Spatial distribution of rainfall and reference evapotranspiration in southeast Nigeria

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Abstract: Spatial trends of rainfall and reference evapotranspiration (ETo) are crucial for sustainable water resources management. Rainfall and ETo trends were evaluated and estimated using FAO Penman Monteith model and their spatial distributions were mapped across the Southeast Nigeria. Two spatial interpolation techniques, Inverse Distance Weighting (IDW) and Kriging in ArcGIS were employed for monthly, annual and seasonal rainfall and ETo. Results showed that rainfall increased gradually from North to South while ETo increased from South to North of the study area. ETo was found to be higher during dry seasons as the average rise in temperature within the period of study stood at 1.1%. There was a positive correlation of the predicted results obtained by the IDW and kriging methods with measured rainfall and ETo data, evaluated at R = 0.87(rainfall) and R = 0.83 (ETo) for IDW method, and R = 0.92 (rainfall) and R = 0.50 (ETo) for kriging method. This study provides background information on rainfall, ETo and climatic conditions for climate change studies, efficient crop water and environmental management.

Keywords: rainfall, reference evapotranspiration, inverse distance weighting, kriging, spatial interpolation

Citation: Okechukwu, M. E., and C. C. Mbajiorgu. 2020. Spatial distribution of rainfall and reference evapotranspiration in southeast Nigeria. Agricultural Engineering International: CIGR Journal, 22 (1):1-8.

1 Introduction

Agriculture receives 66% of total water with drawal and 85% of total consumption in the world (Shiklomanov, 2000). Considering population growth and climate change, the total water with drawal is expected to increase by about 10%-12% by 2025 (Shiklomanov, 2000). The situation could be worse in Africa, and particularly Nigeria, which has been projected to be the third most populous nation in the world after India and China by the year 2050 (United Nations [UN], 2015). In order to cope with this situation, it is generally expected that agriculture through irrigation would provide food requirements of the increasing population. This shows that in the future, there would be a high likelihood of water scarcity and this call for good understanding of our weather and environment for efficient and effective management of available water resources. An efficient water management involves saving water with increased agricultural productivity while reducing adverse environmental impacts of irrigation (Saroj et al., 2014). Efficient water use in agriculture requires the accurate determination of irrigation water requirements of crops, applying water only when necessary at the right quantity (Sharma and Irmak, 2012).

However, this cannot be achieved without the knowledge of reference evapotranspiration (ET_o) of various crops of interest. Meteorological data (temperature, solar radiation, relative humidity and wind speed) can be used to estimate ET_o at any location. Meteorological data are spatio-temporal in nature and only direct measurement of ET_o is by lysimetric study which is time-consuming and expensive (Okechukwu and

Received date: 2018-10-24 **Accepted date:** 2019-10-06

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Mbajiorgu, 2012). Lysimetric studies on every location are practically impossible but, spatial interpolations can be used with a geographic information system (GIS) software, to estimate spatial and temporal data of any geographic point. This is done by using known data to estimate the unknown or unmeasured data. A GIS stores, manipulates, analyzes, retrieves, and displays data referenced in space and time. Spatial interpolation techniques have wide applications, including ground water pollution and contamination (Arslan and Turan, 2015; Gong et al., 2014), groundwater level (Xiao et al., 2016), weather variables (Di Piazza et al., 2015; Lanciani and Salvati, 2008; Goodale et al., 1998) and agro-climatic parameters (Dalezios et al., 2002). It has also been applied in irrigation and determination of water requirements of crops. In Nigeria and most developing countries, observation stations are poorly and sparsely distributed and are prone to frequent breakdowns. The weather stations are managed by NIMET (Nigerian Meteorological Agency) but, these stations do not measure ET directly (Ogolo, 2014).

