DEVELOPMENT OF RAINFALL INTENSITY - DURATION – FREQUENCY MODELS FOR AKURE, SOUTH-WEST, NIGERIA

ABSTRACT

The rainfall Intensity-Duration-Frequency (IDF) relationship is widely used for adequate estimation of rainfall intensity over a particular catchment. A 25 year daily rainfall data were collected from Nigerian Meteorological Agency (NIMET) Abuja for Akure station. Twenty five year annual maximum rainfall amounts with durations of 5, 10, 15, 20, 30, 45, 60, 90, 120, 180, 240, 300 and 420 minutes were extracted and subjected to frequency analysis using the excel solver software wizard. A total of six (6) return period specific and one (1) general IDF models were developed for return periods of 2, 5, 10, 25, 50 and 100 years using Gumbel Extreme Value Type I and Log Pearson Type III distributions. Anderson Darling goodness of fit test was used to ascertain the best fit probability distribution. The R^2 values range from 0.982 to 0.985 for GEVT I and 0.978 to 0.989 for Log Pearson type III while the Mean Squared Error from 33.56 to 156.50 for GEVT I and 43.01 to 150.63 Log Pearson Type III distributions respectively. The probability distribution models are recommended for the prediction of rainfall intensities for Akure metropolis.

Keywords: IDF models, log Pearson Type III distributions, Excel Solver, goodness of fit test, Akure.

1. INTRODUCTION

The Rainfall Intensity Duration Frequency (IDF) relationship is one of the most commonly used tools for the design of hydraulic and water resources engineering control structures. The IDF relationship is a mathematical relationship between the rainfall intensity, duration and the frequency (return period). The establishment of such relationship was done as early as 1932 (Bernard, 1932). The knowledge of frequency of extreme events like floods, high winds droughts and rainstorm helps in planning and design for these extreme events (Hosking and Wallis, 1997). The planning and designing of various water resources projects requires the use of rainfall intensity-duration-frequency (IDF) relationship (El-sayed, 2011). This relationship is determined through frequency analysis of data from meteorological stations. The IDF formulae are the empirical equations representing a relationship among maximum rainfall intensity (as dependent variable) and other parameters of interest such as rainfall duration and frequency (as independent variables). There are several commonly used functions found in the literature of hydrology applications (Chow et al., 1988). Owing to its wide applications, accurate estimation of intensity-duration-frequency relationship has received attention from researchers and scientists from all over the world (Mohammad Zakwan, 2016). All functions have been widely applied in hydrology. The IDF relation is mathematically stated as follows:

$$I = f(T,d) \qquad (1)$$

Where T is the return period (years) and d duration (minutes). Examples of three different types of empirical equations was documented by Nwaogazie & Masi (2019); Itolima & Nwaogazie (2017).

2. MATERIALS AND METHODS

2.1 Description of Area of Study

Akure is in Ondo State which is one of the States in Nigeria created on February 3, 1976 from the former Western State. It lies within 7^0 10' N and 5^0 05' E. Akure is located in the rain forest of Nigeria. The available rainfall data (amount and duration) obtained from NIMET covered the period between 1986 and 2010.

Figure 1: Location Map of Akure in South-Western Nigeria (Map data © 2019 Google)

Precipitation is characterized by a double maxima rainfall which starts from April and ends in October, reaching its peak in June and September. The average annual rainfall is about 1,422mm with some variations within the metropolis (analysed NIMET data).

2.2 Data Collection & Analysis

The major material used for this work is rainfall data comprising of rainfall amount and duration. The twenty five (25) year rainfall data included data ranging from 1986 to 2010.The data were obtained from Nigeria Meteorological Centre (NIMET) office Abuja, Nigeria. The data arrangement involved sorting the mean data according to years, rainfall intensities and durations. The rainfall intensities selected were the maximum values for each year for all the years analysed.

