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Exploring the intensity, duration and frequency of rainfall in selected Southern Nigeria's urban landscapes

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Abstract: Southern Nigeria faces recurring challenges from high annual rainfall, thus resulting to frequent floods, gully erosion, damage to agriculture, water systems, and infrastructure. Studies that employed recent long span rainfall data with the use of precipitation duration curves in these areas are sparse. Forty years (1982 to 2021) maximum daily rainfall data for Akure, Calabar, Enugu, Ikeja, Owerri, and Yenegoa were scaled down to sub-daily intensities. The data were analysed using the Gumbel probability plotting position to develop IDF curves and equations for return periods between 1 to 500 years in conjunction with rainfall durations ranging from 0.25 to 24 hours. Performance evaluation tests assessed the suitability of developed IDF equations. The IDF equations demonstrated high accuracy since a determination coefficient (R^2) of 0.97 was obtained. Understanding rainfall characteristics in these locations can inform water policy development and also enhance flood management for the support of water resource planning and governance.

Keywords: rainfall; return period; rainfall intensities; precipitation duration curves; PDCs; Nigeria.

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1 Introduction

Intensity, duration and frequency (IDF) curves and equations are important prerequisites to hydrologic designs, construction of water management and hydraulic structures. IDF's define existing relationships between rainfall intensities, durations and frequencies (Ologhadien and Nwaogazie, 2018). They are useful for the prediction of runoff rates as well as flood (Aybehon, 2022). It is one of the most intensively used tools in

water resources engineering for planning, design as well as management of water resources-related projects (Minh Nhat et al., 2006), since it provides adequate information on the probability of rainfall intensity with its accompanying runoff. IDFs serve as stochastic foundations for the design of hydraulic and hydrologic structures (Ologhadien and Nwaogazie, 2014; Kawara and Elsebaie, 2022). They rank amongst some of the most commonly used methods for planning, designs and risk analysis in water resources management (Awofadeju et al., 2018). According to Ologhadien and Nwaogazie (2018), IDF equations can be categorised into four types, based on the number of parameters present in the equations. These are in line with the IDF equations templates, as categorised by Minh Nhat et al. (2006), Ragunath (2006) and Kareem et al. (2022) given as equations (1)–(5).

- Talbot equation:

$$i = \frac{a}{t+b} \quad (1)$$

- Bernard equation:

$$i = \frac{aT^m}{t^n} \quad (2)$$

- Kimijima equation:

$$i = \frac{aT^m}{b+t^n} \quad (3)$$

- Sherman equation:

$$i = \frac{aT^m}{(t+b)^n} \quad (4)$$

A more generalised IDF equation can be given as

$$i = \frac{aT^m}{(t^v+b)^n} \quad (5)$$

where i = rainfall intensity in (mm/hr); t is the duration in minutes or hours; T is the return period in years; a , b , m , n and v are constants.

In recent times, several pieces of research have been carried out on the existing relationships between rainfall intensity/depth, durations and frequencies in different locations. However, more research on the development of IDF relationships in more locations is increasingly becoming important, due to the temporal and spatial variability of rainfall as well as increasing climate change. Aybehon (2022) analysed IDF curves for some meteorological stations in North Shao, Ethiopia. It was reported from the study that predicted shorter durations of rainfall intensities from the developed curves resulted in higher intensities while longer duration rainfall events resulted in lower intensities and spread over the duration. Kawara and Elsebaie (2022) developed an IDF relationship for the Yalamlam area of Saudi Arabia using daily and sub-daily rainfall data. The authors further proposed new ratios for the conversion of daily rainfall data to sub-daily data in Yalamalam. Kareem et al. (2022) compared, analysed and developed rainfall IDF for

Erbil using maximum rainfall data for 39 years (1980–2018). The developed IDF curves and empirical formulas were compared with previously developed ones in Iraqi cities to determine their dependability. Gioia et al. (2021) estimated peak discharges from different rainfall depths, duration, frequency curves (DDF) using the soil conservation service curve number (SCS-CN) method. The study confirmed that the three-parameters DDF outperformed the two-parameters DDF for the estimation of peak discharges and rainfall depth, especially for a duration greater than or equal to 30 minutes. Furthermore, Gámez-Balmaceda et al. (2020) developed a rainfall IDF relationship for a semi-arid region of Mexico with a particular focus on the depth-duration ratio. The depth-duration ratio obtained ranged between 0.35 and 0.44. Perera et al. (2017) studied the rainfall intensity duration threshold in Sri Lanka. The study concluded that the last six years from the study period had experienced a more frequent occurrence of extreme rainfall. Mohammed and Kumsa (2021) developed a rainfall IDF curve for some selected western Ethiopia towns. Elsebaie et al. (2022) as well studied the spatial and temporal variability of IDF curves in the Wadi AL-Lith, Saudi Arabia. The authors claimed that the developed IDF curves can be used to determine flood vulnerability in flood-prone areas such as Wadi AL-Lith.

In Nigeria, IDF curves and equations had also been developed for some cities in the past. Nwogazie and Okonkwo (2017) developed IDF for Abakaliki city in Nigeria using ten years rainfall data (2004–2013). IDF models with two and three parameters were developed to establish the relationship between rainfall intensities, durations and frequencies in Abakaliki City. Ahmed et al. (2021) developed location-specific rainfall IDF curve and equation for Abuja, Nigeria, using 35 years daily rainfall data. This enabled the predictability of rainfall intensities, durations and return periods. Awofadeju et al. (2018) developed IDF curves for the design of storm drainages in eight towns of five southwestern states, Nigeria. Ologhadien and Nwaogazie (2018) compared the differences and similarities in rainfall intensities predicted from four types of developed IDF equations with varying numbers of parameters. The IDF equations were developed for five southern Nigerian cities including Benin, Calabar, Port Harcourt, Onitsha and Warri using historical rainfall data of 31, 21, 23, 26 and 17 years, respectively. The study recommended the two-parameter equations as tools for hydrologic and hydraulic design of water structures. Furthermore, Ozota and Ukpaka (2017) developed IDF for Omoku River, Rivers State, Nigeria using 14 years' rainfall data. In the same vein, Ogbozige (2021) developed IDF for Port Harcourt City from a manually operated 50 years rain gauge record. The data were fitted to Gumbel, Pearson type III and Log-Pearson type III probability distributions at frequencies 50%, 20%, 10%, 4% and 2% with duration ranging from 0.33 to 7 hours. IDF equation developed from the Gumbel distribution was recommended in the study because it resulted in the highest determination coefficient (0.9865).

