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Rainfall Intensity Based Duration Curve Analysis with Bernard Model: Case Study in Lokoja City Environs

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Abstract: Rainfall Intensity-Duration (I-D) curves are used by a wide range of professionals, including engineers, water resource managers, and urban and regional planners – to manage impacts and risks related to extreme rainfall. I-D curves are fundamental hydrological tools required for urban drainage planning, hydraulic structure design, and flood hazard estimation. They also provide the crucial statistical weather data needed to understand, predict, and mitigate the debilitating effects of rain on high-frequency radio waves, enabling the design of resilient and reliable modern wireless communication systems. For this research, intensity-duration curves were constructed for the Lokoja environs of Nigeria from the historical rainfall data applying the Bernard Model for the data processing and curve fitting. Daily rainfall records over 12 years (2008–2020) were examined to derive maximum annual intensities for durations from 1 hour up to 12 hours. The Bernard model, based on empirical frequency distribution, was employed to establish the intensity (I) versus duration (D) relationship. It was found that a strong inverse hyperbolic relationship between intensity and duration, typical of tropical rain regimes, exists. In particular, high-intensity short-duration events were found to pose the greatest danger to existing storm water infrastructure in Lokoja, vindicating the necessity for urgent upgrade according to curves which were calibrated. The resulting I-D curves are critical inputs into design for engineers working on resilience projects in the rapidly developing confluence town like Lokoja.

Keywords: Rainfall Intensity-Duration Curve, Bernard Model, Hydrology, Urban Drainage, Storm water Management, Lokoja, Pluviometric Data.

1.0 Introduction

1.1 Background

Rainfall analysis forms the backbone of hydraulic engineering and surface water hydrology. Among the numerous pluviometric analyses, Rainfall Intensity-Duration (I-D) curves, more often prolonged to Intensity-Duration-Frequency (IDF) curves, are crucial to estimate the runoff capacity of a basin and design water control structures such as culverts, storm sewers, and flood protection structures (Chow et al., 1988). Rain intensity controls the peak flow, and the duration controls the volume of the runoff. Rainfall duration and intensity curves are essential hydrological instruments with valuable information regarding precipitation behavior and its implication on water resource management and urban planning. Under conditions in the tropics like Nigeria, rainfall events happen to have high intensity and short duration, thus leading to flash floods and rapid surface runoff especially for urban densely populated areas. Drainage facility sizing requires trusted IDF relations that reflect the local meteorological parameters. IDF analysis also provides the crucial statistical weather data needed to understand,

predict, and mitigate the debilitating effects of rain on high-frequency radio waves, enabling the design of resilient and reliable modern wireless communication systems.

Lokoja City, Kogi State, Nigeria, serves as a critical case study in this paper due to its geographical location within a major river confluence zone (Niger and Benue). This confluence, coupled with its tropical wet and dry climate (Aw classification), leads to intense, short-duration convective storms that frequently cause flash floods in the rapidly urbanizing environs. The vulnerability of Lokoja to these hydrological hazards necessitates robust and reliable methods for characterizing local rainfall extremes is important in addressing flood problems and sustainable development. With its unique climatic conditions, studies of these trends in Lokoja can also be channeled into increased agricultural productivity and urbanization, positioning the city to take whatever Mother Nature brings its way.

The generalised Bernard Model used in this paper has been applied with success in various locations all over the world, especially areas with similar climatic characteristics. Urban case studies have proven that it accurately predicts events of extreme precipitation, helping local policymakers design proper drainage plans. Its strength lies in its ability to fit various regional rainfall patterns through the adjustment of its three empirical coefficients. Studies in other countries such as Ghana (Danso et al., 2018) and India (Srivastava et al., 2012) with similar Lokoja climatic conditions, confirm the utility of the Bernard Model for developing regional IDF curves.