Spatial interpolation techniques can be employed to estimate missing data and to interpolate value for unknown location from known ones. Some of the commonly used spatial interpolation methods include Inverse Distance Weighting (IDW), Spline, and Kriging (K). There are no best methods of interpolation but, in choosing a particular interpolation method, the quality of the interpolated surface is dependent on the accuracy of the original point data and how well the selected method reflects the underlining spatial structure (Rana and Katerji, 2000; Blöschl and Grayson, 2000). The objectives of this study were to obtain historical climatic data and determine reference evapotranspiration (ET_o) using the data; develop spatially interpolated maps of rainfall and ET_o across the Southeastern Nigeria using ArcGIS software and compare the performance of IDW and kriging interpolation methods in prediction of annual and seasonal rainfall and ET_o in the study area.

2 Materials and Methods

2.1 The study area

The study area comprises the five states of the Southeast geopolitical zone of Nigeria (Abia, Anambra, Ebonyi, Enugu and Imo). It is located between latitudes 04.5° N and 07.5° N and longitudes 06.75° E and 08.75° E (Figure 1). The area is well drained with lakes, rivers and streams which include the Niger, Imo, Nike Lake, Anambra, Ebonyi, Idemili, Njaba, Oguta Lake, Nkisi, Ezu, Oji etc. (Igbokwe et al., 2008). The total area is approximately 29,000 km^2.

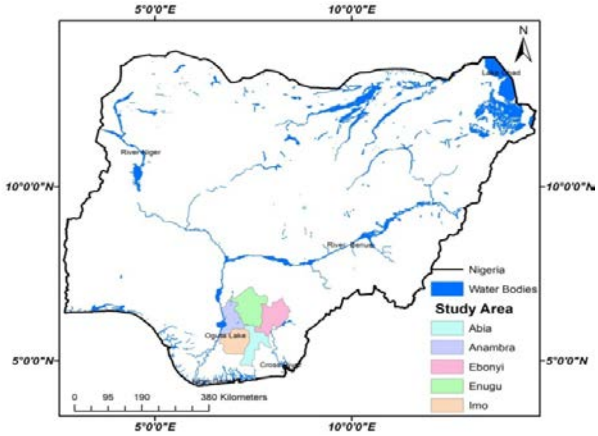


Figure 1 Map of Nigeria showing the study area in Southeastern Nigeria and the 5 States of the study area

2.2 Data requirement, acquisition and preparation

Long term climatic daily data were obtained from NIMET Lagos and the Center for Basic Space Science (CBSS) Nsukka, for 17 weather stations in and around the study area. The data include rainfall (mm), temperature (°C), wind speed (m s^{-1}), relative humidity (%) and solar radiation (MJ m^{-2} day^{-1}) for a 21-year period (1993 to 2013). Daily ET_o was determined for each of the weather stations using the FAO Penman- Monteith model and the ET_o data were processed into monthly, annual and seasonal averages (Allen et al., 1998). ArcGIS 10.2.2 software package was used for spatial interpolation mappings of rainfall and ET_o of the study area.

2.3 Reference evapotranspiration determination

ET_o was calculated on a daily time step using the FAO-Penman-Monteith (FAO-PM) method (Equation 1). The equation uses standard data of solar radiation, temperature, humidity and wind speed. The computations were at a 2 m reference height of green grass, shading the ground and not short of water (Allen et al., 1998).

$$ET_o = \frac{0.408\Delta(R_{n-G})+\gamma\frac{900}{T+273}\mu_2(e_{s-}e_a)}{\Delta+\gamma(1+0.34_{u_2})} \quad (1)$$

where, ET_o = Alfalfa reference evapotranspiration (mm day^{-1});R_n = net radiation at the crop surface (MJ m^{-2}

day^{-1});G = soil heat flux density (MJ m^{-2}day^{-1});T =mean daily air temperature at 2 m height (^{o}C); u_2 = mean daily wind speed at 2 m height (m s^{-1}); e_s = saturation vapour pressure (kPa); e_a = actual vapour pressure (kPa); e_s - e_a = saturation vapour pressure deficit (kPa); Δ = slope of the saturation vapour pressure curve (kPa^{o}C^{-1}); γ = psychrometric constant (kPa ^{o}C^{-1}).

