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Development of Satellite Data-Based Rainfall Intensity-Duration-Frequency Curves for Nigeria

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Abstract The paucity of spatially representative sub-daily rainfall data in Nigeria has caused difficulty in the determination of design rainfall necessary for event-based flood modelling. Previous work on the development of Intensity-Duration-Frequency (IDF) curves for Nigeria was done in the 1980s based on historical rainfall data between 1948-1978 at 35 locations in the country (referred to as Federal Ministry of Works-IDF: FMW-IDF); however, extensive application of these IDF curves has been hampered by the vagaries of climate change. Taking advantage of current technological advancements in remote sensing for rainfall estimation, the Tropical Rainfall Measuring Mission (TRMM) Satellite-based estimates was selected amongst four other rainfall products for developing the updated IDF curves. Results indicate that the TRMM product can successfully be applied to develop more spatially representative IDF curves for Nigeria. This work hereby provides 72 locations nationwide with relevant parameters to readily compute rainfall intensity values for the 2yr, 5yr, 10yr, 25yr, 50yr, and 100yr return periods, this carries overarching implications for urban flood design and management in the Country.

Keywords: *TRMM, IDF, design storm, satellite rainfall estimate, Nigeria*

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1. Introduction

The lack of discharge data at most locations of interest for the design of stormwater drainage systems, dams, bridges, and flood management studies, has necessitated the transformation of more readily available rainfall data to design flow using hydrological models. For event-based models, the hypothetical rainfall value or hyetograph is referred to as the design rainfall or design storm [1].

The design storm selection is based on a relationship between the rainfall depth/intensity, duration, and the frequency or return period appropriate for the facility to be designed or studied. Frequency analysis in hydrology is used to correlate the magnitude of extreme events to their frequency of occurrence using probability distributions [1]. To further facilitate rigorous frequency analysis, sufficiently long time series data for the selected location is required, there is however a general paucity of rainfall data at the required temporal resolution for most locations in Africa due to capital, technical, and managerial issues, especially in Nigeria.

The spatial coverage of meteorological stations in Nigeria is currently inadequate and falls far below the requirements of the World Meteorological Organization [2]. From the beginning of 1900s, the number of rain gauges in the country increased from 11 to 368 in the year 1992, representing a gauge density of one per 2,500 km^2 [3]; these gauges were maintained by the Federal Department of Meteorological Services (FDMS), now Nigerian Meteorological Services Agency (NIMET), and some agricultural institutions. Currently, most of the gauging stations have become moribund and data collection has been reduced to few synoptic stations (less than 100) managed by NIMET; this has significantly reduced the required gauge density. Sub-daily rainfall data required for generation of design storms for urban drainage design are rarely collected. Thus, the estimation of design rainfall intensity across the country is difficult and prone to errors.

Majority of reputable studies on the development of rainfall intensity-duration-frequency (IDF) relationships for Nigeria were based on daily rainfall records [4,5,6], the only study that employed “short duration rainfall records” was by [7,8]. Reference [8] (1983) obtained rainfall data from 35 recording stations for the period 1948 to 1978 and generated IDF curves for each location using the Method of Maximum Likelihood estimation and fitted using the Gumbel (EV-I) distribution. Considering that the length of records used varied from 5yrs to 30yrs with 18 stations exceeding 20yrs and only 3 exceeding 25yrs, Reference [7] (1982) employed a regionalization approach by dividing the country into 10 zones based on climatic and topographic characteristics thereby increasing the records length per region to between 20yrs and 115yrs. IDF parameters were computed by fitting the Gumbel

(EV-I) distribution to the annual maximum series for each duration. The result obtained from [7,8] were adopted in the latest edition of the Nigeria Highway Manual [9].

Scientists have however developed methods of rainfall data estimation using remote sensing via satellite, and Geographic Information Systems (GIS) interpolation techniques [4,5,10,11,12]. Satellite rainfall datasets are available in geographic gridded (raster) formats which provide sufficient spatial coverage for most engineering design requirements so far as the datasets are calibrated and verified using in-situ gauge measurement. Against this backdrop, this work therefore focuses on the determination of intensity-duration-frequency (IDF) relationships using sub-daily satellite rainfall estimates.

2. Materials and Methods

2.1. Study Area

Nigeria is located within the western sub-region of Africa. It shares international borders with Benin (West), Cameroun (East), Niger (North), Chad (North East) and to the South by the Atlantic Ocean with about 850km of coastline. It has a total land surface area of approximately 920,000 km^2 and is bounded by Latitudes 4° 16' 20.3" N and 13° 53' 40.6" N, and Longitudes 2° 40' 09.7" E and 14° 40' 46.0" E (Figure 1).

The climate is influenced mainly by rainfall that varies in latitude from humid in the southern coastal zone which receives high rainfall over 2,500 mm, and declines progressively towards the semi-arid northern regions with low rainfall below 500 mm. The local weather consists of distinct dry and wet seasons, the onset of rainfall defines the wet (rainy or monsoon) season and it begins when the rain-belt (zone of maximum rainfall) traverses the southern region in the month of March or April and proceeds to the middle zone by April or May and finally reaches the northern zone in May or June. The peak of the rainy season usually occurs in the month of August for the Middle/Northern zones while the rain ceases by October. The southern parts however experience a double peak (in the months of July and September) separated by a trough in the month of August termed “the August break”. The rain-belt eventually recedes towards the equator by late November.

The generation mechanism and seasonal occurrence of rainfall in the tropics follows the movement of the earth around the sun and consequent insolation and heating of the Earth surface along the equator which induces a low pressure zone wherein the trade-winds converge and rise vertically due to convection into the upper troposphere (Hadley cells). Over West Africa, the moisture laden Tropical Maritime (TM) air mass which comes over the Atlantic Ocean from the south meets with the dry and dust laden Tropical Continental (TC) air mass which originates from the north-east over Sahara Desert [13]. This low pressure region wherein the TM and TC converge and rise is aptly called the Inter-Tropical Convergence Zone (ITCZ).

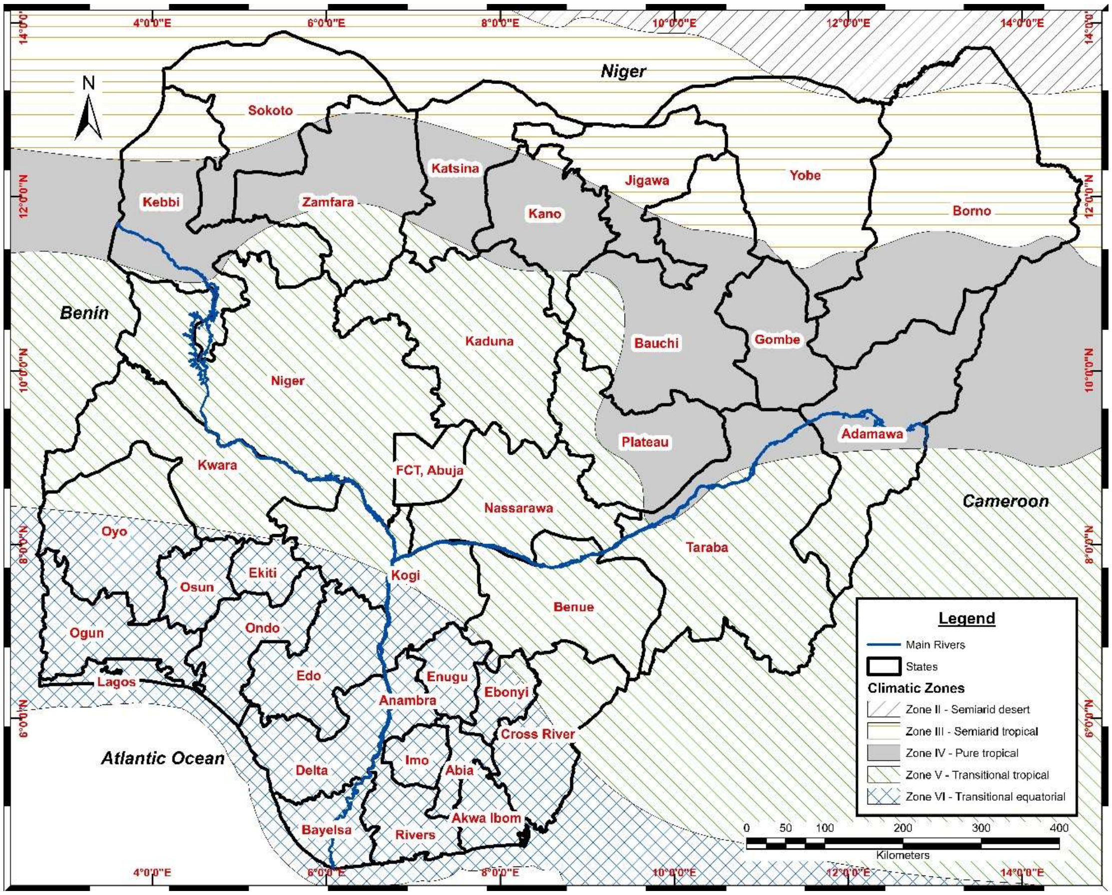


Figure 1. Political Map of Nigeria and Climatic Zones

Table 1. Satellite Rainfall Products Summary

S/N	Class	Description	Mean Annual Rainfall	Annual Wet Season
1	Zone I	Desert	100mm	1
2	Zone II	Semiarid Desert	400mm	1
3	Zone III	Semiarid Tropical	700mm	1
4	Zone IV	Pure Tropical	700mm to 1000mm	1
5	Zone V	Transitional Tropical	> 1000mm	1
6	Zone VI	Transitional Equatorial	> 1000mm	2

The subdivision of Nigeria into climatic zones is based on one or more combinations of geographic and climatic variables. It is necessary at this point to distinguish strict climatic subdivisions from other classifications that include biome and agriculture, these are appropriately named as ecological, eco-climatic, agro-climatic, bioclimatic, agro-ecological, or vegetation zones. Reference [13] reported six zones for hydrological studies in West African and implemented by [14] using the Tropical Rainfall Measuring Mission (TRMM) daily rainfall data for 1998-2014. The climatic subdivisions include six zones (Figure 1) which are based on mean annual and seasonal rainfall as defined in Table 1. Thus, Nigeria is covered majorly by four zones: Zone III (semiarid tropical), Zone IV (pure tropical), Zone V (transitional tropical), and the Zone VI (transitional equatorial); with a northern fringe of Zone II (semiarid desert).