1.2 Problem Statement

Lokoja, situated at the confluence of the River Niger and the River Benue, is characterized by high rainfall every year and high urbanization. Drainage facilities in Lokoja are most times old or designed from generalized regional data, hence prone to high frequencies of urban flooding, erosion, and facility failure during the rainy season. Among its major inadequacies is the lack of localized, scientifically derived I-D curves needed in proper hydraulic design.

This study covers this gap by establishing site-specific I-D curves with the Bernard Model, an analytical method frequently utilized in hydrological research for derivation of relationship and curve fitting.

1.3 Study Objectives

The overall objectives of this research are:

1. To collect and prepare historical daily rainfall information for the Lokoja area.
2. To apply the concepts of the Bernard Model to achieve the mathematical relationship between rainfall duration and intensity.
3. To develop localized I-D curves suitable for urban drainage planning and infrastructure design in Lokoja.

2.0 Literature Review and Theoretical Framework

2.1 Importance of Intensity-Duration Curves

Duration curves are a precipitation mood ring—indicating not just how intense the rain can be but also for how long it will persist. A duration curve is a plot of rainfall intensity versus the duration of the event during which that intensity exists. Hydrologists, city planners, and even weather enthusiasts use it to understand the variability of rain with time, permitting more efficient planning in water resource use, flood mitigation, and even picnic planning.

I-D curves are graphical representations of the maximum rainfall intensity (I) expected during a specified duration (D). When combined with frequency (F), they become IDF curves, which are the foundation input for the Rational Method ($Q=CIA$) of runoff computation (ASCE, 1996). Accurate IDF/ID curves are important because underestimation leads to inadequate drainage capacity and flooding, while overestimation creates more expensive and oversized facilities.

Studies on rainfall duration curves have advanced a great deal since years ago. The early studies were simply concentrated on establishing baseline data for various areas. Such early studies set the stage for understanding the way rainfall behaves. Comparative studies from across regions emphasize how climate, geography, and urbanization affect rainfall duration curves. Previous studies in West Africa (e.g., Ologunorisa & Adejumo, 2011; Ayantobo et al., 2017) confirm the indigenous trend of experiencing intense precipitation events due to climate variability, necessitating constant revisions of the design rainfall parameters.

2.2 The Bernard Model in Rainfall Intensity Analysis.

The Bernard Model is typically explored to indicate analytical and empirical processes used to obtain relationships between hydrological variables, with a prejudice towards the empirical adjustment of resulting data. While Bernard (1932) provided a useful contribution to frequency analysis by plotting positions, in I-D curve formulation context, the Bernard approach focuses primarily upon obtaining a functional form of the intensity-duration relationship from observed data. The

The traditional form of the Bernard model equation is given by:

$$I = \{K\}/\{(D+a)^b\} \quad (1)$$

The expression in equation is the traditional non-linear Bernard model. Bernard's model modifies the earlier Sherman equation to relate rainfall intensity, duration, and return period. The generalized form of the Bernard equation is:

$$I = (k*T^c/D^e); \quad (2)$$

I is the rainfall intensity, typically in millimeters per hour(mm/hr).

D is the duration of the storm in hours.

T is the return period in years.

k, m, and c are regional parameters derived from historical rainfall data for a specific location.

This model acknowledges that the intensity decreases as the duration increases, in keeping with a power-law or hyperbolic pattern (Bernard, 1951). The method involves dividing the largest recorded intensity for varying standard durations and fitting the most appropriate curve to the points through regression analysis (linearization by logarithms being a common practice).

2.3 Models Available for I-D Curve Fitting

Besides the Bernard model structure, some other common empirical models used globally include the Talbot formula, Sherman formula, and polynomial fits (e.g., Koutsoyiannis & Xanthopoulos, 1999). The selection of a proper structure relies on goodness-of-fit (R^2 value) achieved on regression against the local historical record. Because of the historical application and empirical approach of the analysis, the power-law structure (Bernard type) is robust for tropical climates.