2.4 Spatial interpolation methods

There are many interpolation methods available for use in ArcGIS but, IDW and kriging were chosen because they are widely used for spatially explicit hydrologic/ watershed models that require continuous data surfaces like temperature and evapotranspiration. Another reason was that one deterministic (IDW) interpolation method and one geostatistical interpolation method (kriging) from different interpolation family could be compared. The IDW is a simple and intuitive deterministic interpolation method based on the principle that sample values closer to the prediction location have more influence on prediction value than sample values farther apart and its “bull's eye” effect (higher values near observed location) and edgy surface are advantages. The kriging tool it fits a mathematical function to a specified number of points, or all points within a specified radius, to determine the output value for each location. The basic tool of geostatistics and kriging is the semivariogram. It captures the spatial dependence between samples by plotting the semivariance against separation distance. In kriging, the weights are based not only on the distance between the measured points and the prediction location, but also on the overall spatial arrangement of the measured points.

3 Results and Discussion

3.1 Rainfall in the study area

The long term average annual rainfall across the study area ranged from 1536 mm in Enugu State to 3400 mm in Abia State. This shows southwards increase from the north. The average long term monthly rainfall across the study area showed an increase from 17 mm in January to 291 mm in July with a decrease to 253 mm in August before peaking at 320 mm in September and thereafter decreasing steadily to 13 mm in December (Figure 2).

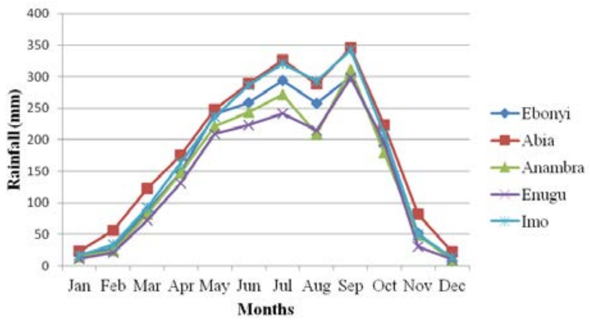
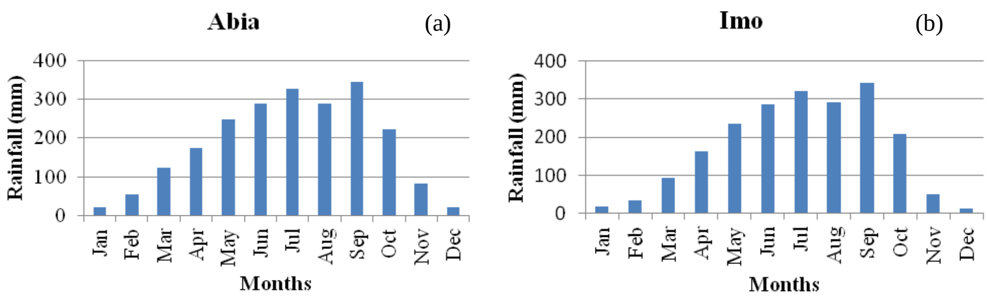
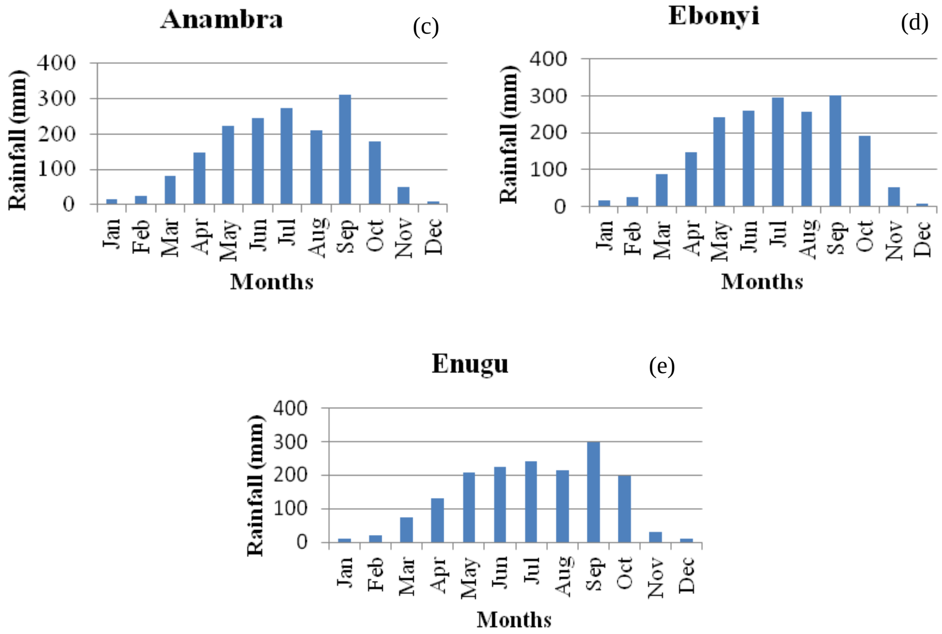


