2037.37	682.13	1759.64	693.42	2058.79	712.53
2014	2115.94	568.26	1812.2	582.77	2124.16	589.96
2015	2074.47	624.85	1827.38	650.83	2082.69	647
2016	2080.3	643.48	1825.77	653.68	2097.46	662.92

3.3 Comparison of the Predicted Results of PET and ET for the selected Methods

Based on the results obtained, the predicted annual means of potential evapotranspiration using Penman-Monteith (2036.68mm) compared well with the value obtained using Hargreaves (20149.76mm) with standard deviation values of 124.7 and 100.4, respectively. However, it was discovered that there were discrepancies in the spatial and temporal distribution of the maximum and minimum predicted values for both methods. The maximum predicted value for Penman Monteith occurred in subbasin 1 in the year 2003, while that of Hargreaves occurred in sub basin 49 in the year 2003. The minimum values also occurred at different location (Sub basins 53 and 91) and in different year (1998 and 1991) respectively for the two methods.

On the other hand, it was also observed that the average predicted value of PET (1699.48mm), the maximum and minimum values predicted 1827.38mm (2015) and 1601.63mm (1995) respectively using Priestley

Taylor method were quite low when compared with the other two methods; Penman Monteith and Hargreaves. This result implies that Priestley Taylor may have clearly underestimated PET. This might not be unconnected with the different model structures and dominant meteorological drivers, the interannual variability of PET may vary significantly among the models. The statistical relationship between Penman Monteith (PM) and Priestley Taylor (PT) estimation of PET gave a correlation coefficient in of 0.4352 and is expressed as:

$$PM = 1.3023PT + 176.55 \quad (4)$$

The corresponding statistical relationship between Penman Monteith (PM) and **Hargreaves** (HGR) in the estimation of PET revealed a correlation coefficient of 0.9396 and is expressed mathematically as in equation 2.

$$PM = 1.2032HGR + 429.66 \quad (5)$$

This assertion is in tandem with the results of [25] that Priestley Taylor method underestimates PET in arid and semiarid regions of the world while Hargreaves method is generally more correlated with the value obtained from estimates using Penman-Monteith procedure.

Generally, the average annual AET predicted by the three methods adopted in this study showed a very good correlation with standard deviation of 82.59, 84.40 and 87.47 for Penman Monteith, Hargreaves and Priestley Taylor procedures, respectively.

4.0 CONCLUSIONS

Based on the outcome of this study, the following conclusions were drawn:

- All the three methods predicted the Potential Evapotranspiration and actual Evapotranspiration of the study area in a similar order but with different parameter response.
- Penman-Monteith and Hargreaves methods exhibited a high level of correlation in the predicted values of PET while Priestley Taylor results for PET are least correlated with results obtained using other methods.
- All the three methods predicted actual evapotranspiration in a similar order with high correlation of the output results.
- Priestley Taylor method was observed to have underestimated the PET in the study area, thus it is not recommended for the prediction of PET in Arid and Semi-Arid region of Nigeria and Africa while PM and Hargreaves are recommended for the estimation of PET in the region.

Overall, the outcome of this research could be adopted as a decision support tool by relevant professionals in water resources management in selecting appropriate method for the estimation of potential evapotranspiration in the watershed and other sub region in West Africa.

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