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Proceeding Paper

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 the Gumbel distribution. Results revealed that the magnitude of trend for the 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 ±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

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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 h. 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 of rainfall intensity–duration–frequency (IDF) models has 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 systems 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. A regional climate model (RCM) is a small-scale mathematical representation of the climate system 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 an RCM is a 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 CO_2 emissions and the resulting atmospheric concentration from year 1950 to 2100.

From the assessment of [3], CORDEX realistically captured the West African monsoon. In furtherance of the work of [3], Ref. [4] proved its ability to forecast rain-onset dates. Using Togo as case study, Ref. [5] observes that CORDEX predicted 52.2% and 53.6% reduction in daily rainfall amounts 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 a similar temporal scale.

An RCM was applied by [6] to assess the impact of climate change on rainfall and runoff. Detailed work on climate change undertaken using an 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; ±10%, ±20%, ±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's aim is to improve the work of these researchers. Hence, the major goal of this study is to develop a non-stationary rainfall IDF through a climate factor obtained analytically. To achieve this, two types of data will be collected and analyzed: synthetic (RCM) and data from field measurements. The synthetic data will be divided into baseline and future RCMs.

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

In the studies carried out by Refs. [17,18], 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 latter. Both parties achieved this feat using 21 and 23 years data, respectively. Ref. [19] analyzed a 21-year rainfall data and employed a four-parameter model to obtain lower rainfall intensity values compared to the other two sets of researchers. Both Refs. [20,21] employed a two-parameter model and used a data length of 10 years and 13 years, respectively, whereas Ref. [22] was not certain of the magnitude of disparity posed by a non-stationary rainfall IDF. To unfold this, Ref. [2] attempted to statistically extrapolate rainfall IDF curves to infer future climate, but discontinued this 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. However, RCMs have been at the forefront recently. Firstly, this evidence 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, in addition to updating the rainfall IDF for Calabar, the impact of climate change was considered.

2. Materials and Methods

2.1. Profile of the Area

The Calabar basin covers an area of about 1514 km^2 of the Nigerian Niger Delta. It is located between longitudes 4°.15′ and 5°.15′ N and latitudes 8°.55′ and 8°.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 100 m and 2 m above mean sea level. Calabar has a drainage density of 0.34 km^{-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 the years 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 a similar temporal domain as the measured data. Bias-corrected CORDEX data was obtained from https://www.nsc.liu.se/storage/esgf-datanode/ (accessed on 28 March 2019) through the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) at the 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, 0.25 h, 0.5 h, 1 h, and so on. Unfortunately, only 24 h 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.

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

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

The 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 a method of ordinary moments where the cumulative distribution function (CDF), $F(x)$, and probability density function (PDF), $f(x)$, are defined, respectively, as follows:

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

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

where

$$\text{position parameter}, x_0 = \mu - 0.577216s \quad (5)$$

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

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).

$$log\ I = log\ k - alog\ t, \quad (7)$$

$$\text{It is assumed that } k = CT^m \quad (8)$$

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):

$$Log\ k = log\ C + m\ log\ T \quad (9)$$

To determine *C* and *m*, values of *log k* were plotted against those 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 Ref. [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):

$$CF_{mul} = \frac{\overline{\overline{RCM_f}}}{\overline{\overline{RCM_b}}}, \quad (10)$$

The local scaled future value ($LS_{fmul,i}$) was obtained by applying Equation (10):

$$LS_{fmul,i} = LO_{bi} x CF_{mul} \quad (11)$$

where LO_{bi} is the value of locally observed (measured data) rainfall at the *i*-th time step.

3. Results and Discussion

A summary of the output from the GEV probability distribution analysis is shown in Table 1. It is noted that the measured data has more spread than the 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 a coefficient of correlation of 0.97, 0.95, and 0.99 for measured, baseline, and future RCMs, respectively. This was confirmed by using the 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.

