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Research Article

Modeling Rainfall Intensity-Duration-Frequency (IDF) and Establishing Climate Change Existence in Umuahia - Nigeria Using Non-Stationary Approach

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Abstract

The aim of this study is to develop non-stationary rainfall Intensity-Duration-Frequency (IDF) models or curves for Umuahia, in South East Nigeria. The IDF model development was actualized using a 31-year rainfall record (1992-2022), obtained from the Nigerian Meteorological Agency, NIMET. The research employed trend analysis using Mann-Kendall test and change point detection through CUSUM and Sequential Mann Kendall tests to establish the presence of non-stationarity in rainfall patterns. Three different General Extreme Value (GEV) distribution models were evaluated to determine the best-fit non-stationary model using Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). Results revealed a significant increasing trend in rainfall intensity (p-value = 0.006) with change points identified in 2002-2003. The GEVt-I model consistently demonstrated superior performance across all duration intervals (5-1440 minutes) with the lowest AIC values. A generalized non-stationary IDF model was developed, showing excellent predictive capability (R^2 = 0.992, MSE = 38.09). The findings highlight the importance of adopting non-stationary approaches for infrastructure design in Umuahia, as traditional stationary methods may significantly underestimate rainfall intensities in the context of climate change. The result from the trend and change point revealed that climate change influences rainfall pattern in Umuahia. Interestingly, the findings of this study align with global trends in climate change impacts on precipitation patterns and underscore the urgent need to update design standards and infrastructure planning approaches in Umuahia, South East of Nigeria.

Keywords

Rainfall Intensity-Duration-Frequency (IDF), Non-stationary Modeling, Climate Change, General Extreme Value (GEV), Distribution, Mann-Kendall Trend Analysis, Change Point Detection

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1. Introduction

Rainfall Intensity-Duration-Frequency (IDF) relationships are hydrological tools that aids engineers in the design of hydraulic structures and urban drainage systems [12, 15]. The IDF curves enables engineers to estimate the intensity of rainfall that would be produced for a particular duration and return period thereby enabling engineers and planners to develop resilient infrastructure that can withstand extreme precipitation events. However, many IDF curves developed for most cities still assume stationarity. Stationarity is the concept where the statistical parameters of the rainfall or the rainfall patterns remain constant over time. However, utilization of this assumption for the development of all IDF curves is flawed as there have been emerging evidence that climate change impacts the precipitation patterns across most cities [8-10, 13]. Willem et al. stated that the climate change should be considered when designing sewer systems or urban drainage as it reduces the vulnerability of cities as lesser sewer system surcharge or urban drainage flooding are experienced due to extreme events [16]. In recent decades, climate change has significantly altered precipitation patterns globally, leading to more frequent and intense rainfall events in many regions [6]. This shift has particularly affected tropical regions like Nigeria, where rapid urbanization compounds the challenges posed by changing rainfall patterns. The need to understand and quantify these changes has become increasingly urgent, especially in urban areas where infrastructure design depends heavily on accurate rainfall predictions [1].

Utilization of non-stationary approach for development of IDF curves help quantify the effect that climate change has on rainfall intensity. The utilization of non-stationary approach for IDF analysis represents a significant advancement over traditional stationary methods as it provides accurate representation of the rainfall intensity in areas experiencing significant climate change. Non-stationarity assumes that the rainfall parameters change with time. By incorporating time-varying parameters, non-stationary models can better capture the evolving nature of rainfall patterns influenced by climate change [2]. This approach is particularly relevant for regions like Umuahia, Nigeria, where rapid urbanization and climate change impacts intersect to create complex hydrological challenges. Ekwueme et al. reported that Umuahia was significantly impacted by climate change, as there was significant increasing trend in the rainfall intensity in the last three decades [5].

The assessment of rainfall patterns in Umuahia is crucial due to its location within the Niger Delta region and its vulnerability to flooding events. Traditional IDF curves, based on stationary assumptions, may no longer provide adequate design standards for infrastructure for Umuahia. The General Extreme Value (GEV) distribution widely recognized for its ability to model extreme events, offers a robust framework for incorporating non-stationarity in rainfall analysis [3]. This study aims to develop non-stationary IDF curves for Umuahia using long-term rainfall data and evaluate the existence of climate change signals in local precipitation patterns.