None of these extensive pieces of research developed IDF equations and curves using most recent long-span rainfall data. Furthermore, studies on precipitation duration curves (PDCs) are sparse for the selected location in this study. The objective of this study is to develop IDF curves and equations as handy tools for rainfall forecast as well as flood studies for Akure (P1), Calabar (P2), Enugu (P3), Ikeja (P4), Owerri (P5) and Yenegoa (P6); which are capital cities of Ondo, Cross-River, Enugu, Lagos, Imo and Bayelsa States, respectively all located in southern, Nigeria. These objectives were achieved by:

- 1 developing PDCs for each city
- 2 fitting Gumbel distribution to the rainfall data from each city
- 3 the determination of rainfall frequencies
- 4 the development of IDF curves and equations.

2 Materials and methods

2.1 Data collection and study area

Forty years rainfall data for six independent locations were obtained from the website (<https://power.larc.nasa.gov/data-access-viewer/>) of the National Aeronautics Space and Administration (NASA) for the periods between 1982 and 2021 (40 years) [the entire data for this study was archived in data repositories and can be accessed from Sasanya and Adesogan (2022c)]. The locations include Akure (P1), Calabar (P2), Enugu (P3), Ikeja (P4), Owerri (P5) and Yenegoa (P6). From the obtained data, these cities experience some of the highest rainfall amount in Nigeria, annually. Table 1 shows more details including altitude, population averages, land area (km²) as well as annual rainfall amount. The dry and rainy seasons are the two major seasons experienced in these cities, annually. The rainy season spans from March to October, while the dry season extends from November (Chineke et al., 2010). The term ‘August break’ often comes into play annually when minimal rainfall is experienced during the rainy periods (Chineke et al., 2010). Figure 1 delineates the capital cities of focal federal states in this study.

Table 1 Location, land mass and population details of study areas

<i>Cities</i>	<i>Longitude (0E)</i>	<i>Latitude (0N)</i>	<i>Average annual rainfall (mm)</i>	<i>Land area (km²)</i>	<i>Altitude (m)</i>	<i>Average population</i>
P1	5.180	7.249	1,737.48	991.00	208.09	717,000
P2	8.333	4.977	2,911.90	406.00	39.38	631,000
P3	7.531	6.453	1,596.55	556.00	151.33	820,000
P4	3.345	6.594	1,392.03	49.92	25.29	861,300
P5	7.037	5.491	2,035.52	104.00	62.54	945,000
P6	6.279	4.922	2,677.60	1,698.00	17.26	266,000

2.2 Statistical analysis of rainfall data

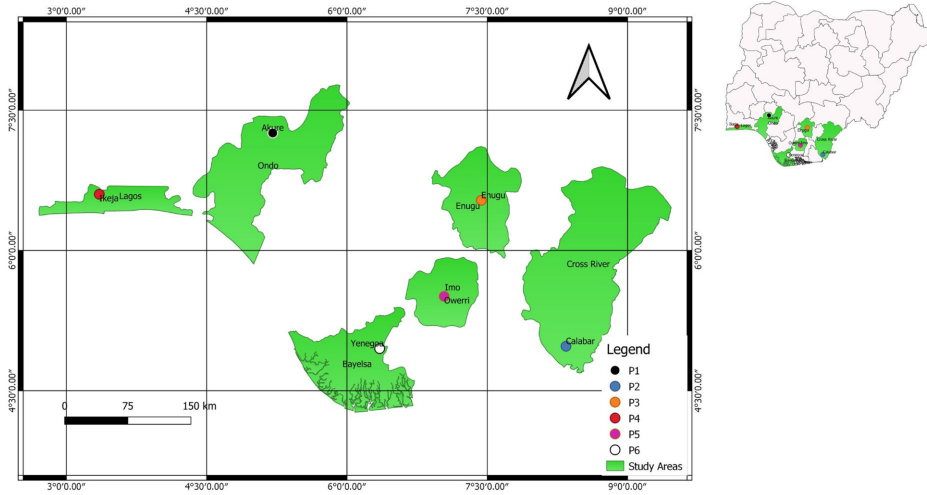
Annual rainfall intensities for each city were described by the maximum intensity, coefficients of variation (CV), and coefficient of skew (CS). CV and CS were estimated from equations (6) and (7).

$$CV = \frac{\sigma}{\bar{x}} \tag{6}$$

$$CS = \frac{\sum (x - \bar{x})^3}{(n - 1)\sigma^3} \tag{7}$$

where σ is the standard deviation, $\bar{x}$ is the mean of rainfall intensity, n is the number of historic rainfall records and x is the rainfall intensity. The CV describes the rainfall variability as low when $CV \leq 0.2$, moderate when $0.2 < CV < 0.3$ and high when $CV \geq 0.3$.

Figure 1 Map delineating the six study areas (see online version for colours)



2.3 Construction of PDC

PDCs represent rainfall occurrences (Yokoo and Sivapalan, 2011). They can effectively replace cumulative distribution functions of precipitation (Yokoo and Sivapalan, 2011). PDC in this study were used as the graphical representation of probability plotting positions in hydrological analysis (Shah et al., 2024). Flow duration curves are essential for decision-making on water availability, reliability, hydropower estimation of water resources and prediction of temporal series flow in un-gauged catchments (Ragunath, 2006; Ziegeweid et al., 2015; Muller and Thompson, 2016). PDC illustrate the average number of times a discharge/flow or rainfall depth is equalled or exceeded within a certain period (annually, monthly, daily, or hourly) (Ragunath, 2006; Davie, 2008). PDCs are helpful to determine the variability of water as a resource in time and space for effective adequate management (Westerberg et al., 2014).

The PDC was derived using the method described by Ragunath (2006). PDC was constructed for each city from the annual maximum daily rainfall depth (mm). The rainfall intensities were grouped into class intervals of 0–40, 41–80, ..., and 161–200 for each city. The number of times each class interval can be equalled or exceeded was obtained by adding up the numbers of rainfall depths in each class interval to obtain the cumulative sum. The percentage of each class interval making up the cumulative sum was found. The lower limits of the class intervals were plotted against the corresponding percentages to derive the PDC which can be used to predict the likely number of times a particular rainfall is equalled or exceeded in each location.

