

Development of Non-Stationary Rainfall Intensity-Duration-Frequency Curves for Calabar City, Nigeria[†]

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Abstract: Rainfall Intensity-Duration-Frequency (IDF) relationships are crucial in the design and management of hydraulic structures. At the core of the assumption for IDF development is that, the statistics of past rainfall events will represent future rainfall events. It has been proven that climate change is a major trigger for non-stationarity therefore, the assumption is untenable. This work is aimed at considering the impact of climate change in the development of IDF curves for a city. To account for this non-stationarity, an RCM was combined with measured data through a climate factor (CF) to develop a rainfall IDF for the coastal city of Calabar. The baseline and future climatic periods of the RCM were 1971-2010 and 2021-2060 respectively. The Annual Maxima Series (AMS) were disaggregated and fitted to Gumbel distribution. Results revealed that, the magnitude of trend for measured AMS and measured annual rainfall are -0.351 and +3.628 respectively. A CF value of 0.86 was obtained and a generalized non-stationary rainfall IDF model was derived. When compared to models from similar studies, this model has conserved values with $r^2=1$ and an error margin of $\pm 6\%$ for all return periods. This will introduce economy in the design of hydraulic structures. Excess runoffs in Calabar were therefore related to frequent short duration rainfall with low intensities.

Keywords: Rainfall Intensity-Duration-Frequency; Non-stationarity; Regional Circulation Model; Bias-correction in climate data; Trend analysis; Gumbel distribution

1. Introduction

The design and operation of hydraulic structures rely on appropriate quantification of peak rainfall intensity and its probability of occurrence at a given duration. The interactions between these variables can be depicted in an empirical model and are best suited for rainfall durations between 5 min and 24 hrs. These models need to be regularly updated through the use of long term synthetic and/or observed data. The synthetic data is advantageous where observed records are missing, scarce or need adjustment to meet current climatic realities. Dependence on experience and observed data only in the development rainfall intensity-duration-frequency (IDF) models have been rendered inadequate by climate change [1]. This has caused researchers to factor-in non-stationarity where extreme rainfall and its frequency are considered to change with time. The implication of this hypothesis is that, the climatic conditions and its processes that occurred years ago are no longer constant. Due to the local climate and topography of an area, these models are also unique to a particular catchment.

Climate change is usually noted by a significant deviation of temperature or rainfall from normal. The impact of climate change on hydrologic system is widely recognized to be geographic location-specific [2]. State-of-the-art hydrological impact studies are based on weather data from climate models (also called synthetic or modelled data) and require a certain degree of accuracy. These climate models could be global or regional. Regional Climate Model (RCM) is a small-scale mathematical representation of the climate system

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based on the physical properties of its components, their interactions and feedback processes. It could be used to model future and past meteorological variables. A typical example of RCM is Coordinated Regional Climate Downscaling Experiment (CORDEX). The emission of greenhouse gases is introduced into the model by means of Representative Concentration Pathways (RCPs). RCPs are scenarios that describe alternative trajectories for CO₂ emissions and the resulting atmospheric concentration from year 1950 to 2100.

From the assessment of [3], CORDEX realistically captured West African Monsoon. In furtherance of the work of [3], [4] proved its ability to forecast rain-onset dates. Using Togo as case study, [5] observes that, CORDEX predicted 52.2% and 53.6% reduction in daily rainfall amount for RCP 4.5 (mild case scenario) and RCP 8.5 (worst case scenario) respectively. In the study of climate change impact using climate models, the baseline data and the future data must have similar temporal scale.

RCM was applied by [6] to assess the impact of climate change on rainfall and runoff. Detailed works on climate change undertaken using RCM can be seen in [7]. For other methods of climate change impact studies; sensitivity analysis was used to assess the potential impact of changing rainfall intensity on urban drainage infrastructures by [8]; however, the future changes were arbitrarily selected (example; $\pm 10\%$, $\pm 20\%$, $\pm 30\%$). Trend analysis through linear regression was able to describe realistically the non-stationarity of rainfall because it is based on specific local scale data [9]. The work of [10] is an example.

This study is to improve the works of these researchers. Hence, the major goal of this study is to developed a non-stationary rainfall IDF through a climate factor obtained analytically. To achieve this, two types of data will be collected and analysed; synthetic (RCM) and data from field measurement. The synthetic data will be divided into baseline and future RCMs.