The annual maximum rainfall amount was obtained by selecting the maximum amount of rainfall for each year for 5, 10, 15, 20, 30, 45, 60, 90, 120, 180, 240, 300, and 420 (duration - minutes) for the 25 years. Table1 shows the ranked observed annual maximum rainfall amounts for Akure.

Table 1: Ranked Observed Annual Rainfall Amounts for Different Durations for Akure

Annual Maximum Rainfall Amount (mm)													
	Duration of rainfall (minutes)												
Rank	*5*	*10*	*15*	*20*	*30*	*45*	*60*	*90*	**120**	**180**	**240**	**300**	**420**
1	27.0	35.7	49.6	54.9	68.1	78.4	87.4	94.3	94.3	150.0	150.0	150.0	150.0
2	26.7	34.8	48.9	52.2	64.1	75.2	83.8	87.4	87.4	94.3	94.3	94.3	110.8
3	22.7	33.4	43.9	49.6	60.3	75.0	78.4	84.0	86.8	87.4	87.4	88.9	99.5
4	21.3	32.3	35.7	48.9	57.1	74.6	75.2	83.8	84.0	86.8	86.8	87.4	89.8

5	20.6	32.2	33.4	43.9	54.9	68.1	75.0	78.4	83.8	86.6	86.6	86.8	87.4
6	19.2	31.1	32.8	43.0	53.0	64.1	74.6	75.2	79.6	84.0	84.0	86.6	86.8
7	17.3	30.3	32.3	36.1	49.6	60.3	68.4	75.0	75.2	79.6	82.5	84.0	86.6
8	14.5	29.0	32.2	35.7	48.9	57.1	68.1	74.6	75.0	79.0	79.6	79.6	84.0
9	14.3	28.6	32.1	33.4	43.9	56.8	60.3	68.4	74.8	75.2	79.0	79.0	79.6
10	13.6	23.2	31.6	32.3	41.3	54.9	59.3	68.1	74.6	75.0	78.0	78.0	79.0
11	13.2	21.2	31.1	32.2	40.8	53.0	57.1	60.3	68.4	74.8	75.2	75.2	78.0
12	13.1	20.6	30.6	32.1	35.1	49.6	56.8	59.5	68.1	74.6	74.8	74.8	75.2
13	13.1	20.6	30.3	30.6	33.4	48.9	54.9	59.3	65.5	71.7	74.6	74.6	74.8
14	12.7	20.2	29.0	30.3	32.3	47.2	54.8	57.1	60.3	70.7	71.7	71.7	74.6
15	12.3	18.1	28.3	29.0	32.2	44.9	53.0	56.8	59.3	68.6	68.6	68.6	71.7
16	12.3	18.0	25.8	28.3	30.3	44.3	52.0	54.9	57.1	68.4	68.4	68.4	68.4
17	12.1	17.1	24.1	24.1	29.3	43.9	49.6	54.8	56.8	68.1	68.1	68.1	68.1
18	12.1	17.1	21.2	22.7	29.0	40.8	44.9	53.0	54.9	64.3	64.3	64.3	64.3
19	12.0	16.7	20.6	21.5	25.9	35.1	44.3	52.4	52.4	64.1	64.1	64.1	64.1
20	11.8	16.6	20.6	21.2	24.7	34.1	43.9	50.6	50.6	60.3	60.3	60.3	62.5
21	11.4	16.5	20.2	21.0	24.1	33.4	40.8	49.6	48.2	59.3	59.3	59.3	60.3
22	11.3	16.5	19.6	20.9	24.0	32.3	39.3	48.2	43.9	57.1	57.1	57.1	59.4
23	11.3	16.0	19.1	20.8	23.9	29.7	38.8	43.9	41.8	56.8	56.8	56.8	59.3
24	10.9	15.2	19.0	20.6	23.8	28.2	35.4	40.8	41.2	52.1	52.1	55.9	59.2
25	10.7	15.2	18.9	20.2	23.1	27.5	32.7	39.7	40.8	47.2	51.9	54.0	58.0

The rainfall amounts in Table 1were converted to intensity (mm/hr) by dividing the amount of rainfall by the duration then multiplying by 60. For instance given an amount of 70.3mm and duration of 15 minutes yields 281.3 mm/hr. Table 2 shows all the intensities for various durations.