2.4 Deriving other intensities from daily rainfall intensities

The transformation of daily rainfall data to sub-daily data is germane to hydrological research (Kawara and Elsebaie, 2022). The 40 years daily maximum rainfall intensities obtained for the six cities were scaled down to smaller time units (sub-daily data) of 0.25, 0.5, 0.75, 1, 3, 6, 12 and 18 hours. Equation (8) was used to scale the time units down (Kareem et al., 2022; Kawara and Elsebaie, 2022).

$$I_i = I_{24} \left[\frac{t}{24} \right]^{\left(\frac{1}{3} \right)} \quad (8)$$

where I_i is the rainfall amount (mm) for the sub-daily time scale, I_{24} is the daily rainfall depth (mm) in 24 hours and t is the required sub-daily time.

2.5 Frequency distribution of rainfall data

Frequency analysis of rainfall is important in hydraulic engineering research as well as water resources planning, management and distribution (Hasan et al., 2019). The Gumbel method of plotting probability positions or frequency analysis of rainfall is the most widely used for the construction of IDF (Kareem et al., 2022). Most hydrological processes vary with time and space, therefore, the most prevalent or maximum value within the historical data gathered over time is usually used for frequency analysis and estimation (Hasan et al., 2019). Annual maximum daily rainfall depths (mm) were arranged in descending order of magnitudes and fitted to the Gumbel probability plotting position [equations (9) and (10)]. The recurrent periods for the annual maximum daily rainfall data for each city were thus determined using the Gumbel (1943) distribution method as given by Ragunath (2006).

$$T = \frac{1}{1 - e^{-e^{-y}}} \quad (9)$$

$$y = \frac{1}{0.78\sigma} (X - \bar{X} + 0.45\sigma) \quad (10)$$

where T is the return period in years, y is the reduced variate, σ is the standard deviation of the dataset while $\bar{X}$ is the mean of the maximum rainfall intensities.

2.6 Development of intensity duration frequency (IDF) curves and models

Another prerequisite for hydrologic designs is the IDF curves and equations which define the relationship between rainfall intensity, rainfall durations and return periods (Ologhadien and Nwaogazie, 2018). The intensity duration curves and equations give valid relationships between the rainfall duration, rainfall intensity and return period. IDFs for each city were derived using the Sherman [equation (4)] format (Kareem et al., 2022). Duration of 15 mins (0.25 hrs), 30 mins (0.5 hrs), 45 mins (0.75 hrs), 1 hr, 3 hrs, 6 hrs, 12 hrs and 18 hrs were used for the computations. Return periods of 1–331 yrs, 1–53 yrs, 1–63 yrs, 1–276 yrs, 1–374 yrs, and 1–727 yrs were used for the IDF derivations for P1, P2, P5, P3, P4, and P6, respectively as obtained from the frequency analysis.

The equations and curves for the forecast of rainfall intensity I (mm/hr) from return period (years) and rainfall duration t (hours) were derived from the methods described by Ragunath (2006), Kareem et al. (2022) and Kawara and Elsebaie (2022). The rainfall intensity (mm/hr) for each return period (T) was plotted against duration (t) (hours) on a normal graph and the logarithmic graph. The logarithmic format of equation (4) is given as equation (11).

$$\log i = \log K - n \log(t + b) \quad (11)$$

where $K = aT^m$, a , b , m and n are constants. ' a ' was obtained from the intercept of logarithmic line $T = 1$ yr on the intensity axis, m was obtained from the differences in vertical distances of points on the logarithmic line $T = 5$ yrs and $T = 50$ yrs, n is the slope of the logarithmic line $T = 50$ yrs and b were obtained by trial and error to ensure proper accuracy of predicted intensities. The derived IDF equation was used to predict rainfall intensities for a given duration and return periods. The accuracy of predicted intensities was compared with observed values using some performance and goodness of fit tests.

2.7 Performance and goodness of fit tests

Six performance and goodness of fit tests were used to assess the accuracy and performance of developed IDF models for each city. Rainfall intensities were predicted for return periods of 1, 2, 5, 10, 20, 30, 50, 100, 200 and 500 years and from rainfall durations of 0.25, 0.5, 0.75, 1, 3, 6, 12, 18, and 24 hours from the developed models. The performance and goodness of fits tests employed include root mean square error (RMSE), the Kolmogorov Smirnov (KS) test, Chi-square (X^2) test, volume error (VE) test, correlation coefficient (R) and coefficient of determination (R^2). Equations supporting the various tests are given as in equations (12) to (17) (Sasanya and Adesogan, 2022a, 2022b).

- The RMSE

$$RMSE = \sqrt{1/n \sum_{i=1}^n (e - o)^2} \quad (12)$$

- The Kolmogorov Smirnov test (KS)

$$D = \max \left| F(x_i) - \frac{i-1}{n}, \frac{1}{n} - F(x_i) \right| \quad (13)$$

- The Chi-square goodness of fit (X^2)

$$X^2 = \sum_{i=1}^n \frac{(O_i - e_i)^2}{e_i} \quad (14)$$

- The volume error (Vol Err)

$$Vol\ Err = \left| \frac{\left(\sum o - e \right)}{o} \right| \quad (15)$$

- The correlation coefficient (R)

$$R = \frac{n(\sum oe) - (\sum o)(\sum e)}{\sqrt{[n\sum o^2 - (\sum o)^2][n\sum e^2 - (\sum e)^2]}} \quad (16)$$

- The coefficient of determination (R^2)

$$R^2 = \left[\frac{n(\sum oe) - (\sum o)(\sum e)}{\sqrt{[n\sum o^2 - (\sum o)^2][n\sum e^2 - (\sum e)^2]}} \right]^2 \quad (17)$$

‘o’ represents the observed values and e represents the estimated values.

3 Results and discussion

3.1 Statistical analysis of rainfall data

Rainfall data from six Nigerian cities that are prominent for receiving high rainfall amounts annually were analysed and characterised for modelling. Annual rainfall characteristics, including maximum rainfall, CV and CS for the periods between 1982 and 2021 are shown in Table 2. The CV is an indicator of slopes of the Gumbel frequency log-log plots for each city (Sasanya and Adesogan, 2022b), and measures the variability of rainfall within a particular period (Zakwan and Ara, 2019).

