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Development of rainfall intensity – duration – frequency models for Benin city in south-south Nigeria

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Abstract

A major challenge in water resources engineering is the lack of adequate meteorological data for designing and managing infrastructure against extreme rainfall events. This study analyzed 30 years (1993–2022) of daily rainfall data from Benin City, Nigeria, using the annual maximum series method. Rainfall intensities were calculated for durations ranging from 10 to 360 minutes and return periods of 2 to 100 years using Gumbel and Log Pearson Type III distributions. These models address both short-duration storm events and long-term recurrence probabilities, which are essential for flood risk management. Rainfall Intensity-Duration-Frequency (IDF) models were developed using non-linear regression in Microsoft Excel, Model performance was evaluated using statistical metrics like Chi-square, Correlation coefficient (R), Coefficient of determination (R^2), and Root Mean Square Error (RMSE). Both models showed excellent fits with low RMSE (0.26- 9.89) , R and R^2 values ranged between 0.98 -1.00 and 0.99-1.00 respectively . These IDF models are valuable tools for engineers and hydrologists in flood risk mitigation, drainage design, and water resource planning in Benin City, Nigeria.

Keywords: Development; Rainfall; Intensity; Duration; Frequency; Model

1. Introduction

Urban flooding is one of the most significant consequences of meteorological and climate change, posing a major environmental challenge for city authorities in developing nations. It represents a persistent and critical hazard that undermines the effective functioning of urban areas, particularly in terms of infrastructure and essential service delivery—both of which are vital for sustainable livelihoods. When severe floods occur in populated regions, they often result in the loss of lives and property, and they significantly disrupt social and economic activities in both urban and rural communities. The economic impacts are far-reaching, including loss of business assets, decreased customer engagement, and interruptions to key services such as electricity, water supply, and transportation networks.Flooding has become a global concern, affecting all aspects of human society. In Nigeria, the increasing frequency and intensity of floods—driven by climate variability and unsustainable human practices—threaten to reverse developmental gains. These events jeopardize the attainment of the United Nations' 17 Sustainable Development Goals (SDGs), particularly by endangering progress in eradicating extreme poverty, improving health, and ensuring environmental sustainability.Benin City experienced heavy rains in 2010, 2012, 2020 that led to severe flooding causing displacement of inhabitants and infrastructural damage. Residents attributed the disaster to poor storm drains and inadequate flood adaptation programs [10, 6, 11].

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The Rainfall Intensity-Duration-Frequency (IDF) analysis is a fundamental tool in hydrology, crucial for understanding and quantifying rainfall patterns necessary for effective flood risk management [13,18]. Precipitation, as a key component of the hydrologic cycle, plays a central role in the planning and design of water-related infrastructure. According to [4], rainfall frequency analysis is essential for the development and engineering of hydraulic structures such as storm water sewers, culverts, and other drainage systems. They emphasize that extreme rainfall events can compromise water quality, cause extensive property damage, and lead to the loss of lives due to flooding and associated pollution. Hence, the assessment of hazardous precipitation is critical for hydrologic risk analysis and infrastructure design. [4], further highlighted that evaluating excess rainfall through IDF relationships remains a primary focus in both theoretical and applied hydrology. [9], described IDF curves as graphical representations that show the expected amount of rainfall over a given duration for a specific return period, especially within catchment areas. These curves serve as vital tools for engineers in the design of urban drainage systems. Likewise, [20], stressed the necessity of detailed rainfall event statistics—specifically intensity, duration, and return period—for the design of flood control and hydrologic infrastructure. [12] also defined the IDF relationship as a mathematical correlation between rainfall intensity (I), storm duration (d), and return period (T). This relationship underpins most modern hydrologic design practices. In Nigeria, efforts to develop IDF models have been undertaken by researchers such as [2,16, 17], who employed statistical methods such as least squares regression. However, most IDF studies in Nigeria are concentrated in the southern regions, and there remains a significant gap in data availability for short-duration rainfall events. The manual plotting of IDF curves in some past studies has introduced a risk of inaccuracies and made the process costly and time-consuming.

