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# A Study on Rain Rate Prediction of Southwestern Nigeria

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***Authors' contributions***

*This work was carried out in collaboration among all authors. Author FAS designed the study, managed the analyses of the study and manuscript editing. Authors AA performed the statistical analysis, developed the required models and wrote the first draft of the manuscript. Author ROA managed the literature searches. All authors read and approved the final manuscript.*

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## ABSTRACT

Rainfall parameters can be utilized to investigate the effect of climate change through scientific methods. However, data on rainfall rate exceeded for a fraction of an average year is grossly unavailable over Nigeria's climate, thereby diminishing the capability of existing models to adequately estimate the effect of degradation due to rain. Hence, more accurate estimation is required for better predictions. Rainfall volume data for six different locations in the south-western region of Nigeria were obtained for rain rate computation using Semire and Rosmiwati model. The curve-fitted Cumulative Distribution Functions were compared with the ITU-R rain rate model (Recommendation P.837-6) and compensation function was obtained using error analysis while the performance was evaluated with respect to existing models using Chi-square, and Percentage Error and Root Mean Square Error (RMSE) metrics. The outcome of this study can be adopted for better understanding of spatial rainfall intensity in this region and other climatic zones of similar rainfall characteristics.

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*Keywords: Rain rate; cumulative distribution function; Southwestern Nigeria.*

## 1. INTRODUCTION

The variation of climatic condition in deserts, heavy rain regions and areas affected by oceanic winds results in diversity in geographical parameters. Rain, as opposed to other kinds of precipitation such as snow, hail and sleet, is liquid precipitation formed by the condensation of atmospheric water vapor into drops of water (of up to 0.5 mm), often large enough to fall from clouds in the sky to the earth surface [1]. Rainfall event is a natural, time varying phenomenon having complex structure due to its variability in space, duration and frequency of occurrence. This has non-uniform distribution in both horizontal and vertical directions along the slant path [2]. However, the rain attenuation characteristic is affected by spatial distribution of the rain rate.

Rainfall rate distribution is a function of how rainfall occurrence changes in time and space, in terms of daily, monthly, yearly and seasonal variability [3]. The availability of spatial rain rate statistics, and the drop-size distribution of any climatic zone is essential for the accurate prediction of attenuation characteristic due to rain. Hence, the seasonal variability of rain rate distribution is one of the important factors to link engineer for calculating rainfall attenuation when providing adequate link budget estimate for communication link [4].

The rain rate statistics can either be in the form of point rain rate data or cumulative distributions, so that rain rate exceeded at different percentages of time can be determined. The long-term behavior of rainfall rate is expressed by a cumulative probability distribution usually referred to as Cumulative Distribution Function (CDF). This rain rate CDF, commonly referred to as an exceedance curve is the percentage of time that rainfall rate exceeds a given value [5]. According to ITU-R, the estimation of induced attenuation due to rain requires the knowledge of rain rate exceeded 0.01% of the time with one minute integration time in predicting induced rain attenuation [6].

The characteristic difference between rain in tropical and temperate climate is that rainfalls in the tropics are largely convective and characterized by higher rates of precipitation which occur within short duration over limited extensions while that of temperate climate are from stratiform cloud and characterized with lower rain rates being widespread, and as such, extend over a longer propagation path. Hence, the empirical relationships adaptable for propagation predictions in the temperate regions are not suitable in the tropical climates and this critically affects countries located in equatorial regions that experience a high rainfall rate of up to120 mm/h throughout the year.

In order to estimate the effect of climate change due to rain, previous studies have utilized rainfall parameters in predicting rain rate using existing models but the capability of such models to adequately predict the effect of degradation is grossly diminished due to dearth of meteorological data of Nigeria's climate. This study therefore strove to adopt suitable analytical approach in utilizing widely acceptable scientific methods and procedures on the limited meteorological data to estimate rain rate prediction of Nigeria's climate despite the few experimental setups of point rainfall measurements in the region which is tropical.

Generally, tropical regions possess two climatic seasons; wet and dry season. The equatorial climate is wet and hot throughout the year and experiences rainfall all months throughout the larger part of the year with a mean precipitation values of at least 60 mm. The wet season is usually characterized with high rain rates while the range of temperature variation is small both within the day and throughout the year.

When planning a radio system, rain rate data for the various locations which is measured in millimetres per hour (mm/hr) are essential, the most important meteorological statistic being the rainfall rate exceeded for 0.01% of the time, $R_{0.01}$% [7]. Extensive studies have been carried out by researchers on rain characteristic, prediction and modelling based on physical facts and using available meteorological data but most of these predictions and models being statistical in nature are highly geographically dependent. While majority of the contributors tend to use the empirical method extensively to convert from higher integration time to lower equivalent because of its simplicity and experimental dependent, Adenugba, et al. [8] emphasized that system engineers are interested in rain-rates with short integration time. Also, according to Obiyemi, Ojo and Ibiyemi [9], no single model provides a good fit but to obtain a stable estimate of the rainfall rate distribution, up to 10 to 20 years of observations is required to estimate long-term reliability. For a radio system to take rain attenuation into account in its design, not less than 9 years of data is sufficient for a stable estimation [10].