Between the years 1982 and 2021, the highest rainfall depths per day were experienced in 2019 for P1 (169 mm/day), 1983 for P2 (174 mm/day), P3 (163 mm/day) and P5 (153 mm/day), in 2020 for P4 (166 mm/day) and 2017 for P6 (324 mm/day). The smallest of the daily maxima per annum were experienced in 2014 for P1 (25 mm/day), P5 (16 mm/day) and P6 (28 mm/day) and 1990, 2012, 1984, for P2 (35 mm/day), P3 (23 mm/day) and P4 (27 mm/day), respectively. The variabilities between daily rainfall for each year are shown in Table 2. The CV for P1 ranged between 0.5 and 0.9. For P2, P3, P4, P5 and P6, the CV ranged between 0.5 to 1.0, 0.4 to 0.93, 0.35 to 0.84, 0.51 to 0.92 and 0.4 to 0.9, respectively. These imply that the variability of rainfall events in all the southern Nigerian cities considered are all-time high and above moderate, since $CV \geq 0.3$.

The CS usually measures the deviation curves plotted on normal graphs (Nasiru et al., 2023). The CS determined the direction of skewness of the rainfall distribution for each city. The CS are all positive as shown in Table 2. This implies the rainfall distributions for the six cities are rightly skewed. The ranges of skewness coefficients for P1, P2, P3, P4, P5 and P6 are between 0.7 and 1.5. For the maximum rainfall, CV and CS are all shreds of evidence that the cities considered in southern Nigeria experience a high level of variability in annual rainfall and the distribution of such rainfall are characterised by positive skewness.

Table 2 Statistical analysis of rainfall data for six southern Nigerian cities

Year	P1			P2			P3			P4			P5			P6		
	MAX (mm/day)	CV	CS	MAX (mm/day)	CV	CS	MAX (mm/day)	CV	CS	MAX (mm/day)	CV	CS	MAX (mm/day)	CV	CS	MAX (mm/day)	CV	CS
1982	66	0.7	1	123	0.9	0.9	50	0.8	0.79	102	0.4	0.9	75	0.8	1	116	0.7	1.03
1983	88	0.6	1.1	174	0.6	1.2	163	0.5	1.14	44	0.5	1.3	153	0.6	1.2	136	0.6	1.32
1984	36	0.8	0.9	60	0.9	0.8	57	0.7	1.04	27	0.7	1	65	0.7	1	60	0.7	1.02
1985	36	0.7	1.1	52	0.8	1	26	0.8	1	29	0.7	1.2	47	0.7	1.1	50	0.7	1.03
1986	31	0.8	1.1	79	0.7	1	37	0.7	0.96	38	0.7	1.3	57	0.7	1	83	0.7	1.14
1987	50	0.7	1.2	108	0.8	0.9	41	0.7	1.12	45	0.6	1.3	56	0.7	1.3	96	0.7	0.96
1988	68	0.8	0.8	66	0.9	0.8	51	0.8	0.83	86	0.6	0.9	77	0.8	0.9	82	0.8	1.01
1989	36	0.8	1.1	55	0.8	1	43	0.7	1.34	53	0.7	1.2	66	0.7	1.2	114	0.7	1.08
1990	25	0.8	1.1	35	0.9	0.7	41	0.8	0.88	32	0.7	1.1	46	0.7	1.1	72	0.7	1.01
1991	62	0.6	1	50	0.7	1.1	32	0.7	1.15	65	0.6	1.1	42	0.6	1.2	72	0.6	1.22
1992	36	0.8	1.1	64	0.9	0.8	50	0.7	1.13	31	0.6	1.2	69	0.7	1.2	123	0.7	1.07
1993	35	0.9	0.8	74	0.9	0.9	54	0.8	0.94	61	0.6	1.1	48	0.9	1	40	0.9	0.95
1994	43	0.9	0.7	50	0.9	0.9	55	0.8	0.7	32	0.8	1	88	0.8	0.7	88	0.8	1.06
1995	41	0.9	0.9	144	0.8	0.7	49	0.9	0.81	52	0.8	1	51	0.9	0.6	62	0.9	0.72
1996	38	0.8	0.9	126	0.7	0.8	66	0.7	0.89	39	0.7	1.1	66	0.8	0.9	95	0.7	0.97
1997	38	0.8	0.9	45	0.9	1.1	62	0.7	0.93	53	0.7	1	70	0.7	1	67	0.7	1.28
1998	27	0.7	1.2	49	0.8	1.1	65	0.6	1.08	34	0.7	1.1	59	0.6	1.1	68	0.6	1.27
1999	35	0.7	1.1	81	0.7	0.8	28	0.7	0.98	42	0.6	1.2	22	0.7	1.1	33	0.7	1.15
2000	41	0.7	1.2	100	0.7	1.2	78	0.6	1.35	30	0.7	1.1	112	0.6	1.4	79	0.6	1.46
2001	30	0.7	1.2	164	0.7	0.8	44	0.7	0.98	47	0.6	1.3	62	0.6	1	51	0.6	1.13
2002	59	0.7	1	72	0.7	1	48	0.7	1.1	48	0.6	1.1	54	0.6	1.2	52	0.7	1.14
2003	58	0.7	1	50	0.9	1	57	0.7	1.07	61	0.6	1	63	0.6	1	106	0.6	0.97
2004	42	0.8	0.9	66	0.8	1.1	38	0.8	1.04	50	0.7	1.2	33	0.8	1.2	87	0.6	1.02

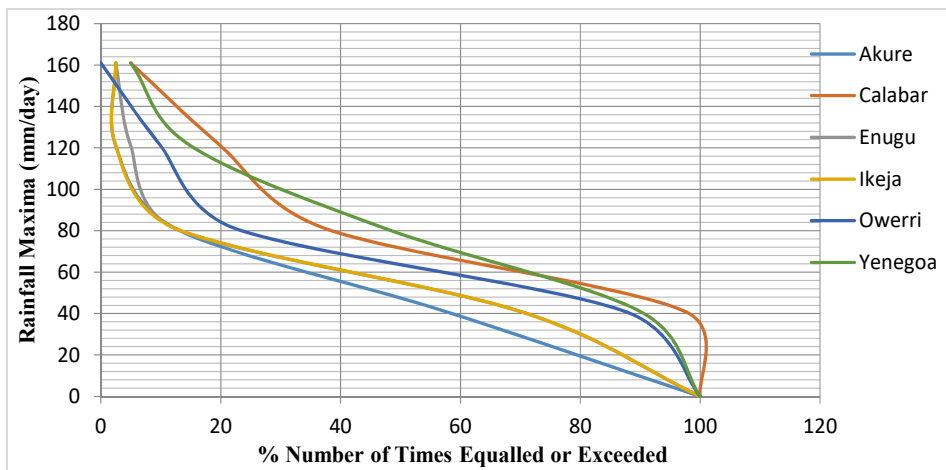
Table 2 Statistical analysis of rainfall data for six southern Nigerian cities (continued)