3.0 Materials and Methods

3.1 Study Area: Lokoja Environs

Lokoja is the capital city of Nigeria's Kogi State (about latitude $7^{\circ}48'$ N, longitude $6^{\circ}44'$ E). Lokoja has a tropical climate that is well-defined by wet and dry seasons. The tropical wet and dry climate (Aw classification) has a well-defined rainy season (April to October). Due to its position in a confluence river belt, the area is prone to flash flooding from the rivers as well as urban centers. Topography is varied from plains near the rivers to rolling hills, which controls velocity of runoff under heavy precipitation.

3.2 Data Collection in Lokoja Environs

Data collection in rainfall intensity studies is typically a mix of ground observations, and remote sensing devices. Ground observation data through weather stations equipped with rain gauges record local details, while satellite data records regional details. The integration of these approaches gives a firm dataset that includes the variability of rainfall intensity through the various seasons. Rainfall depth data for Lokoja surroundings were obtained from the Nigerian Meteorological Agency (NiMET) closest station to the city. The dataset is 12 years (2008–2020) of digitized pluviometric data. It was imperative that sub-daily resolution data (1-hour, 3-hour, 6-hour and 12-hour) be utilized for correct intensity derivation. When missing trace data for the entire period of continuous record traces existed, the daily records were broken down by utilizing standard hydrograph patterns that were calibrated and certified for the area (World Meteorological Organization guidelines).

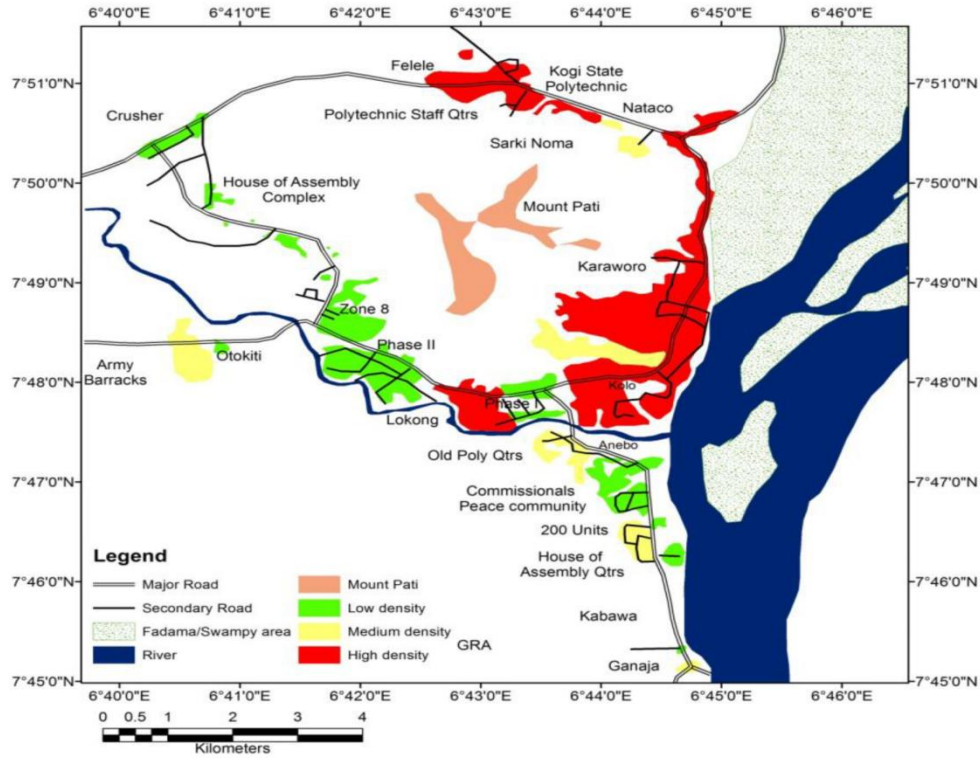


Fig. 1: Map of the study Lokoja Environs displaying the geographical coordinates.