2.2. Satellite Rainfall Data Validation

The prohibitive cost of maintaining a dense network of in-situ gauges or radar installations necessitates the recourse to satellites as a practical means of large area or global scale rainfall monitoring. Considering also that satellite measurement are indirect and special algorithms are required to correlate the measured attributes to actual rainfall rates, the application of Satellite-based Rainfall Estimates (SRE) in hydrology and engineering requires validation vis-a-vis in-situ measurements [15].

Several studies on the performance evaluation of SRE with respect to ground-based gauge rainfall at varying temporal accumulations (daily, monthly, seasonal, annual) have been carried out with promising results within Nigeria [12,16,17,18,19], Africa [20-39], and other continents [40-61]. For the purpose of SRE applications in extreme frequency analysis and computation of IDF parameters however, and based on current knowledge available during this work, no study has been done in Nigeria. Only two have been conducted in Africa for Angola [62] and Ghana [63], and some in other parts of the world [64-77].

Five (5) satellite rainfall products were selected based on criteria of spatial resolution (national coverage), temporal resolution (sub-daily records), and sufficiently long time series (greater than 15 years of records); more especially, all the selected satellite rainfall products are available free of charge.

The products include:

a) Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis (TRMM) [78].
b) Climate Prediction Centre Morphing technique (CMORPH) [79].
c) Precipitation Estimation From Remotely Sensed Information Using Artificial Neural Networks (PERSIANN) [80].
d) Precipitation Estimation From Remotely Sensed Information Using Artificial Neural Networks Cloud Classification System (PERSIANN CCS) [80].
e) Integrated Multi-satellite Retrievals for the Global Precipitation Measurement (GPM IMERG) [81].

Table 2 contains a summary of each SRE product, a comprehensive review of the satellite rainfall structure and estimation algorithms is beyond the scope of this work, more information is available at the aforementioned references and thus the details will not be repeated in this paper. It is however worthy of note that according to [82] the TRMM satellite ran out of fuel in July 2014 and commenced descent until it fell back to earth on 17th June 2015, users have been advised that "projects that require the best homogeneity only use 3B42 for the period January 1998 to September 2014", hence only this period has been considered for use in this study.

Table 2. Satellite Rainfall Products Summary

S/N	Product Name	Short Name	Abbrev	Temporal Resolution	Temporal Range	Spatial Resolution	Spatial Range
1	Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis.	TRMM 3B42 Version 7	TRMM	3-Hourly	1998-2014 (17 yrs)	0.25° (≈27 km)	Latitudes 50°N – 50°S
2	Climate Prediction Center Morphing technique.	CMORPH	CM	3-Hourly	2003-2019 (17 yrs)	0.25° (≈27 km)	Latitudes 60°N – 60°S
3	Precipitation Estimation From Remotely Sensed Information Using Artificial Neural Networks.	PERSIANN	PN	Hourly	2001-2019 (19 yrs)	0.25° (≈27 km)	Latitudes 60°N – 60°S
4	Precipitation Estimation From Remotely Sensed Information Using Artificial Neural Networks Cloud Classification System.	PERSIANN-CCS	PS	Hourly	2003-2019 (17 yrs)	0.04° (≈4 km)	Latitudes 60°N – 60°S
5	Integrated Multi-satellitE Retrievals for the Global Precipitation Measurement.	GPM IMERG Version 6	IM	Half-Hourly	2001-2019 (19 yrs)	0.1° (≈10 km)	Global

Extraction of the SRE time series for validation at each rain gauge location (Figure 2) was done using a “Point to Pixel” approach whereby the coordinates of each ground gauge coincident with the SRE grid cell was used to extract the time series. Figure 3 shows the gauge data availability chart for the 25 ground stations which span a period of 1971 to 2017, data validation was performed between the respective SRE annual values that coincide with the gauge data.

Five validation metrics (Table 3) were adopted to compare the five SRE with in-situ rain gauge data to facilitate the selection of the most appropriate satellite product. Two validation categories were considered for each satellite product (total annual rainfall, and annual maximum daily rainfall); the product that performed well persistently out of the five validation metrics was selected for each station and the final SRE to be chosen will be the best performing for both validation categories.

