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Modelling and Estimation of the Rainfall Intensity and Flood Management in Efab-Estate, Abuja

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Abstract

Dimensional analysis technique was used to develop model equations that was applied for re designing of an existing drainage for management of flood at Efab- Estate, Lokogoma FCT-Abuja. Data comprising (41) years of monthly rainfall for Lokogoma was analyzed for return periods and rainfall intensities. The analyzed data estimated a 166.5mm/hr rainfall intensity. The hydraulic design of rectangular open channel presented optimal hydraulic area of 0.39m^2 *when compared to the existing rectangular channel which has hydraulic area of 0.3m*^{2}*. The existing channel is smaller, this is an indication of the inadequacy of the existing channel to convey storm water safely from the estate without overflowing.*

1. Introduction

The passage in which liquid is not completely enclosed by a solid boundary, but has a free surface exposed to the atmosphere is called open channel and the flow of liquid in open channel is called open channel flow [1]. Artificial open channels are designed and built to specified regular geometric properties according to their flow and discharge requirements. Increased amount of precipitation worldwide over last decade has resulted in consistent flooding in many areas of the world; this is not unconnected to climate change situation of the world. Floods are recurrent phenomena in the world, resulting from a number of basic causes of which the most common is rainfall [2]. Rapid urbanization without due planning is also a major cause of flooding in some urban areas [3]. In terms of flood risk, urbanization is increasing the percentage of total impervious covers of the urban center and some of these urban centers especially in the developing countries have poorly and defectively designed drainage systems that cannot effectively convey the surface runoff generated from storm water [4], [5]. This necessitates the need for assessment of the drainage systems. In improving storm water drainage system for flood risk management,[6] considered determination of the locations and volumes of existing drainage structures by evaluating the time of concentration, rainfall intensity, runoff coefficient and return periods as design variables for estimating discharges and subsequently using the Manning's equation for design of drainage sizes. Among the technique for the assessments is the dimensional analysis technique. The dimensional analysis technique assists in modelling an effective and functional open channels.

Dimensional analysis is a systematic procedure for identifying variables in a physical phenomenon and correlating them to form a set of dimensionless groups. Broadly speaking, the dimensional analysis can be defined as a research method to deduce more information about certain phenomenon relying on the postulate that any phenomenon can be described through a dimensionally homogeneous equation [7].

The aim of this study is to model the flow in an open channel using dimensional analysis by identifying the geometric and hydraulic variables of an existing drainage, correlate these variables and develop a functional relationship among these variables using dimensional analysis. Identifying these variables enables a comparison among the geometric section of the existing drainage, the geometric section derived from the IDF and the geometric section modelled using dimensional analysis.

2.0. Methodology

2.1. The Study Area and Data

Efab estate-Lokogoma district, is part of Abuja Municipal Area Council (AMAC) of the Federal Capital Territory (FCT), Abuja Nigeria. It is located in the eastern region of AMAC and bordered by the following districts; Gaduwa district to the north, Kabusa district to the south, Dakwo district to the west and Wumba district to east. It is primarily a residential area. Federal Capital Territory (FCT), Abuja is geographically located, approximately in the center of Nigeria with a landmass of about 8000km², it lies between Latitudes 8° 25´and 9° 25´ North of the Equator and longitudes 6° 45´ and 7° 45´ east of Greenwich Meridian [8]. The lowest elevation is found in the extreme southwest where the flood plain of the river Guraja is, at an elevation of about 70m above sea level. The highest part of the territory is in the northeast where there are many peaks over 760m above sea level [9]. The underlying rocks consist basically of sedimentary rocks and basement complex. The basement complex rocks made up of igneous and metamorphic rocks covering about 48% of the total area and in some places the land is occupied by hills and dissected terrain [10]. Abuja is drained by many rivers in and around Abuja but mainly by Rivers Gwagwalada and Usmanu. These rivers depend on rainfall for their recharge. As such, their stakes are high in rainy season and decrease appreciably in the dry season. [11]. EFAB estate, Lokogoma-Abuja is located on Longitude 8° 58´ 22’’ N and Latitude 7° 27´ 39’’ E, with an estimated size of 384,121 m². EFAB estate is predominantly paved with drainages on both sides of the road. The drainage considered in the study on Fabian Nwaora Avenue (Figure 1.), the drainage length and contributing area are: Length, L=643m, Drainage slope, S=2.022%, and Contributing area =30797m^2. The geometric measurement of drainage (rectangular channel) is 0.6m depth (y) and 0.5m width (B).