2. Materials and Methods

2.1. Study Area

Umuahia, the capital city of Abia State, is situated in southeastern Nigeria within the Niger Delta region, at 5.5544°N latitude and 5.7932°E longitude, Figure 1. The city experiences a tropical climate characterized by a rainy season from April to October and a dry season from November to March. Umuahia's climate is influenced by its proximity to the Atlantic Ocean and its location within the Guinea Forest-Savanna mosaic ecoregion. The area typically receives significant annual rainfall, making it susceptible to flooding events and other rainfall-related challenges. Rapid urbanization in recent years has further heightened the city's vulnerability to climate change impacts, particularly concerning changing rainfall patterns.

2.2. Data Collection

The study utilized long historical rainfall data of about three decades. A 31-year rainfall records starting from 1992 to 2022 were obtained from the Nigerian Meteorological Agency (NIMET) for Umuahia. The data obtained were the 24-hour monthly rainfall record for Umuahia. Smaller rainfall duration records were obtained by downscaling the 24-hour rainfall record utilizing Indian Meteorological Department (IMD) model which is given by Equation (1) [11]. The shorter duration record obtained included 5, 10, 20, 30, 60, 120, 360, and 720 minutes.

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

Where R_t = Downscaled rainfall precipitation, R_{24} = daily rainfall precipitation (mm), t = time.

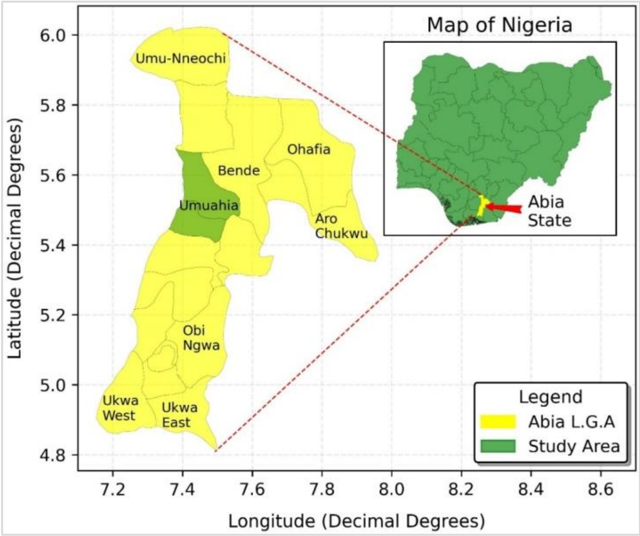

Figure 1. *Map of Study Area, Umuahia City in South Eastern Nigeria.*

2.3. Development of Non-Stationary IDF Model

Prior to the development of the rainfall intensity duration frequency models, trend and change point analysis were carried out. The trend analysis was carried out to establish that the statistical parameter of the rainfall varied over time and validate the utilization of non-stationary IDF model development. Also, change point analysis was carried out to identify when there was significant change in the rainfall data. Mann Kendall was utilized for the trend change while Distribution free CUSUM and Sequential Mann Kendall were used in establishing the change point year. Ekwueme et al. presented the detailed description on how trend and change point analysis were carried out for Umuahia [5].

The development of the non-stationary IDF model was based on the General Extreme Value (GEV) distribution [13]. The GEV distribution was adapted for modeling different behavioural extremes with three distribution parameters, notably: location, scale, and shape parameters [3]. The standard cumulative distribution function (CDF) of the GEV as given by Coles et al. (2001) is presented in Equation (2).

$$F(x) = \exp\left[-\left(1+\xi(t)\frac{x-\mu(t)}{\sigma(t)}\right)^{-1/\xi(t)}\right] for \xi \neq 0 \quad (2)$$

Where F(x) = Cumulative distribution function, μ = mean (location), σ = standard deviation (scale) and, ξ = shape parameter of three behavioral parameter extremes.

The maximum likelihood estimator was the statistical procedure used for estimating the distribution parameters, because the method could easily be extended to the non-stationary evaluation. Non-stationarity is introduced by virtue of expressing one or more of the statistical parameters of the GEV as a function of time [4, 7]. Three linear non-stationary expressions were employed for the development of the IDF models, and they are presented in Table 1. The best non-stationary model was selected based on the AIC and BIC goodness of fit. The non-stationary model with the lowest AIC and BIC were deemed to be the expression that best fit the non-stationarity of the rainfall. R-studio was utilized for obtaining the non-stationary model parameters and computing the rainfall intensity.