Table 2: Ranked Observed Annual Rainfall Intensities (mm/hr) for different Durations (mins) for Akure

Year	Convert to intensity (mm/hr)												
	5	10	15	20	30	45	60	90	120	180	240	300	420
1	324.0	214.2	198.4	164.7	136.2	104.5	87.4	62.9	47.2	50.0	37.5	30.0	21.4
2	320.4	208.8	195.6	156.6	128.2	100.3	83.8	58.3	43.7	31.4	23.6	18.9	15.8
3	272.6	200.4	175.6	148.8	120.6	100.0	78.4	56.0	43.4	29.1	21.9	17.8	14.2
4	255.6	193.8	142.8	146.7	114.2	99.5	75.2	55.9	42.0	28.9	21.7	17.5	12.8
5	247.2	193.2	133.6	131.7	109.8	90.8	75.0	52.3	41.9	28.9	21.7	17.4	12.5
6	230.4	186.6	131.0	129.0	106.0	85.5	74.6	50.1	39.8	28.0	21.0	17.3	12.4
7	207.6	181.8	129.2	108.2	99.2	80.4	68.4	50.0	37.6	26.5	20.6	16.8	12.4
8	174.0	174.0	128.8	107.1	97.8	76.1	68.1	49.7	37.5	26.3	19.9	15.9	12.0
9	171.4	171.7	128.4	100.2	87.8	75.7	60.3	45.6	37.4	25.1	19.8	15.8	11.4
10	162.8	139.2	126.4	96.9	82.5	73.2	59.3	45.4	37.3	25.0	19.5	15.6	11.3
11	158.8	127.2	124.4	96.6	81.6	70.7	57.1	40.2	34.2	24.9	18.8	15.0	11.1
12	157.7	123.6	122.4	96.3	70.2	66.1	56.8	39.7	34.1	24.9	18.7	15.0	10.7
13	157.4	123.6	121.2	91.8	66.8	65.2	54.9	39.5	32.8	23.9	18.7	14.9	10.7
14	152.6	121.2	116.0	90.9	64.6	63.0	54.8	38.1	30.2	23.6	17.9	14.3	10.7
15	147.6	108.6	113.2	87.0	64.4	59.9	53.0	37.9	29.7	22.9	17.2	13.7	10.2
16	147.6	107.9	103.2	84.9	60.6	59.1	52.0	36.6	28.6	22.8	17.1	13.7	9.8
17	144.8	102.6	96.4	72.3	58.6	58.5	49.6	36.5	28.4	22.7	17.0	13.6	9.7

18	144.6	102.6	84.8	68.0	58.0	54.4	44.9	35.3	27.5	21.4	16.1	12.9	9.2
19	143.6	100.0	82.4	64.6	51.9	46.8	44.3	34.9	26.2	21.4	16.0	12.8	9.2
20	141.7	99.4	82.4	63.6	49.3	45.5	43.9	33.7	25.3	20.1	15.1	12.1	8.9
21	136.6	99.1	80.8	63.0	48.2	44.5	40.8	33.1	24.1	19.8	14.8	11.9	8.6
22	135.9	99.0	78.3	62.6	48.1	43.1	39.3	32.1	22.0	19.0	14.3	11.4	8.5
23	135.6	96.2	76.4	62.4	47.8	39.6	38.8	29.3	20.9	18.9	14.2	11.4	8.5
24	130.3	91.2	75.8	61.8	47.7	37.6	35.4	27.2	20.6	17.4	13.0	11.2	8.5
25	127.9	91.1	75.7	60.6	46.2	36.7	32.7	26.5	20.4	15.7	13.0	10.8	8.3
Mean	181.2	138.3	116.9	96.7	77.9	67.1	57.2	41.9	32.5	24.7	18.8	15.1	11.2
Standard Deviation	59.0	43.2	35.3	32.8	28.5	21.2	15.7	10.2	8.1	6.6	4.9	3.9	2.9
Coefficient of Skewness	1.16	0.54	0.85	0.72	0.62	0.29	0.33	0.43	0.06	2.36	2.36	2.39	2.07

The magnitude of rainfall intensities were obtained using frequency analysis. Log Pearson Type III distribution was used to obtain the magnitude of rainfall intensities for different return periods.