Figure 1: Digital Map highlighting the considered drainage length and the contributing area

DATA

Figure 2 shows the graphical representation of 41 years monthly rainfall data (1980-2020) of Lokogoma-Abuja, collected from the Nigerian Meteorological Agency (NIMET).

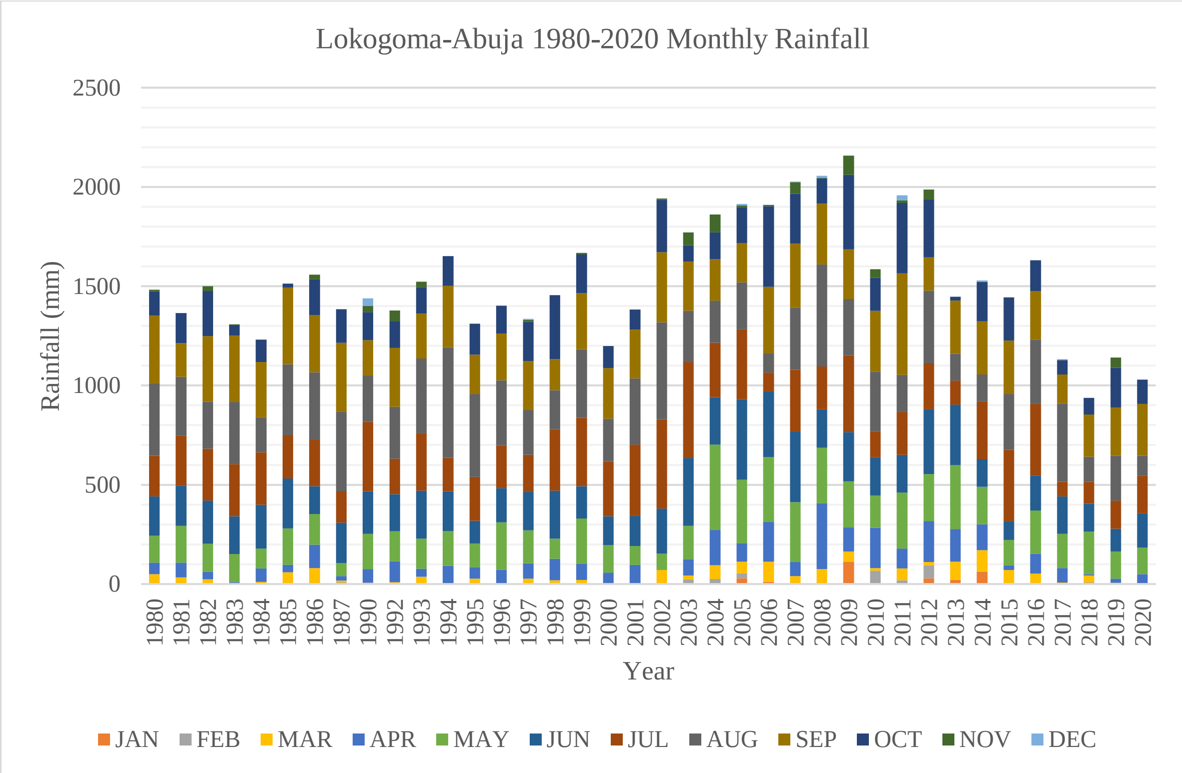

Figure 2: Graphical Representation of Lokogoma-Abuja 41-years Monthly Rainfall (1980-2020) (collected from NIMET)