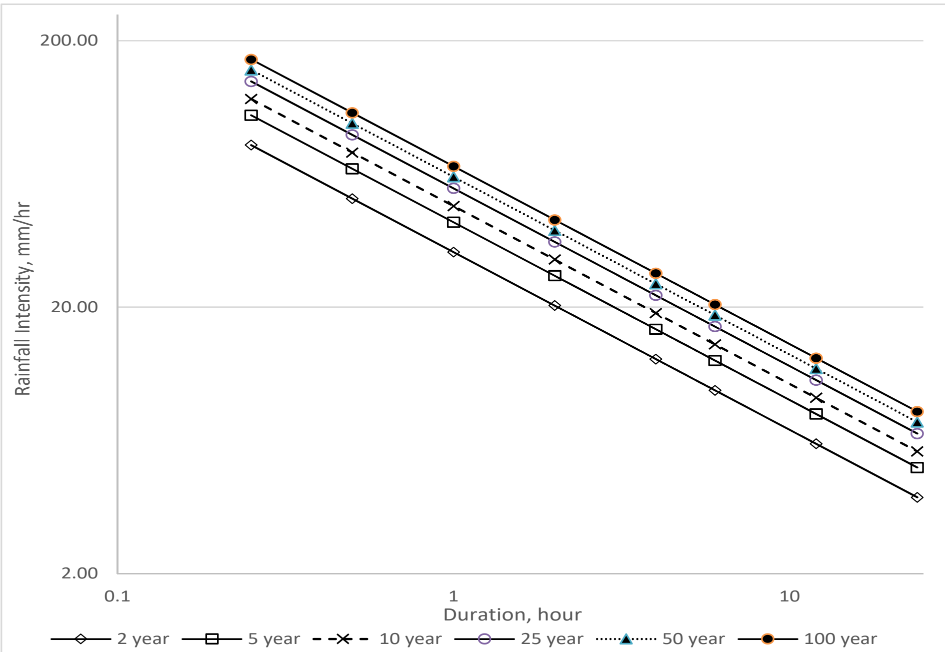

Figure 1. Non-stationary rainfall IDF curves for Calabar on logarithmic scales.

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, the 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 [17,18], Equation (12) predicts lower rainfall intensities. This will incorporate economy when applied in the design and management of engineering systems.

$$I = \frac{30.2872\ T^{0.1955}}{t^{0.6667}} \tag{12}$$

4. Conclusions

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 a 14% decrease in rainfall intensity in the future due to climate change through RCP 8.5. Therefore, a 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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References

1. Martel, J.; Brissette, F.P.; Lucas-Picher, P.; Troin, M.; Arsenault, R. Climate Change and Rainfall Intensity-Duration-Frequency Curves: Overview of Science and Guideline for Adaptation. *J. Hydrol. Eng.* **2021**, *26*, 03121001. [CrossRef]
2. Ologhadien, I. Assessment of the Impact of Climate Change on Intensity-Duration-Frequency (IDF) Equations in Benin City, Nigeria. *Int. J. Hydrol.* **2019**, *3*, 107–113. [CrossRef]
3. Nikulin, G.; Jones, C.; Giorgi, F.; Asrar, G.; Buchner, M.; Cerezo-Mota, R.; Christensen, O.B.; Deque, M.; Fernandez, J.; Hansler, A.; et al. Precipitation Climatology in an ensemble of CORDEX-Africa Regional Climate Simulations. *J. Climatol.* **2012**, *25*, 6057–6078. [CrossRef]
4. Mounkaila, M.S.; Abiodun, B.J.; Omotosho, J.B. Assessing the Capability of CORDEX Models in Simulating onset of rainfall in West Africa. *Theor. Appl. Climatol.* **2015**, *119*, 255–272. [CrossRef]
5. Batabinle, L.; Lawin, E.; Agnide, S.; Celestin, M. Africa-CORDEX Simulations Projection of Future Temperation, Precipitation, Frequaency and Intensity Indices Over Mono Basin in west Africa. *J. Earth Sci. Clim. Chang.* **2018**, *9*, 490.
6. Sheshukov, A.Y.; Siebenmorgen, C.B.; Douglas-Mankin, K.R. Seasonal and Annual Impacts of Climate Change on Watershed Response Using an Ensemble of Global Climate Models. *Trans. ASABE* **2011**, *54*, 2209–2218. [CrossRef]
7. Oudier, P.R.; Ducharne, A.; Eyen, L.F. Climate Change Impacts on Runoff in West Africa: A Review. *Hydrol. Earth Syst. Sci.* **2014**, *1*, 2789–2801.
8. Niemczynowicz, J. Impact of the Greenhouse Effect on Sewerage Systems. *Hydrol. Sci. J.* **1989**, *34*, 651–666. [CrossRef]
9. Sule, B.F.; Ajala, O.F. Investigating the Non-stationarity of Historical Data on Rainfall at Illorin, North Central Nigeria. *J. Sci. Eng. Res.* **2016**, *3*, 537–548.

