



APPLICATION OF GIS TECHNIQUES IN GENERATING RAINFALL-IDF MAPS FOR UNGAUGED CATCHMENT: A CASE OF YENAGOA CITY, NIGERIA

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Abstract

Certain areas in Yenagoa city, the capital of Bayelsa state in Southern Nigeria have been experiencing flooding whenever rainfall occurs despite the presence of surface drainages. Past literatures attributed the cause to many factors with emphasis on negligence of hydrologic analysis during drainage design. The Rainfall-Intensity-Duration-Frequency (IDF) curve or model is a well-known hydrologic tool used in the design of surface drainages and culverts. However, Yenagoa city has no existing IDF model due to lack of sufficient rainfall data since a functional meteorological station had not been installed in the state. Hence, this research employed Geographic Information System (GIS) to establish the rainfall IDF map model of the ungauged Yenagoa city via Inverse Distance Weighted (IDW) Interpolation technique, for 2, 5, 10, 25 and 50years return periods. Thereafter, a mathematical relationship was developed to determine any desired value of IDF parameters for the catchment once other parameters are known.

Keywords: Flood, Hydrology, Interpolation, Ungauged, Yenagoa

Introduction

Flooding in tropical countries such as Nigeria are caused by many factors including heavy rainfall, failure of dams or release of excessive water from dams, overflow of rivers and streams due to siltation, poor design and maintenance of drainages, urbanisation, etc. However, massive rainfall is known to be the governing factor for flooding hence, hydraulic structures such as surface drainages and culverts are usually constructed both in urban and rural areas to drain runoff into nearby rivers and streams.

The recent flood disaster experienced in Nigeria in 2012 and 2022 had more effect on riverine communities including those in Bayelsa state in South-Southern Nigeria. This is because during these floods, rivers in the affected areas were overflowed and the water inundated across the banks. Notwithstanding, Yenagoa being the state capital of Bayelsa state has been experiencing flooding in certain areas of the city even when the draining streams and rivers in the basin are not overflowed. Hence, drainages and culverts were constructed in most of these identified areas but the problem remains unsolved despite desilting the drainages thus, suggesting that the drainages and culverts were not properly designed. Ideally, the design of hydraulic structures such as drainages and culverts entail the hydrological analysis of the catchment to understand the highest amount of runoff

to be drained within the designed period, followed by the hydraulic design to determine the appropriate dimensions of the channel for efficient discharge and finally, geotechnical considerations and structural design (reinforcement). However, the hydrological analysis of the catchment which involves selection of appropriate rainfall intensity for a given return period and storm duration equivalent to the concentration time of the basin is often omitted in many developing countries. This is due to lack of hydrological data as most of the catchments are not gauged (Ogbozige, 2021; Nwaogazie and Agiho, 2019). Thus, most surface drainages in developing countries including Nigeria are not properly designed before construction. This was earlier reported by Ezugwu and Eze (2019) who stated that most drainages in Nigeria were just dug and cast without proper design.

Yenagoa city has no reliable meteorological (weather) station at the moment hence, researchers have not been able to develop rainfall Intensity-Duration-Frequency (IDF) curves to be used in hydrological analysis of the catchment during design of hydraulic structures, due to lack of previous recorded rainfall values for at least 30years. Therefore, this research applied scientific principles to generate the IDF model of the ungauged Yenagoa catchment as well as the IDF map of the entire Niger Delta River Basin which comprises of Rivers state, Bayelsa state and major part of Delta state. This will serve as a reliable tool for Civil (Water Resources)

Engineers in subsequent design of hydraulic structures within the basin to reduce the effects of flash flooding.

Methodology

Three meteorological stations in nearby states sharing common boundary with Bayelsa state (where Yenagoa is situated) were identified in Port Harcourt (Rivers state), Warri (Delta state) and Asaba (Delta state). The aerial distance between the aforementioned meteorological stations and Yenagoa are 76.09 km, 93.38 km and 144.80 km, respectively. The maximum daily rainfall depth of each year between January, 1971 to December, 2020 (i.e. 50years), recorded by the identified weather stations at Port Harcourt, Warri and Asaba were obtained from the headquarters of the Nigerian Meteorological Agency, Abuja. The obtained rainfall records were used in developing the IDF curves of the respective cities hosting the weather stations (i.e. Port Harcourt, Warri and Asaba) for 2, 5, 10, 25 and 50 years return periods at 5, 10 30, 45, 60, 120, 180 and 210 minutes storm durations. However, the IDF curves were developed using Gumbel's distribution based on the recommendations of Ogbozige and Otokpa (2022), Ogbozige (2021) as well as Nwaogazie and Sam (2019) who reported that IDF curves from Gumbel's distribution are more suitable in most of the catchments in Nigeria compared to other distribution functions. A mathematical relationship between the rainfall intensity (*i*), storm duration (*t*) and return period (*T*) was developed using Sherman's model so that any of the IDF parameters (*i*, *t* and *T*) that was not captured in the developed IDF curves can be calculated once any two parameters are known.