2.2. Rational Method

Rational method is the process of determining the maximum surface runoff in a drainage area. Functionally, it relates the quantity of surface runoff (Q) in m^3/sec of the watershed area (A) in km^2, the rainfall intensity (I) in mm/hr and the runoff coefficient (C) as shown in equation (1). It has simplifying assumptions, which include uniform rainfall with uniform intensity over the entire watershed for the time of rainfall concentration [12]. The runoff coefficient is determined based on land-cover, topography, and soil type and storm period within the study area.

$$Q = 0.278*CIA \quad (1)$$

Where Q is the surface runoff, C is the runoff coefficient, I is the rainfall Intensity and A is the drainage area.

The direct measurement from "google earth" image from Figure 1, highlighted in green outline estimates; the contributing area to be 30797m^2, the length of drainage corresponding to the length of the contributing area to be 680m, and the slope determined at 2.022%.

The runoff coefficient (C) is a dimensionless coefficient relating the amount of runoff to the amount of precipitation received. It has larger value for areas with low infiltration and high runoff (pavement, steep gradient), and lower for permeable, well vegetated areas (forest, flat land). Runoff coefficient, C=0.95 used for the study was extracted from [13].

The time of concentration is a concept used in hydrology to measure the response of a watershed to a rainfall event. It is the time needed for water to flow from the inlet of the catchment area to the outlet of the catchment area`. It is a function of topography, geology and land use within the watershed. This study adopts the Kirpich formula to estimate the time of concentration. The Kirpich equation was developed in 1940. This equation is given as

$$t_c = KL^{0.77}S^{-0.385} \quad (2)$$

Where
t_c =the time of concentration, in minutes
K =0.0195 for SI units and 0.0078 for US units.
L = channel flow length =680m
S= dimensionless main channel slope = 2.022%
Hence,

$$t_c = 0.0195 \times 643^{0.77} \times 0.02022^{-0.385} = 12.72 mins = 763 secs$$

Rainfall intensity is defined as the ratio of the total amount of rain (rainfall depth) falling during a given period to the duration of the period, it is expressed in depth units per unit time, usually as mm per hour (mm/h). The intensity of rain is measured as the height of the water layer covering the ground in a period. A millimeter of water equals a liter of water on a square meter. This study employed the use of Intensity-Duration-Frequency (IDF) curve to obtain rainfall intensities for a number of years of return periods. Intensity-Duration-Frequency (IDF) curves describe the relationship between rainfall intensity, rainfall duration, and return period (or its inverse, probability of exceedance). IDF curves are commonly used in the design of hydrologic, hydraulic, and water resource systems and are obtained through frequency analysis of rainfall observations. The rainfall intensity corresponding to various return periods is presented in Figure 3.