Statistical data of rain rate ($R_{0.01}$) exceeded for 0.01% of an average year (with an integration time of 1 min) have been suggested as good fits to empirically measured rain fade duration with examples of power-laws and log-Normal [6,11,12]. For temperate regions, $R_{0.01}$% can be around 30 mm/hr while for arid regions it is only few mm/hr. For tropical regions that experience monsoon seasons, the $R_{0.01}$% can be as large as 150 mm/hr. Several procedures exist to estimate the statistics of rain rate in a particular region. Statistics of rain rate can also be found in ITU-R Rec. P.837-6 [13] or in the global crane model [14]. The ITU-R Rec. P.837-6 model provides the annual distribution of rainfall rate with an integration time of 1 minute for the entire globe, derived from numerical weather prediction, but recommends the use of locally measured rain rates if available. The authoritative rain models that are of global acceptance are the Crane model and the ITU-R model [5].

The ITU-R adopted the Laws-Parsons DSD model which has taken a functional form of the negative exponential distribution of Marshall-Palmer [15]. This method provides an estimate of long-term statistics due to rain with global climatic classification into zones A to H for propagation predictions and interference calculations. Analysis on rain rate prediction has been done with techniques for predicting short integration time rainfall rate from long term precipitation data presented [16-20]. Further research of several authors [21-24] revealed that the cumulative distribution is based on rainfall rates and percentage of time, stressing that the higher the rain intensity the lower the corresponding percentage of time, while the lower the rain intensity the higher the percentage of time. Rain rate maps at 0.1%, 0.01% and 0.001% exceedance value for Nigeria were presented using rain rate models that have been developed for tropical zones. Although several methods have been reported in the literatures on rain rate estimation, only a few has however been adopted for Nigeria's climate which is in the tropical region. Since prediction models adaptable for temperate regions are inadequate for tropical regions, further research is required to suitably estimate for Nigeria which is characterized by heavy monsoon rains.

## 2. DESCRIPTION OF THE DATA

Nigeria lies between latitude 4ºN and 14ºN, and between longitude 2ºE and 15ºE. It has a total area of 923.77 $km^2$ and land mass coverage of 910.77 $km^2$. Climate is the average state of the lower atmosphere, and the associated characteristics of the underlying land or water, in a particular region, usually spanning at least several years (World Health Organization, 2003). The Nigerian climate is dominated by the influence of the Tropical Maritime (TM) air mass and the Tropical Continental (TC) air mass. The TM air mass originates from the southern high-pressure belt located off the coast, which picks up moisture from over the Atlantic Ocean, thus becoming a moisture-laden air mass which is characterized by high humidity and heavy rainfall [25]. According to the CHIRPS rainfall dataset [26], FEWS NET/USGS explored trends in rainfall over Nigeria during a period of 1981-2015, suggesting that rainfall has increased across much of the country since the 1980s, highlighting that the large amount of rainfall are typically received in the central and southern parts of the country. Total rainfall is highest in the south where more than 1,400 mm are received; the central band of Nigeria receives 800-1,200 mm while the Northern areas receive less than 800 mm, with some northeastern areas bordering Niger and Chad receiving less than 400 mm.

The locations under study were drawn from three states of the Southwest region of Nigeria which are Ogun State (Abeokuta), Lagos State (Itoikin), and Oyo State (Ibadan, Iseyin, Saki and Sepeteri). Lying within the rain forest climatic zone and having a rugged and undulating topography with rivers of many tributaries, annual mean temperature during the day varies from 20º to 34º and rainfall from 928 mm to 3240 mm per year with its relative humidity ranges between 65% and 75%. Basically having two seasons which are dry season (majorly November between February) and wet season (within the rest of the calendar year), rainfall of the locations of study usually falls during the wet season and during this period, the Intertropical Convergence Zone (ITCZ) moves across the country. The average monthly rainfall depends on the effects of movement of the ITCZ. The rainy season is interrupted by short breaks which usually occur in August, but heavy rain in September [15] hence having tropical rainfall pattern with seasonal distribution.

**Table 1. Geographical parameters of locations under study**

| Location | Longitude (degrees) | Latitude (degrees) | Height above sea level (m) | Mean annual accumulated rainfall (mm) | Observation period (Years) |
|---|---|---|---|---|---|
| Abeokuta | 3.35 | 7.16 | 66 | 1299.81 | 33 |
| Ibadan | 3.91 | 7.39 | 230 | 1380.27 | 28 |
| Itoikin | 3.79 | 6.65 | 43 | 1245.69 | 27 |
| Sepeteri | 3.65 | 8.63 | 348 | 1257.95 | 21 |
| Iseyin | 3.60 | 7.37 | 308.22 | 1193.78 | 21 |
| Saki | 3.38 | 8.67 | 457 | 1165.99 | 21 |

Rainfall data of not less than twenty (20) years were obtained from Weather Stations as provided by the Nigerian Meteorological Agency (NIMET), a Federal Government Agency in charge of Weather parameters and atmospheric conditions in Nigeria, and also from the Ogun-Osun River Basin Development Authority (OORBDA). Obtained data are of monthly integration time which according to Ajayi [3] may be adequate for providing enough information for rainfall estimation for the purpose of attenuation prediction along terrestrial or satellite communications link. The rain gauge has a bucket size of 0.1 mm to 0.5 mm per tip. The locations and their geographical parameters are as presented in Table 1.