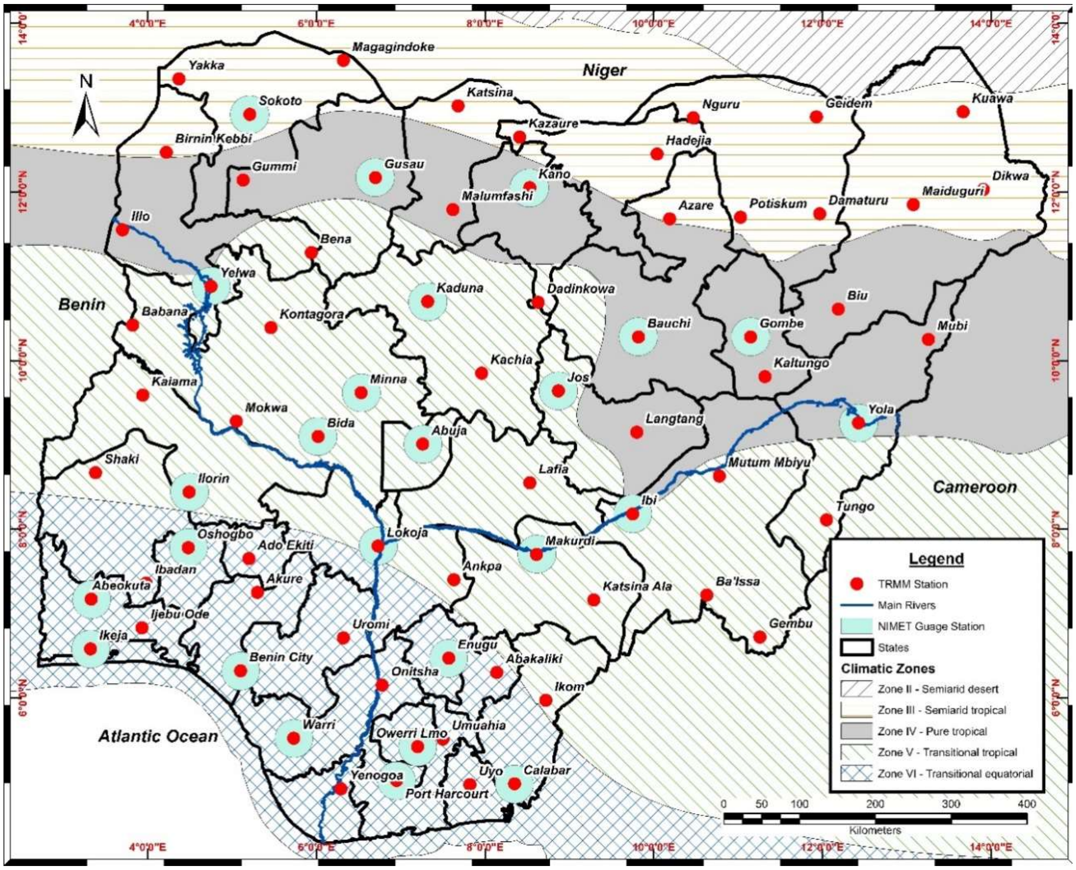


Figure 2. SRE Data Extraction and Rain Gauge Locations in Nigeria

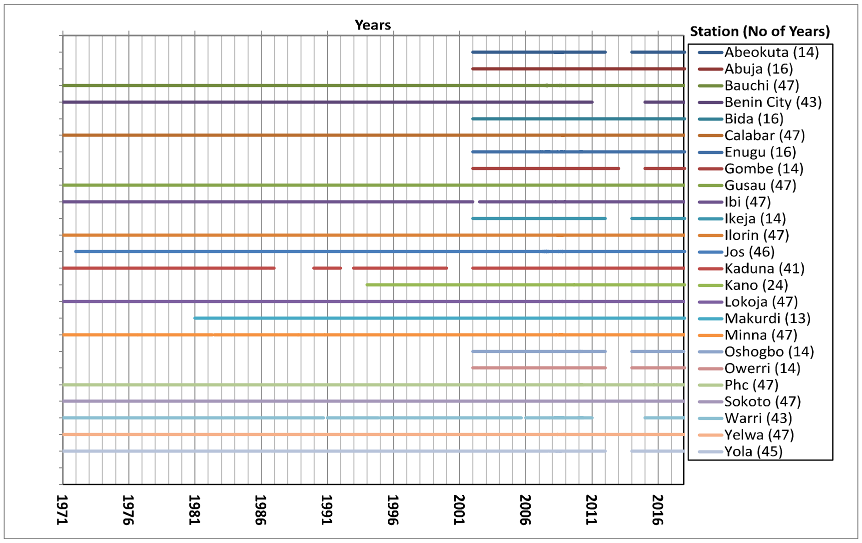


Figure 3. Gauge Data Availability Chart

Table 3. Validation Metrics

S/N	TEST	ABBREV	MIN	OPTIMUM	MAX	EQUATION
1	Mean Absolute Error	MAE	0	0	∞	$mae = \frac{1}{N}\sum_{i=1}^{N}\left\|(S_i - O_i)\right\|$
2	Root Mean Square Error/Deviation	RMSE	0	0	∞	$rmse = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)^2}$
3	Percent bias	PBIAS	-∞	0	∞	$pbias = \left[\frac{\sum_{i=1}^{N}(S_i - O_i)}{\sum_{i=1}^{N}(O_i)}\right]\times 100$
4	Pearson's correlation coefficient	r	-1	1	1	$r = \frac{\sum_{i=1}^{N}(O_i - \bar{O}_i)(S_i - \bar{S}_i)}{\sqrt{\sum_{i=1}^{N}(O_i - \bar{O}_i)^2 \cdot \sum_{i=1}^{N}(S_i - \bar{S}_i)^2}}$
5	Volumetric Efficiency	VE	0	1	1	$VE = 1 - \left[\frac{\sum_{i=1}^{N}\|S_i - O_i\|}{\sum_{i=1}^{N}(O_i)}\right]$

2.3. Data Extraction and IDF Analysis

After selection of the candidate SRE, a GIS based extraction of the gridded raster datasets at the 25 daily rain gauge stations (Figure 2) maintained by Nigeria meteorological Agency (NIMET) and an additional 45 locations at major cities around the country (72 locations in total) was undertaken. Based on the works of [83] data extraction of the annual maximum rainfall series was done using a 25 km buffer around the respective station coordinates, this is to guard against a situation whereby a grid cell with higher rainfall intensity than the gauge point location is present in the vicinity, thereby underestimating the extreme value.

The IDF analysis involved fitting the annual extreme data (for each duration) to a probability distribution [7,84,85,86]. According to [84], IDF formulae can be generalized in the form of the equation 1.

$$i = \frac{w(T)}{b(d)} \tag{1}$$

This depicts the intensity, $\boldsymbol{i}$ (mm/hr) as a separate function of the return period, $\boldsymbol{T}$ (year) and duration, $\boldsymbol{d}$ (hr). The term $\boldsymbol{w(T) = a}$; is directly proportional to the return period and can be theoretically determined based on the inverse function of the statistical distribution used to fit the annual extreme values. It suffices to note that: $\boldsymbol{b(d) = (d + \theta)^{\eta}}$; where $\boldsymbol{\theta}$, and $\boldsymbol{\eta}$ are parameters ($\theta > 0$, $0 < \eta < 1$) which vary with location only.

By substituting into equation 1, the general form becomes

$$i = \frac{a}{(d+\theta)^{\eta}} \tag{2}$$

In view of the documented superiority of the three-parameter Fréchet (extreme value type II distribution–EV2) over the two-parameter Gumbel (extreme value type I-EV1) distribution [87,88,89], the EV2 distribution was used for fitting the annual extreme values, thus:

$$a = \lambda\Psi + \frac{\lambda}{\kappa}\left[\left(-\ln\left(1-\frac{1}{T}\right)\right)^{-\kappa} - 1\right] \tag{3}$$

where $\boldsymbol{\Psi}$ is the dimensionless location parameter, $\boldsymbol{\lambda}$ is the scale parameter in mm/hr ($\lambda > 0$) and $\boldsymbol{\kappa}$ is the dimensionless shape parameter ($\kappa > 0$). Substituting into equation (2) gives the final IDF formula shown in equation (4).

$$i = \frac{\lambda\Psi + \frac{\lambda}{\kappa}\left[\left(-\ln\left(1-\frac{1}{T}\right)\right)^{-\kappa} - 1\right]}{(d+\theta)^{\eta}} \tag{4}$$

For each location, parameter estimation for equation (4) was done using the two-step procedure described in [84]. Initially, parameters $\boldsymbol{\theta}$ and $\boldsymbol{\eta}$ were determined using the trial and error method of minimization of the Kruskal-Wallis statistic. As a consequence, parameters $\boldsymbol{\Psi}$, $\boldsymbol{\lambda}$, and $\boldsymbol{\kappa}$ were computed using the more robust L-moments method [90]. Based on the tendency of the $\boldsymbol{\kappa}$ parameter to approach negative values due to small record lengths, the value of $\mathbf{0.114}$ was used as proposed in [91].

Parameter estimation using a point/location based approach was favoured over the regional approach because of the sufficient spatial coverage characteristic of the SRE datasets and also considering the observed rain gauge and IDF datasets to be used for validation are point based. The essence of regionalization is to capture ungauged sites and also reduce computational rigour, however, the development of Isopleths for the IDF parameters will assist in parameter estimation for ungauged areas outside the point locations. The IDF curves for 29 stations in Nigeria based on the SRE dataset were compared with the IDF curves reported in [9]. For objectivity, percentage error was also computed for each duration and return period.

3. Results and Discussion

3.1. SRE Validation and Candidate Selection

Results of the validation exercise are summarized in Table 4. For the annual total category, the TRMM 3B42 Version 7 data performed overwhelmingly with 17 out of the 25 stations, with CMORPH being the next contender with just 4 stations. For the annual daily maximum category there is a tie between TRMM 3B42 Version 7 and PERSIANN data with both performing at 8 stations each, CMORPH and GPM IMERG are runner ups with 4 stations each. TRMM 3B42 Version 7 was selected as the final candidate SRE considering that it performs the best of the two final candidates for both categories.

3.2. Data Extraction and EV2 Parameters

Considering that the TRMM datasets come in 3hr intervals, the first step is to aggregate the data over 6hr, 12hr, and 24hr durations, then maximum values were extracted using a block maxima approach which employs a moving (sliding) annual window corresponding to the relevant duration. Annual maximum values for accumulated durations of 3, 6, 12, and 24 were computed for 17 years of TRMM annual maximum rainfall series (1998 to 2014) at the 72 locations. The depths were divided by the corresponding durations to obtain the average intensity values.

The parameters of the EV2 distribution vary with stations. Figure 4 to Figure 9 show the spatial variation of the L-Moments (L1, L2, and L3), and the three EV2 parameters ($\boldsymbol{\Psi}$, $\boldsymbol{\lambda}$ and $\boldsymbol{\kappa}$). The location parameter, $\boldsymbol{\Psi}$ displays no specific zonal variation, rather there is a North-West to South-Eastern gradient from high to low values, with a maximum of 6.17 at Ijebu Ode (Zone VI), minimum of 2.22 at Kuawa (Zone III), and a national average of 4.17. The scale parameter, $\boldsymbol{\lambda}$ however, displays a variation in the opposite direction (South-East to North-Western) with maximum of 34.51 at Lokoja (Zone V), minimum of 11.77 at Dadinkowa (Zone V) and average of 20.50. The dimensionless shape parameter, $\boldsymbol{\kappa}$ shows no defined spatially variation; it ranges from 0.643 at Minna (Zone V) to -0.440 at Dikwa (Zone III), with a national average of -0.026. Values of $\boldsymbol{\kappa} < 0$ cannot be considered in the analysis of maximum rainfall intensities because it implies an upper bound of the parameter [84], hence the value of **0.114** as recommended by [87] was adopted.