Year	P1			P2			P3			P4			P5			P6		
	MAX (mm/day)	CV	CS	MAX (mm/day)	CV	CS	MAX (mm/day)	CV	CS	MAX (mm/day)	CV	CS	MAX (mm/day)	CV	CS	MAX (mm/day)	CV	CS
2005	46	0.5	0.9	82	0.8	1	37	0.7	1.04	113	0.3	0.7	46	0.5	1.1	66	0.5	1.17
2006	112	0.5	0.9	96	0.7	1.1	51	0.7	1.21	49	0.6	0.9	53	0.6	1.2	68	0.6	1.14
2007	53	0.7	1	125	0.7	1	81	0.7	1.04	55	0.7	1	65	0.7	1	138	0.6	0.98
2008	76	0.7	0.9	45	0.9	0.8	24	0.9	0.89	50	0.7	1.1	41	0.7	1.1	37	0.8	1.25
2009	39	0.9	0.6	62	0.9	1	25	0.9	0.67	78	0.7	0.8	45	0.8	0.8	79	0.7	0.85
2010	53	0.8	0.9	82	0.8	1	44	0.8	1.01	52	0.8	0.9	88	0.6	1	83	0.6	1.1
2011	31	0.9	0.8	70	0.8	0.9	42	0.9	0.92	47	0.8	0.9	49	0.8	1.2	70	0.7	1.08
2012	36	0.9	0.9	70	0.8	0.9	23	0.9	0.87	49	0.8	1	30	0.8	1.1	47	0.8	1.19
2013	44	0.9	0.7	47	1	0.8	35	0.9	0.83	33	0.8	0.8	43	0.9	0.9	41	0.8	1.04
2014	25	0.9	1	47	0.8	1	34	0.8	0.99	33	0.8	0.9	16	0.9	1.1	28	0.8	1.23
2015	32	0.8	0.9	77	0.7	0.9	41	0.7	0.82	33	0.7	1.2	40	0.7	0.9	82	0.6	1.05
2016	63	0.7	1	66	0.8	1	37	0.7	1.07	81	0.6	1	55	0.7	0.9	67	0.6	0.86
2017	73	0.7	0.9	136	0.6	0.9	108	0.5	0.86	80	0.6	0.8	133	0.5	1	324	0.4	0.86
2018	93	0.6	1	133	0.6	1	85	0.5	0.96	43	0.7	1.1	87	0.6	1.1	102	0.6	1.09
2019	169	0.5	0.9	56	0.6	1.3	63	0.5	1.09	54	0.7	1.1	82	0.7	1.2	115	0.7	1.18
2020	102	0.5	0.8	67	0.7	1.2	131	0.4	0.99	166	0.4	0.7	143	0.5	0.9	180	0.6	1.01
2021	76	0.7	1.1	115	0.5	0.9	45	0.6	0.97	79	0.6	1	136	0.6	1	153	0.6	0.93

3.2 Precipitation duration curves

Figure 2 represents the PDCs, a graphical illustration of recurrence, for the six cities, whose rainfall patterns and distributions were studied in the southern region of Nigeria. The curves show the number of times that annual maximum or extreme rainfall was exceeded. Forty annual maximum rainfall intensities were grouped into intervals of 0–40, 41–80, ..., and 161–200 mm/yr. Out of 40 annual maxima, 17 were within the intervals 0–40 at P1, 1 at P2, 12 at P3 and P4, 5 at P5 and 4 at P6. The latter are shreds of evidence that P2, P5 and P6 often experience high rainfall amounts because many maximum rainfall intensities at these cities are not within the 41–80 mm/day interval. In the same vein, P2 (7), P5 (5) and P6 (13) had more numbers of maximum daily rainfall intensities within the interval 81–120 mm/day. In the same order, their maximum intensities within the 121–160 mm/day interval are 6, 4 and 4, while P1, P3 and P4 had 0, 1 and 0 maximum intensities, respectively. The highest interval (161–200 mm/day) had 1 rainfall intensity for P1, P3, P4 and P6. but P5 had none, while P2 had 2. These translate that daily maximum rainfall within this range is extreme, thus they rarely occur. This gives a clue on the recurrence period, probabilities of occurrences and non-occurrence as well as probabilities of exceedance and non-exceedance, by plotting the lower limits of the intervals against the probability or percentage of time the limits were equalled or exceeded. The lowest interval (0 to 40 mm/day) has a 100% possibility of being equalled or exceeded, while the highest interval (161 to 200 mm/day) had just a 2.5% possibility or 0.025 probability of being equalled or exceeded for all the cities, except at P2 and P5 which had 5% and 0% exceedance probabilities, respectively (Figure 2).

Figure 2 Annual PDCs for southern Nigerian cities (see online version for colours)



According to Davie (2008), the shapes of PDC have lots of implications on the property of precipitation or flow in a catchment. Shapes for annual PDCs shown in Figure 2 indicate strong differences between the highest annual daily maximum intensities and the lowest intensities for cities such as P2, P5 and P6. This suggests the possibility of dryness during some years; that is within the same location, some years have more rainfall or lesser rainfall than other years. This could be investigated from drought indices as applied by Adesogan and Sasanya (2021). However, the PDC shapes of P1, P3 and P4 show

minimal variation between the highest maximum rainfall intensities in comparison with the lowest intensities, since the steepness of their curves is minimal as compared to the curves of P2, P5 and P6. The continuous steep slope of the annual PDC attested to this high variation of rainfall in all the cities (Ahmed et al., 2023).

3.3 Intensity duration frequency curves and equations

The return periods obtained from the maximum rainfall intensities for each city ranged from 1 to 331 years (P1), 1 to 53 years (P2), 1 to 276 years (P3), 1 to 374 years (P4), 1 to 63 years (P5) and 1 to 727 years (P6). The rainfall intensities plotted against return periods and reduced variates for each city are shown in Figures 3 and 4. Having used equation (12) to scale down the daily rainfall intensities into smaller rainfall durations, it was observed that the rainfall intensities decreased for the same return periods as the rainfall duration increased (Kareem et al., 2022). Maximum rainfall intensities were also observed to be associated with high return periods.