1.1. Rainfall IDF Models

The ability of Rainfall IDF to predict rainfall extremes accurately can be affected by the number of parameters in the model and size of data. The Sherman's 3-parameter general rainfall IDF model given in Equation 1 will be adopted for this study. The equation which encompasses three unknowns is robust in rainfall predictions and the return period, T is not specified.

$$I = \frac{CT^m}{t^a} \quad (1)$$

where, the constants (C , m and a) are empirical parameters which depend on rainfall data, shape, size and location of the study area. I and t represent rainfall intensity and duration respectively.

Since [11] observed negative rainfall trend in Calabar, then why did [12] linked its flood to 26.3% heavy rainfall when [13] is in doubt that its rainfall intensity and frequency has changed? [14] agreed that there is a change in climate within Niger Delta (it covers region under study), Nigeria, particularly, with an increased temperature trend, but the extent of this change was not revealed. [15] discovered that climate change is the only reason annual rainfall decreased by 0.45mm/year in Warri (nearby Niger Delta city). [16] applied an RCM with 2000-2029 and 2070-2099 as present and future climatic periods respectively and observed that, rainfall decreased by 0-2mm/day along and close to the coastlines of West Africa.

In the studies carried out by [17] and [18], both parties ignored the significance of climate change in the predictive rainfall IDF models developed for Calabar. The former predicted lower rainfall intensity values when compared to the later. Both parties achieved this feat using 21 and 23 years data respectively. [19] analysed a 21-years rainfall data and employed four-parameter model to obtain lower rainfall intensity values compared to other two set of researchers. Both [20] and [21] employed a two-parameter model and used data length of 10-years and 13-years respectively, whereas [22] was not certain

of the magnitude of disparity posed by non-stationary rainfall IDF. To unfold this, [2] attempted to statistically extrapolate rainfall IDF curves to infer future climate, but discontinued when it was noticed that, short duration rainfall intensities had downward trends. This implied that, climate change will have low-level negative impacts on flooding. He recommended this method, but further opined that, there is no standard or accepted methodology to derive IDF curves or equations for future climate conditions but recently RCMs has been on the fore. Firstly, these evidences shows that, statistical and CF methodologies could be employed to derive rainfall IDF and secondly, enough representative data are needed to obtain quality results. Furthermore, rainfall IDF models with more parameters have better predictive capabilities. In this study, aside updating the rainfall IDF for Calabar, the impact of climate change was considered.

2. Materials and Methods

2.1. Profile of the Area

Calabar Basin covers an area of about 1514 km² of the Nigerian Niger Delta. It is located between longitudes 24°.15' and 5°.15'N; and latitudes 8°.55' and 80.25'E. It is 60 km from the Atlantic Ocean at its southern end and is encompassed by numerous creeks and rivers with 60% of its area on a lowland flood plain. Its highest and lowest points are respectively at about 100m and 2m above mean sea level. Calabar has a drainage density of 0.34km⁻¹ [23]. This low value implies that surface runoff is not quickly removed from the basin, making it susceptible to flooding, gully erosion and landslides.

2.2. Data Requirement, Acquisition and Analysis

Daily rainfall data spanning 1971-2010 compiled by the Nigerian Meteorological Agency (NIMET) was organized and analyzed. CORDEX-RCM Tier two rainfall outputs corresponding to years 1971-2010 and 2021-2060 formed the baseline and future climatic periods respectively. It should be noted that for climate impact studies using an RCM, the baseline data must have similar temporal domain as the measured data. Bias-corrected CORDEX data was obtained from <https://www.nsc.liu.se/storage/esgf-datanode/> through West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) at Federal University of Technology, Akure, Nigeria.

The data were screened for missing records and inconsistency. Annual maxima Series (AMS) of both synthetic (CORDEX) and measured rainfall were used in the analysis. The AMS consists of the largest daily values observed in each year. The data required were AMS of rainfall depths for short durations, that is, 0.25hr, 0.5hr, 1hr, and so on. Unfortunately, only 24hr rainfall data were available for the area of study. The Indian Meteorological Department one-third model (Equation 2) was applied to disaggregate the rainfall data into short durations. It is known to maintain the statistics of the rainfall event.

$$R_t = R_{24} \left(\frac{t}{24} \right)^{\frac{1}{3}} \quad (2)$$

where, R_t is the required precipitation depth (in mm) for duration less than 24hrs, R_{24} is the daily precipitation depth in mm and t is the required duration in hours.