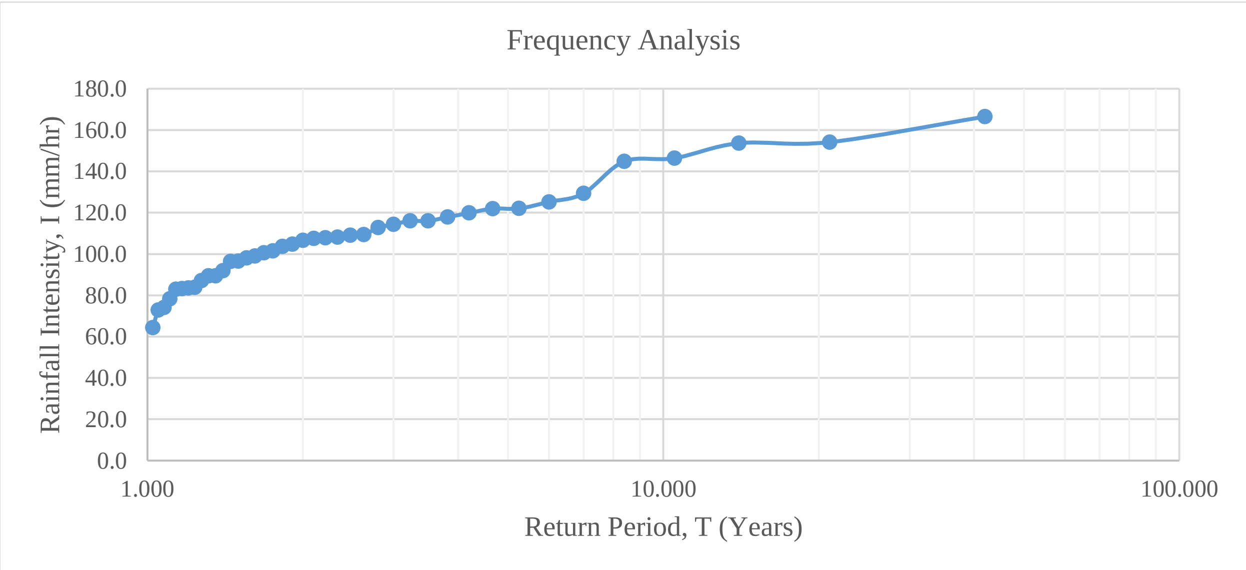

Figure 3: Frequency Analysis for 41-Years Lokogoma-Abuja Rainfall Observation (IDF)

2.3. Hydraulic Design of Rectangular Open Channel

Manning's formula was used to determine geometric properties (Width, B and Depth y), hydraulic velocity and capacity of an open channel. Manning's formula is given as

$$Q = n^{-1} AR^{2/3} S^{1/2} \quad (3)$$

Where
Q is the discharge (m^3/s)
A is the cross-sectional area of the stream/Line Drain (m^2)
R is the hydraulic radius (m) (area/wetted perimeter of the channel) = A/P
S is the slope of the water surface, S=2.022% (obtained from contour lines of EFAB Estate)

n is the roughness coefficient of the channel = 0.015 (using smooth finish concrete)
Peak discharge, Q_{PEAK} estimated from Equation (1) and applied in Equation (3)
Thus,
$AR^{2/3} = (n\ Q_{PEAK})/\sqrt{S}$

2.4. Best Hydraulic Section

It is known that the conveyance of water in an open channel section increases with increase in the hydraulic radius or with decrease in wetted perimeter. The best hydraulic section will accommodate the design flow at reasonable cost and limit erosion/deposition of sediment and other materials. For rectangular channel:

Wetted perimeter, $P = B + 2Y = \frac{A}{Y} + 2Y$.

For minimum wetted perimeter, differentiating P with respect to y gives

$Y = \frac{B}{2}$ and hydraulic radius $R = \frac{Y}{2}$.

Figure 4 illustrates the evaluated peak discharge, Q_{peak} from Equation (1) with corresponding evaluated hydraulic area, A. The optimal hydraulic depth, y and width, B can be designed from the best hydraulic section expression for rectangular sections.