Table 4. SRE Validation Summary

S/N	STATION	ABBREV	ANNUAL TOTAL	ANNUAL MAX	S/N	STATION	ABBREV	ANNUAL SUM	ANNUAL MAX
1	Abeokuta	Abe	TRMM	PN	**14**	Kaduna	Kad	TRMM	TRMM
2	Abuja	Abj	TRMM	PN	**15**	Kano	Kan	CM	PN
3	Bauchi	Bau	CM	CM	**16**	Lokoja	Lok	TRMM	CM
4	Benin City	Bni	CM	TRMM	**17**	Makurdi	Mkd	TRMM	PN
5	Bida	Bid	IM	TRMM	**18**	Minna	Mna	TRMM	PN
6	Calabar	Cal	IM	CM	**19**	Oshogbo	Osh	TRMM	TRMM
7	Enugu	Enu	TRMM	PN	**20**	Owerri	Owe	TRMM	TRMM
8	Gombe	Gom	TRMM	IM	**21**	Phc	Phc	TRMM	PN
9	Gusau	Gus	TRMM	IM	**22**	Sokoto	Sok	TRMM	PS
10	Ibi	Ibi	TRMM	IM	**23**	Warri	War	PN	TRMM
11	Ikeja	Ikj	CM	CM	**24**	Yelwa	Yel	TRMM	TRMM
12	Ilorin	Ilr	TRMM	TRMM	**25**	Yola	Yol	TRMM	PN
13	Jos	Jos	IM	IM					

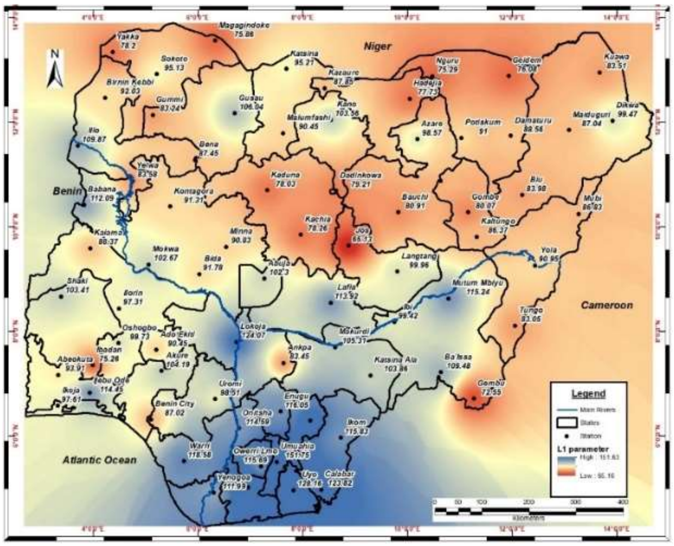


Figure 4. L1 Parameter

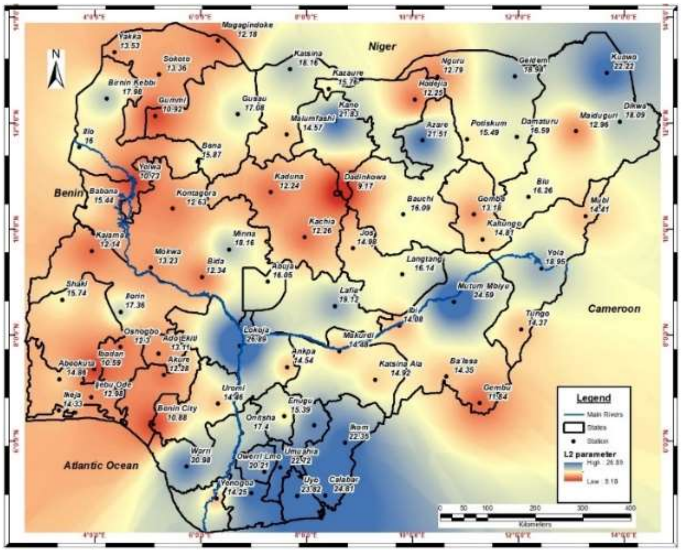


Figure 5. L2 Parameter

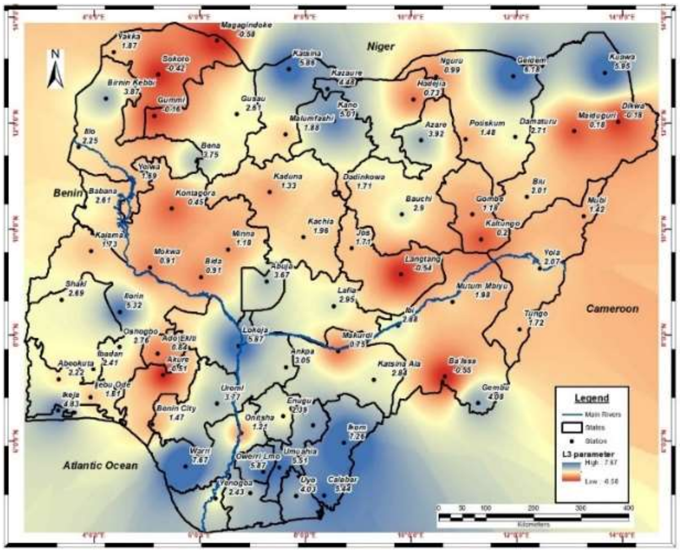


Figure 6. L3 Parameter

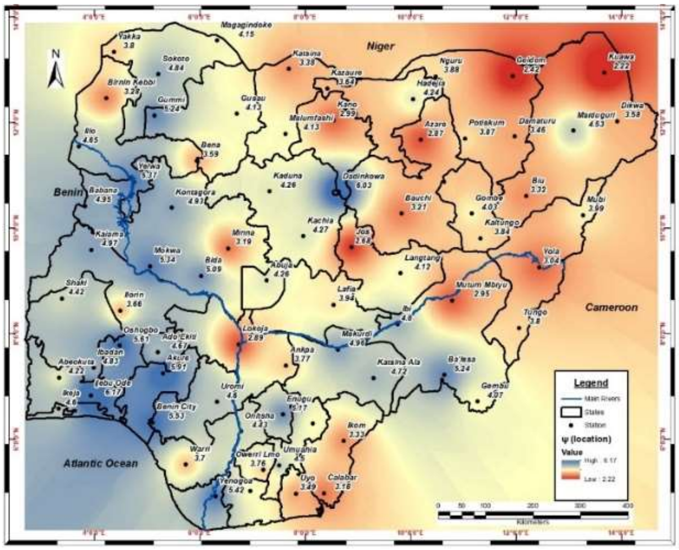


Figure 7. *ψ* (location) Parameter

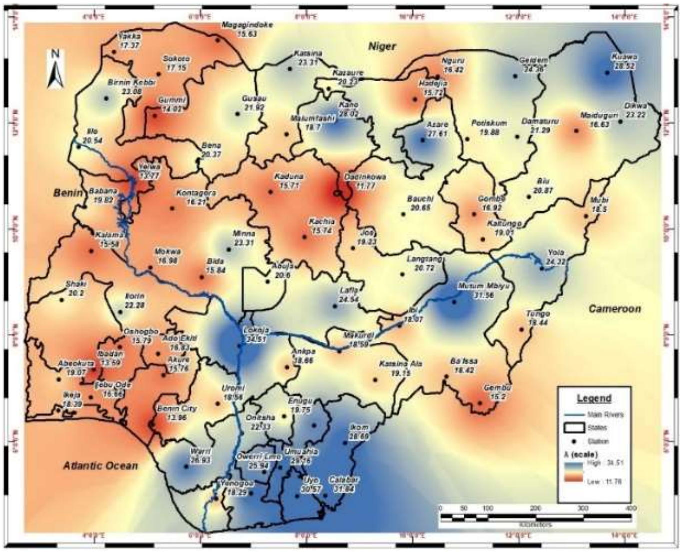


Figure 8. λ (scale) Parameter

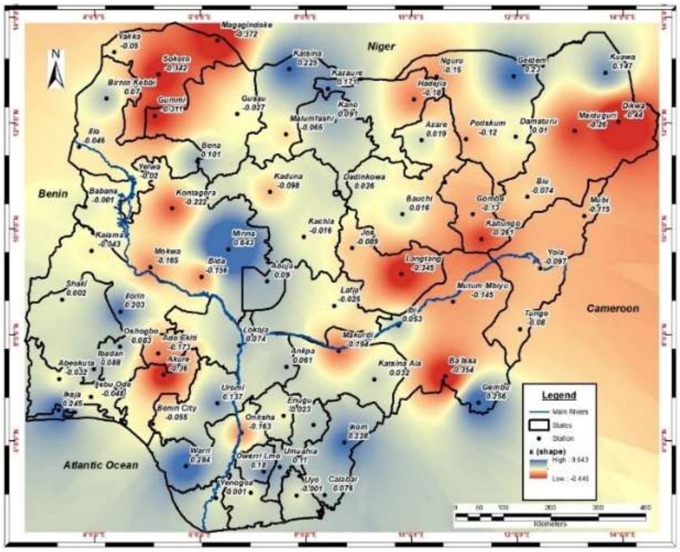


Figure 9. $\boldsymbol{\kappa}$ (shape) Parameter

3.3. IDF Parameters

The parameters ($\boldsymbol{\alpha}, \boldsymbol{\theta}, and\ \boldsymbol{\eta}$) of the IDF curves based on TRMM dataset (TRMM-IDF) are presented in Table 5 to Table 7. The parameter, $\boldsymbol{\alpha}$, varies with location and return period, showing a directly proportional increase in value with increase in return period; and also an average zonal increase from higher to lower latitudes. There is no discernible pattern in the zonal variation of $\boldsymbol{\theta}$, the maximum value of the parameter is 0.998 in Lokoja (Zone V) and minimum of 0.3 in Minna (Zone V), and Ibadan (Zone VI). The $\boldsymbol{\eta}$ parameter however shows overwhelmingly high values in Zones III, IV, and V, and low values in Zone VI. A maximum of 0.997 occurs in Kontagora (Zone V), and minimum of 0.856 in Ikeja (Zone VI). Sample IDF curves for selected stations are presented in Figure 10.