The inverse distance weighted (IDW) interpolation technique, a tool in ArcGIS has been successfully used by different researchers to determine unknown values that falls between known values since its principles is in line with the Waldo Tobler's first law of Geography which states that "everything is related to everything

else, but near things are more related than distant things". Some of the researchers who used IDW interpolation method to produce fruitful results include Bhat and Singh (2023), Ohlert *et al.* (2022), Ogbozige and Toko (2022), Khouni *et al.* (2021), Kamaruddin *et al.* (2021), Ogbozige *et al.* (2018), Sapna *et al.* (2018), Stachelekef and Madden (2015) as well as Chen and Liu (2012). Since Bayelsa state lies in between Rivers and Delta states, the rainfall IDF relationships of Yenagoa being the Bayelsa state capital, were estimated by means of the well-known IDW interpolation technique. The technique makes use of linear combination of weights at known locations to evaluate values for unknown locations (ESRI, 2015). Mathematically, it is expressed as shown in Equations (1).

$$Z_p = \frac{\sum_{i=1}^n \left\{ \frac{Z_i}{[d_{(p,i)}]^2} \right\}}{\sum_{i=1}^n \left\{ \frac{1}{[d_{(p,i)}]^2} \right\}} \tag{1}$$

where Z_p is the predicted rainfall intensity at unknown point p for a given return period and storm duration, Z_i is the rainfall intensity at known point $d_{(p,i)}$ is the linear distance between the unknown or new point, p and the known point i while n is the number of known points. QGIS version 3.16.4 software was used to perform the IDW interpolation while ArcGIS version 10.8 was used to prepare the maps of the interpolated values. The IDF curves for the ungauged Yenagoa catchment was thereafter developed from the corresponding values in the generated maps.

Results and Discussion

The developed Gumbel's IDF curves for the cities (Port Harcourt, Warri and Asaba) hosting the identified weather stations are shown in Figure 1, Figure 2 and Figure 3 respectively.