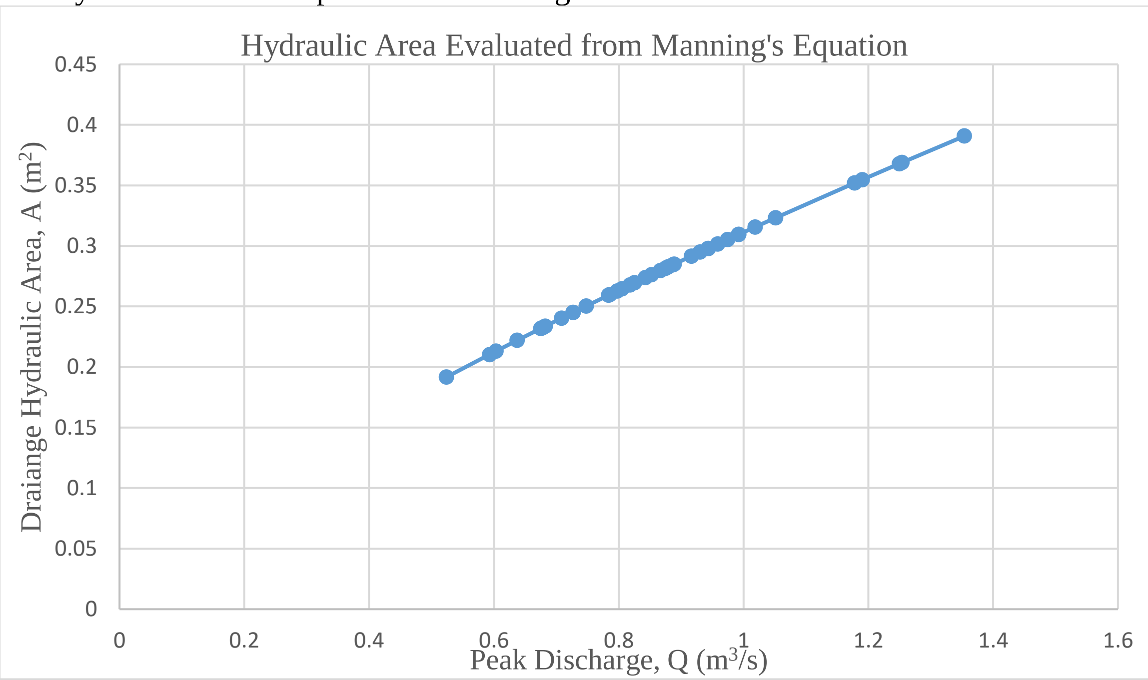

Figure 4: Illustration of peak discharge with corresponding evaluated hydraulic area with the aid of data analyzed using IDF

2.5. Dimensional Analysis

Dimensional analysis is a tool for used in analyzing and understanding problems in engineering especially in mechanics and transport phenomena. Dimensional analysis is useful for computing dimensionless parameters and provides answer to what group of parameters that may be affecting the problem. It can be accomplished by using Buckingham π-theorem. This leads to a reduction of the number of independent parameters involved in a problem. These independent parameters are expressed as dimensionless groups. These dimensionless groups are always ratios of important physical quantities involved in the problem of interest. In modelling an experiment, its main function is to reduce the number of independent variables, to simplify the solution and to generalize the results thereof. It can become an effective method, especially if a complete mathematical model of the investigated process is not known. [14]

2.5.1 Determination of Pi-terms

Edgar Buckingham (1867 – 1940), stated that if an equation involving k variables is dimensionally homogeneous, it can be reduced to a relationship among k-r independent dimensionless products, where r is the minimum number of reference dimensions required to describe the variables (the reference dimensions are the basic three dimensions; M, L and T).

Buckingham referred to these independent dimensionless products as π-terms. The final equation obtained is in the form of: $\pi_l = f(\pi_2, \pi_3 \ldots \pi_{n-m})$. There are several methods that can be used to form the pi-terms in dimensional analysis, however, a systematic procedure known as the Method of Repeating Variables is employed in this study.

Using dimensional analysis, a relationship among discharge, Q, return period, T, rain intensity, I and drainage sectional flow area, A (and by extension, flow depth, y) can be established by determining the pi terms. This will enable a designer to estimate and select a suitable drainage sectional size capable of service for a selected number of years corresponding to a return period.

The discharge, Q depends on; the intensity, I, the return period, T, the drainage area, A and the flow velocity (estimated from the time of concentration and the catchment length). This functional relationship is expressed as

$$Q = f(I, T, A, V) \quad (4)$$

Selecting a number of repeating variables (equal to the number to the number of reference dimensions); and forming pi terms by multiplying one of the non-repeating variables by the product of the repeating variables, each raised to an exponent that will make the combination dimensionless:

$\Pi_1 = T^a I^b Q$

$\Pi_2 = T^a I^b A$

$\Pi_3 = T^a I^b V$

Expressing the final form as a relationship among pi terms.