3.4. Comparison of IDF Curves

Figure 11 displays the 29 coincident [9] IDF locations amongst the 72 TRMM-IDF locations. Figure 12 to Figure 15 illustrate results of the zonal comparisons between the TRMM and the Reference [9] IDF values. The percentage difference (PBIAS) between the intensities for each duration and corresponding return period is clearly visualized, with positive values indicating higher TRMM relative to [9] and negative values indicating otherwise.

a) In Zone III (Semiarid Tropical), which comprises five stations (Katsina, Maiduguri, Nguru, Potiskum, and Sokoto), there is a general tendency for underestimation below and over overestimation beyond the 1-hour duration for all return periods. With maximum deviation of **99.36%** for the 6hr duration-50yr return period at Katsina, and minimum deviation of **-46.68%** at the 0.1hr duration-2yr return period at Nguru.

b) Zone IV (Pure Tropical) includes four stations (Bauchi, Gusau, Kano, and Yola) with maximum deviation of **92.36%** for the 48hr duration-100yr return period in Gusau, and minimum deviation of **-**

33.04% at the 0.1hr duration-2yr return period in Bauchi.

c) Zone V (Transitional Tropical) consists of ten stations (Bida, Ibi, Ilorin, Jos, Kaduna, Lokoja, Makurdi, Minna, Mokwa, and Yelwa) with a maximum deviation of **113.40%** for the 48hr duration-2yr return period in Lokoja, and minimum deviation of **-50.23%** at the 0.1hr duration-100yr return period in Mokwa.

d) Zone VI (Transitional Equatorial) contains ten stations (Akure, Benin City, Calabar, Enugu, Ibadan, Ikeja, Oshogbo, Port Harcourt, Umuahia, and Warri) with a maximum deviation of **86.33%** for the 48hr duration-5yr return period in Umahia, and minimum deviation of **-47.23%** at the 0.1hr duration-2yr return period in Benin City.

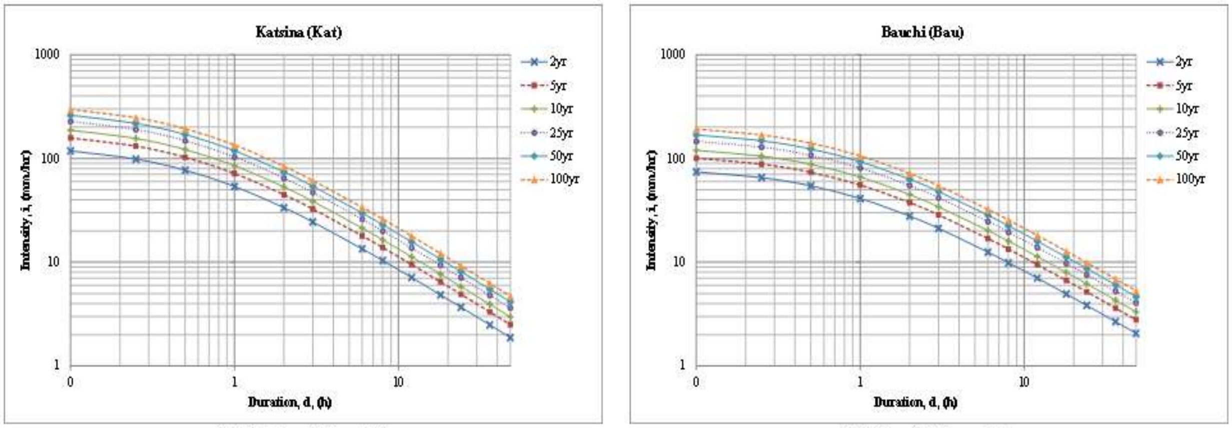
The greatest deviations in intensity values between TRMM-IDF and the [9] can be observed in Zone V corresponding to Lokoja (**113.40%)** at the 48hr duration-2yr return period, and Mokwa (**-50.23%**) at the 0.1hr duration-100yr return period. It is worthy of note that factors such as data source, number of data years, temporal resolution, and climate change play an important role in the disparities between both datasets which cannot readily be quantified.

Table 5. IDF Parameters (Zone III and Zone IV)

S/N	STATION	LONGITUDE	LATITUDE	ZONE	α (2yr)	α (5yr)	α (10yr)	α (25yr)	α (50yr)	α (100yr)	θ	η
1	Azare	10.19	11.68	Zone III - Semiarid Tropical	89.48	124.31	149.98	185.71	214.82	246.13	0.970	0.984
2	Birnin Kebbi	4.22	12.47		84.43	113.55	135.00	164.87	189.20	215.37	0.988	0.943
3	Damaturu	11.97	11.74		81.55	108.41	128.21	155.77	178.22	202.37	0.774	0.992
4	Dikwa	13.91	12.03		91.83	121.12	142.70	172.75	197.24	223.57	0.664	0.987
5	Geidem	11.93	12.89		68.06	98.79	121.44	152.97	178.66	206.28	0.536	0.991
6	Hadejia	10.04	12.45		72.56	92.39	107.01	127.35	143.94	161.76	0.375	0.985
7	Katsina	7.68	13.02		87.54	116.94	138.61	168.78	193.36	219.79	0.638	0.989
8	Kazaure	8.41	12.65		81.19	106.71	125.51	151.69	173.03	195.96	0.418	0.995
9	Kuawa	13.67	12.95		74.12	110.10	136.61	173.52	203.60	235.94	0.579	0.987
10	Magagindoke	6.32	13.56		70.71	90.44	104.97	125.20	141.69	159.41	0.323	0.981
11	Maiduguri	13.08	11.85		81.57	102.55	118.01	139.54	157.08	175.94	0.712	0.982
12	Nguru	10.47	12.88		69.89	90.60	105.86	127.10	144.41	163.03	0.739	0.986
13	Potiskum	11.03	11.70		84.46	109.54	128.02	153.75	174.72	197.26	0.707	0.986
14	Sokoto	5.21	12.92		89.49	111.12	127.06	149.25	167.33	186.78	0.705	0.994
15	Yakka	4.37	13.34		72.48	94.39	110.54	133.01	151.32	171.01	0.802	0.989
				Average	**79.96**	**106.06**	**125.30**	**152.08**	**173.91**	**197.37**	**0.662**	**0.985**
16	Bauchi	9.82	10.28	Zone IV - Pure Tropical	74.11	100.17	119.36	146.09	167.87	191.29	0.896	0.921
17	Biu	12.19	10.61		77.11	103.44	122.84	149.85	171.86	195.52	0.678	0.985
18	Gombe	11.15	10.28		74.50	95.84	111.57	133.46	151.30	170.48	0.980	0.979
19	Gummi	5.13	12.14		78.63	96.31	109.34	127.48	142.26	158.15	0.501	0.993
20	Gusau	6.70	12.17		98.82	126.48	146.86	175.23	198.35	223.21	0.773	0.985
21	Illo	3.70	11.55		103.11	129.02	148.11	174.69	196.34	219.63	0.995	0.987
22	Kaltungo	11.32	9.81		80.11	104.09	121.76	146.36	166.41	187.97	0.870	0.990
23	Kano	8.53	12.05		94.34	129.69	155.73	191.99	221.54	253.31	0.803	0.988
24	Langtang	9.80	9.15		93.14	119.28	138.53	165.34	187.19	210.68	0.636	0.986
25	Malumfashi	7.62	11.79		84.30	107.89	125.27	149.47	169.19	190.40	0.352	0.986
26	Mubi	13.26	10.25		80.74	104.08	121.27	145.20	164.71	185.68	0.800	0.932
27	Yola	12.43	9.26		82.94	113.63	136.24	167.72	193.37	220.95	0.426	0.995
				Average	**85.16**	**110.83**	**129.74**	**156.07**	**177.53**	**200.61**	**0.726**	**0.977**

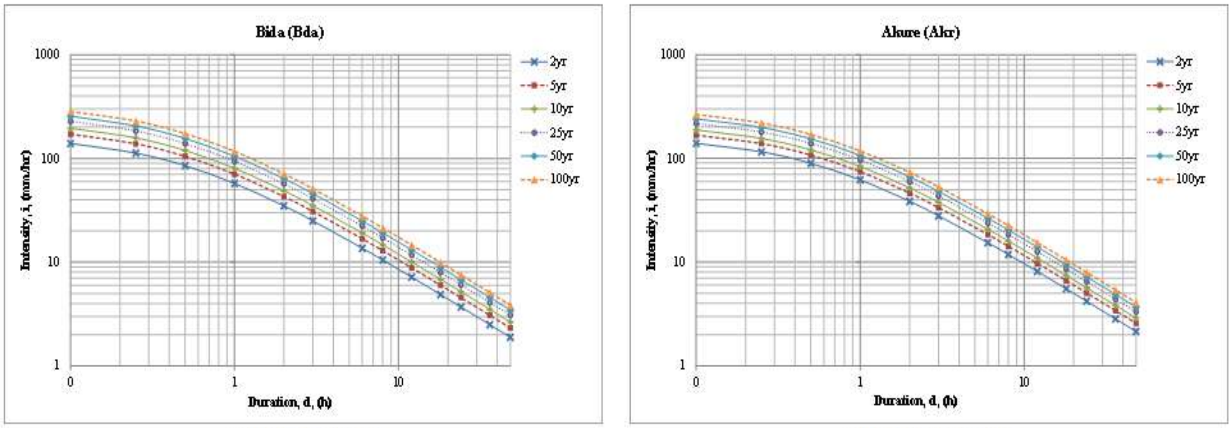
Table 6. IDF Parameters (Zone V)