Figure 2 State-wide average monthly rainfall across the study area

The average monthly rainfall recorded in the rainy season was high between April and September, which ranged from 370 mm in Abia State to 126 mm in Nsukka, Enugu State. The low average rainfall occurred during the dry season between December and March ranging between 9 mm (Ebonyi State) and 123 mm (Abia State).

The state-wide average monthly rainfall followed the same pattern across the five states of the study area and their slight variations in values are shown in Figure 3(a)-(e). In decreasing order from the north, the state-wide average annual rainfall were; 2203 mm, 2058 mm,1885 mm,1764 mm and 1663 mm for Abia, Imo, Ebonyi, Anambra and Enugu States, respectively. The long term average annual rainfall trend showed gradual increase over the years of study, from 1993 to 2013. The average annual rainfall in the study area was found to be 1914 mm, which is close to 2000 mm reported by Okonkwo and Mbajiorgu (2010).





(a)Abia; (b)Imo; (c)Anambra; (d)Ebonyi; (e)Enugu

Figure 3 Distribution of average monthly rainfall in the states of the study area

3.2 Air temperature

Air temperature is an important driver of climate variability. Average monthly air temperatures varied between 30.6°C (March) and 24.7°C (August). The long term average air temperatures across the states were; 28.2°C (Ebonyi), 26.2°C (Anambra), 27.7°C (Imo), 27.6°C (Enugu) and 27.4°C (Abia). The average annual air temperature in the study area was 28°C. The average annual air temperatures for the states in the study area were; 28.1°C, 27.5°C, 27.6°C, 27.7°C and 27.4°C for Ebonyi, Anambra, Enugu, Imo and Abia States, respectively. Figure 4 shows the variations of average annual air temperatures in the states of the study area. Nwaiwu et al. (2014) reported a temperature range of between 25.95°C and 27.65°C for the same study area, based on data from 1972 to 2011. The difference can be attributed to the varying periods of study and climate change.

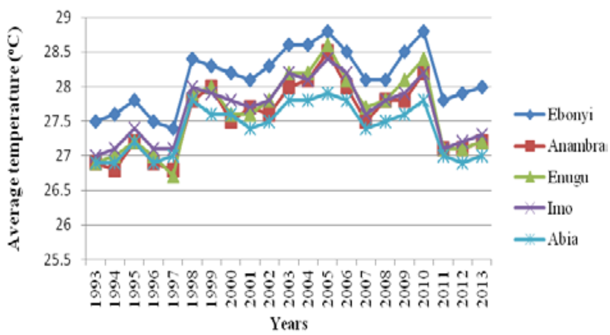


Figure 4 Variation of annual air temperatures in the states of the study area

3.3 Wind speed

The average annual wind speed for the study area was 1.7 m s^{-1} which can be said to be moderate speed (Allen et al., 1998). The monthly variation in wind speed is shown in Figure 5. Oyedepo et al. (2012) reported average monthly values of 5.42 m s^{-1}, 3.36 m s^{-1} and 3.59 m s^{-1} for Enugu, Owerri and Onitsha, respectively, based on measurements at 10 m height as against 2 m height used for this study because, it is believed that higher altitudes results to higher wind speed values.