Therefore, the primary goal of the present study was to develop accurate and reliable IDF models for Benin City, employing two statistical distribution methods: Gumbel distribution and Log Pearson Type III distribution. These models aim to estimate rainfall intensities for various durations and return periods, thus aiding in the planning and design of storm water infrastructure and enhancing flood resilience.

2. Materials and method

Benin City serves as the administrative, political, and economic nucleus of Edo State, Nigeria and represents one of the most prominent urban centers in the country's South-South geopolitical zone. The city lies within the humid tropical climatic zone of West Africa and comprises three principal Local Government Areas (LGAs): Oredo, Egor, and Ikpoba Okha, which collectively define its metropolitan structure.

Geographically, Benin City occupies a narrow, key-shaped expanse of land aligned along a north-to-south orientation, encompassing a total land area of approximately 1,125 square kilometres. The city is situated on gently undulating terrain, with an average elevation of 8.5 meters above sea level, which influences its surface hydrology and drainage characteristics. It is geographically positioned (Figure 1)between latitudes 6°21′N and 6°44′N, and longitudes 5°35′E and 5°44′E, placing it within the lowland rainforest belt of southern Nigeria and the West African sub-region [14,1]. Benin City experiences a hot and humid tropical climate, characterized by distinct wet and dry seasons. The rainy season typically spans from April to November while the dry season extends from December to March. Average daily temperatures are relatively high throughout the year, ranging from approximately 28 °C during the dry season to 24 °C in the wet season, indicating a narrow annual temperature range. The city and its surrounding areas are subject to intense and prolonged rainfall, particularly during the wet season, with annual precipitation totals between 2,000 and 2,300 mm, and a monthly average of approximately 180 mm. This significant rainfall is largely attributed to elevated rates of evapotranspiration, a consequence of consistently high temperatures. Relative humidity levels are also elevated, averaging around 80% in the wet season and 70% in the dry season [15, 19].

The vegetation in and around Benin City is diverse and varies with topography and land use. To the north of the city, savannah-type vegetation predominates, with wild-growing oil palms being a common feature. Areas of higher elevation are characterized by gravelly soils, which gradually transition into sandy soils toward the Orle Valley. The eastern plateau exhibits a mix of vegetative types: savannah in the northern section and tropical rainforest in the south. In regions subjected to deforestation, elephant grass and secondary vegetative growth have become dominant. The Benin lowlands, which were once covered by dense rainforest, have been extensively altered by rubber plantations. In contrast, the riverine areas in the southern part of the region are dominated by mangrove swamp vegetation [21].

Figure 1 Map of Edo showing Benin City

2.1. Data Collection

This study utilized precipitation depth data corresponding to short-duration intervals of 10, 15, 20, 30, 60, 120, 180, 240, 300, and 360 minutes. The differentiation between duration (measured in minutes) and return period (measured in years) in Rainfall Intensity-Duration-Frequency (IDF) modelling stems from their distinct roles in hydrological analysis: while duration captures the temporal extent of storm events, return period quantifies the likelihood of occurrence over a specified time horizon. Effective infrastructure design necessitates consideration of both short-term, high-intensity rainfall events and their long-term recurrence probabilities. The rainfall data used were sourced from the Nigerian Meteorological Agency (NIMET), Abuja, Nigeria, covering a 30-year period (1993 to 2022).

2.2. Development of Intensity-Duration-Frequency (IDF) Curves

To establish the relationship between rainfall intensity, storm duration, and return period, two widely used frequency analysis techniques were applied: the Gumbel distribution and the Log-Pearson Type III (LPT III) distribution.