Gumbel Extreme Value (GEV) distribution was selected to perform the rainfall probability analysis since it is widely used in the region for IDF analysis owing to its suitability for modelling maxima. This was achieved by using method of ordinary moments where the cumulative distribution function (CDF), $F(x)$ and probability density function (PDF), $f(x)$ are defined respectively as follows:

$$F(x) = \exp \left[-\exp \left(-\frac{x - x_0}{s} \right) \right] \quad (3)$$

$$f(x) = -\frac{1}{s} \exp\left(-\frac{x-x_0}{s} - \exp\left|-\frac{x-x_0}{s}\right|\right) \tag{4}$$

where,

$$\text{position parameter, } x_0 = \mu - 0.577216s \tag{5}$$

$$\text{scale parameter, } s = \frac{\sqrt{6\sigma^2}}{\pi} \tag{6}$$

and μ and σ are respectively the mean and variance of the distribution.

2.3. Derivation of IDF Equation and Change Factor

- i. The proposed model is in the form expressed in Equation 1. To obtain the constants, the equation was linearized into Equation (7).

$$\log I = \log k - a \log t, \tag{7}$$

$$\text{It is assumed that, } k = CT^m \tag{8}$$

- ii. From Equation (7), a plot of the values of $\log I$ on the y-axis and the values of $\log t$ on the x-axis for each recurrence interval was realized. The term $\log k$, which represents the intercept from the plot for each returning period was estimated.

where,

a represents the average slope of the straight lines for each T and \log is the natural log.

- iii. Taking \log of both sides of Equation (8) resulted into Equation (9):

$$\log k = \log C + m \log T \tag{9}$$

To determine C and m , values of $\log k$ was plotted against that of $\log T$. therefore, the parameter m , which represents the slope, was estimated. The value of the anti-log of the intercept from the plot represents the parameter, C . The local scaled future values were then subjected to the steps outlined by [24].

while; the multiplicative CF (that is, the ratio of the mean of future RCM ($\overline{RCM_f}$) to baseline RCM ($\overline{RCM_b}$)) was estimated using Equation 4;

$$CF_{mul} = \frac{\overline{RCM_f}}{\overline{RCM_b}}, \tag{10}$$

the Local Scaled future values ($LS_{f_{mul,i}}$) was obtained by applying Equation 10:

$$LS_{f_{mul,i}} = LO_{bi} \times CF_{mul} \tag{11}$$

where, LO_{bi} is the values of Locally Observed (measured data) rainfall at i^{th} time step.

3. Results and Discussion

Summary of the output from GEV probability distribution analysis is shown in Table 1. It is noted that, the measured data has more spread than other two data sets. This is attributed to the greater rainfall values collected. The analysis also revealed a strong relationship between the measured and predicted probabilities of rainfall occurrence with coefficient of correlation of 0.97, 0.95 and 0.99 for measured, baseline and future RCMs respectively. This was confirmed by using Kolmogorov-Smirnov (K-S) test which was performed on the CDF of the datasets at 0.05 significance level.

Table 1. Summary of Gumbel Distribution Modelling.

Datasets	Position Parameter, x_0	Scale Parameter, s	Coefficient of correlation, r	K-S test statistic, D
Measured data	108.84	27.39	0.97	0.075

Baseline RCM	34.66	12.02	0.95	0.1
Future RCM	35.44	8.21	0.99	-0.0099

Table 2 provides summary of Mann-Kendall trend analysis. It is shown that, annual measured rainfall has an increasing trend (Sen’s slope of +3.628) unlike its AMS with a decreasing trend (Sen’s slope of -0.351). This is attributed to low intensity rainfalls that are not serially correlated over time.

Table 2. Summary of Mann-Kendall (M-K) Trend Analysis.