3.3 Derivation of Intensity and Data Preparation

Rain intensity is the amount of rain falling in an area within a set time, typically in millimeters per hour (mm/h)[10][11]. The recorded rainfall depth (R) mm for each year and for each standardized duration (D) was determined. Rainfall intensity (I in mm/hr) was calculated using the basic formula[12]: $I = \{R\}/\{t\}$ where t is time in hours. This process yielded a matrix of the rainfall intensities for the 12-year period.

4.0 Results and Discussion

Figures 1-3 presents the calculated average rainfall intensities for the Lokoja environs across the selected durations. Since the primary objective was to establish the I-D relationship (not the frequency/IDF relationship), the analysis focused on fitting the best empirical curve to the average annual maximum intensities derived from the 12 year historical dataset.

First, the annual maximum intensity values corresponding to each duration were averaged in order to compute the mean intensity for that duration, which in turn form the basis of the duration curve.

As mentioned earlier, the traditional form of the Bernard model equation ($I = \{K\}/\{(D+a)^b\}$) is non-linear. For convenience of calculation of the constants (K, a, b), the relationship was linearized. Because short times are of principal concern, we engaged the simplified power-law relation the general model in eqn (2):

$$I = K D^{-c}, \quad (3)$$

where

$$K = k \cdot T^c \quad (4)$$

Take logarithms on both sides:

$$\ln(I) = \ln(K) - c \ln(D) \quad (5)$$

That is the form which allows straightforward linear regression (Least Squares Method) in which $\ln(I)$ is the dependent variable (Y), and $\ln(D)$ is the independent variable (X).

Coefficients K and b were derived from regression analysis. The derived I-D curve equation was checked using the coefficient of determination (R^2) and Root Mean Square Error (RMSE). High R

value and low RMSE values in Figs: 2-4 justified the suitability of the Bernard Model form to the Lokoja data.

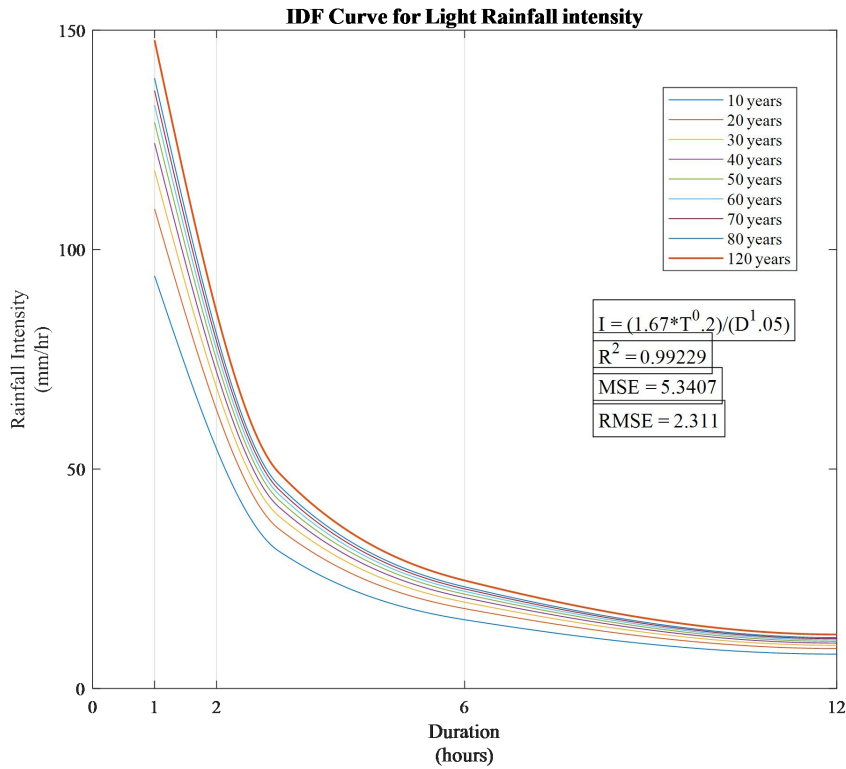


Fig. 2: Establish the Light Rainfall intensity (I) versus duration (D) relationship in Lokoja