Table 1. *Types of Selected GEV Linear Parameter Models.*

Model Type	Parameter Combination	Remark
(i) $GEV_t - 0$	$\mu(t) = \mu$ $\sigma(t) = \sigma$ $\xi(t) = \xi$	Stationary parameter model
(ii)GEVt – I	$\mu(t) = \mu_0 + \mu_1 t$ $\sigma(t) = \sigma$ $\xi(t) = \xi$	Non-stationary parameter model
(iii)GEVt – II	$\mu(t) = \mu$ $\sigma(t) = \sigma_0 + \sigma_1 t$ $\xi(t) = \xi$ $\mu(t) = \mu_0 + \mu_1 t$	Non-stationary parameter model
(iv) GEVt – III	$\mu(t) = \mu_0 + \mu_1 t$ $\sigma(t) = \sigma_0 + \sigma_1 t$ $\xi(t) = \xi$	Non-stationary parameter model

Source: [14]

3. Results

The results of the trend and change point analysis for Umuahia are presented in Table 2. The Mann-Kendall test revealed a statistically significant increasing trend in rainfall, with a test statistic of 1.1418 and a p-value of 0.006. This finding indicates that the rainfall or precipitation has been on the rise in the last 31 years (1992 to 2022). The change point analysis result in Table 2 showed that both change point methods produce similar result. The CUSUM test identified 2002 as a significant change point year at both 90% and 95% confidence intervals, suggesting a marked shift in rainfall patterns around this period. This observation was further corroborated by the Sequential Mann Kendall (SQMK) test, which detected a change point in 2003, characterized by a single intersection of the prograde and retrograde curves. The temporal proximity of these change points (2002-2003) strengthens the evidence for a substantial modification in rainfall patterns during this period for Umuahia. The result obtained from Mann Kendall and change point analysis provide sufficient evidence that the effect of climate change influence rainfall or precipitation in Umuahia, therefore non-stationary method should be utilized for the IDF model development.

Table 2*. Mann Kendall and Change Point for Umuahia.*

Test Type	Statistic	p-value	Trend/Change Point	Remark
Mann-Kendall	1.1418	0.006	Increasing	Significant
CUSUM	9.0	-	2002	Significant (CI: 90%, 95%)
SQMK	-	-	2003	Just one interception of the prograde and retrograde

The development of the non-stationary IDF model is presented in Table 3. The analysis of GEV parameters reveals interesting patterns across different time durations ranging from 5 to 1440 minutes. For the 5-minute duration, the GEVt-I model demonstrated the best fit with the lowest AIC value of 196.264 and BIC of 202.00. This pattern of GEVt-I showing superior performance consistently appears across all time durations, as evidenced by it consistently achieving the lowest AIC values. For intermediate durations (10-60 minutes), the models maintained similar behavioural patterns. The 10-minute duration analysis showed the GEVt-I model performing optimally with an AIC of 212.487. This trend continued through the 20-minute duration (AIC = 227.338) and 30-minute duration (AIC = 236.338), with the location parameters gradually adjusting but maintaining the model's superior fit. For longer durations (120-1440 minutes), the pattern persisted with GEVt-I consistently showing the best fit. The 720-minute duration analysis revealed an AIC of 302.018 for GEVt-I, while the 1440-minute duration showed an AIC of 316.344, both being the lowest values among their respective duration groups.

The computed rainfall intensity utilized GEV-I model is visualized in Figure 2. The rainfall intensity is plotted against the log of the durations for different return periods. The curves exhibit the characteristic hyperbolic shape typical of IDF relationships, with intensity decreasing as duration increases, and higher curves corresponding to longer return periods. Figure 2 provide a valuable tool that can be utilized by engineers in obtaining the rainfall intensity for any duration and return period for Umuahia. For ease of obtaining the rainfall intensity for any duration and return period, a general IDF model was developed, and the result is presented in Table 4. The model developed showed excellent predictive capability with a very high coefficient of determination ($R^2 = 0.992$) and a relatively low Mean Square Error (MSE = 38.09). The high R^2 value indicates that the model explains approximately 99.2% of the variability in rainfall intensity, suggesting it is highly reliable for predicting rainfall intensities across various durations and return periods.