## 3. METHODOLOGY

Owing to lack of measured one-minute data for the locations under study, measurement data of annual accumulated rainfall volume obtained were used to generate rain rate Cumulative Distributions Functions (CDFs) over the locations. Since obtained data are in millimeter (mm), then it is necessary to first convert the available rainfall volume data into rainfall rate of one minute integration time at 1%, 0.1%, 0.01% and 0.001% of time exceedances and Semire and Rosmiwati model [27] which was generated from Ogbomoso in Oyo state was adopted. Their equations are as shown below:

$$\boldsymbol{R_{1.0} = 1.496\, M^{0.332}} \quad \text{(i)}$$

$$\boldsymbol{R_{0.1} = 0.627\, M^{0.6}} \quad \text{(ii)}$$

$$\boldsymbol{R_{0.01} = 4.866\, M^{0.431}} \quad \text{(iii)}$$

$$\boldsymbol{R_{0.001} = 21.338\, M^{0.3372}} \quad \text{(iv)}$$

where M is the accumulated annual volume and $R_{1.0}$, $R_{0.1}$, $R_{0.01}$, $R_{0.001}$ are one-minute rain rates at 1%, 0.1%, 0.01% and 0.001% exceedances respectively.

The Semire and Rosmiwati model was then used to predict the point rainfall-rate cumulative distribution of the locations and the rain rates obtained from above were used to generate a regression equations using MATLAB 2013a curve-fitting tool which was subsequently used to compute for rain rates at other time percentages. The curve fitting method used in this work is the MATLAB Toolbox program which can be called for on the command line environment using ”cftool” command. The regressed CDFs generated using MATLAB 2013a curve-fitting tool was of a hybrid relationship of power and exponential law between the rain rate and exceedance probabilities of the form:

$$R_p = a\,.p^b + c.exp\,(d.p) \quad \text{(v)}$$

where $R_p$ is the rain rate at p exceedance and a, b, c, and d are the model coefficients as given in Table 2.

The generated CDF was thus used to compute rain rate at other exceedance probabilities within the said range, i.e. 1% and 0.0001%, owing to lack of measured one-minute rain rate data for the percentages within this scope.

Rain rate estimation was also done using ITU-R model [13] based on the geographic coordinates of the locations. This ITU-R model requires $M_S$ defined as the mean annual straitform rainfall amount (mm), $M_C$ defined as the mean annual convective rainfall amount (mm) and $P_{r6}$ defined as the probability of a given rainy period (%) as inputs. The model was run on MATLAB to obtain the associated data from ESARAIN_PR6_v5.TXT, ESARAIN_MT_v5.TXT and ESARAIN_BETA_v5.TXT files which contained the numerical values for the variables $P_{r6}$ , $M_T$ and β respectively while data files ESARAINLAT_v5.TXT and ESARAINLON_ v5.TXT contain the latitude and longitude of each of the data entries. The step-wise procedures taken to obtain rain rate can be found in ITU-R Rec. P.837-6 [13].