Figure 3 Relationship between rainfall intensities and frequencies for studied cities (see online version for colours)

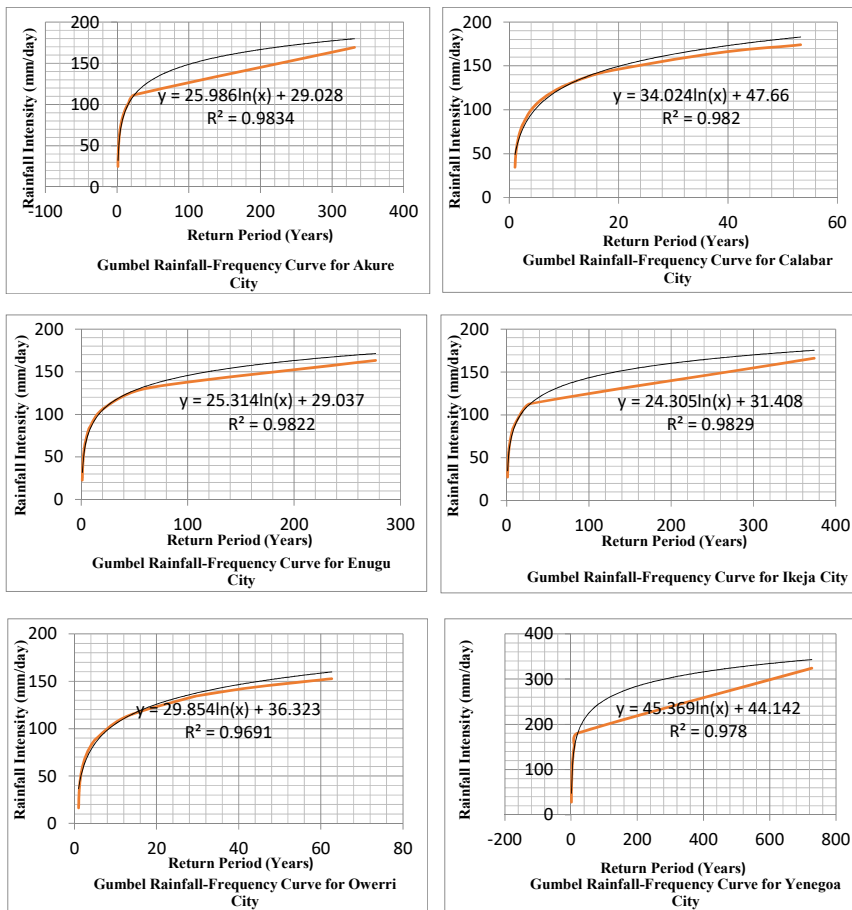
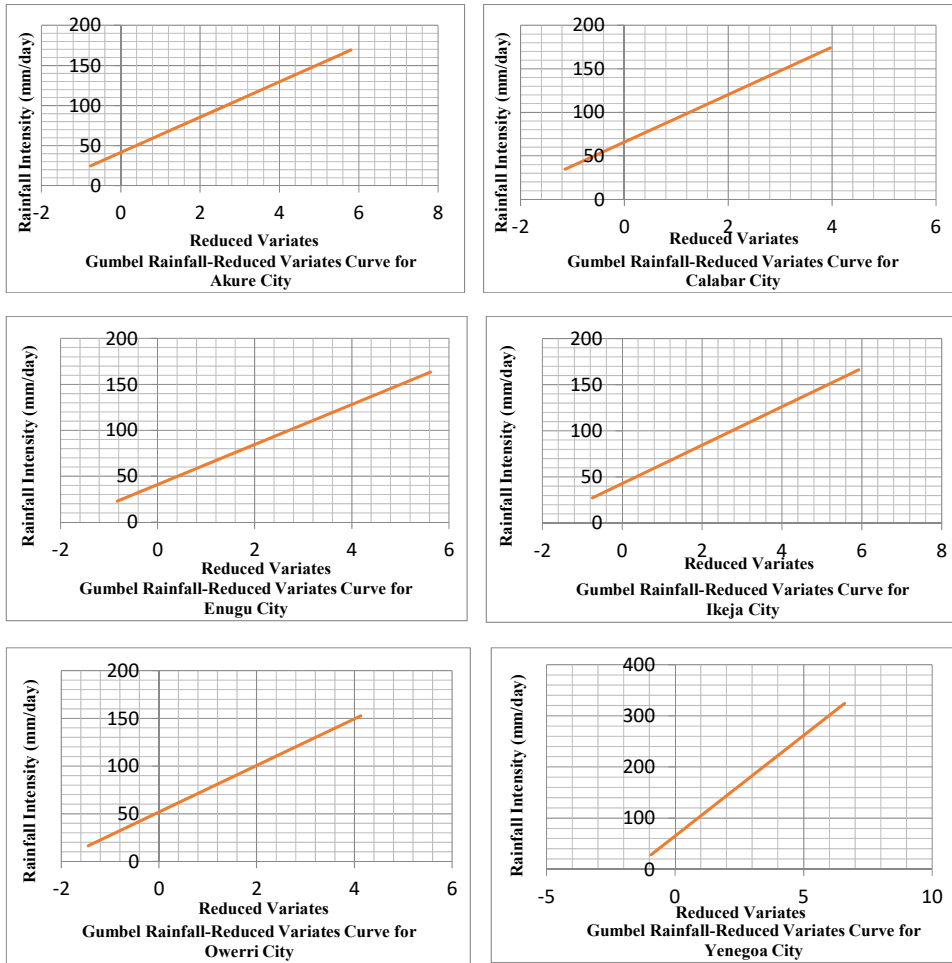
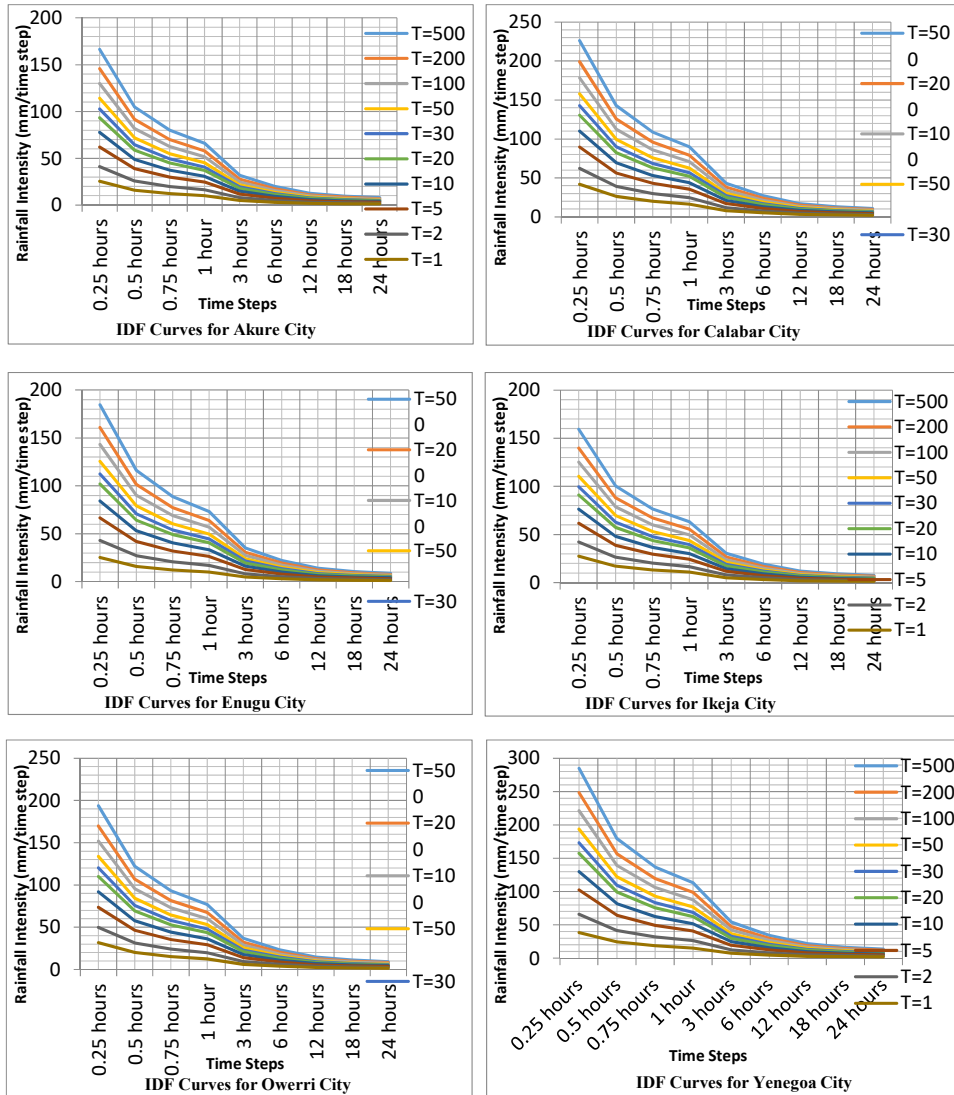