2.3 Gumbel's Extreme Value Type I (GEVT- 1) Distribution

Gumbel distribution is one commonly used probability distribution for obtaining the rainfall intensity values. The rainfall intensity values were obtained using Equation (2) (Nwaogazie & Masi, 2019)

$$X_T = \bar{X} + K_T S \quad (5)$$

Where X_T = rainfall intensity values (magnitude of hydrologic event)

$\bar{X}$ = mean; K_T = Gumbel's frequency factor; S = standard deviation

The Gumbel's frequency factor is obtained using Equation (3).

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

Where T = return period (years)

For example, Gumbel frequency factor for a 5 years return period

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + In\left[In\left(\frac{5}{5-1}\right)\right]\right\} = 0.719$$

The resulting Gumbel K_T values for different return periods as calculated are shown in Table 3.

Table 3: Gumbel frequency factor for Akure IDF modeling

Return Period	2	5	10	25	50	100
K_T values	-0.16425	0.719	1.304	2.044	2.592	3.1363

2.4 Log Pearson Type III (LPT III) Distribution

Log Pearson type III distribution is one commonly used probability distribution for obtaining the rainfall intensity values. The rainfall intensity values were obtained using Equation (5)

$$\text{Log } X_T = \text{Log } \bar{X} + K_T \text{ LogS} \quad (7)$$

Where X_T = rainfall intensity values (magnitude of hydrologic event)

$\bar{X}$ = mean; K_T = Log Pearson frequency factor; S = standard deviation

Log-Pearson frequency factor can be obtained from the frequency table given in standard textbook using the return period and the skewness from Table 3 as follows:

For example, Log-Pearson distribution frequency factor for a 10 mins duration and 5 years return period with coefficient of skewness = 0.366734 was calculated to be 0.81866.

Table 4 gives the computed summary of K_T values for Log-Pearson distribution for various durations and different return periods computed.

Table 4: Log-Pearson frequency factors for various durations and return periods

Frequency Factor K_T							
Duration (mins)	**C_s**	Return Period					
		2	5	10	25	50	100
5	1.091564	-0.17865	0.746097	1.340916	2.06406	2.581372	3.081517
10	0.366734	-0.06068	0.818661	1.314339	1.869688	2.244367	2.591381
15	0.251671	-0.04178	0.8269	1.305134	1.834018	2.185869	2.509203
20	0.305351	-0.05086	0.823572	1.309428	1.850659	2.213676	2.547799
30	0.272066	-0.04525	0.825676	1.306765	1.840341	2.196474	2.523888
45	-0.15695	0.026112	0.848278	1.263166	1.695498	1.968677	2.209856
60	-0.09628	0.016367	0.845851	1.270447	1.717303	2.002011	2.254756
90	0.051879	-0.00882	0.838887	1.287188	1.768639	2.081496	2.36439
120	-0.2684	0.044629	0.852052	1.249108	1.654691	1.907378	2.127382
180	1.037152	-0.16994	0.75317	1.340372	2.051545	2.557975	3.046149
240	1.115837	-0.18238	0.742941	1.340842	2.069326	2.591493	3.096819
300	1.232979	-0.19995	0.727713	1.33967	2.093926	2.639191	3.169447
420	1.209953	-0.19649	0.730706	1.3399	2.08909	2.629981	3.155171

Calibration of Sherman (1932) IDF model

Sherman's modified IDF model is given as (Chow et al, 1988)

$$I = \frac{C{T_r}^m}{{T_d}^a} \qquad (6)$$

Equation (6) is non-linear power law that was calibrated for c, m, a parameters using intensity, duration and return period values in Table 1 and Excel Optimization Solver (Nwaogazie & Masi, 2019).