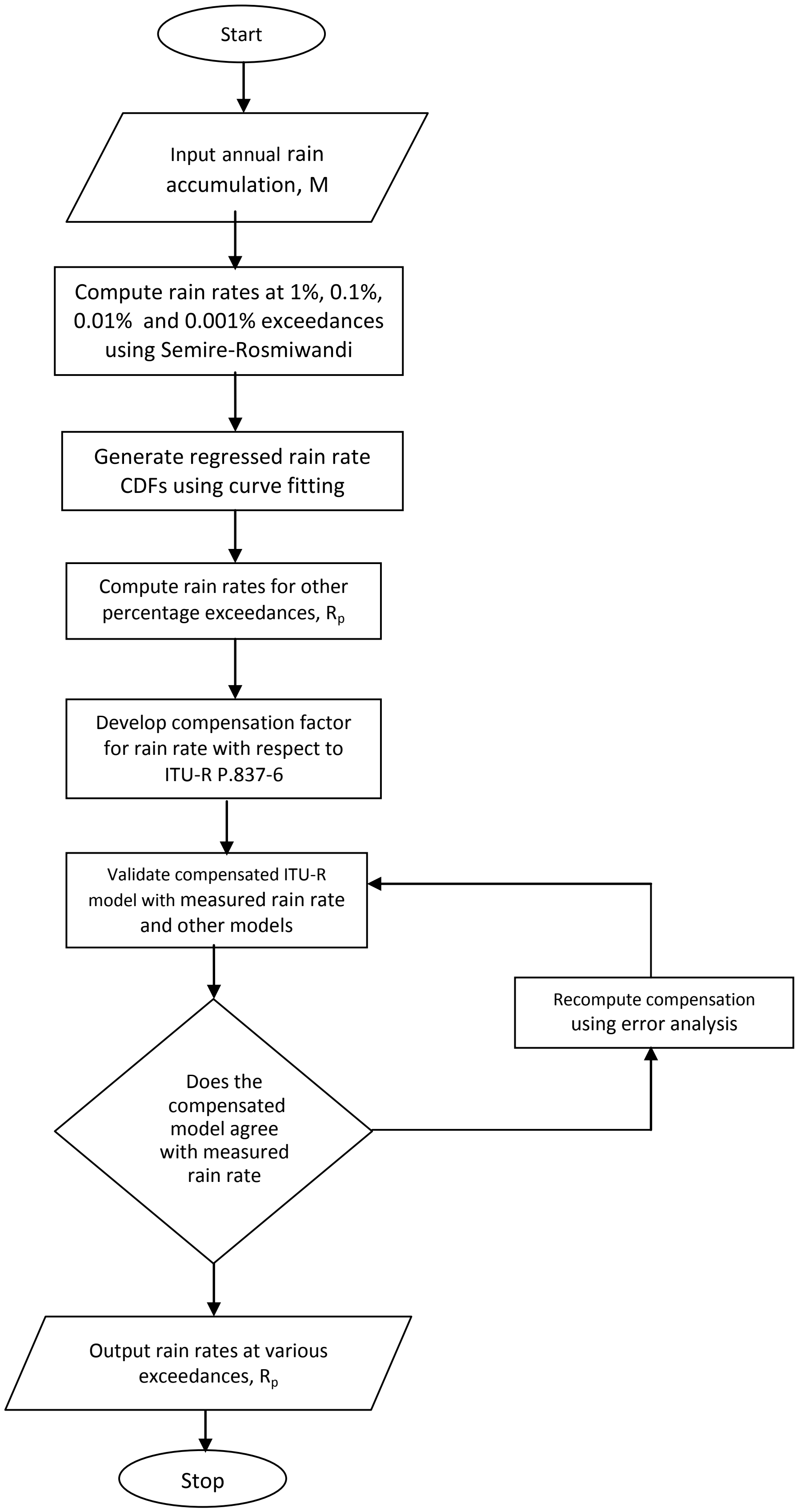


**Fig. 1. Flowchart showing the methodology of computing rain rate**

**Table 2. Regressed rain rate Cumulative Distribution Function (CDF) coefficients for the locations**

| Location | CDF coefficients | | | | Goodness of fit | |
|---|---|---|---|---|---|---|
| | a | b | C | d | SSE | R-square |
| Abeokuta | 15.93 | -0.3816 | 13.89 | -6.462 | 5.102e-27 | 1 |
| Ibadan | 16.28 | -0.3813 | 14.9 | -6.253 | 3.03e-16 | 1 |
| Itoikin | 15.83 | -0.3817 | 13.51 | -6.671 | 7.839e-19 | 1 |
| Sepeteri | 15.7 | -0.382 | 12.95 | -6.996 | 4.42e-24 | 1 |
| Iseyin | 15.66 | -0.3821 | 12.66 | -7.285 | 1.06e-27 | 1 |
| Saki | 22.12 | -0.3421 | -5.55 | 0.1746 | 1.308e-20 | 1 |

Estimations of the curve-fitted rain rate CDFs obtained via curve fitting were compared with rain rate estimations using ITU-R P.837-6 model. The outcome of the relative error analysis carried out on the ITU-R rain rate with respect to the regression rain rate values obtained from the measured data was used to compute a propose correction factor so as to compensate the estimation of ITU-R P.837-6 for the study area. The correction factor, also generated from MATLAB using curve-fitting tool is of the form:

$$cf = a.exp(b.p) + \frac{c}{p^b} exp(e.p) \quad \text{(vi)}$$

with the coefficients being averaged over the six locations as follow:

a = 0.612283, b= 1.248733, c = 0.074348, d = 0.3546 and e = 2.359.

Since estimations of prediction models should be close representation of actual measurements, therefore comparison of the proposed model against the other published models had been done to evaluate its performance. This analysis was done with range of exceedance percentages from 1% to 0.0001% in steps of 0.0002%. In order to judge the relative merits of the prediction methods, performance metrics used as testing parameters were Chi-square($\chi^2$), Percentage Error (%ε) and Root Mean Square Error (RMSE) [28,29] illustrated as:

$$\chi^2 = \sum \frac{(X_{predicted} - X_{measured})^2}{X_{measured}} \quad \text{(vii)}$$

$$\%\varepsilon = \frac{X_{predicted} - X_{measured}}{X_{measured}} \, x\, 100 \quad \text{(viii)}$$

where $X_{predicted}$ and $X_{measured}$ are predicted and measured values exceeded for a given percentage of time respectively, μ is the mean error and σ is the standard deviation.