S/N	STATION	LONGITUDE	LATITUDE	ZONE	α (2yr)	α (5yr)	α (10yr)	α (25yr)	α (50yr)	α (100yr)	θ	η
28	Abuja	7.26	9.01	Zone V - Transitional Tropical	95.52	121.51	140.66	167.32	189.04	212.40	0.531	0.952
29	Ankpa	7.63	7.40		77.31	100.85	118.20	142.35	162.03	183.19	0.558	0.976
30	Babana	3.82	10.42		105.57	130.57	148.99	174.64	195.54	218.01	0.990	0.990
31	Ba'Issa	10.63	7.22		103.42	126.65	143.77	167.61	187.04	207.92	0.866	0.993
32	Bena	5.94	11.28		80.75	106.44	125.38	151.74	173.22	196.32	0.434	0.921
33	Bida	6.02	9.10		86.57	106.55	121.27	141.77	158.47	176.43	0.516	0.985
34	Dadinkowa	8.63	10.69		75.34	90.18	101.13	116.36	128.77	142.12	0.772	0.985
35	Gembu	11.26	6.72		67.55	86.72	100.85	120.51	136.54	153.77	0.742	0.915
36	Ibi	9.75	8.18		93.47	116.27	133.07	156.46	175.52	196.01	0.645	0.987
37	Ikom	8.72	5.97		106.39	142.58	169.24	206.37	236.62	269.15	0.300	0.881
38	Ilorin	4.49	8.44		89.98	118.09	138.80	167.63	191.13	216.40	0.646	0.982
39	Jos	8.87	9.64		58.80	83.06	100.93	125.81	146.09	167.89	0.602	0.987
40	Kachia	7.96	9.85		73.08	92.93	107.56	127.92	144.52	162.36	0.807	0.950
41	Kaduna	7.32	10.70		72.86	92.68	107.28	127.61	144.18	162.00	0.300	0.922
42	Kaiama	3.94	9.59		83.24	102.90	117.38	137.55	153.98	171.65	0.525	0.951
43	Katsina Ala	9.29	7.16		97.56	121.72	139.52	164.30	184.50	206.21	0.734	0.953
44	Kontagora	5.46	10.39		85.97	106.43	121.49	142.47	159.57	177.95	0.676	0.997
45	Lafia	8.53	8.55		105.84	136.80	159.61	191.37	217.26	245.08	0.794	0.987
46	Lokoja	6.73	7.80		112.71	156.25	188.33	233.00	269.40	308.53	0.998	0.981
47	Makurdi	8.61	7.70		99.19	122.64	139.92	163.97	183.57	204.64	0.580	0.987
48	Minna	6.53	9.62		83.16	112.56	134.23	164.40	188.98	215.41	0.300	0.986
49	Mokwa	5.05	9.28		97.08	118.50	134.29	156.26	174.17	193.43	0.738	0.990
50	Mutum Mbiyu	10.78	8.63		104.85	144.67	174.01	214.85	248.14	283.93	0.709	0.992
51	Shaki	3.38	8.67		96.76	122.25	141.03	167.17	188.48	211.39	0.992	0.973
52	Tungo	12.05	8.11		76.98	100.25	117.39	141.26	160.71	181.63	0.463	0.951
53	Yelwa	4.75	10.88		79.05	96.42	109.22	127.05	141.57	157.19	0.502	0.988
				Average	**88.81**	**113.71**	**132.06**	**157.61**	**178.42**	**200.81**	**0.643**	**0.968**



(a) Katsina (Zone III)

(b) Bauchi (Zone IV)



(c) Bida (Zone V)

(d) Akure (Zone VI)

Figure 10. IDF Curves for selected stations

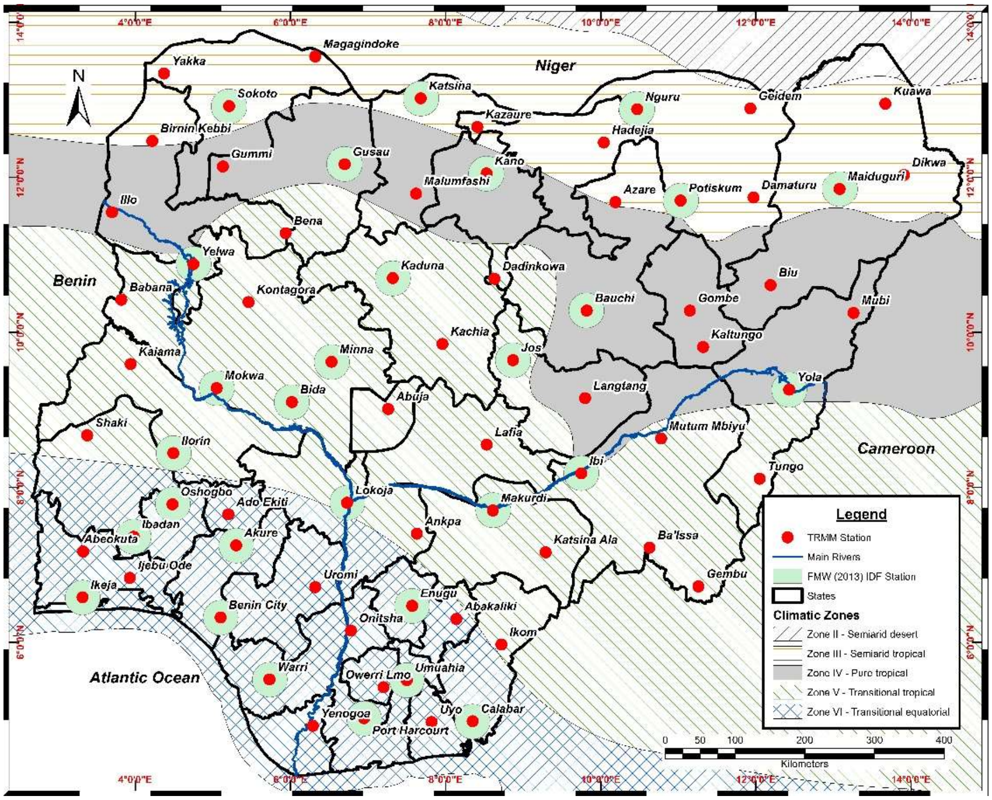
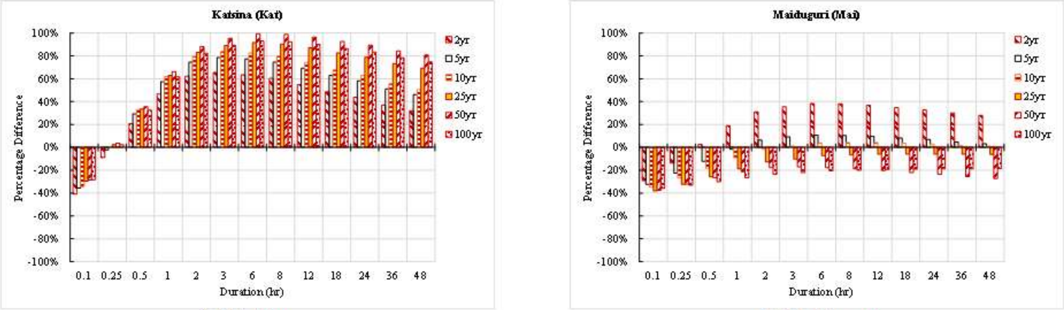
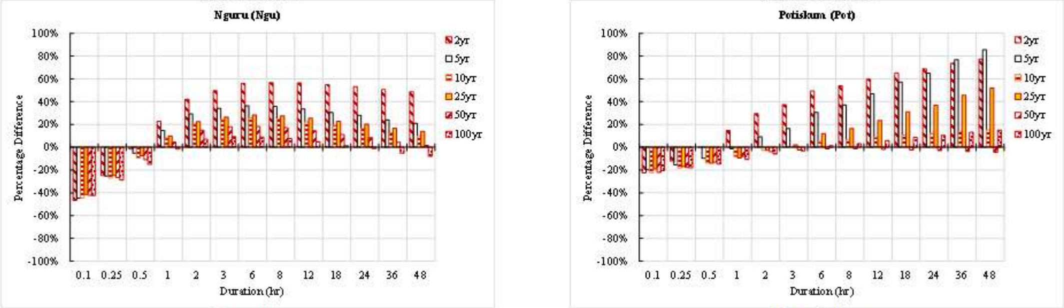


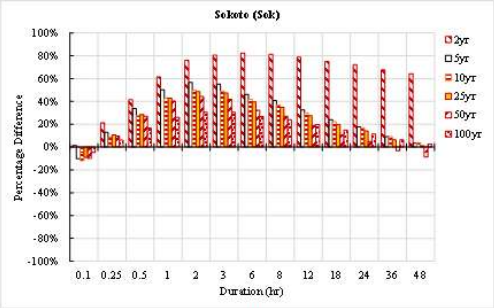
Figure 11. TRMM IDF and [9] IDF Locations in Nigeria