2.3. Gumbel Distribution Method

The Gumbel distribution was employed to estimate extreme precipitation values and return intervals. This method is widely adopted in hydrologic studies due to its suitability for modelling maxima. The frequency precipitation corresponding to a specific return period (T) is calculated using:

$$PT = Pave + KS \quad \ldots\ldots\ldots.. \quad (1)$$

Where, K is the Gumbel frequency factor, given by:

$$K = \frac{\sqrt{6}}{\pi}\left[0.5772 + In\left[In\left[\frac{T}{T-1}\right]\right]\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots.. \quad (2)$$

Pave is the arithmetic mean of the annual maximum precipitation for a given duration:

$$P_{ave} = \frac{1}{n}\sum_{i=1}^{n} P\,i \quad \ldots\ldots\ldots\ldots \quad (3)$$

The standard deviation S is calculated as:

$$S = \left[\frac{1}{n-1}\sum_{i=1}^{n}(Pi - Pave)^{2}\right]^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots. \quad (4)$$

Rainfall intensity IT (mm/h) for each return period is determined by:

$$I_T = \frac{P_T}{T_d} \quad \text{……………….} \quad (5)$$

Where, T_d is the duration in hours.

2.4. Log-Pearson Type III Distribution

The LPT III distribution involves logarithmic transformation of precipitation values (P). The transformed values P* are used to compute frequency precipitation for various return periods as follows:

$$P^* = \log(P_i) \text{………………..} \quad (6)$$

$$P^*_T = P^*_{ave} + K_T S \quad \text{………………} \quad (7)$$

$$P^*_{ave} = \frac{1}{n}\sum_{i=1}^{n} P^* \quad \text{……………………} \quad (8)$$

$$S^* = \left[\frac{1}{n-1}\sum_{i=1}^{n}(P^* - P^*_{ave})^{2\,1/2}\right] \quad \text{………………..} \quad (9)$$

Where, P*T is frequency precipitation and P*ave is the average of the maximum precipitation corresponding to a specific duration based on the logarithmically transformed Pi values; i.e. P* of Equation (6). KT is the Pearson frequency factor which depends on return period (T) and skewness coefficient (Cs). The skewness coefficient (Cs) is required to compute the frequency factor for this distribution.

The skewness coefficients were computed using Equation (10) as suggested by [5].

$$Cs = \frac{n\sum_{i}^{ni}(P^*i - P_{ave})^3}{(n-1)(n-2)(S^*)^3} \quad \text{………………..} \quad (10)$$

Using the skewness coefficient and recurrence interval, K_T values were extracted from standard hydrology reference tables.

2.5. Empirical IDF Model Development

To empirically model the IDF relationship, the Sherman equation was employed:

$$\text{Sherman equation} \quad i = \frac{aT^b}{(t+d)^c} \quad \text{………………} \quad (11)$$

Where,

i is rainfall intensity (mm/hr), t is duration(minutes), T is return period (years) and a, b, c, d = regional model parameters.

These parameters were optimized using the Generalized Reduced Gradient (GRG) Solver in Microsoft Excel. The objective function minimized was the sum of squared errors (SSE):

$$\text{Min SSE} = \sum_{i=1}^{n}(i_{obs} - i_{est})^2 \quad \text{………………..} \quad (12)$$

Where i_{obs} is the observed rainfall intensity and i_{est} is the model-estimated intensity.

2.6. Model Performance Evaluation

The performance of both Gumbel and LPT III-based IDF models was assessed through statistical metrics including the Chi-square goodness-of-fit test, coefficient of determination (R^2), and Root Mean Square Error (RMSE).

The chi-square statistic was calculated as:

$$\chi^2 = \sum_{i=1}^{k} \frac{(Oi-Ei)^2}{Ei} \quad \text{.....................} \quad (13)$$

Where, O_i and E_i are observed and expected frequencies, respectively.

The coefficient of determination R^2 and RMSE were computed using:

$$R^2 = \frac{\sum_{i=1}^{n}(\text{Iobs}-\text{Iavg})^2 - \sum_{i=1}^{n}(\text{Iobs}-\text{Ipred})^2}{\sum_{i=1}^{n}(Iobs-Iavg)^2} \quad \text{.................} \quad (14)$$

$$\text{RMSE} = \sqrt{\frac{1}{N}} \sum_{i=1}^{N}(Ii - \hat{I}*)^2 \quad \text{...................} \quad (15)$$

The correlation coefficient (CC) was determined using:

$$\text{CC} = \sum_{i=1}^{N} \left(\frac{(Ii-\hat{I})(I*i-\hat{I}*)}{\sqrt{\sum_{i=1}^{N}(Ii-\hat{I})^2 + \sum_{i=1}^{N}(I*i-\hat{I}*i)^2}} \right) \quad \text{...............} \quad (16)$$

Where, I_i and I_{*i} are observed and predicted rainfall intensities respectively, and Î and Î* are their respective averages.