A flowchart of procedure is shown in Fig. 1.

## 4. RESULTS

The mean rain rates at 0.01% time unavailability over various months of the year for the locations within the observation period is shown in Fig. 2. Also, the statistical distribution of the annual one-minute cumulative rainfall rates derived at 0.01% time ordinate (corresponding to 52.56 minutes in a year) unavailability for the locations is represented in the scatter plots as revealed in Fig. 3.

Abeokuta experienced its peak rainfall rate of 163.2809 mm/h in the year 2011 while that of Ibadan was 128.0198 mm/h in the year 1991. The peak rain rates of Itoikin, Sepeteri, Iseyin and Saki within the observation periods were 126.30 mm/h, 140.52 mm/h, 117.32 mm/h and 109.20 mm/h in the years 1996, 2008, 2014 and 2006 respectively. On the average, Ibadan had the highest mean rain rate of 109.32 mm/h while Saki with 101.87 mm/h ranks the lowest. The trend lines of the rain rate are also indicated in the Figures with the respective trend equations. The occasional overshoot of the steady rain rate trend is largely due to variability caused by climate change.

The obtained coefficients of the regressed rain rate CDF as well as the test for goodness of fit parameters which is indicative of the accuracy of the fitted model on MATLAB for the locations is presented in Table 2. The correction factor was curve-fitted against the exceedance percentage using MATLAB 2013a as represented in Fig. 4.

According to ITU-R, the considerations for the propagation prediction models with global validity are necessary and the propagation as well as radio meteorological data is of fundamental importance for the development and testing of such prediction models. Hence, the one-minute measured rainfall rate data for the locations have been plotted in Fig. 5 with selected rain rate models including the ITU-R P.837-6 [13], Rice-Holmberg [30], Ito-Hosaya [31], Moupfouma-Martin [32] as well as the compensated ITU-R model. These models were selected because they have been known to give accurate results for predicting the rain rate for tropical regions.

Observations from the Figures show that the Moupfouma and Martins model extremely overestimated rain rate while both Ito-Hosaya model and Rice and Holmberg model underestimated rain rate in all cases. Only ITU-R P.837-6 model estimation was relatively accurate between time exceedance 1% and 0.01% but also underestimated beyond 0.01%. It can also be observed that estimations of the proposed compensated ITU-R rain rate models makes the best representative of actual measurements with just slight deviations as compared to other models. This is might be largely due to the fact that the empirical measurement analysis gives more accurate values for specific locations as against regional values that are more generalized.

In case of rainfall rate data, the cumulative distribution has to follow the train of the measured cumulative distribution data carried out on the full data set that is applicable. The Root Mean Square Error (RMSE) of the models is illustrated in Fig. 6. Judging from the metrics, the compensated ITU-R rain rate models gave the least deviation from the measured rain rate value for all the locations considered. Detailed performance of the metrics have been presented in Table 3.