2.5 Goodness of fit test

The result in Table 1 was subjected to Anderson-Darling test to ascertain the probability distribution that best fit the rainfall annual maximum amount. This is a nonparametric test of the equality of continuous, one dimensional probability distributions that can be used to compare a sample with a reference probability distribution. Gumbel Extreme Value Type I (GEVT-1) and Log-Pearson Type 3 (LPT-3) best fit the rainfall intensities with significant values of 0.7570 and 0.7538 at 5% confidence level respectively.

3. RESULTS

3.1 Development of Intensity Duration Frequency (IDF) Models

Figure 2 represents the rainfall intensity values for various durations for the different return periods using Gumbel Extreme Value Type I distribution.

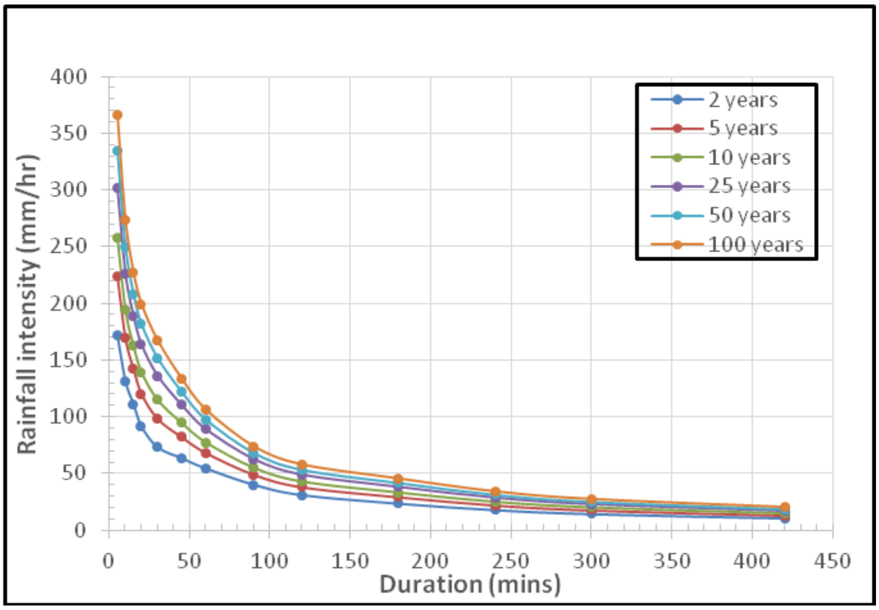

Figure 2: Intensity Duration Curve (IDF) curves for Gumbel Extreme Type 1 distribution plotting Intensities (mm/hr) against durations (mins) for Akure

The intensity duration frequency models were calibrated using the Microsoft Excel Solver. The method adopted uses the least square criteria to obtain the model parameters. Table 4 gives a distribution of developed IDF models for Gumbel Extreme Value Type 1 distribution.

Table 5 gives a distribution of developed IDF models for Gumbel Extreme Value Type 1 distribution.

Table 5: Developed IDF Models for different return periods using Gumbel Extreme Value Type 1 distribution rainfall intensities values for Akure.

Return Period	IDF Model ±	Coefficient of Determination (R^2)	Mean Squared Error (MSE)
2	$I = \frac{4.766{T_r}^{6.428}}{{T_d}^{0.512}}$	0.985	33.56
5	$I = \frac{2.181{T_r}^{3.426}}{{T_d}^{0.519}}$	0.985	60.27
10	$I = \frac{1.646{T_r}^{2.582}}{{T_d}^{0.522}}$	0.984	84.55
25	$I = \frac{1.291{T_r}^{1.972}}{{T_d}^{0.525}}$	0.983	122.738
50	$I = \frac{1.170{T_r}^{1.675}}{{T_d}^{0.527}}$	0.982	156.496
100	$I = \frac{1.098{T_r}^{1.457}}{{T_d}^{0.528}}$	0.982	194.51

± return period specific IDF models

The general IDF models was developed using Excel Spread Sheet Solver tool. The least squares equations were programmed accordingly.

$$I = \frac{407.886{T_r}^{0.175}}{{T_d}^{0.525}} \quad (7)$$

We note the following results: coefficient of determinant (R^2) = 0.982; Mean Squared Error = 125.70 mm/hr

3.2 Development of Intensity Duration Frequency (IDF) Models

Figure 3 shows the rainfall intensity values for various durations for the different return periods using Log Pearson Type III distribution.