3. Results and discussion

3.1. Intensity Duration Frequency (IDF) Curves by Gumbel and Log Pearson Type (LPT) III Methods for Benin City

The results of the Intensity Duration- Frequency curves by Gumbel and Log Pearson Type methods for Benin City are shown in Figures 2 and 3 respectively.

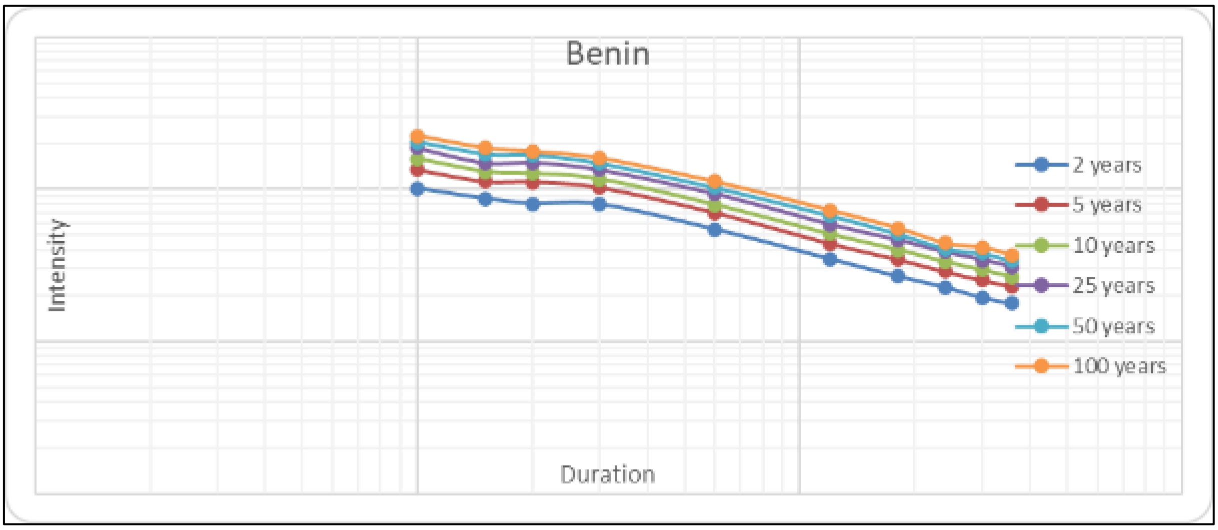

Figure 2 IDF curves by Gumbel method at Benin City (South-South Nigeria)