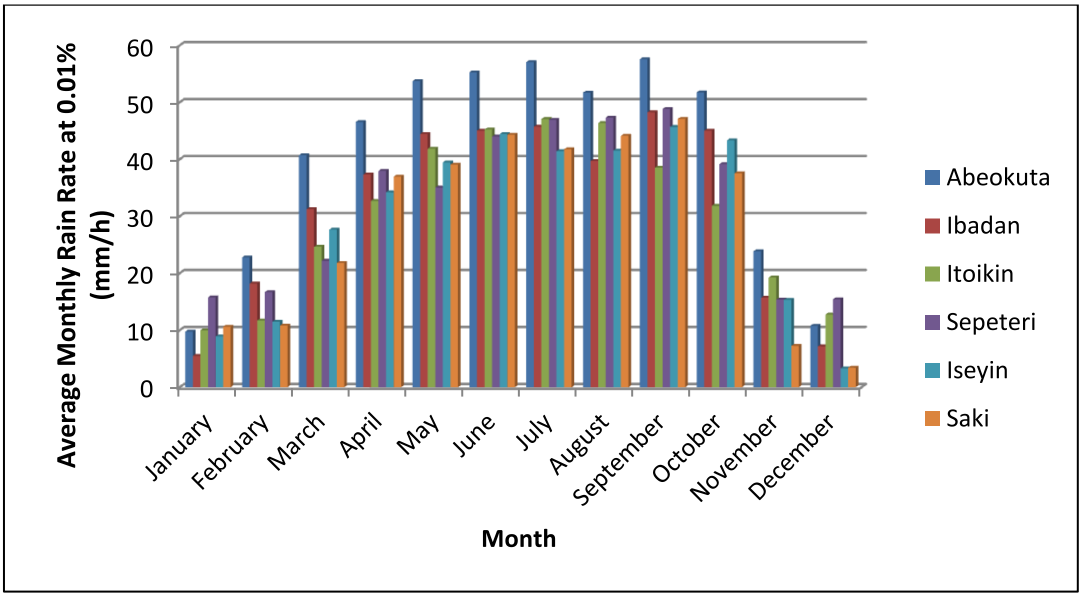


**Fig. 2. Chart of average monthly rain rate for the locations**

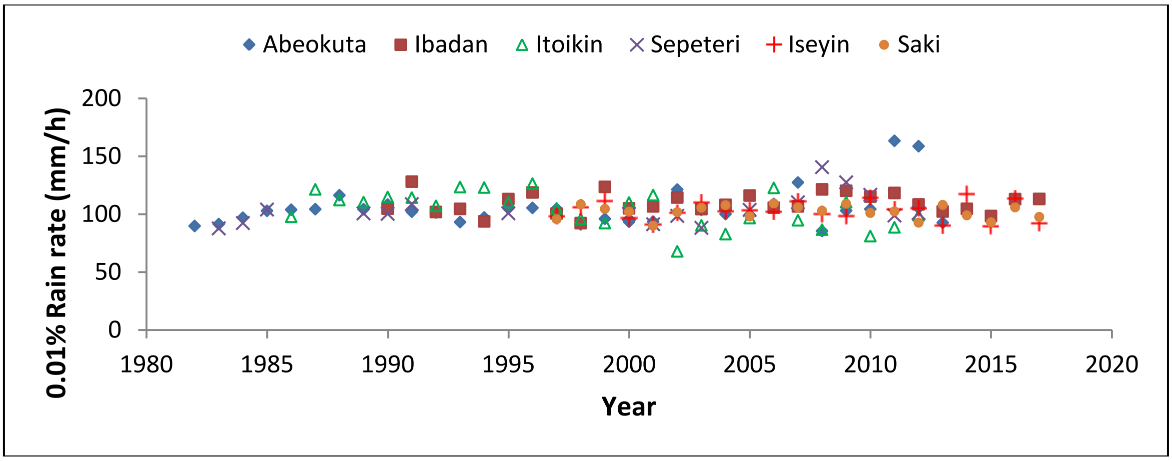


**Fig. 3. Scatter plot of annual rain rate at 0.01% for the locations**

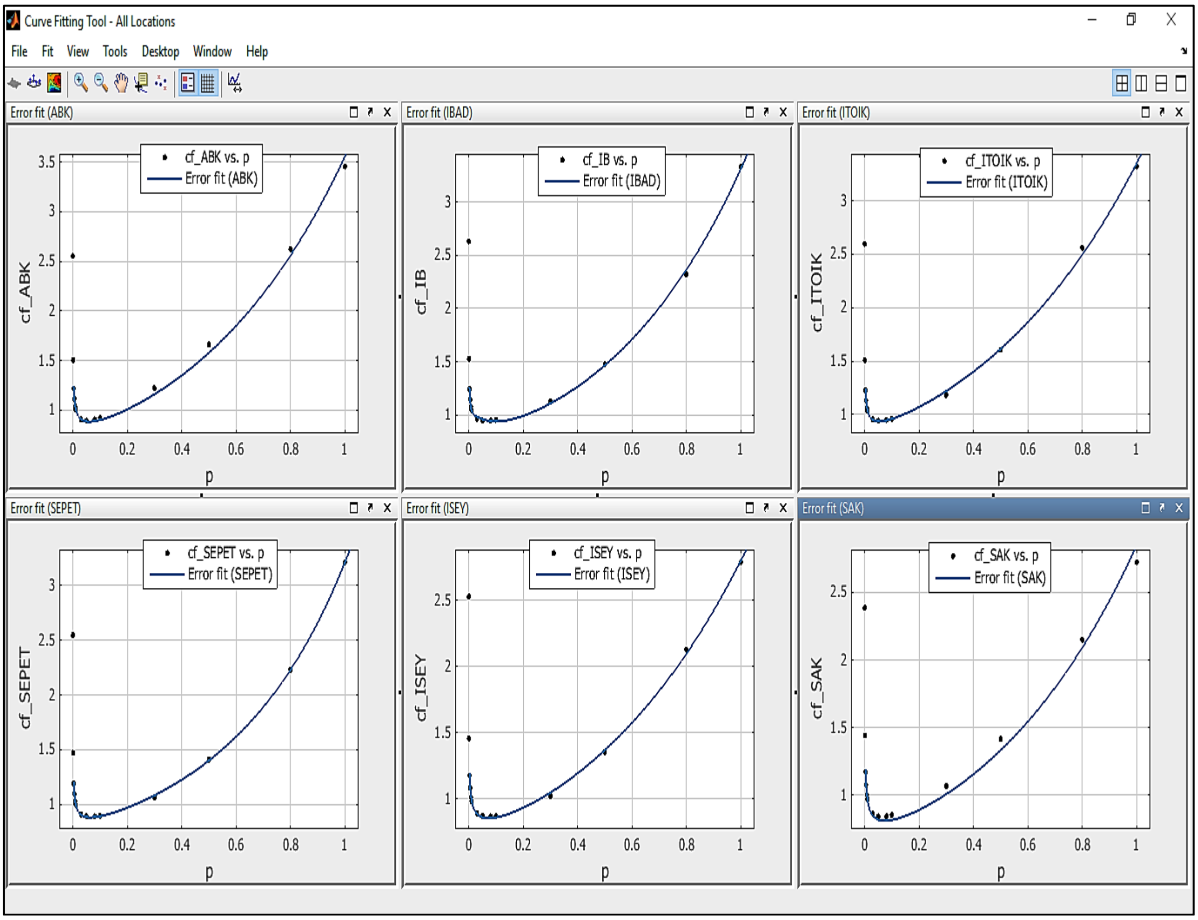


**Fig. 4. Plot of rain rate correction factor against exceedances using MATLAB 2013a curve fitting toolbox**

**Table 3. Performance evaluation of rain rate models**

| Location | Performance metrics | ITU-R P.837-6 | Rice & holmberg | Ito-hosaya | Moupfouma & martins | Compensated ITU-R |
|---|---|---|---|---|---|---|
| Abeokuta | Chi Square | 18.52 | 23.88 | 640.02 | 1346.59 | 3.98 |
| | Percentage Error | 19.74 | 48.95 | 80.55 | 516.96 | 3.41 |
| Ibadan | Chi Square | 19.31 | 20.64 | 33.30 | 1311.66 | 0.00 |
| | Percentage Error | 20.67 | 42.20 | 52.36 | 468.58 | 0.13 |
| Itoikin | Chi Square | 18.50 | 15.67 | 25.16 | 1463.65 | 0.29 |
| | Percentage Error | 21.24 | 32.88 | 43.48 | 572.22 | 1.03 |
| Sepeteri | Chi Square | 17.36 | 22.74 | 38.00 | 1458.60 | 0.02 |
| | Percentage Error | 16.59 | 47.46 | 57.46 | 574.67 | 0.29 |
| Iseyin | Chi Square | 3.40 | 5.20 | 26164.56 | 1579.18 | 0.05 |
| | Percentage Error | 19.93 | 32.45 | 455.68 | 622.68 | 3.15 |
| Saki | Chi Square | 15.57 | 19.85 | 34.52 | 1431.02 | 0.03 |
| | Percentage Error | 13.43 | 45.66 | 55.82 | 568.50 | 0.41 |