10. Jung, M.; Kim, H.; Mallari, K.J.B.; Pak, G.; Yoon, J. Analysis of Effect of Climate Change on runoff in an Urban Drainage System: A case study from Seoul, Korea. *Water Sci. Technol.* **2015**, *75*, 653–660. [CrossRef]
11. Udoimuk, A.B.; Osang, J.E.; Ettah, E.B.; Ushie, P.O.; Egor, A.O.; Alozie, S.I. An Empirical Study of Seasonal Rainfall Effect in Calabar, Cross River State, Nigeria. *IOSR J. Appl. Phys.* **2014**, *5*, 7–15.
12. Ndoma, E.E.; Ahmed, U.M.; Idris, A.S. Effectiveness of Drainage Networks on Floods in Calabar Metropolis, Nigeria. *J. Meteorol. Environ.* **2020**, *3*, 106–120.
13. Okon, I.E.; Ogba, C.O.; Idoko, M.A.; Eni, D.D.; Sule, R.O. Climate Change and the Challenges of Flood Mitigation in Calabar Urban, South-South Nigeria. *Int. J. Ecol. Ecosolution* **2015**, *2*, 41–48.
14. Mangodo, C.; Lawrence, A.E.; Isese, L. A Analytical Study of the Climatic Trend in the Niger Delta Region of Nigeria. *J. Soc. Sci.* **2017**, *7*, 54–59. [CrossRef]
15. Olanrewaju, R.; Ekiotuasinghan, B.; Akpan, G. Analysis of Rainfall Pattern and Flood Incidences in Warri Metropolis, Nigeria. *Geogr. Environ. Sustain.* **2017**, *10*, 83–97. [CrossRef]
16. Adefisan, E. Climate Change Impact on Rainfall and Temperature Distributions over West Africa from Three IPCC Scenarios. *J. Earth Sci. Clim Chang.* **2018**, *9*, 2–14.
17. Ogarekpe, N.M. Development and Comparison of Different Intensity Duration Frequency Models for Calabar, Nigeria. *Niger. J. Technol.* **2014**, *33*, 33–42. [CrossRef]
18. Antigha, R.E.; Ogarekpe, N.M. Development of Intensity Duration Frequency Curves for Calabar Metropolis, South-South, Nigeria. *Int. J. Eng. Sci.* **2013**, *2*, 39–42.
19. Ologhadien, I.; Nwaogazie, I.L. Rainfall Intensity-Duration-Frequency Models for Selected Cities in Southern Nigeria. *Sci. Res. Essays* **2014**, *2*, 509–515.
20. Akpan, S.U.; Okoro, B.C. Developing Rainfall Intensity-Duration-Frequency Models for Calabar City, South-South, Nigeria. *Am. J. Eng. Res.* **2013**, *2*, 19–24.
21. Oyegoke, S.O.; Adebanjo, A.S.; Ajani, E.O.; Jegede, J.T. Analysis of Rainfall Intensity for Southern Nigeria. *J. Eng. Res.* **2017**, *22*, 107–118.
22. Ganguli, P.; Coulibaly, P. Does Non-stationarity in Rainfall Require Non-Stationary Intensity-Duration-Frequency Curves? *Hydrol. Earth Syst. Sci.* **2017**, *21*, 6461–6483. [CrossRef]
23. Eze, E.B.; Efiong, J. Morphometric Parameters of the Calabar River Basin: Implication for Hydrologic Processes. *J. Geogr. Geol.* **2010**, *2*, 18–26.
24. Hamaamin, Y.A. Developing of Rainfall Intensity-Duration-Frequency Model for Sulaimani City. *J. Pure Appl. Sci.* **2017**, *19*, 10634. [CrossRef]