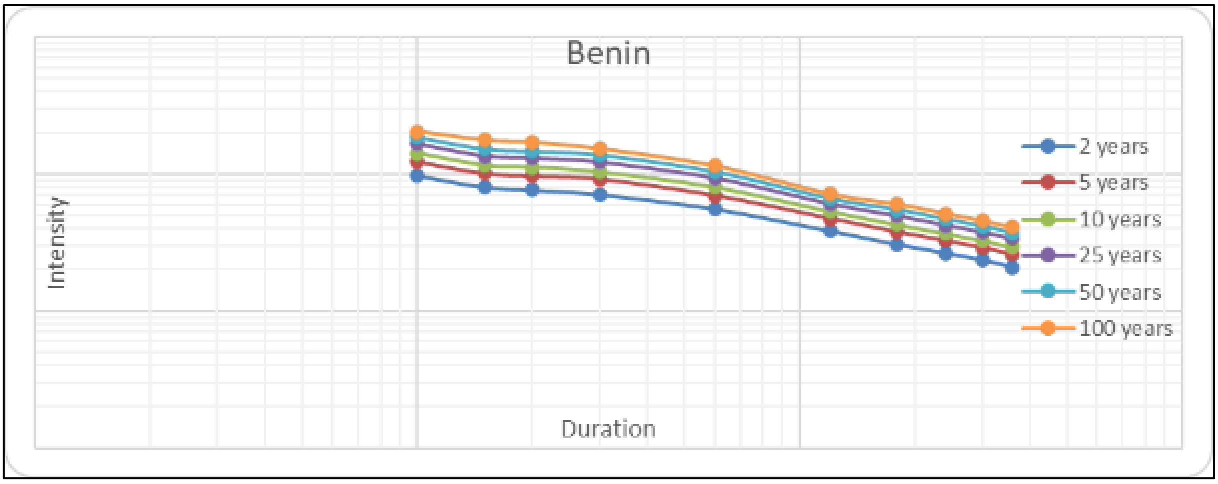

Figure 3 IDF curves by LPT III method For Benin City (South-South Nigeria)

Figures 2 and 3 illustrate the Intensity-Duration-Frequency (IDF) curves generated using the Gumbel and Log Pearson Type III (LPT III) distribution methods, respectively for Benin City. The trends observed in both sets of IDF curves exhibit a high degree of consistency, affirming the reliability of the applied statistical approaches. In both models, rainfall intensity was observed to decrease with increasing storm duration. Additionally, for any fixed duration, rainfall intensity increased with the return period, a finding consistent with the observations of [8].

Notably, the IDF curves derived from the LPT III distribution exhibited a more pronounced increase in rainfall intensity with return period and duration compared to those obtained using the Gumbel distribution. This suggests that the LPT III method tends to yield higher estimates of extreme rainfall intensities, potentially offering a more conservative approach for hydrologic and infrastructure design in regions prone to intense precipitation events.

3.2. Rainfall Intensity Duration Frequency Models and their Parameter Values

The parameter values used in deriving the Gumbel and Log Pearson Type III models, including the models for the region are shown in table 1

Table 1 Parameters values used in deriving models for rainfall intensity at Benin City region

S/No.	Location	Distribution	Parameters				Models
			a	B	c	D	
1.	Lagos	Gumbel	132	1.49	0.85	44.22	$I = \frac{132^{1.49}}{(t+44.22)^{0.85}}$
		Log Pearson Type III	141	1.72	0.87	41.26	$I = \frac{141{T_r}^{1.72}}{(t+41.26)^{0.87}}$

The Gumbel and Log Pearson Type 111 models, including the parameter values used in deriving the models for the region studied are shown in table 1. The parameter values used in deriving the models are a, b, c and d. For Benin city, the values of parameters a(141), b(1.72) and c(0.87) are higher for Log Pearson Type 111 method, except for d (41.26) that is lower than Gumbel's a value which is 44.22.The interpretation is that Log Pearson 111 predicts higher rainfall Intensity values than Gumbel at same durations and return period.

3.3. Model Performance/Validation for Benin City IDF models

The results of the computed indicators of goodness of fit between Gumbel and Log Pearson Type III Models, namely Chi Square (χ^2), Root Mean Square Error (RMSE), Correlation Coefficient (R) and Coefficient of Determination (R^2) are given in Tables 2 to 3.

Table 2 Model Performance/Validation for Benin City IDF Model Obtained by Gumbel Method

			Duration (min)									
Location	Distribution	Model validation	10	15	20	30	60	120	180	240	300	360
Benin City	Gumbel	$\chi2$	2.50	3.46	1.60	4.66	0.54	1.70	0.26	0.28	0.76	2..26
		RMSE	7.38	9.00	5.88	9.30	2.22	3.68	1.28	1.30	1.70	2.49
		R	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.98	0.98
		R^2	1.00	1.00	1.00	1.00	0.98	0.98	0.99	0.99	0.98	0.98
		P-value	0.74	0.60	0.86	0.40	0.96	0.85	0.99	0.99	0.98	0.97