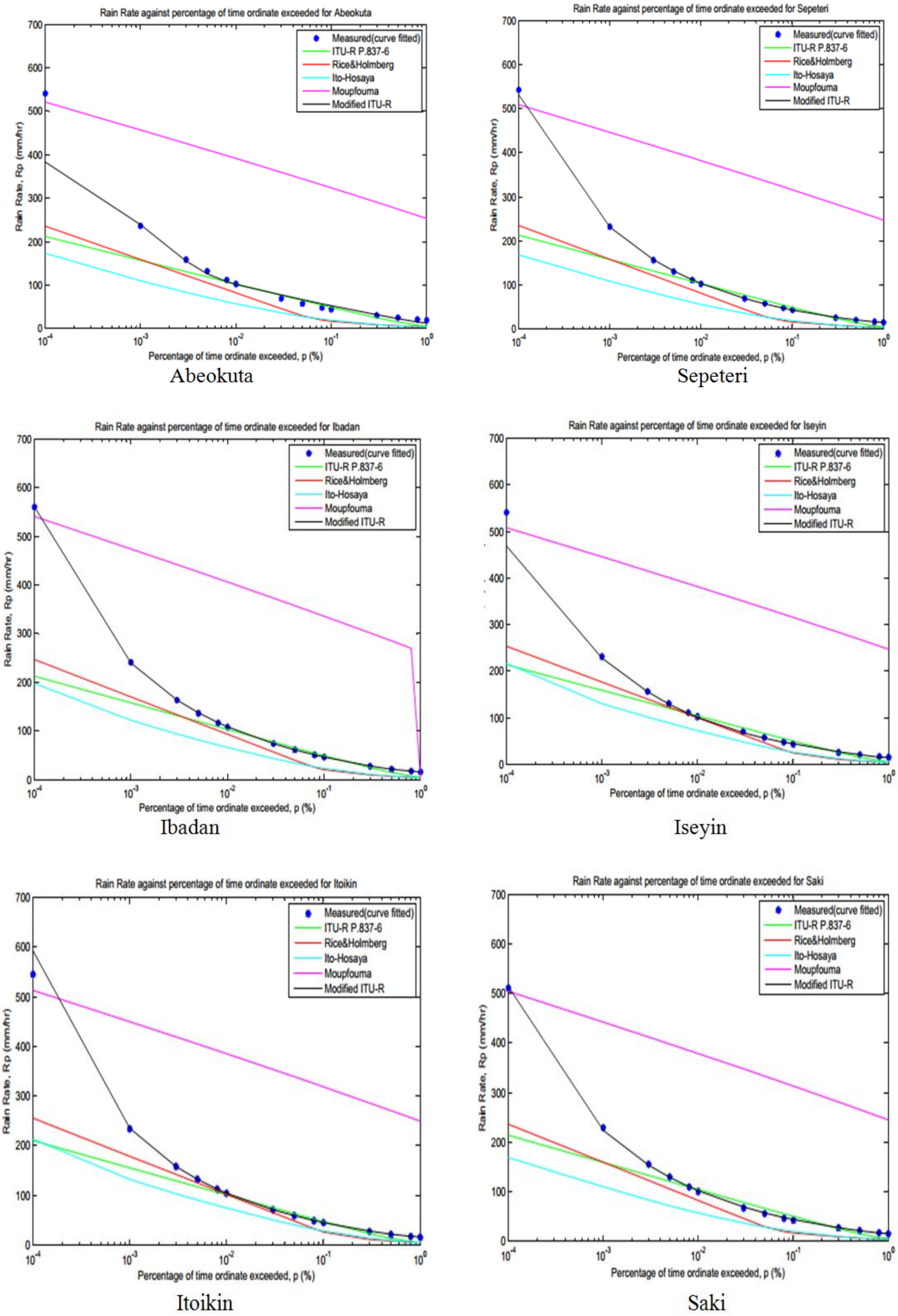


**Fig. 5. Estimation plot of rain rate models for the locations of study**

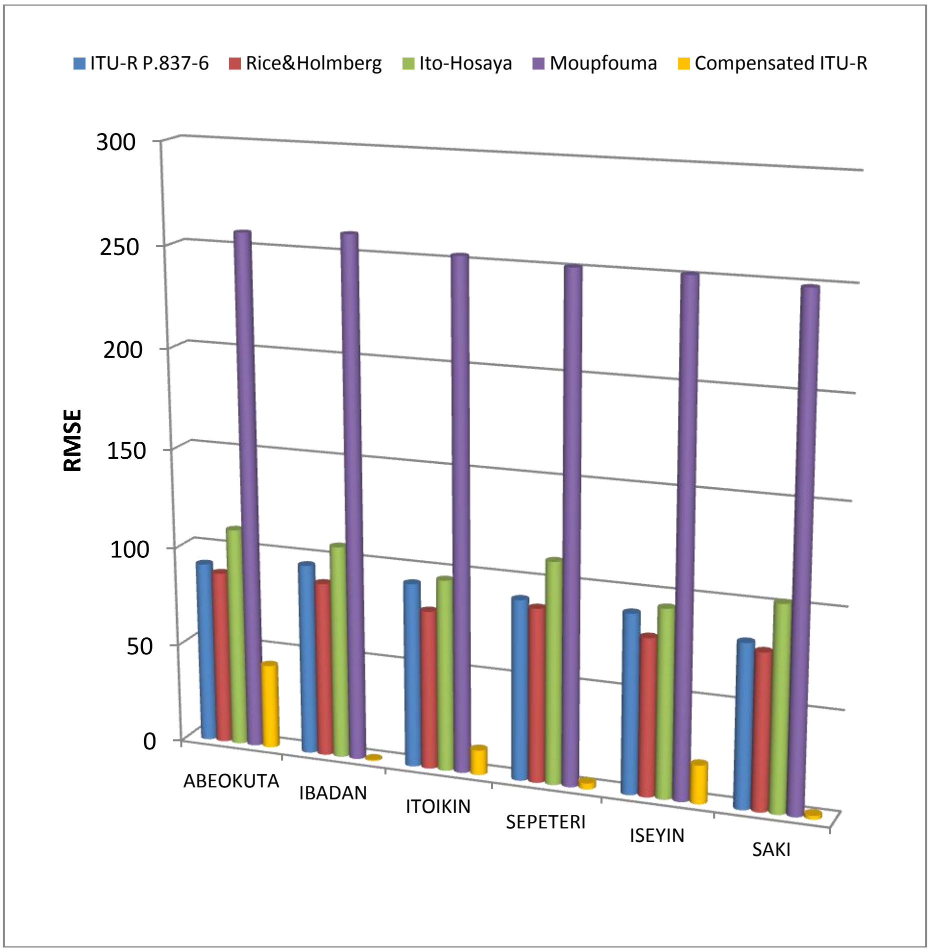


**Fig. 6. RMSE performance of rain rate for the locations**

## 5. CONCLUSIONS

This research has provided information on the intensity of rain as it relates to rain rate in six cities in the southwest zone of Nigeria. It was found that the months of June, July, August, September and October experienced heavy and more intense rain, thereby implying high probabilities of the fade occurrence for these months. Cumulative Distributions Functions (CDFs) regressed from measured data had been used to obtain rainfall rate conversion models at one-minute integration time for the locations and rainfall distributions for other exceedances were generated. Probably because of difference in regional parameters, the ITU-R global model of one-minute rain rate distributions i.e. Rec. ITU-R P.837-6 slightly underestimated rain rate. Hence, error analysis on the ITU-R P.837-6 model was utilized to propose compensation function for rain rate and this showed to be best suited for rainfall measurements, performing better in comparison to other suitable tropical models. Outcome of this study can be adopted for better understanding of spatial rainfall intensity in this Nigerian region and extended to other climatic zones of similar rainfall characteristics.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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