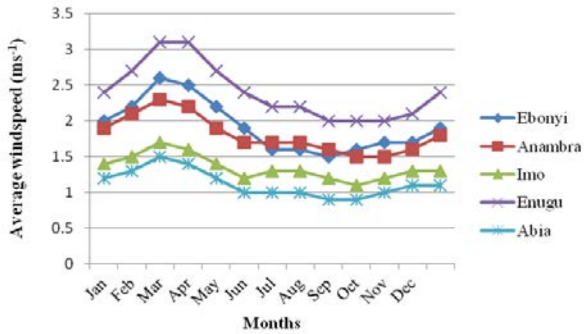


Figure 5 Average monthly wind speed across the states of the study area

3.4 Solar radiation

The average monthly solar radiation data were plotted in Figure 6 to illustrate their trends. Values decreased between the month of March (21 MJ m^{-2} day^{-1}) and April (20 MJ m^{-2} day^{-1}) to July/August (15 MJ m^{-2} day^{-1}) before increasing in November to 20 MJ m^{-2} day^{-1}) (dry season). Ebonyi State received the highest average monthly radiation of 19.16 MJ $m^{-2}day^{-1}$), followed by

Enugu State (19.0 MJ m^{-2} day^{-1}), Anambra (18.36 MJ m^{-2} day^{-1}), Abia (18.31 MJ m^{-2} day^{-1}) and Imo (18.27 MJ m^{-2} day^{-1}). The average annual solar radiation across the study area was 18.64 MJ $m^{-2}day^{-1}$).

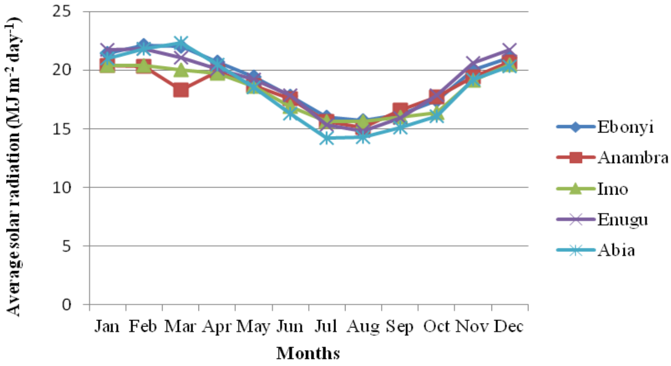


Figure 6 Average monthly solar radiation across the states of the study area

3.5 Relative humidity in the study area

The average monthly relative humidity (RH) for the states showed high percentages in July, August and September (rainy season) averaging 89%, 89% and 90% respectively. The lowest percentages were in January (dry season), averaging 54.32%. Figure 7 shows the trend of variation across the year and that relative humidity increases southwards of the study area. It was noted that while temperature and solar radiation decreased at the onset of the rainy season, relative humidity increased in the study area. All the States had values of between 80% and 90% RH at the full commencement of the rainy season between May and September.

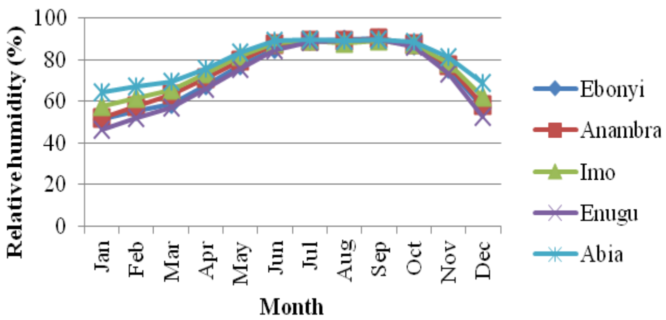
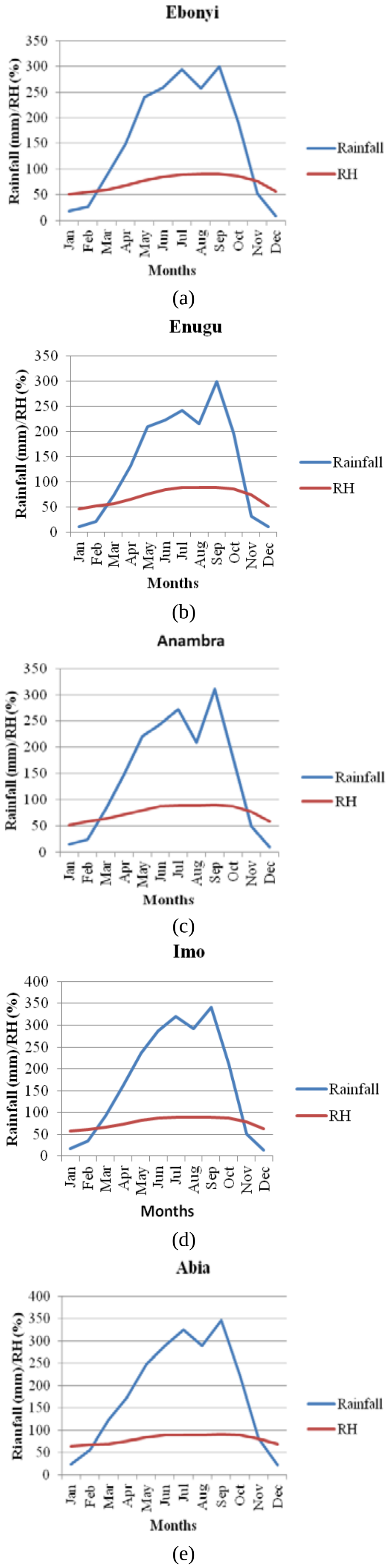