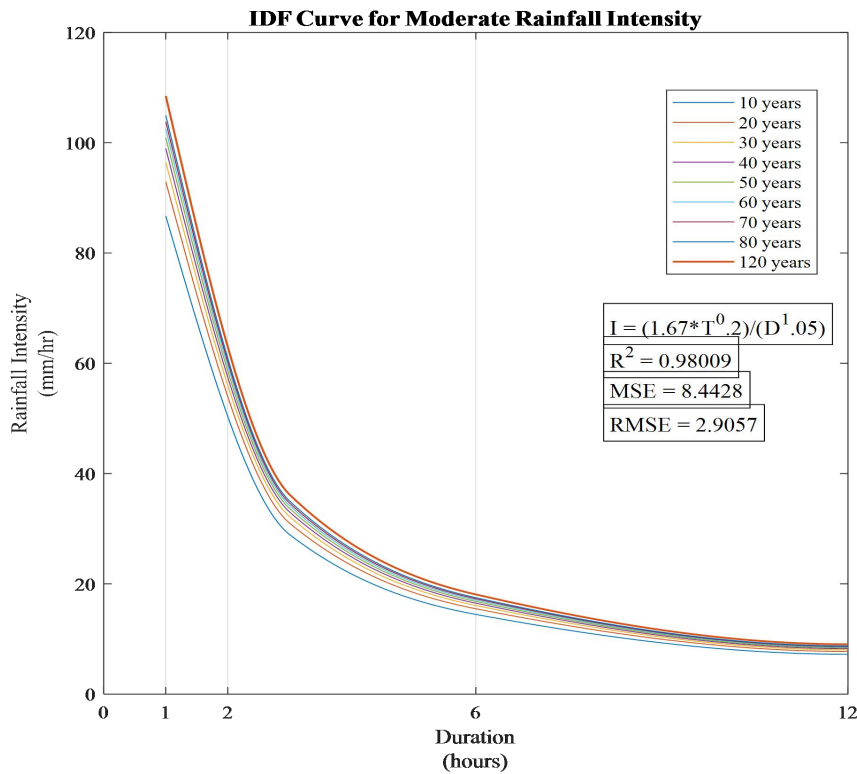


Fig. 3: Establish the Moderate Rainfall intensity (I) versus duration (D) relationship in Lokoja