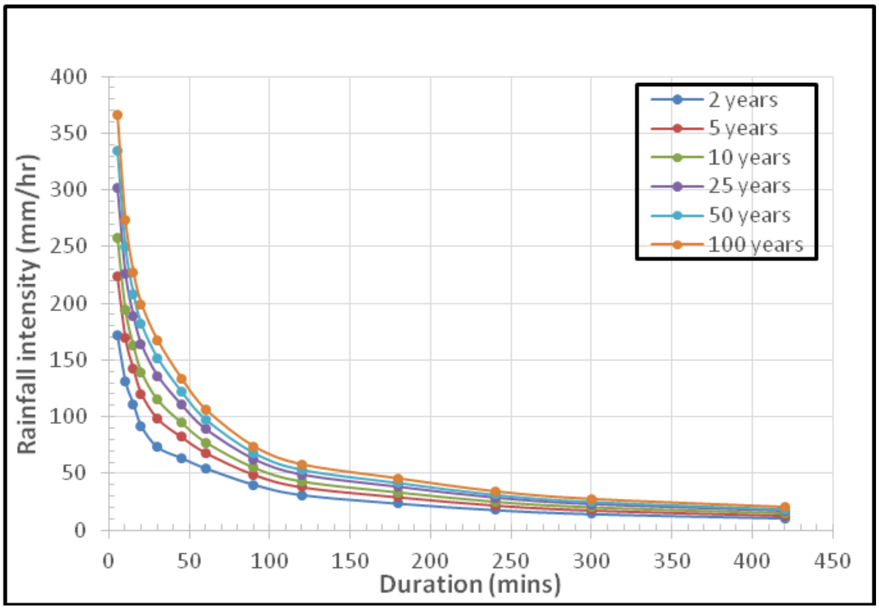

Figure 3: Intensity Duration Frequency (IDF) curves for Log Pearson Type III distribution for Akure.

The intensity duration frequency models were developed using the Microsoft Excel Solver. The method employs the least square criteria to obtain the model parameters.

Table 6 gives a distribution of developed IDF models for Log Pearson Type III distribution for Akure

Table 6: Developed IDF Models for different return periods using Log Pearson Type III distribution rainfall intensities values for Akure.

Return Period	**IDF Model**	**Coefficient of Determination (R^2)**	**Mean Squared Error (MSE)**
2	$I = \frac{4.74 T_r^{6.366}}{T_d^{0.500}}$	0.980	43.01
5	$I = \frac{2.167 T_r^{3.400}}{T_d^{0.505}}$	0.978	83.48
10	$I = \frac{1.642 T_r^{2.576}}{T_d^{0.516}}$	0.980	105.23
25	$I = \frac{1.295 T_r^{1.986}}{T_d^{0.534}}$	0.984	125.12
50	$I = \frac{1.185 T_r^{1.698}}{T_d^{0.550}}$	0.987	136.96
100	$I = \frac{1.105 T_r^{1.493}}{T_d^{0.568}}$	0.989	150.63

A general IDF model was also developed. This model enables one to predict the intensity of rainfall of any duration and any return period.

$$I = \frac{402.607\, T_r^{\,0.201}}{T_d^{\,0.540}} \quad (8)$$

We note the following results: coefficient of determinant (R^2) = 0.984; and Mean Squared Error = 127.47

Excel Solver Log Pearson Type III model parameters trial solution for 5 year return period specific IDF model has eleven (11) iterations before convergence (see Table 7).