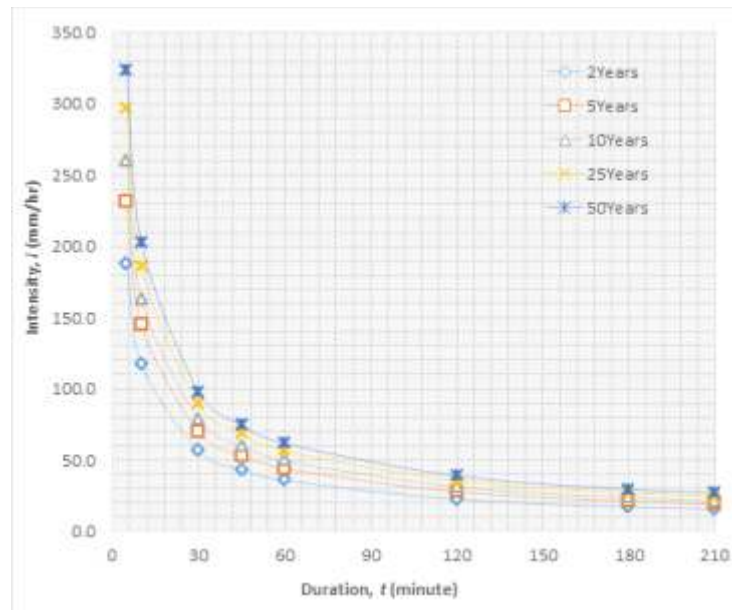


Figure 1: Gumbel's IDF curves for Port Harcourt

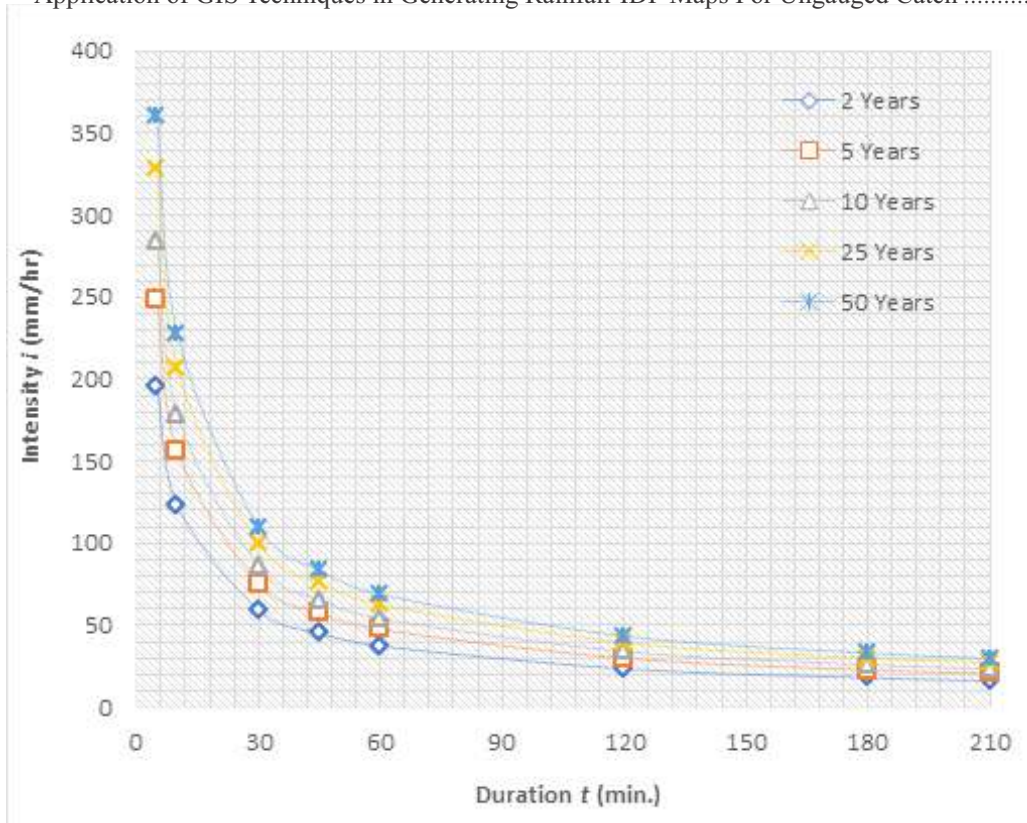


Figure 2: Gumbel's IDF curves for Warri

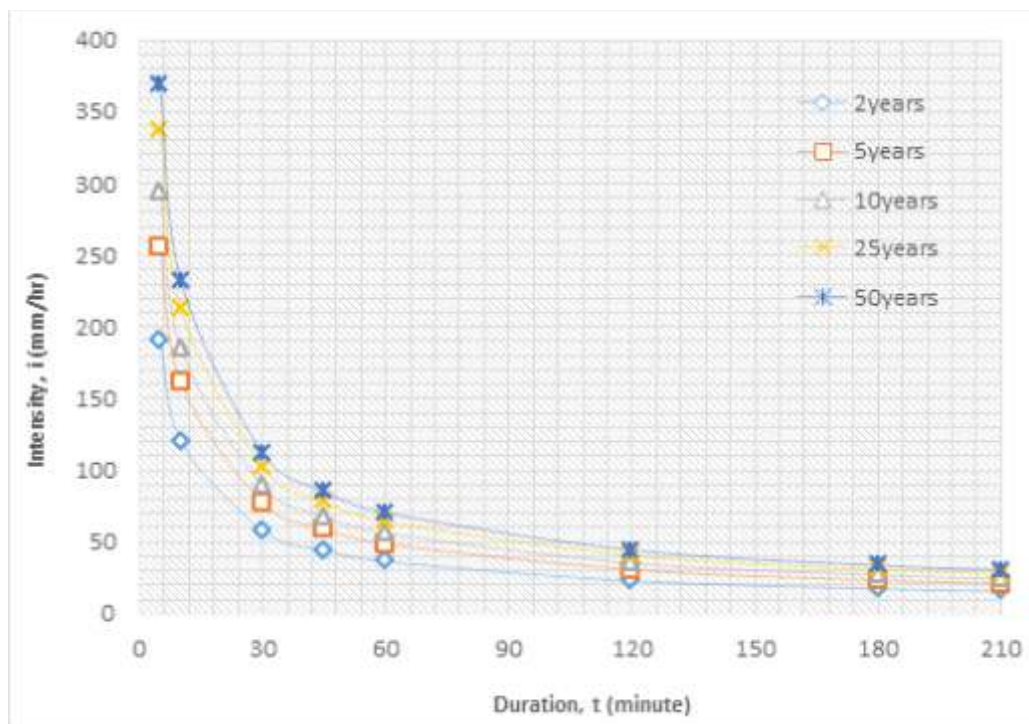


Figure 3: Gumbel's IDF curves for Asaba

The IDW interpolation mapping of the catchment using the developed IDF curves are presented in Figure 4 to 8.