$\Pi_1 = f(\Pi_2, \Pi_3)$, i.e.

$$T^{-2} I^{-3} Q = f(A I^{-2} T^{-2}, V/I) \quad (5)$$

This study seeks to achieve similarity between the model and the prototype of the open channel to be designed. Equation (5) can be represented in graphical from to establish a mathematical model among the pi terms and hence determine the relationship among the variables. Considering Π_1 and Π_3 which are most relevant to our purpose in this study, the graphical relationship illustrated in Figure 5 depicts the relationship.

The mathematical model generated from the graph of Figure 5 from MS Excel is thus

$y = 5E{+}12x^{12.835}$

Where $y = \Pi_1$ and $x = \Pi_3$.

Therefore,

$$\Pi_1 = 5E{+}12\ \Pi_3^{\ 12.83} \quad (6)$$

$$\frac{Q}{T^2 I^3} = 8 \times 10^{14} \left[\frac{V}{I}\right]^{12\cdot 835} \quad (7)$$

Substituting Equation (1) into Equation (7)

$$\frac{0.278CIA}{T^2 I^3} = 5 \times 10^{12} \left[\frac{V}{I}\right]^{12\cdot 835}$$

$$\frac{1}{I^2} = \frac{T^2}{0.278CA} \times 5 \times 10^{12} \left[\frac{V}{I}\right]^{12\cdot 835}$$

$$I^{10.825} = \frac{T^2}{0.278CA} \times 5 \times 10^{12} \times V^{12\cdot 835} \quad (8)$$

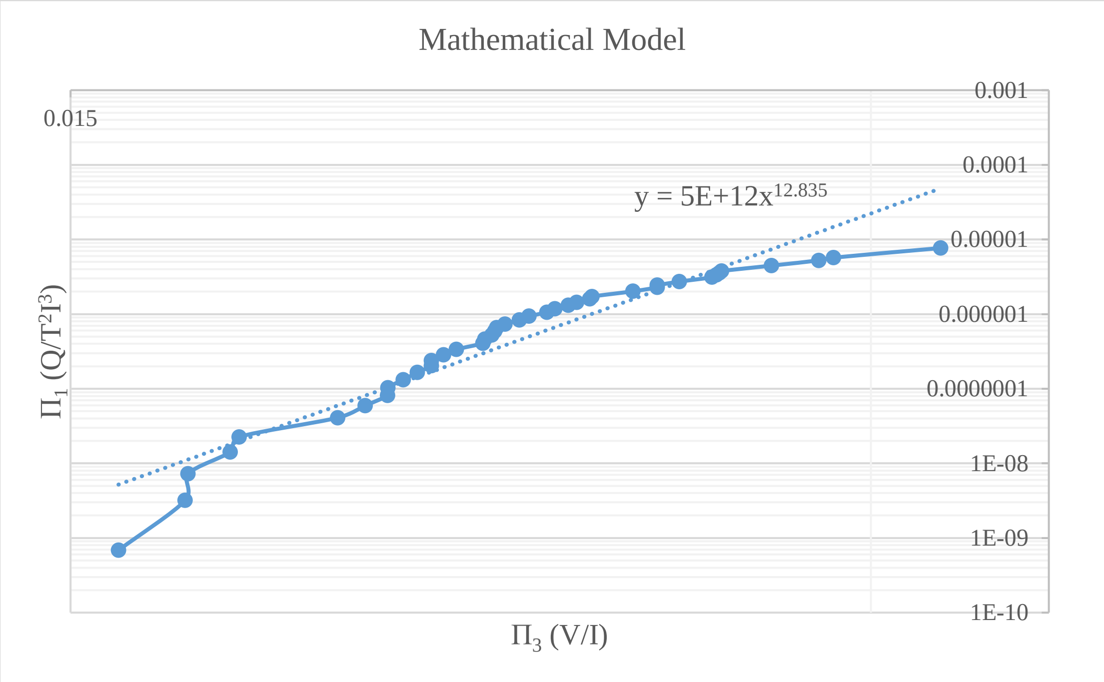

Figure 5: Graphical Representation of the relationship between Π_1 and Π_3

Equation 8 is a model equation. The coefficient of runoff, C; the catchment area A; and the velocity, V (which is a function of time of concentration and catchment length) are all measurable characteristics of the location under consideration.