Table 7: Excel Solver iteration distribution to convergence

S/NO	c	M	a
1	1	1	1
2	1.458558	1.738022	0
3	1.754711	2.433231	0
4	1.752072	2.426307	0.06467
5	2.033457	3.163496	0.32475
6	2.116698	3.355978	0.42475
7	2.145857	3.352741	0.479676
8	2.165626	3.398482	0.502807
9	2.167149	3.40017	0.505001
10	2.167155	3.400187	0.505003
11	2.167155	3.400187	0.505003

3.2 Comparison of Observed and Predicted Rainfall Intensity

The intensity duration frequency curves were obtained by plotting the predicted rainfall intensity values against corresponding durations for different return periods. The IDF curves for Akure are as shown in Figures 4 - 6.

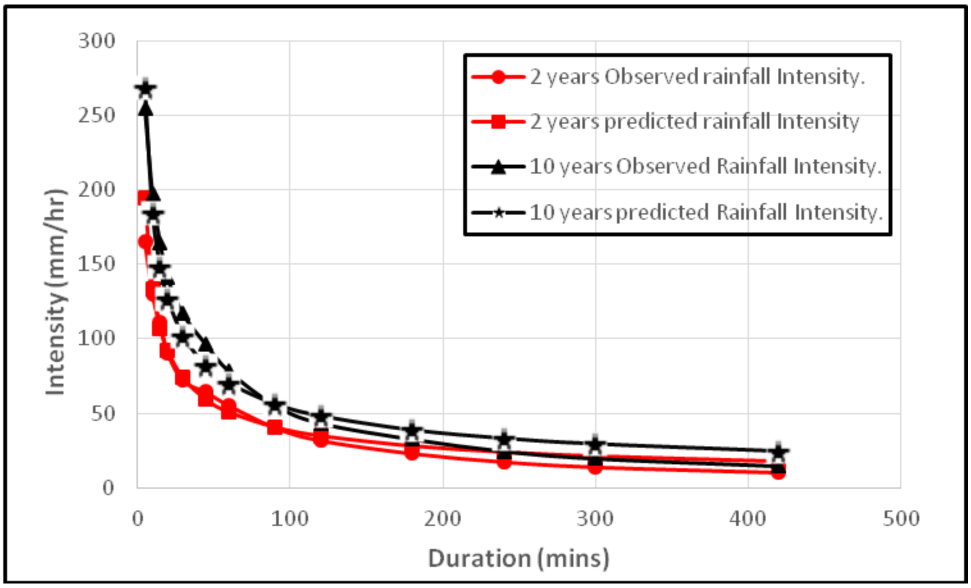

Figure 4: Observed rainfall intensity compared with predicted for 2 and 10 year return period for Log-Pearson Type-3 distribution