Table 3 Model Performance/Validation for Benin City IDF Model Obtained by Log Pearson Type III Method

Location	**Distribution**	**Model validation**	**Duration (min)**									
			10	15	20	30	60	120	180	240	300	360
Benin City	Log Pearson Type III	$\chi2$	2.40	4.48	1.84	4.78	0.30	1.34	0.17	0.01	0.04	0.30
		RMSE	7.44	9.89	6.40	9.50	2.01	3.78	1.10	0.26	0.57	1.54
		R	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
		R^2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
		P-value	0.70	0.46	0.84	0.40	0.99	0.96	1.00	1.00	0.99	0.99

Tables 2 and 3 showed the model performance / validation of IDF Model obtained for Benin City using Gumbel and Log Pearson Type III distributions respectively. Results of chi square goodness of fit test between the observed and predicted intensities for both Gumbel and LPT 111 method revealed that most of the data fit the distributions at level of significance of 5%, except the data for 15 minutes and 30 minutes duration that do not give good fit using both distributions.

The results obtained revealed that in all cases the correlation coefficient (R) and coefficient of determination (R^2) obtained from the fitted IDF Models adopting both Gumbel and Log Pearson Type 111 distributions ranged between 0.98 -1.00 and 0.99-1.00 respectively. This indicates the goodness of fit of the models in estimating rainfall intensities in Benin City. This result is in agreement with work done by [8] indicating that the two probability distribution models are fit for prediction of rainfall intensities for Benin City.

The values of Root Mean Square errors (RMSE) obtained using Gumbel and Log Pearson Type 111 distributions for Benin City are lower at higher durations from 60 minutes to 360 minutes, but higher for lower durations from 10 minutes to 30 minutes for both. This shows that the derived formulae can be used to estimate any frequency rainfall data for Benin City, especially at higher durations using both methods.

3.4. Comparison of Observed and Predicted Rainfall Intensities

The results of the predicted rainfall intensities for different durations and return Periods are shown in Tables 4 and 5. Also some selected index values of predicted intensities for comparison of short, medium and higher durations are shown in Table 6.

Table 4 Predicted Intensity-Duration frequencies for different return periods by Gumbel method at Benin (South-South (Nigeria)

Return Period (Years)		**2**		**5**		**10**		**25**		**50**		**100**
Duration (min)	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
10	100.99	93.947	133.875	128.925	158.157	152.153	186.813	179.632	204.08	195.92	225.667	216.136
15	86.852	89.856	112.492	119.433	130.908	139.027	149.024	158.883	170.60	181.665	187.704	199.783
20	80.448	83.667	112.012	116.404	126.896	132.066	150.064	156.239	167.292	174.236	177.68	185.902
30	79.642	76.389	102.648	94.873	116.608	107.691	134.204	123.802	147.442	135.994	160.484	148.153
60	54.522	59.961	70.21	69.741	79.011	78.379	93.215	92.285	102.304	101.125	112.516	111.450
120	34.906	40.879	44.064	46.610	50.664	53.545	58.753	61.989	67.158	70.433	73.009	76.685
180	26.909	28.775	34.703	35.708	40.003	41.176	46.372	47.722	51.068	52.157	55.753	56.935
240	22.796	21.507	28.864	29.007	33.31	33.535	38.608	38.925	40.833	42.771	44.318	46.599
300	19.432	16.566	25.323	24.694	29.404	28.557	34.261	33.143	37.913	36.173	41.534	39.393
360	17.807	12.057	23.007	21.699	26.504	24.109	30.872	29.382	33.988	31.992	37.077	34.763

Table 5 Predicted Intensity-Duration frequencies for different return periods by Log Pearson Type 111 method at Benin (South-South Nigeria)