Table 3*. Evaluation of the performance of GEV parameters used for non-stationary and stationary models for Umuahia.*

Time (mins)	Models	Location Parameter	Scale	Shape Parameter	BIC	AIC
5	GEV_t – I	-181.219 + 0.097t	4.766	-0.204	202.00	196.264
	GEV_t – II	13.694	4.907 – 0.0001t	-0.231	205.06	199.319
	GEV_t - III	-241.848 + 0.127t	14.439– 0.005t	-0.204	204.94	197.766
10	GEV_t – I	-63.339 + 0.040t	6.306	-0.222	218.222	212.487
	GEV_t – II	17.253	6.182 - 0.0002t	-0.231	219.386	213.650
	GEV_t - III	-188.624 + 0.103t	13.781– 0.004t	-0.210	220.125	212.955
20	GEV_t – I	-31.406 + 0.027t	8.0489	-0.225	233.074	227.338
	GEV_t – II	21.737	7.787 + 0.0002t	-0.231	233.700	227.964
	GEV_t - III	-3.476+1.841t	2.028– 0.0006t	-0.218	233.623	*226.453*
30	GEV_t – I	24.015 + 0.0004t	9.424	-0.230	242.075	236.338
	GEV_t – II	24.884	8.915 + 0.0002t	-0.231	242.082	236.347
	GEV_t - III	-63.906 + 0.044t	12.204– 0.002t	-0.236	244.682	*237.512*
60	GEV_t – I	23.921 + 0.0037t	11.865	-0.233	256.343	250.607

Time (mins)	Models	Location Parameter	Scale	Shape Parameter	BIC	AIC
	GEV_t – II	31.523	3.342 + 0.0003t	-0.231	256.404	250.668
	GEV_t - III	-487.80 + 0.259t	31.580– 0.010t	-0.211	256.38	*249.214*
	GEV_t – I	36.189 + 0.0017t	14.909	-0.232	270.707	264.971
120	GEV_t – II	39.503	14.15 + 0.0004t	-0.231	270.729	264.993
	GEV_t - III	-53.978 + 0.047t	17.478 – 0.002t	-0.227	273.55	*266.385*
	GEV_t – I	56.024 + 0.0005t	21.489	-0.231	293.428	287.692
360	GEV_t – II	56.978	20.41 + 0.0005t	-0.231	293.432	287.696
	GEV_t - III	-30.889 + 0.044t	23.496– 0.001t	-0.239	296.475	*289.305*
	GEV_t – I	70.603 + 0.0006t	27.078	-0.232	307.754	302.018
720	GEV_t – II	71.787	25.71 + 0.0007t	-0.232	307.759	302.023
	GEV_t - III	20.065 + 0.0259t	27.47– 0.0003t	-0.231	311.005	*303.835*
	GEV_t – I	88.962 + 0.0008t	34.120	-0.232	322.080	316.344
1440	GEV_t – II	90.478	32.39 + 0.0009t	-0.232	322.085	316.349
	GEV_t - III	88.902 + 0008t	32.40 + 0.0009t	-0.232	325.514	*318.344*

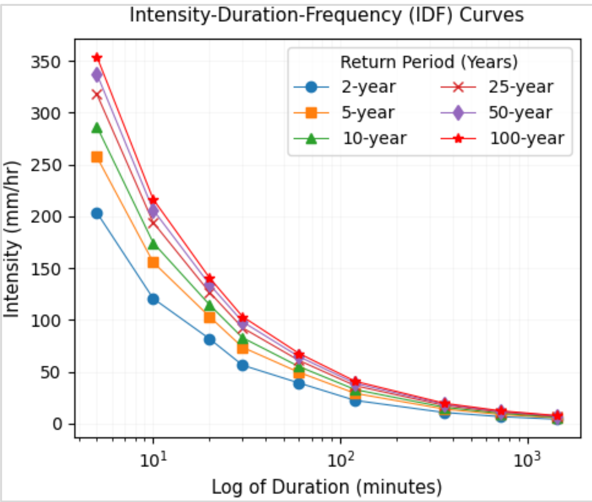

***Figure 2**. Computed Rainfall Intensity Duration Curves.*

***Table 4**. GEV fitted General Non-stationary IDF (GNS-IDF) models for Umuahia.*

S/N	Stations	IDF Models	R^2	*MSE*
1	Umuahia	$I = \frac{315.26 T_r^{0.315}}{T_d^{0.685}}$	0.992	38.09

4. Discussion

The analysis of rainfall patterns in Umuahia revealed that there would be significant implications on infrastructure design if stationary models are utilized in developing IDF models. The Mann-Kendall test results showing an increasing trend (p-value = 0.006) and the identification of change points in 2002-2003 strongly indicate non-stationarity in rainfall patterns. Ekwueme et al. in a previous study have documented that Umuahia exhibits significant increasing trends in rainfall/precipitation [5]. The finding provide evidence that non-stationary model must be utilized for development of rainfall intensity duration models.