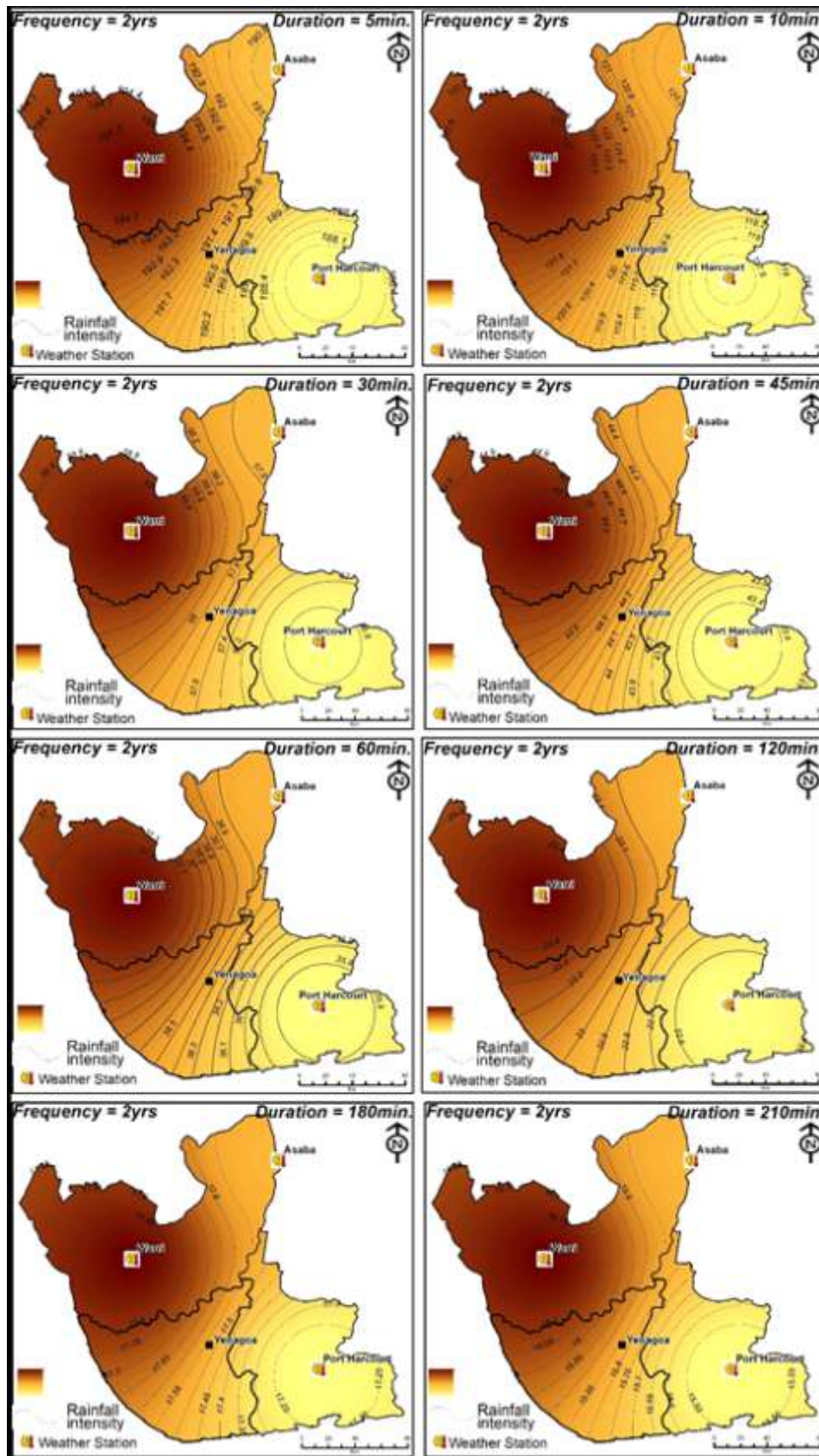


Figure 4: Rainfall IDF map for 2years return period at different durations

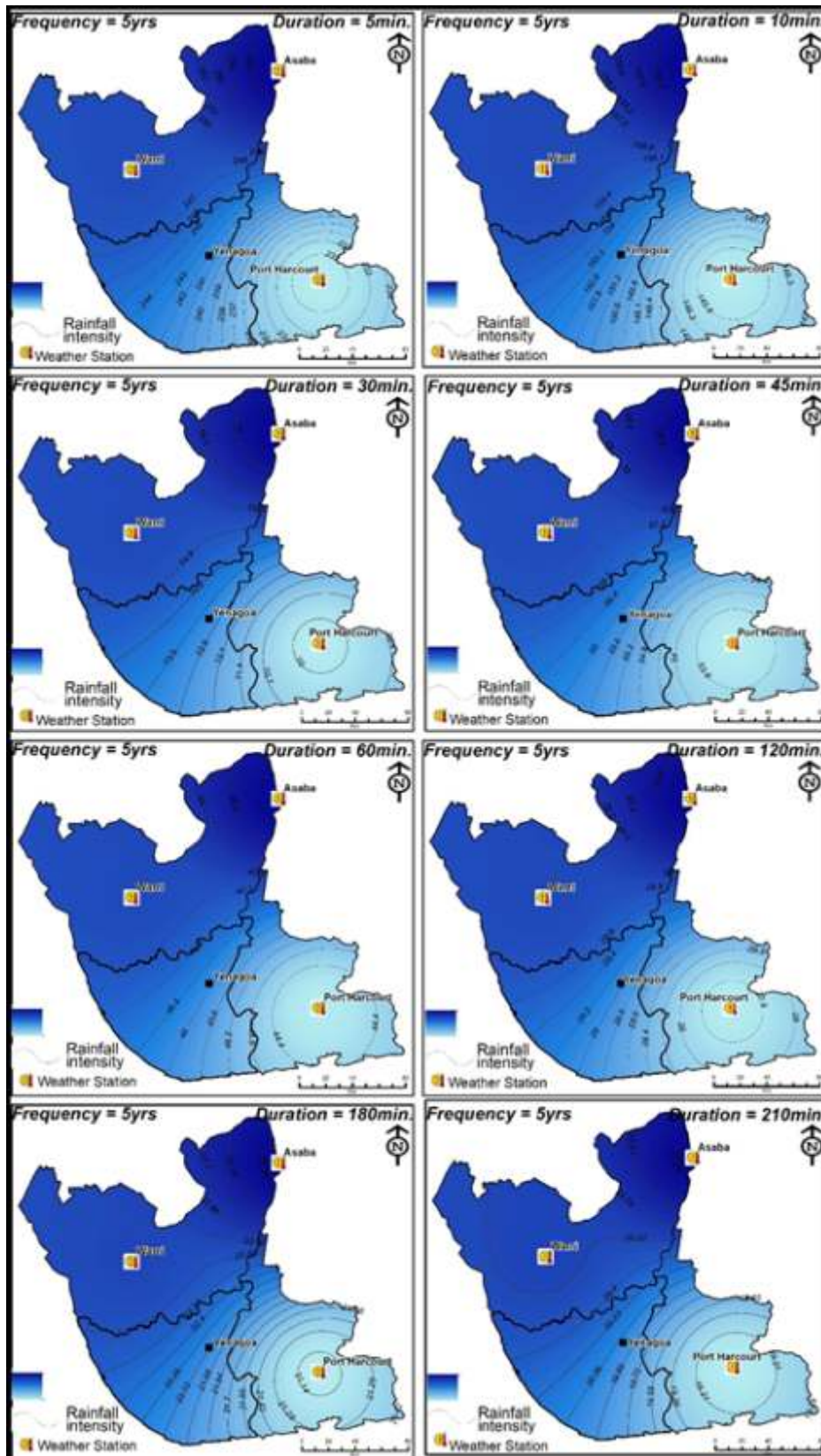


Figure 5: Rainfall IDF map for 5years