(a) Katsina (b) Maiduguri

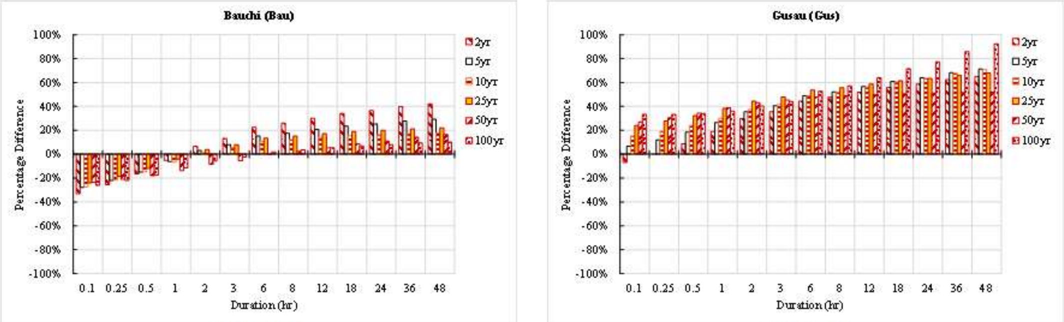


(c) Nguru (d) Potiskum

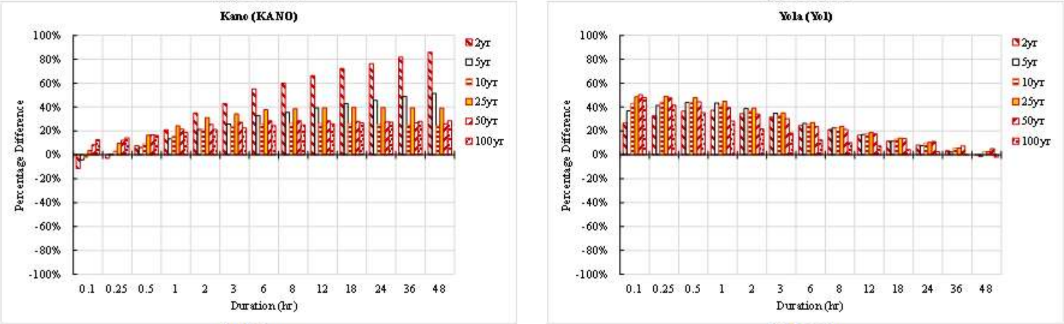


(e) Sokoto

Figure 12. Comparison of IDF curves for Zone III

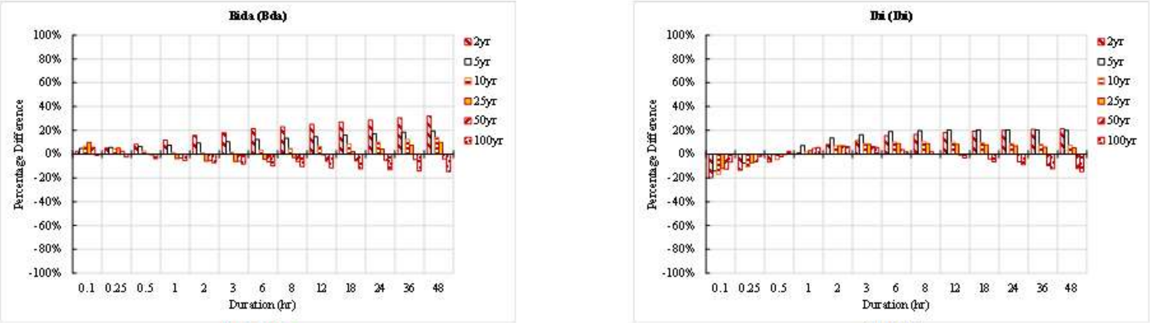


(a) Bauchi (b) Gusau

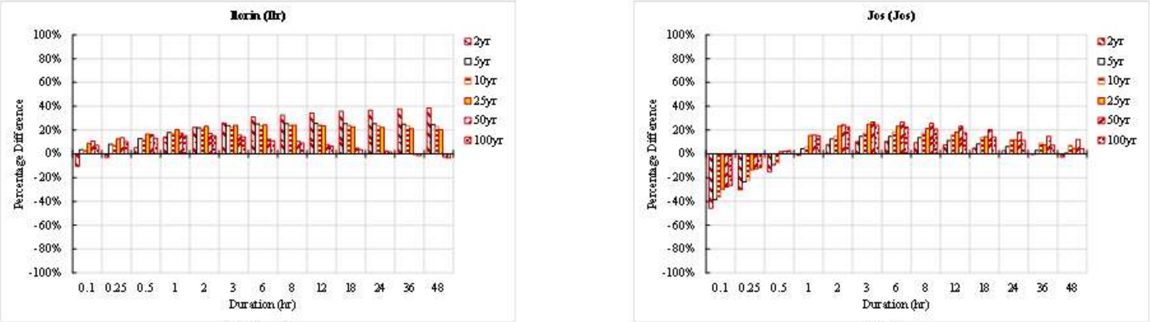


(c) Kano (d) Yola

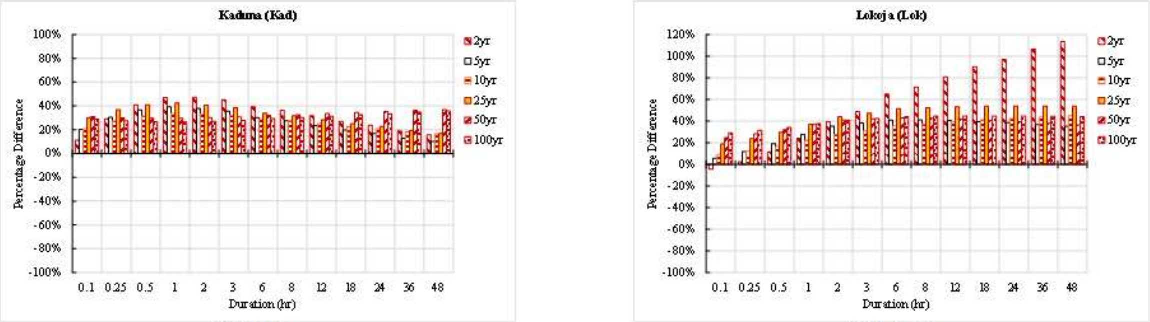
Figure 13. Comparison of IDF curves for Zone IV