This study area of consideration has the following values for C, A and V respectively as 0.95, 0.025km^2 and 0.843m/s (catchment length divided by time of concentration). As expressed in Equation (2).

Hence, the model Equation (6) peculiar to the study area becomes;

$$I^{10.825} = \frac{T^2}{0.278 \times 0.95 \times 0.025} \times 5 \times 10^{12} \times 0.843^{12 \cdot 835} \quad (9)$$

The return period for a rainfall event is a probabilistic value that enable the hydraulic design engineer to estimate rainfall intensities and further design the hydraulic structure characteristic sizes. Therefore, in the design of open channel drainage and other hydraulic structures, the return period can be equated to the design life of the infrastructure.

Using equation (8) above, rainfall intensities is estimated for the set of return periods, and presented in Figure 6. The discharges corresponding to the evaluated hydraulic area with data analyzed using dimensional analysis is the presented in Figure 7

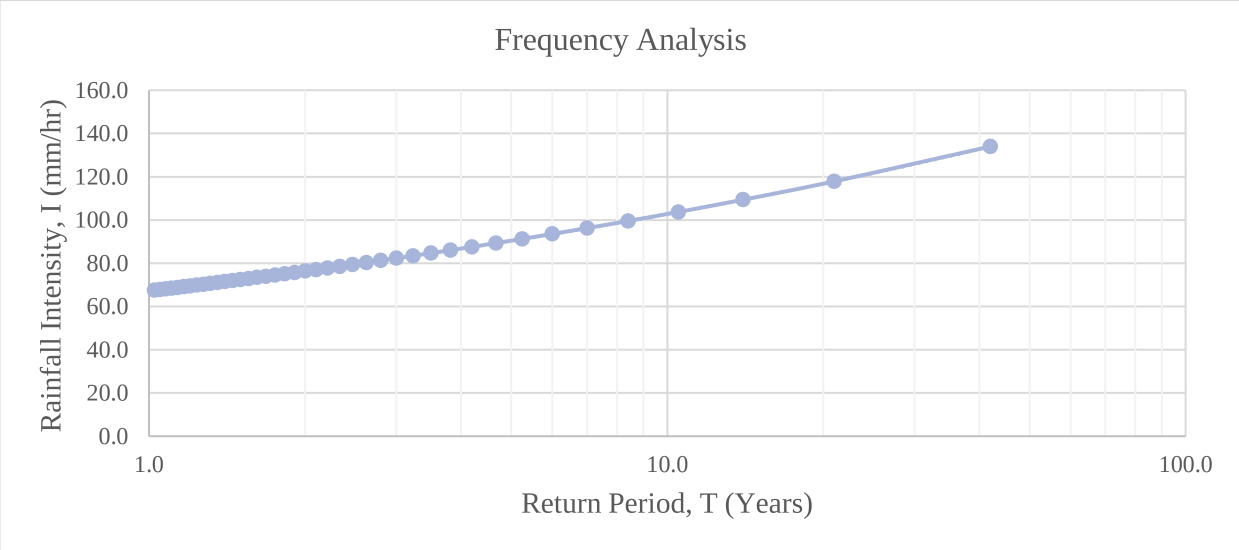

Figure 6: Frequency Analysis with the aid of dimensional analysis

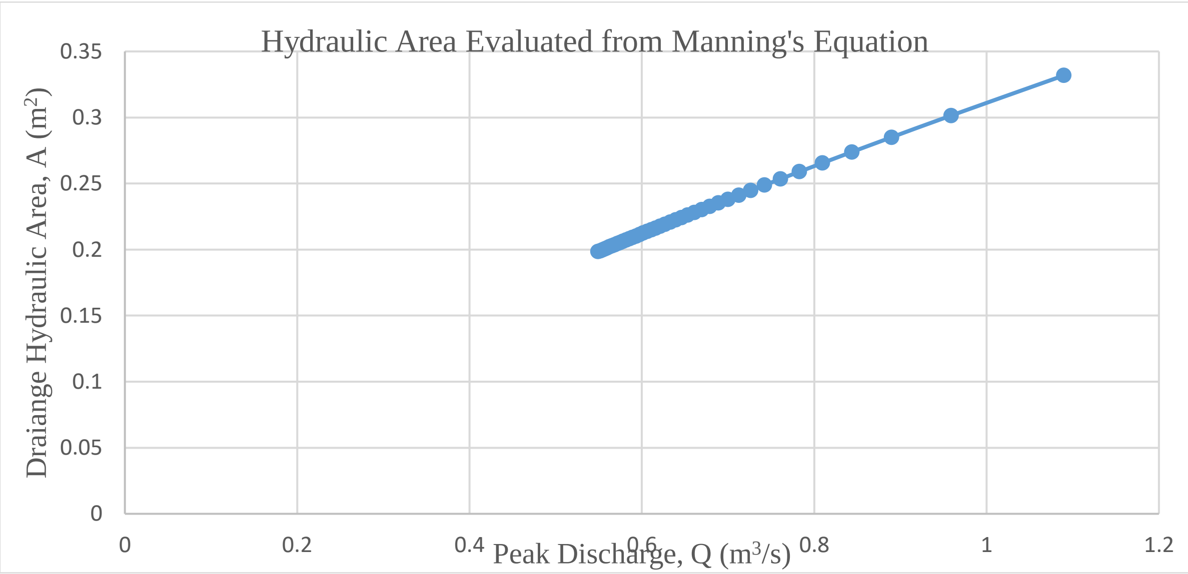

Figure 7: Illustration of discharge with corresponding evaluated hydraulic area with the aid of data analyzed using dimensional analysis

3.0. Results And Discussion

Rainfall intensities were determined with the aid of Intensity Duration Curve (IDF), this is in conformity with the study conducted by [6] where rainfall intensity, time of concentration, runoff coefficient and design periods are evaluated as variables used for estimating discharges capacities in open channels. The frequency analysis illustrated in Figure 3 shows the relationship between the rainfall intensities and return period. Corresponding flow discharges and characteristic rectangular drainage hydraulic area were determined using Manning's formula. This is illustrated in Figure 4. A model equation was established with the aid of dimensional analysis and used to evaluate rainfall intensities by inputting return period times regarded as design life. The rainfall intensities established in this model equation were used to determine corresponding discharge and drainage characteristic areas using Manning's formula. This is illustrated in Figure 7.