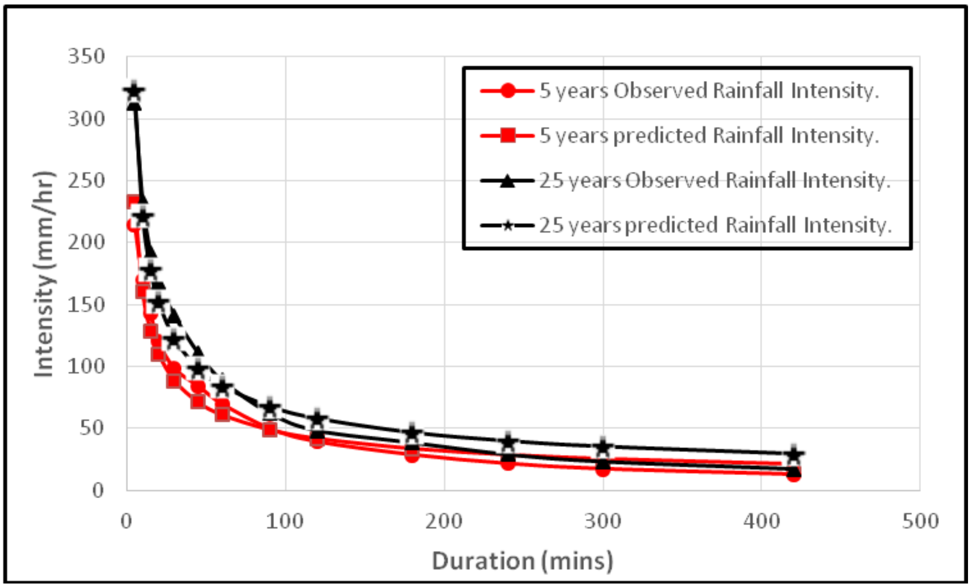

Figure 5: Observed rainfall intensity compared with predicted for 5 and 25 year return period for Log-Pearson Type-3 distribution for Akure

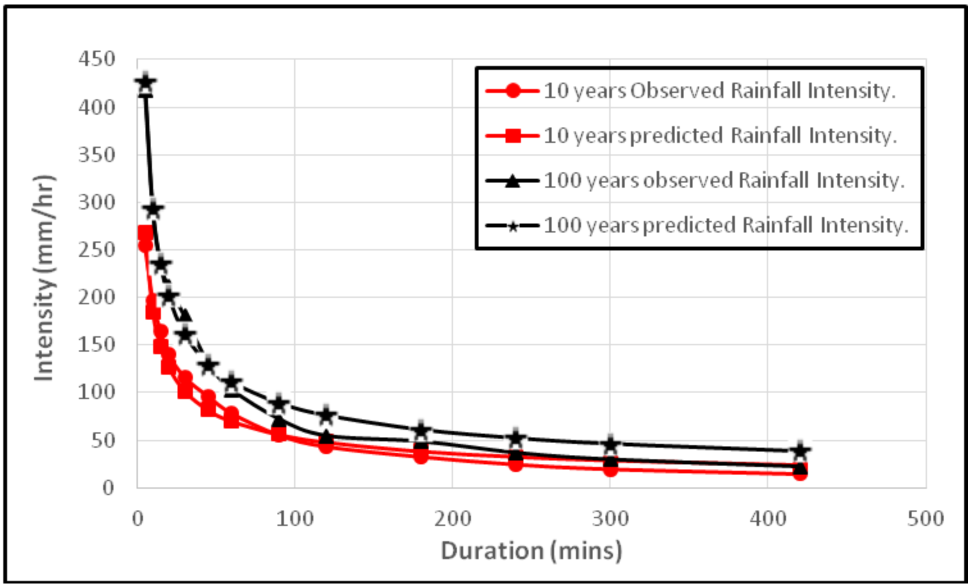

Figure 6: Observed rainfall intensity compared with predicted for 10 and 100 year return period for Log-Pearson Type-3 distribution for Akure

3.3 Comparison of Regression Approach and Excel Optimization Solver results for model parameters, R^2 and MSE

Table 8 (an extension of Table 5) clearly shows the result from Excel Optimization Solver option is superior to the normal regression method, the conventional simultaneous solution using matrix i.e. Gauss elimination, inverse or determinant approach (Nwaogazie & Masi, 2019).

Table 8: Results from regression approach and excel solver optimization approach (Log Pearson Type III, 2 year return period)

Method	C	m	A	R^2	MSE
Regression	65.52	3.544	0.675	0.885	324.40
Excel Solver	4.74	6.366	0.500	0.980	43.01

4. CONCLUSION

The developed model for Log Pearson Type III is in agreement with literature theory which shows higher intensity occurring at lower duration and lower intensity at higher duration. The prediction of rainfall intensity with the PDFs showed a good match with observed intensity values. The log Pearson Type III model ranked as the best with respect to MSE 43.01 and R^2 0.989 in the return period specific model when compared with GEVT-I with MSE 33.56 and R^2 0.985. The comparison of PDF and non-PDFs shows that the former has lesser MSE value than the later; 43.01 and 324.40 respectively.

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