return period at different durations

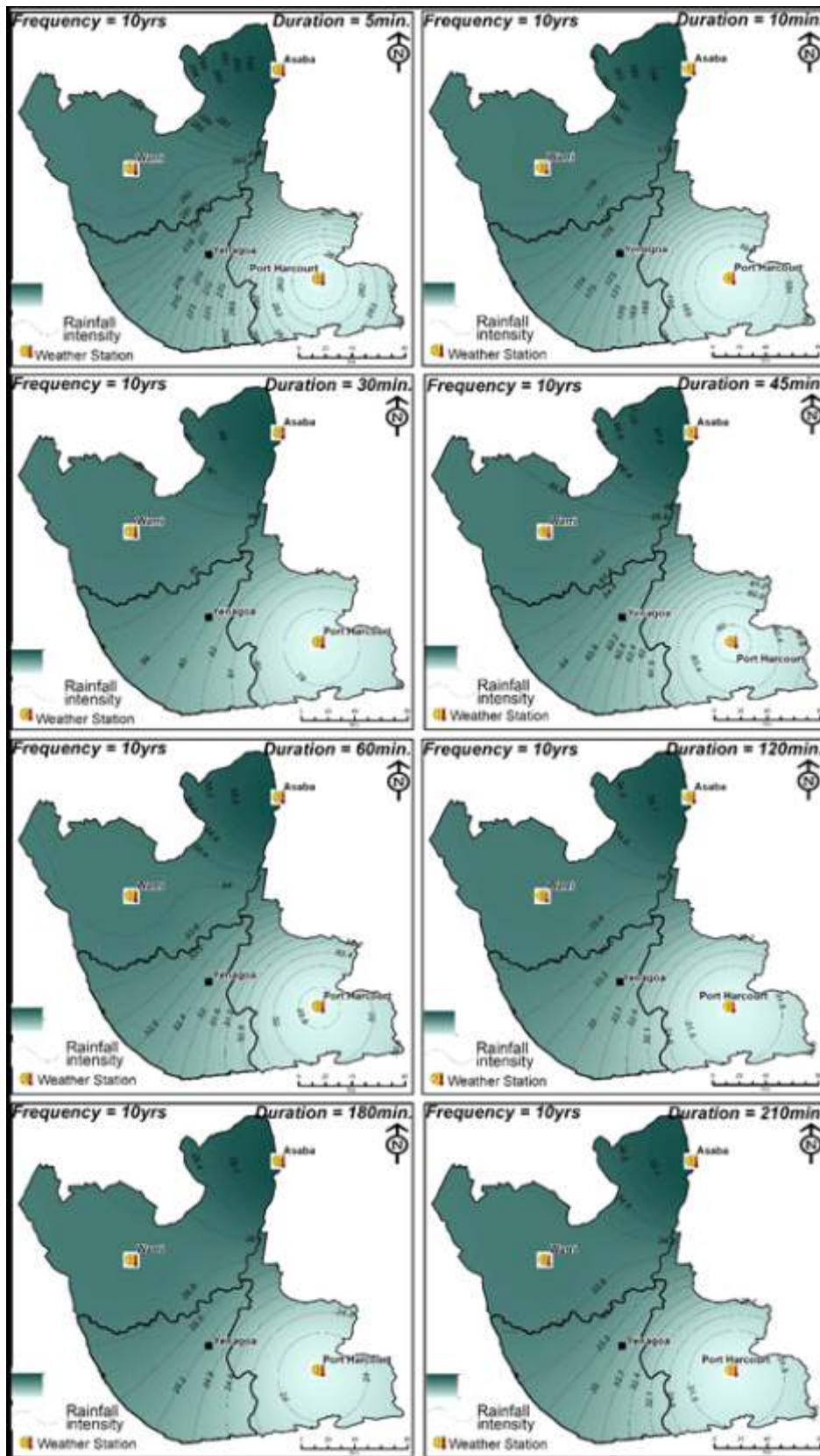


Figure 6: Rainfall IDF map for 10years return period at different durations

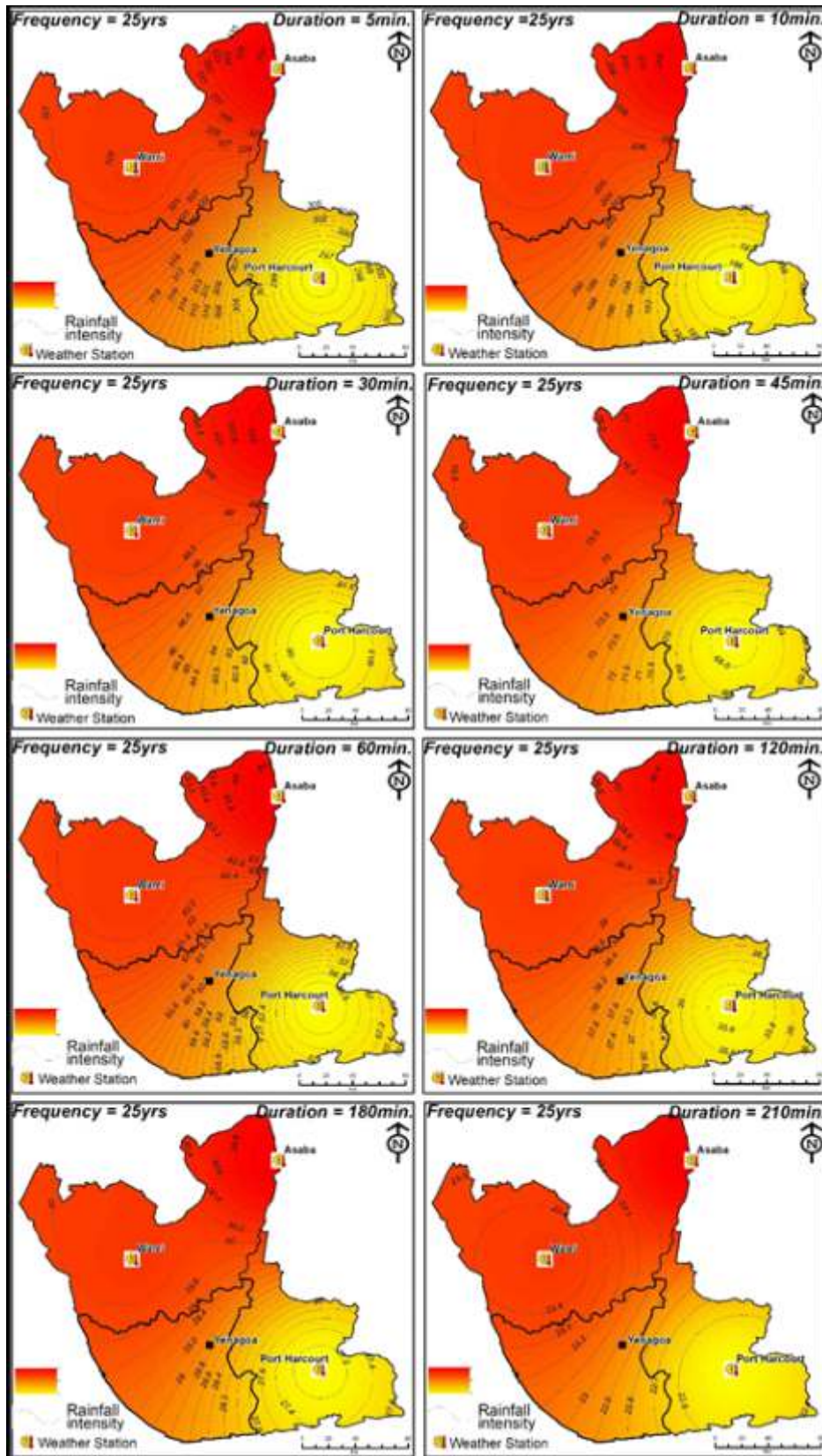