Figure 4 Relationship between rainfall intensities and reduced variates (see online version for colours)



Graphs and formulas depicting the essential connections between rainfall intensities (I), return periods (T), and rainfall durations (t) for the southern Nigerian cities (P1, P2, P3, P4, P5, and P6) can be found in Figures 5 and 6 as well as equations (18) through (23). These IDF representations are of significant importance for water resource management including flood control initiatives in these cities (Bibi and Tekesa, 2023). The IDF curves for each city are presented in pairs. The first of the pairs was presented on a normal scale for return periods (T) = 1, 2, 5, 10, 20, 30, 50, 100, 200, 500 and the second on the double logarithmic scale for return periods (T) = 1, 5, 10, 50, 100, 500. The shapes of constructed IDFs in this study compare accurately with the IDFs earlier constructed for some southern parts of Nigeria, including Akure, Ondo town, Ibadan, Ijebu ode, Iseyin, Osogbo, Abeokuta and Ikeja by Awofadeju et al. (2018) and Omoku River by Ozota and Ukpaka (2017).

Figure 5 Precipitation IDF curves on normal scale for each urban landscape (see online version for colours)

The derived IDF Equations for each city as follows:

$$I_{Akure} = \frac{10T^{0.2}}{(t - 0.01)^{0.67}} \quad (18)$$

$$I_{calabar} = \frac{15T^{0.2}}{(t - 0.4)^{0.67}} \quad (19)$$

$$I_{Enugu} = \frac{10T^{0.2}}{(t - 0.01)^{0.67}} \quad (20)$$

$$I_{Ikeja} = \frac{11T^{0.2}}{t^{0.67}} \quad (21)$$

$$I_{Owerri} = \frac{13T^{0.2}}{(t+0.04)^{0.67}} \quad (22)$$

$$I_{Yenegoa} = \frac{15.3T^{0.2}}{t^{0.67}} \quad (23)$$

Figure 6 Precipitation IDF curves on logarithmic scales for each urban landscape (see online version for colours)