Figure 7 Average monthly relative humidity across the states of the study area

3.6 Rainfall versus relative humidity

The average monthly distribution of rainfall and relative humidity were compared as illustrated in Figure 8(a)-(e). Rainfall intercepted relative humidty in February and November in all the states of the study area, indicating periods of moderate rainfall and RH.



(a)Ebonyi; (b)Enugu; (c)Anambra; (d)Imo and; (e)AbiaStates

Figure 8 Average monthly rainfall versus relative humidity in the states of the study area

3.7 Seasonal rainfall

There was a huge difference in annual seasonal rainfall. The average dry and rainy season rainfall were 217 mm and 1695 mm. The standard deviation (SD) of rainfall increased gradually from January (7.7) and peaked in July (63.1) before decreasing to November (9.4). The coefficient of variation (CV) showed an opposite trend by decreasing from January (44%) to the lowest variation in October (11.5%).

Similarly, in the states of the study area, the SD increased from north to south in both dry and rainy seasons, indicating a high degree of spatial variation in rainfall from north to the south. This can be attributed to low temperatures and high precipitation in the south due to the surrounding area of delta and closeness to the Atlantic Ocean. During the dry season, the SD ranged from 25.5 (Enugu) to 42.7 (Abia) while, that of rainy season were from 50.2 (Enugu) to 64 (Imo). The CV has high variations in dry season ranging from 69.7% (Abia) and 87.2% (Enugu) while, rainy season have low variations from 22% (Abia) and 24.4% (Anambra). The SDs for rainfall have average minimum and maximum values of 7.7 (January) and 63.1 (July) respectively. Correspondingly, the minimum and maximum average monthly CVs are 11.5% (October) and 63.9% (December). The dry and rainy seasons SDs are 91.1 and 270.6 with CVs of 42% and 16%, respectively, indicating that relative spatial variability in rainy season is more than twice that of dry season. Within the states, there's not much spatial variability.

3.8 Seasonal ET_o

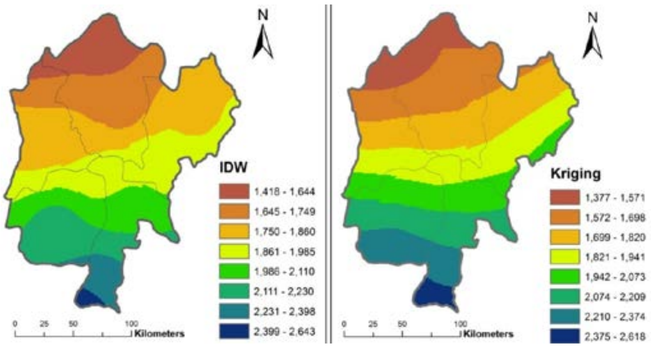
The monthly ET_o and rainfall are inversely proportional to each other, hence ET_o increases as rainfall decreases and vice versa. The average monthly ET_o ranged from 93 mm (August) to 158 mm (January), with an annual average of 1547 mm across the study area. The average seasonal ET_o showed very close values of 765 mm and 782 mm for dry and rainy seasons respectively. The higher rate of ET_o in dry season was balanced by the 7-months duration of rainy season, as against the dry season duration of 5 months.