Figure 7: Rainfall IDF map for 25years return period at different durations

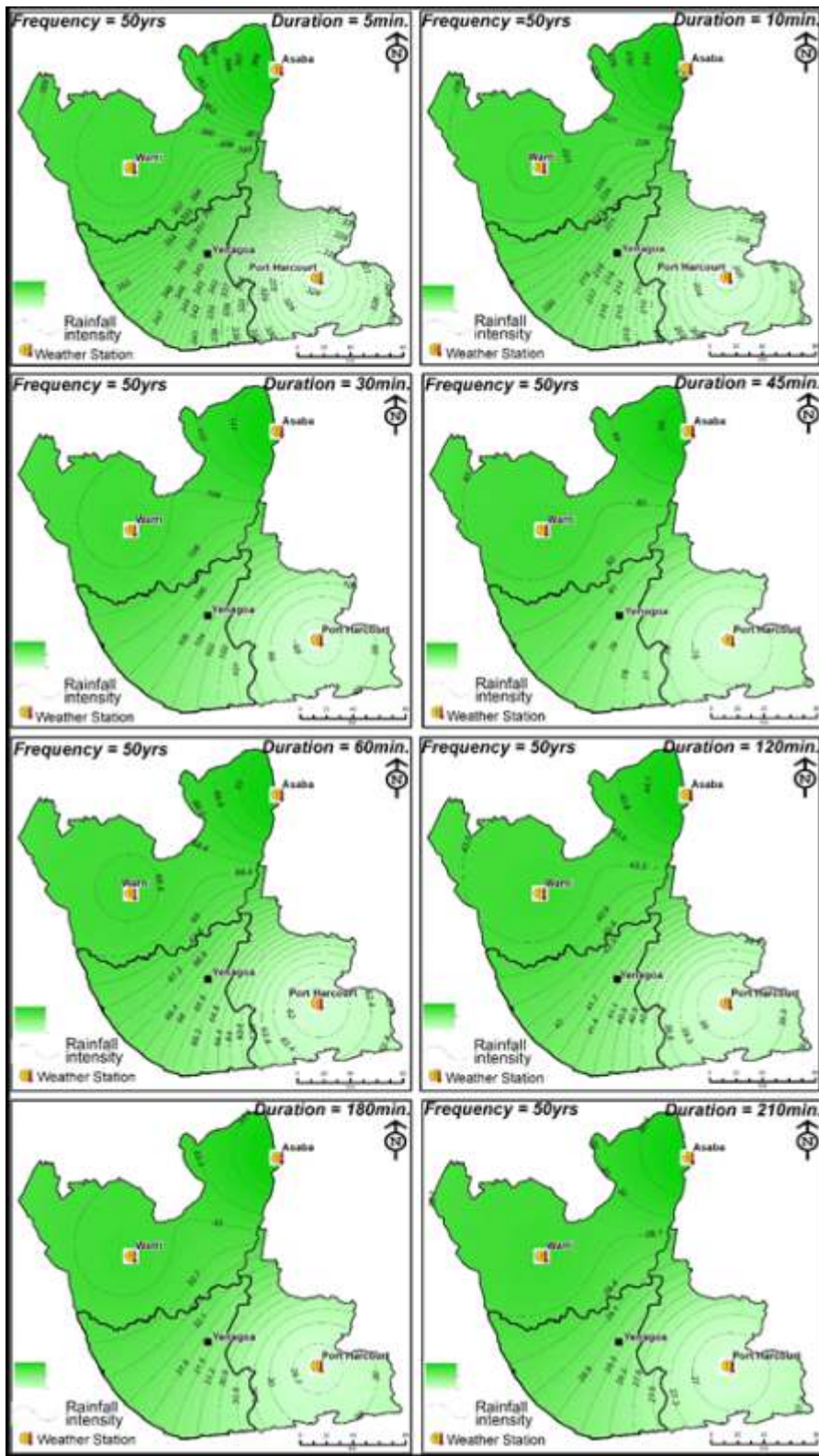


Figure 8: Rainfall IDF map for 50years return period at different durations

The IDF parameters of the ungauged Yenagoa city were extracted from the developed maps as presented in Table 1, which were used to develop the rainfall IDF curves of the ungauged city as shown in Figure 9.