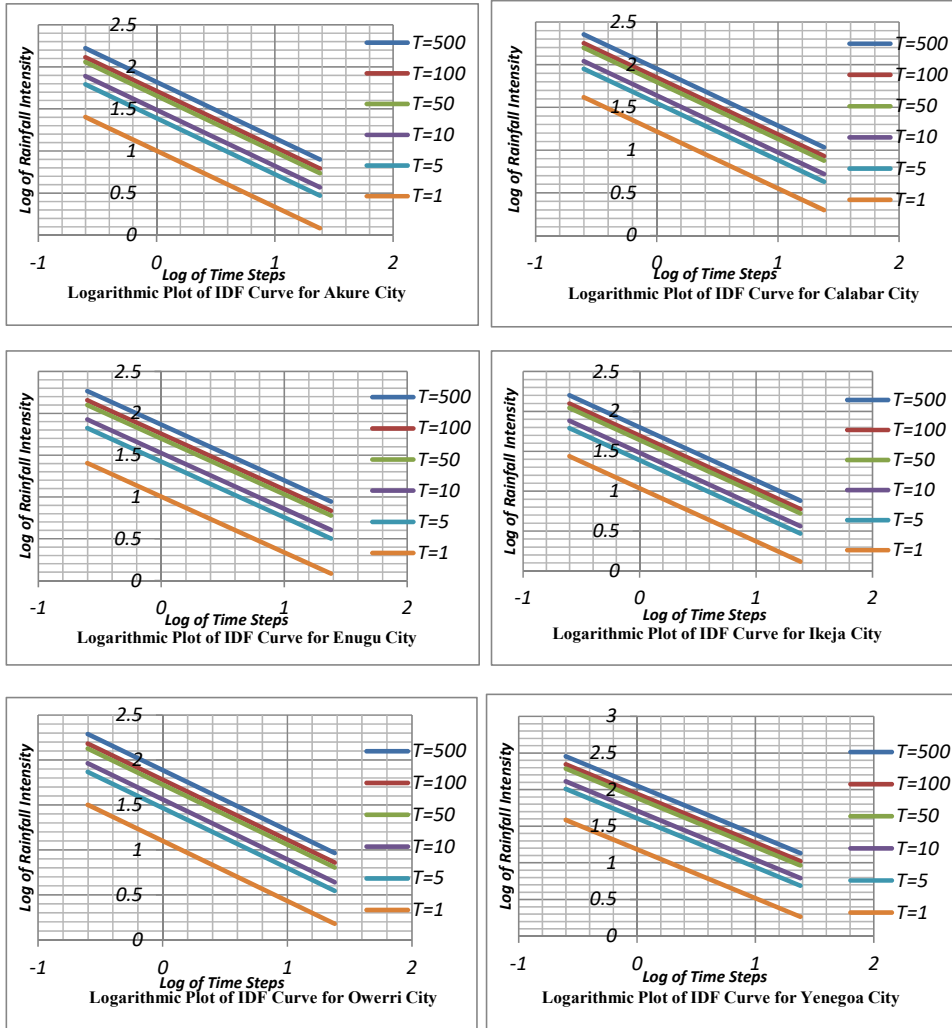


Table 3 Performance evaluation of IDF equations (continued)

	0.25 hrs	0.5 hrs	0.75 hrs	1 hr	3 hrs	6 hrs	12 hrs	18 hrs	24 hrs
<i>Owerri</i>									
RMSE (mm)	168.23	100.46	75.19	61.51	29.09	18.28	11.52	8.80	7.27
KS (mm)	90.54	54.01	40.41	33.03	15.59	9.79	6.17	4.71	3.89
X ² (mm)	258.72	147.37	108.47	87.93	40.87	25.61	16.13	12.33	10.2
Vol. err.	0.47	0.45	0.44	0.44	0.43	0.43	0.43	0.43	0.43
R	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
R ²	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
<i>Yenegoa</i>									
RMSE (mm)	266.52	168.22	128.52	106.17	51.212	32.33	20.41	15.59	12.88
KS (mm)	150.62	95.08	72.65	60.02	28.95	18.27	11.53	8.81	7.28
X ² (mm)	303.05	287.12	219.29	181.59	87.84	55.55	35.13	26.87	22.22
Vol. err.	0.52	0.52	0.52	0.52	0.53	0.53	0.53	0.53	0.53
R	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
R ²	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97

Furthermore, performance goodness of fits tests used to determine the performance of derived IDF equations for each city using different rainfall durations are shown in Table 3. The RMSE value for rainfall intensity prediction at P4 is the lowest (5.82 mm/day). These were closely followed by the RMSE values obtained at P1 (6.94 mm/day). The RMSE value obtained for predicted rainfall intensities at P2, P3, P5 and P6 ranged from 7.27 to 12.88 mm/hr. In the same vein, predicted rainfall intensities at P4 had the lowest Kolmogorov Smirnov test values, Chi-Square and volume error values, which are 5.82 mm/hr, 3.07 mm/hr, 7.93 mm/hr and 0.41, respectively. The performance goodness of fit values of estimated rainfall intensities from developed IDF equations for each southern Nigerian cities were obtained in the following ascending order; P1, P5, P3, P2 and P6. It is important to note that differences in the performance goodness of fits can be attributed to the magnitude of rainfall in these cities. P6 and P2, the cities with the highest error values are known to always experience high annual rainfall than all other cities as evidenced from the collected rainfall data. The reasons for high rainfall intensities can be attributed to the proximity of these cities to water bodies (Yao et al., 2023).

Predicted rainfall intensities decrease with increases in rainfall durations. This was also observed in the error values as shown in Table 3. The correlation coefficient (R) and coefficient of determination (R²) for each city are however not different. They are both 0.98 and 0.97, respectively. IDF equations used for rainfall intensities forecast in Onitsha, Port Harcourt, Calabar, Warri and Benin City by Ologhadien and Nwaogazie, (2014) correlated with values ranging from 0.645 to 0.936. In the same vein, Awofadeju et al. (2018) also obtained a R² of 0.987 for IDF curves developed for Port Harcourt city while Ozota and Ukpaka (2017) obtained a R² ranging from 0.904 to 0.988 when IDFs were constructed for Omoku River. The obtained R and R² indicated a high degree of equations' accuracy since the values obtained were highly correlated with predicted values for specified return periods and rainfall durations (Kioumars et al., 2023).

4 Conclusions

In this study, the rainfall characteristics of six southern Nigerian cities were studied. PDCs as well as IDF curves and equations were also developed for six cities known for receiving high annual rainfall amounts in southern Nigeria. Using the Gumbel probability plotting position method, underlined by the Gumbel probability distribution, the developed IDF curves and equations has a high degree of accuracy in predicting rainfall intensities in the southern Nigeria cities. The accuracies were ascertained from performance and goodness of fit tests. The developed IDF curves and equations are handy tools for predicting rainfall intensities and thus aiding flood control and the construction and design of hydraulic structures in these cities. Slight differences in the IDF equations derived for each location emphasise the need for location specific equations. Such location specific equations would put the unique, peculiar and specific characteristics of such locations in considerations. It is however important to point out the challenges posed by the scarcity of real time data for shorter duration rainfall (below hourly data) as this may have some effects on the validity of these findings. The validity of derived equations and curves were confirmed statistically but not physically.

In the real-life situations, the finding from this study could effectively aid policy formulations, decisions on water management, flood management studies as well as water resources governance. Similar studies are recommended in the drier northern part of Nigeria, which although rear, but sometimes experience flash flood events. Overall, this study would enhance adequate water policies and irrigation planning in the face of changing climate and shrinking water resources.

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