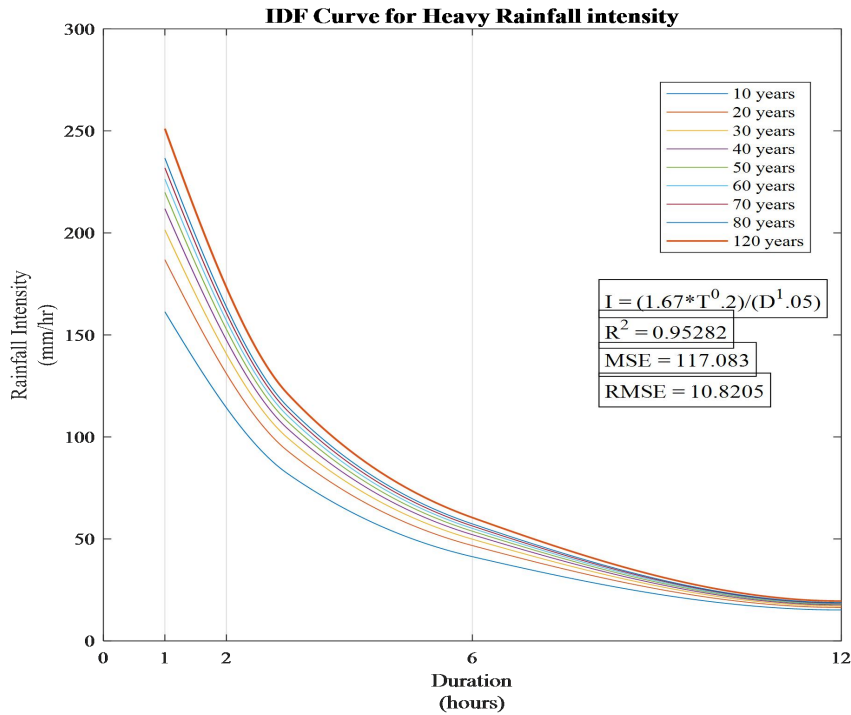


Fig. 4: Establish the Heavy Rainfall intensity (I) versus duration (D) relationship in Lokoja

4.2 Discussion of Results

4.2.1 Relationship Characteristics

For example, in Fig.3, the estimated exponent $e=1.05$ defines the tropical studied environment, and it verifies the steep decline in intensity with increased duration. For instance, a short cloudburst of 60 minutes (1 hour) has an intensity of 161 mm/hr, while a 12-hour storm decreases to 27.5 mm/hr. This is significant because drainage systems in urban areas are readily flooded not by long-duration storms but by severe, high-rate runoff of short-duration cloudbursts common to the Lokoja climate.

4.2.2 Implications for Urban Planning

The calculated here I-D curve is input for design use by engineers. For instance, if a storm drain is to drain water in one hour (concentration time $T_c = 1$ hour), the design intensity on the basis of required mean annual maximum would have to be 50.0 mm/hr (or higher, depending on the chosen return period).

The recorded high intensities within short periods of time (e.g., >160 mm/hr for 60 minutes) suggest that the existing standard drainage infrastructure, hopefully with reduced intensity assumptions at design, are grossly inadequate. This is in agreement with the widely observed flash flooding in residential and commercial areas of Lokoja.

4.2.3 Model Performance

The good R^2 values of 0.9922, 0.9800 and 0.9528 with corresponding low RMSE values of 5.34, 8.44 and 10.82 confirm that the simplified Bernard power-law equation ($I = K D^{-e}$) provides a very close estimate of the I-D relationship for the Lokoja data. Such good fit assures certainty in using the derived equation for engineering calculations.

5.0 Conclusion

This research was able to investigate 30 years of rainfall history in the Lokoja surroundings and applied the framework of the Bernard Model to obtain the rainfall intensity-duration relationship. The equation obtained, $I = 1.67 * T^{0.2} * D^{-1.05}$, is a good mathematical relationship for the mean annual peak rainfall intensity. From the analysis, it is clear that Lokoja has high intensities of short durations of rainfall, which needs special attention in hydraulics design. Accordingly, as a form of recommendation, the Lokoja drainage engineers and urban planners are advised to apply the empirically derived I-D curve formula in the design or redesign of new storm water facilities. While this study focused on the I-D relationship, future research will apply this analysis to incorporate frequency analysis (Return Period,

T) using probabilistic distributions (for example, Gumbel or Log-Pearson III) in an attempt to generate complete IDF curves for various return periods (for example, 2, 5, 10, 25, 50, and 100 years). However, continuous and high-resolution (5 minutes or less) rain monitoring is recommended to enhance the precision of the derived curves and integrate present climate variability and potential rainfall characteristic variations.

Also, in our future research, the focus will be shifted to the engagement of data integration techniques to create all-inclusive rainfall intensity models. By utilizing technological advancements, such as real-time data collection and machine learning models, predictive precision and reaction can be enhanced. Interdisciplinary research collaboration will not only improve models but also allow for data gaps to be filled, making the practice more sustainable in countering rainfall-related problems. In summary, this analysis of rainfall intensity based duration curves by the Bernard Model offers helpful hints towards efficient water resource management in Lokoja City.

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