ReturnPeriod(Years)		**2**		**5**		**10**		**25**		**50**		**100**
Duration (min)	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
10	97.132	98.814	123.09	123.527	141.31	135.509	165.64	157.598	184.74	180.744	204.66	200.255
15	80.015	93.521	101.04	119.181	115.67	136.988	135.51	156.332	151.88	180.265	177.39	197.945
20	76.224	83.96	96.886	108.342	112.04	127.713	130.94	147.143	145.77	164.967	170.25	185.348
30	70.602	70.138	91.924	92.632	103.19	109.228	122.24	121.174	137.30	136.039	152.90	149.634
60	55.28	66.857	69.738	83.125	79.817	98.337	93.269	105.108	103.83	113.235	114.84	121.338
120	38.186	44.455	47.259	55.896	53.226	63.351	60.662	72.626	66.137	79.608	71.671	91.521
180	30.368	35.777	37.609	44.358	42.694	49.715	49.481	55.984	54.809	60.303	60.368	64.387
240	26.296	31.975	32.39	39.072	36.669	43.496	42.383	48.661	46.867	52.210	51.545	55.663
300	23.354	27.117	28.699	33.365	32.543	37.159	37.552	41.581	41.485	44.608	45.589	47.473
360	20.748	23.784	25.632	29.173	29.062	34.604	33.569	38.549	37.154	41.198	40.807	43.797

The developed IDF models were used to predict rainfall intensity for various durations and return periods. Duration and return period are key factors influencing the distribution of both observed and predicted rainfall intensities. To verify the accuracy of the models, comparisons were made between observed and predicted rainfall intensities. As shown in Tables 4 and 5 for the study location, rainfall intensity generally decreased with increasing duration. Additionally, for a fixed duration, higher return periods corresponded to higher intensity values. Among the models presented (Tables 4 and 5), Gumbel gave the highest predicted rainfall intensity values for 10minutes to 20 minutes duration, except for 2-years return period. However, the Log Pearson Type III distribution produced the highest predicted intensity values for 30minutes to 360 minutes.

Table 6 Comparison of selected index values of predicted intensities (mm/hr) for short, medium and higher durations

Method	**Station**	**10 min duration**	**60 min duration**	**300 min duration**
		100 Year Return Period	100 Year Return Period	100 Year Return Period
Gumbel	Benin	216.136	111.450	39.393
Log Pearson	Benin	200.255	121.338	47.473
Type 111				

Table 6 presents a comparison of the predicted rainfall intensities using the Gumbel and Log Pearson Type III models across short, medium, and long durations. For instance, at 10-minute duration with a 100-year return period, the Gumbel model predicted an intensity of 216.136 mm/hr, while the Log Pearson Type III model predicted 200.255 mm/hr. Similarly, at 60-minute duration for the same return period, the predicted intensities were 111.450 mm/hr for the Gumbel model and 121.338 mm/hr for the Log Pearson Type III model. At a longer duration of 300 minutes and a 100-year return period, the Gumbel model yielded a predicted intensity of 39.393 mm/hr, compared to 47.473 mm/hr from the Log Pearson Type III model.

These results, as shown in Table 6, consistently demonstrate the Log Pearson Type 111 model's tendency to predict higher rainfall intensities at higher durations evaluated. This pattern aligns with findings from similar studies on IDF models conducted in Ikeja by [8] and in Lahore City by [3], respectively.

4. Conclusion

This study outlines the methodology for developing Rainfall Intensity-Duration-Frequency (IDF) models for Benin, located in South-South Nigeria. The resulting IDF models provide a practical means for estimating rainfall intensities corresponding to various return periods and storm durations within the study area. The analysis reveals that the highest rainfall intensity occurs at a 100-year return period with 10-minute (0.15 hr) duration, whereas the lowest intensity is recorded at a 2-year return period with 360-minute (6.0 hr) duration.

4.1. Engineering Implications of Findings

The developed IDF models are valuable tools for engineers and hydrologists in estimating storm water runoff for the design and optimization of drainage systems, reservoir operations, and water resources planning. Their application is essential for mitigating urban flooding and minimizing its associated impacts. Furthermore, these models can serve as effective instructional tools in teaching land drainage and hydrology courses to engineering students, thereby enhancing their practical understanding and appreciation of the subject matter.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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