The dry season has a lower range of SD (17.5 to 8.2) than the rainy season (24 to 14.8) across the States of the study area. In dry season, States in the north of the study area had higher SD values than those in the south. The CV increased proportionally with the SD as Ebonyi had the highest variation of 11% among the States. Others are Enugu (9.8%), Anambra (7.2%), Abia (7.5%) and Imo (5.9%).

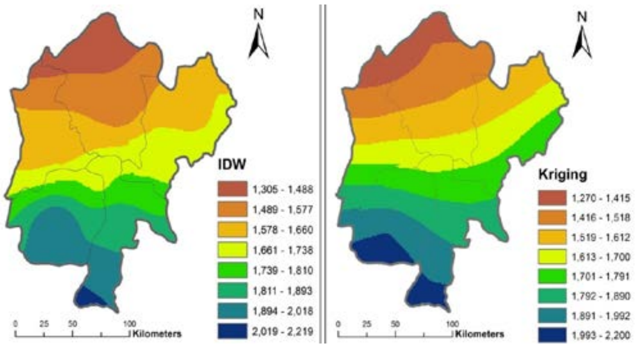
In the rainy season, the SD and CV exhibited similar patterns. The dry and rainy seasons ET_o have SDs of 73.2 and 67.2, respectively, while their CVs are 9.6% and 8.6%, respectively. This indicates not much spatial variability of ET_o in both seasons. Sharma and Irmak (2012) reported ET_o to be twice as much during late summer compared to winter, in a temperate climate.

3.9 Rainfall interpolation

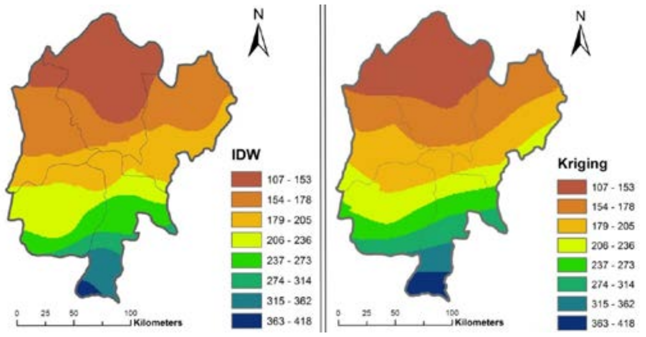
The average annual and seasonal rainfall were 1941 mm (annual), 1729 mm (rainy season) and 212 mm (dry season). The spatial maps exhibit similar patterns across the study area as shown in Figure 9(a)-(c). For the interpolation methods, average annual rainfall ranges were 1418 - 2643 mm (IDW) and 1377 - 2618mm (kriging); similarly, average rainy season rainfall were 1305 - 2219 mm (IDW) and 1270 - 2200 mm (kriging), and average dry season rainfall were 107 - 418 mm (IDW) and 107 - 418 mm (kriging). Both interpolation methods estimated the same range of values in the dry season.



(a) Spatially distributed average annual rainfall (mm)



(b) Spatially distributed average rainy season rainfall (mm)

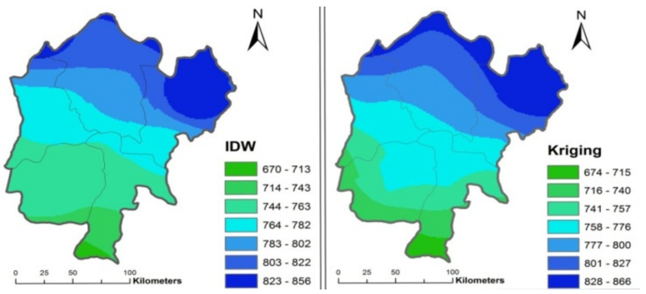


(c) Spatially distributed average dry season rainfall (mm)