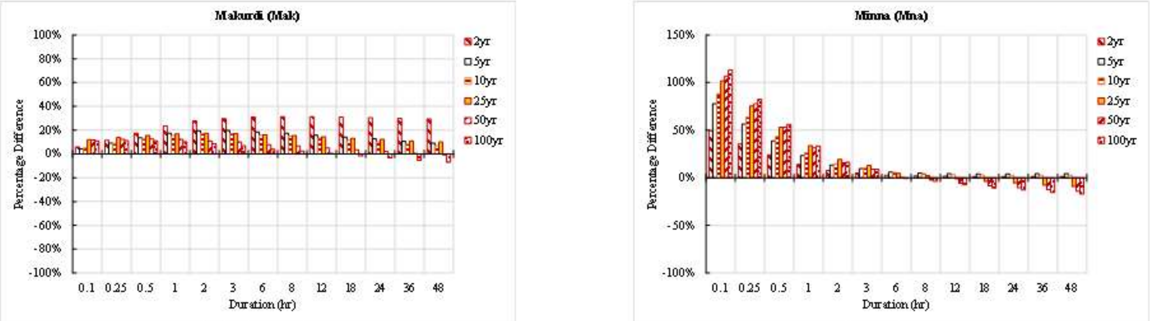
(a) Bida (b) Ibi



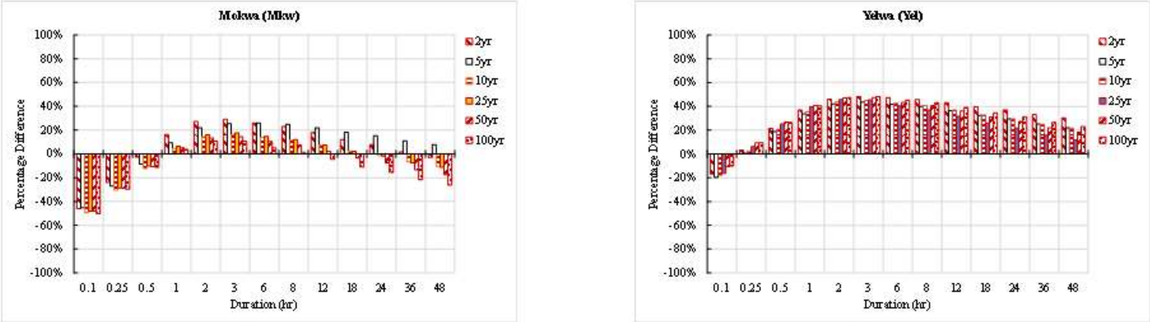
(c) Ilorin (d) Jos



(e) Kaduna (f) Lokoja

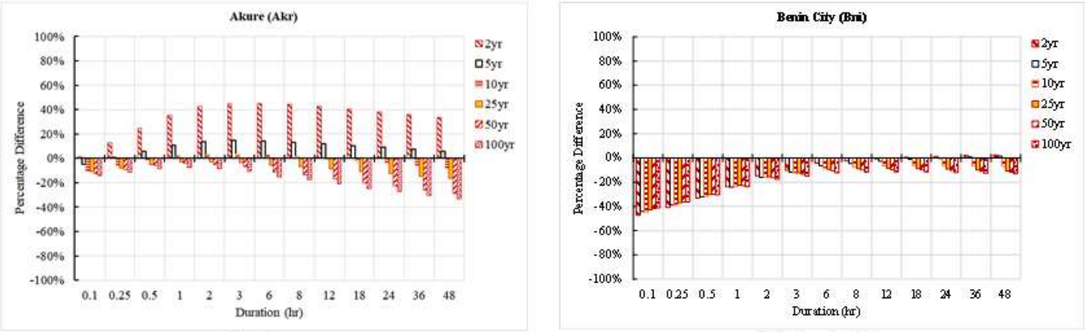


(g) Makurdi (h) Minna

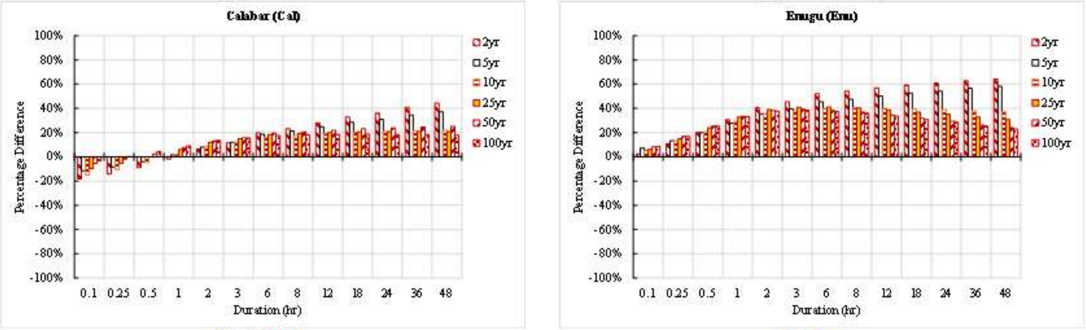


(i) Mokwa (j) Yelwa

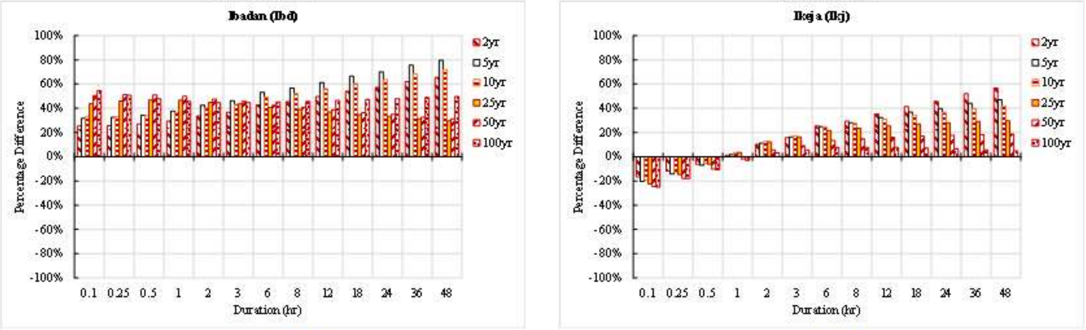
Figure 14. Comparison of IDF curves for Zone V



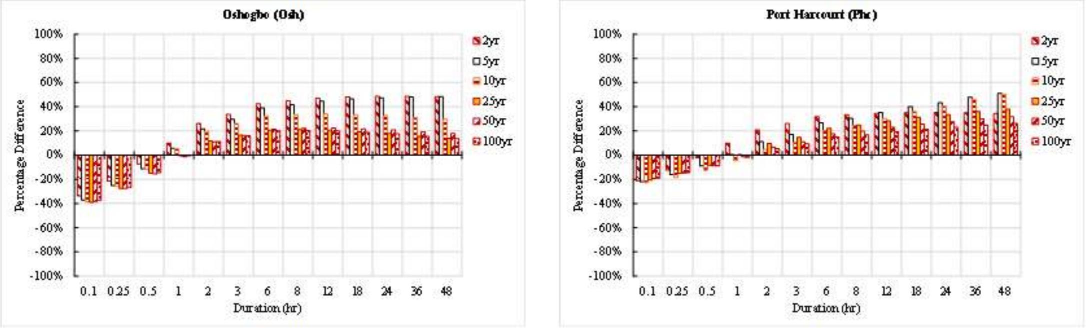
(a) Akure (b) Benin City



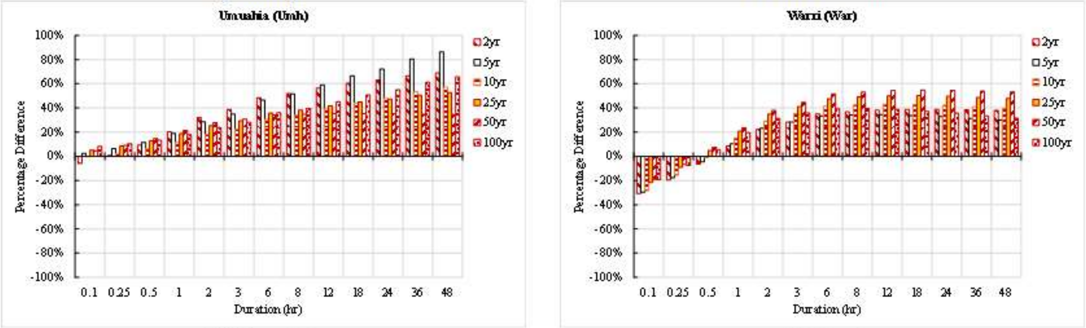
(c) Calabar (d) Enugu



(e) Ibadan (f) Ikeja



(g) Oshogbo (h) Port Harcourt



(i) Umuahia (j) Warri

Figure 15. Comparison of IDF curves for Zone VI

Table 7. IDF Parameters (Zone VI)

S/N	STATION	LONGITUDE	LATITUDE	ZONE	α (2yr)	α (5yr)	α (10yr)	α (25yr)	α (50yr)	α (100yr)	θ	η
54	Abakaliki	8.14	6.30	Zone VI - Transitional Equatorial	118.01	151.48	176.14	210.47	238.45	268.53	0.776	0.983
55	Abeokuta	3.33	7.17		87.63	111.69	129.42	154.11	174.22	195.85	0.561	0.924
56	Ado Ekiti	5.20	7.65		84.91	106.14	121.78	143.56	161.30	180.38	0.962	0.961
57	Akure	5.30	7.25		99.00	118.89	133.54	153.94	170.56	188.43	0.607	0.987
58	Benin City	5.10	6.32		82.42	100.04	113.02	131.09	145.82	161.66	0.986	0.877
59	Calabar	8.35	4.98		113.34	153.51	183.11	224.32	257.91	294.01	0.931	0.956
60	Enugu	7.57	6.47		109.55	134.47	152.83	178.39	199.23	221.62	0.666	0.953
61	Ibadan	3.98	7.36		70.79	87.93	100.57	118.16	132.49	147.91	0.300	0.889
62	Ijebu Ode	3.93	6.83		108.97	129.98	145.47	167.03	184.60	203.49	0.997	0.956
63	Ikeja	3.32	6.58		91.56	114.76	131.86	155.66	175.06	195.91	0.707	0.856
64	Onitsha	6.78	6.15		107.24	135.41	156.17	185.08	208.63	233.95	0.997	0.989
65	Oshogbo	4.48	7.78		94.53	114.45	129.13	149.56	166.21	184.11	0.930	0.958
66	Owerri	7.20	5.42		107.15	139.88	163.99	197.56	224.92	254.33	0.952	0.888
67	Port Harcourt	6.95	5.02		126.95	162.91	189.41	226.30	256.37	288.69	0.916	0.917
68	Umuahia	7.50	5.51		142.15	178.94	206.05	243.79	274.54	307.61	0.997	0.983
69	Uromi	6.32	6.71		92.40	115.82	133.07	157.09	176.66	197.70	0.959	0.932
70	Uyo	7.82	4.97		118.10	156.67	185.09	224.65	256.90	291.56	0.975	0.908
71	Warri	5.73	5.52		109.72	143.69	168.72	203.57	231.97	262.50	0.903	0.871
72	Yenogoa	6.29	4.92		105.97	129.04	146.05	169.72	189.01	209.74	0.774	0.889
				Average	**103.70**	**130.83**	**150.81**	**178.63**	**201.31**	**225.68**	**0.837**	**0.930**

4. Conclusion

This work has demonstrated the use of satellite rainfall estimates, specifically the TRMM dataset for development of IDF data for Nigeria. Spatial variations are evident in the parameters of the IDF curves, the magnitude of these variations cannot be said to be physically deterministic but rather stochastic whose determination is difficult due to the lack of adequate spatially representative sub-daily gauge rainfall data in the country. The comparison between the TRMM-IDF output and existing [9] curves show a maximum percentage difference (positive and negative) of approximately 100% across all durations and return periods considered, with the TRMM-IDF intensity values exceeding [9] IDF values in most of the locations. In the face of climate change effects being experienced globally, the adoption of the TRMM-IDF should be considered for nationwide drainage infrastructure design and flood management projects.

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