From the frequency analysis of Figure 3, a 42-year return period estimated 166.5mm/hr rainfall intensity which evaluated optimal rectangular drainage hydraulic area of 0.39m^2.

The rainfall intensities calculated from model Equation (7) were inputted in Equation (1) to determine their corresponding discharges. Corresponding drainage hydraulic areas were also determined using Manning's formula. Hydraulic areas and their corresponding discharges are illustrated in Figure 7. From the frequency analysis of Figure 6, a 134mm/hr rainfall intensity which evaluated optimal rectangular drainage hydraulic area of $0.33m^2$.
The existing drainage has a hydraulic area of $0.30m^2$. The hydraulic area derived from the IDF is $0.39m^2$ and that from dimensional analysis model is $0.33m^2$. The IDF approach and the dimensional analysis model presented larger hydraulic areas than the existing drainage, this is a probable reason for storm water overflowing the drainage and resulting in flood situations. The two approaches did not evaluate a significantly larger hydraulic area, indicating that there are other factors that may be contributing to flood events such as reduced percolation of storm water as a result of large area of hardscape of the estate.

4.0. Conclusion

The results of the analysis of the existing drainage, indicates that the improvement in the geometric design will help in mitigating storm water over flow in the drainage, thereby containing the flood event in the study location. This study has also shown that dimensional analysis technique can be used to develop a model equation, with the collected rainfall data, to efficiently make assessments on open channels.

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