The development of IDF models utilizing non-stationary models revealed that the GEVt-I was the best non-stationary model for Umuahia. This was confirmed by superior performance of GEVt-I across all durations, as evidenced by consistently lower AIC and BIC values. The GEV-I model that best represent that rainfall pattern in Umuahia suggests that the location parameters varied over the 31 years' study duration. This indicate that the rainfall precipitation gradually increases from year to year while the variation within each year remains constant over the study duration. Utilization of stationary model will result to significantly underestimating the rainfall intensities as the increase in the rainfall precipitation is not captured in the stationary models. Underestimation of the rainfall intensity could lead to the design of inadequate drainage infrastructures thereby increasing the risk of flooding in Umuahia. Cheng and AghaKouchak demonstrated that stationary models could underestimate the 50-year precipitation by as much as 60% in some regions [3]. The global trend towards non-stationary analysis is evident in literature. Sugahara et al. found that non-stationary models better captured the increasing intensity of extreme rainfall events [15]. The use of non-stationary model for development of IDF model have been embraced in other part of the world. However, the adoption of non-stationary approaches in Nigeria has been relatively slow. Very limited studies have been done on non-stationary models in Nigeria. Nwaogazie and Sam found that most IDF studies in Nigeria still relied on stationary approaches despite growing evidence of climate change impacts [10]. The implications of using stationary instead of non-stationary approaches in Umuahia are particularly of concern given its location in the Niger Delta region. AghaKouchak et al. emphasized the importance of non-stationary approaches in regions experiencing rapid climate change [2]. Willem et al. noted that incorporating such non-stationary patterns in urban drainage design could reduce infrastructure vulnerability by up to 30% [16]. These findings suggest an urgent need to update design standards and infrastructure planning approaches in Umuahia. Continuing to use stationary approach would not only underestimate future rainfall intensities but could also lead to systemic infrastructure inadequacies, particularly in urban drainage system.

5. Conclusion

This study aimed to develop non-stationary Intensity-Duration-Frequency (IDF) curves for Umuahia, Nigeria, using a 31-year rainfall record (1992-2022) obtained from the Nigerian Meteorological Agency. The result from the trend and change point revealed that climate change influences rainfall pattern in Umuahia. The detection of a significant increasing trend in rainfall intensity and the identification of change points in 2002-2003 provide strong evidence for the existence of non-stationarity in local precipitation patterns. The superior performance of the GEVt-I model across all duration intervals demonstrates the inadequacy of traditional stationary approach for modeling rainfall in this region. The findings in this study align with global trends in climate change impacts on precipitation patterns and underscore the urgent need to update design standards and infrastructure planning approaches in the region. The study's results suggest that continuing to use stationary IDF curves for infrastructure design in Umuahia could lead to significant underestimation of rainfall intensities, potentially resulting in inadequate infrastructure capacity.

Abbreviations

MSE	Mean Square Error
AIC	Akaike Information Criterion
NIMET	Nigerian Meteorological Agency
SQMK	Sequential Mann-Kendall
CUSUM	Cumulative Sum
BIC	Bayesian Information Criterion
GEV	General Extreme Value
IDF	Intensity-Duration-Frequency

Author Contributions

Chimeme Martin Ekwueme: Conceptualization, Investigation, Methodology, Validation, Writing – original draft

Ify Lawrence Nwaogazie: Conceptualization, Supervision, Validation, Writing – review & editing

Chiedozie Francis Ikebude: Conceptualization, Supervision, Validation, Writing – review & editing

Godwin Otunyo Amuchi: Funding acquisition, Writing – review & editing

Jonathan Onyekachi Irokwe: Funding acquisition, Writing – review & editing

Diaa Wissam El Hourani: Funding acquisition, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Field

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