	Yearly Measured data	Measured AMS	Baseline RCM’s AMS	Future RCM’s AMS
p-value	0.428	0.507	0.401	0.177
Sen’s slope	3.628	-0.351	0.088	0.087
Kendall’s tau	0.087	-0.073	0.092	0.149

The ratio of the means of future and baseline AMS was estimated to obtain a climate factor of 0.86. This signifies a 14% decrease in rainfall intensity in the coming years up to 2060. The climate factor was multiplied with the quantiles of locally observed data to obtain local scaled values. The local scaled values were disaggregated and the result was analyzed to obtain Figure 1, which is the graphical representation of the model proposed in this study.

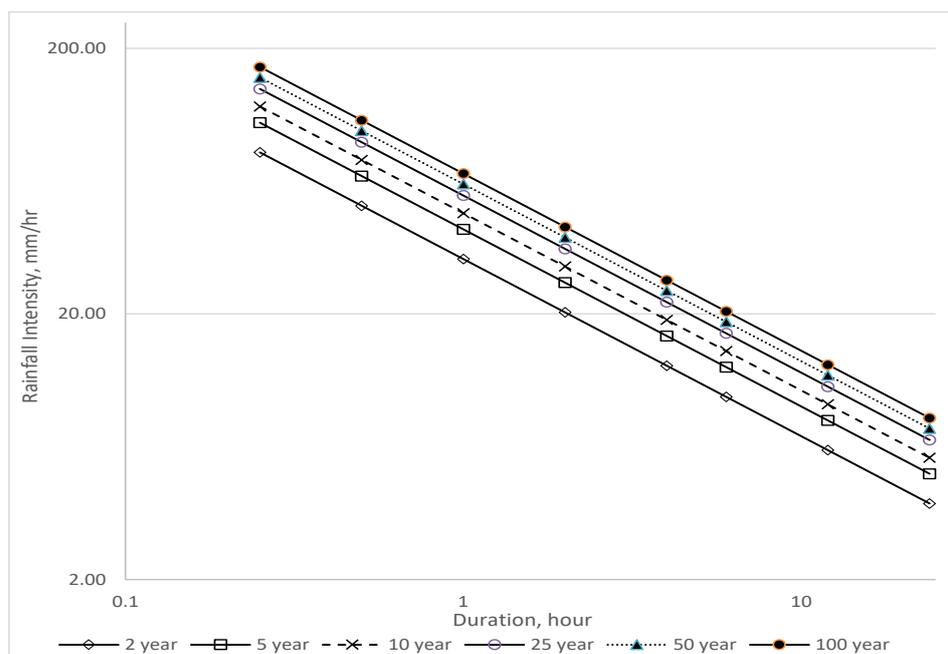


Figure 1. Non-Stationary Rainfall IDF Curves for Calabar on Logarithmic Scales.

3.1 The Generalized Non-Stationary Rainfall IDF Developed

The calculated rainfall intensity for different durations with return periods of 2, 5, 10, 25, 50 and 100 years were analyzed to generalize Figure 1 into Equation (12). The parameters a , C and m were estimated as 0.6667, 30.2872 and 0.1955 respectively. The accuracy and performance of Equation (12) against the calculated values of rainfall intensities was tested for all return periods and durations. To verify this, coefficient of determination $r^2 = 1$ and average chi-square p -value of 0.99 were obtained for all return periods. When compared to the works of [17] and [18], Equation (12) predicts lower rainfall intensities. This will incorporate economy when applied in the design and management of engineering systems.

$$I = \frac{30.2872 T^{0.1955}}{t^{0.6667}} \quad (12)$$

4. Conclusion

Rainfall intensity generally decreases with time. This was observed when rainfall was disaggregated into sub-hourly timescales by an appropriate model. Change factor methodology was used to predict 14% decrease in rainfall intensity in the future due to climate change through RCP 8.5. Therefore, decrease in rainfall intensity is the consequence of climate change in the study area. Flooding in Calabar depends on frequent short duration rainfall with low intensities. It could also be related to other factors like inadequate drainage channel, poor maintenance and clogging of flood control systems, and land use.

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Data Availability Statement: Link to data obtained from Nigerian Meteorological Agency (NIMET) is old and might be broken but the dataset in MS Excel is still with the authors in its original state while RCM raw data is found at <https://www.nsc.liu.se/storage/esgf-datanode>.

Conflicts of Interest: The authors declare no conflict of interest.

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