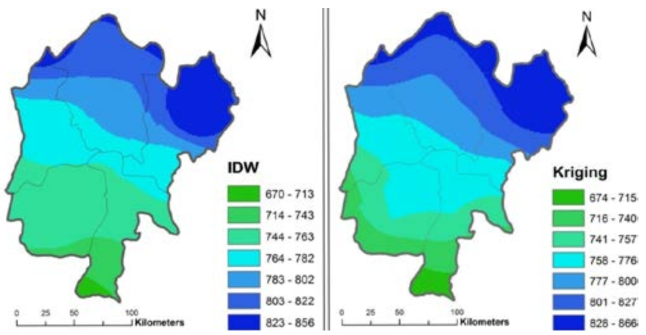
Figure 9 Average annual, rainy and dry season rainfall for IDW and kriging interpolation methods

3.10 ET_o interpolation

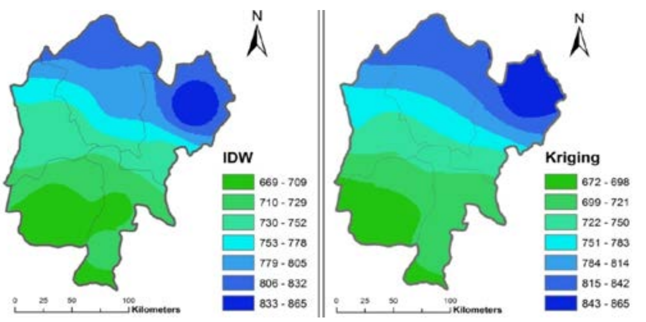
The IDW and kriging interpolation methods were also used to map annual and seasonal ET_o across the study area. The maps developed by each method are shown in Figures 10 (a)–(c).



(a) Spatially distributed average annual ETo (mm)



(b) Spatially distributed average rainy season ET_o (mm)



(c) Spatially distributed average dry season ET_o (mm)

Figure 10 Average annual, rainy season and dry season reference evapotran (spiration for IDW and kriging interpolation methods

The annual average ET_o ranges were 1319 - 1685 mm and 1326 - 1700 mm for IDW and kriging methods respectively. The rainy season values were 670 - 856 mm and 674 - 866 mm, and the dry season values were 669 - 865 mm and 672 - 865 mm, for the IDW and kriging methods, respectively

3.11 Statistical analysis

A comparison of the estimates of IDW and kriging interpolation methods were made with the measured data and there was a positive correlation of the estimates by both methods of interpolation with measured rainfall with correlation coefficients, R = 0.87 and R = 0.92 for IDW and kriging methods respectively.

Further, a regression analysis was performed on the comparisons and the results and the coefficients of determination (R^2) were R^2 = 0.75 and R^2 = 0.85 for IDW and kriging methods, respectively. This showed that both interpolations are performed fairly though kriging appears better.

A similar analysis for the reference evapotranspiration was also performed and estimates by both methods have positive correlations with the observed data and correlation coefficients of R = 0.83 and R = 0.50 for IDW and kriging methods respectively. Co-efficient of determination, were R^2 = 0.69 and R^2 = 0.25 for IDW and kriging methods, which showed that IDW generally performed better than kriging for rainfall and ET_o in the study area.

4 Conclusion

The climatic data obtained was used to estimate ET_o. The spatial mapping of distributed rainfall and ET_o has been successfully undertaken. The maps produced are useful for hydrologic design, climate change prediction and water management studies in the Southeast Nigeria. Annual and seasonal predictions of rainfall and ET_o was compared with IDW and kriging the interpolation methods and both performed fairly well for rainfall analysis but IDW was more consistent than kriging for ET_o in the entire analyses.

Acknowledgement

I wish to acknowledge Mr. Najib Y of center for basic space science Nsukka and Mr. Andrew Oniarah of Nigerian Meteorological Agency Lagos for providing the weather data for this study. I also acknowledge the

University of Nigeria, Nsukka for counterpart fund for this study.

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