Table 1: Rainfall intensities (mm/h) for ungauged Yenagoa

5 minutes	10 minutes	30 minutes	45 minutes	60 minutes	120 minutes	180 minutes	210 minutes	Frequency (years)
191.4	120.2	57.8	44.1	36.5	23	17.55	15.85	2
242	151.9	73.15	55.8	46.0	29	22.12	20.06	5
275	173	83	63.4	52.4	33	25.2	22.7	10
314	198	95.5	72.7	60	37.8	28.9	22.97	25
346	217	104.5	79.8	66	41.4	31.7	28.6	50

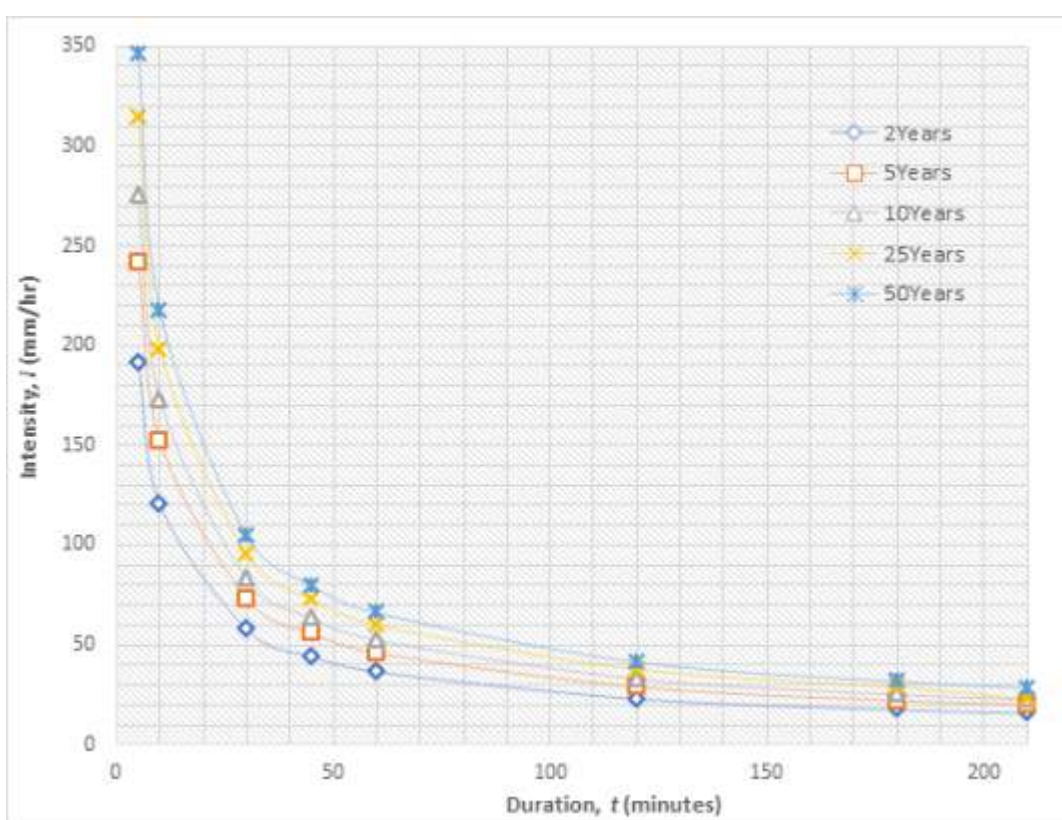


Figure 9: IDF curves for ungauged Yenagoa

The information in the IDF curves for the ungauged city (Yenagoa) revealed that for a given return period, rainfalls with high intensities tend to have short durations and vice versa while for a given storm duration (t), rainfall intensities (i) increased with return periods (T). These claims buttressed the reports of past related works including Ogbozige and Otokpa (2022), Ogbozige (2021), Mohammed *et al.* (2021), Majeed *et al.* (2021), Agarwal *et al.* (2021), Al-Wagdany (2020) and Gratein *et al.* (2019). In order to determine the rainfall intensities for return periods and durations other than those shown in Figure 9, the Sherman's model was used to develop a mathematical relationship between the IDF parameters as shown in Equation (2), using the method illustrated in Ogbozige and Otokpa (2022) as well as Ogbozige (2021).

$$i = \frac{509.687^{0.1863}}{t^{0.6696}} \tag{2}$$

where I , T and t are the rainfall intensity (mm/hr), return period (years) and duration (minutes) respectively. The Sherman's regional constants in Equation (2) which are 509.68, 0.1863 and 0.6696 (i.e. for Yenagoa) are closed to their corresponding values recorded in Port Harcourt by Ogbozige (2021) which are 503.96, 0.1664 and 0.66686. The nearness of these respective values could be attributed to the close proximity of the two cities.

Conclusion

The research has successfully developed IDF maps and mathematical relationship between IDF parameters for the ungauged Yenagoa catchment in Southern Nigeria. It is hereby recommended that Civil and Water Resources Engineers should utilize the developed IDF maps or model when designing hydraulic structures such as drainages and culverts within Yenagoa and its environs. This will eliminate the adverse effects of either under or over design of the said structures.

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