Estimating Rainfall Intensity-Duration-Frequency (Idf) Curves For A Tropical River Basin

Raphael Muli Wambua

Egerton University, Department of Agricultural Engineering, Kenya
wambuarm@gmail.com, Raphael.wambua@egerton.ac.ke

Abstract: Characterization of rainfall based on Intensity-duration-frequency (IDF) curves is crucial in water resources engineering. IDF curves are used in management of hydraulic structures within a river basin. IDF curves for tropical river basins are still scanty. In this research, characterization of rainfall was achieved by developing the IDF curves for Upper Tana River basin using data from eight meteorological stations. Monthly rainfall quantities were first ranked in descending order. The corresponding return period for the data series was determined using Weibull method. An empirical function for IDF curves was then formulated using regression analysis. The IDF curves for different rainfall intensities that correspond to return periods of 2, 5, 10, 25, 50 years and rainfall duration ranging from 1 to 12 hours were generated using the empirical function. The IDF curves are recommended for use as decision support tool in water resource systems within the basin.

Key words: IDF curves, water resource systems, rainfall intensity, return period, Upper Tana River basin

1. Introduction

Upper Tana River basin is a vital water resources system in Kenya. A study on its rainfall intensities of different durations and return periods is paramount in infrastructure planning, design and operation of water resources, hydraulic structures within the basin [7], [4], [12], [8], [11] and hydro-systems [13]. According to [19], and [20], the curves may be needed in some instances to address the impact of global warming and climate change on urban arid environments (IDF curves for instance are crucial and may be used by engineers for design of runoff disposal structures, soil erosion control, highway, culvert and irrigation canal design. According [22], there are major tributaries of Tana River whose total length from the source to the Indian Ocean is approximately 1,000 km. The Tana River tributaries originate from slopes of Mount Kenya and Aberdares range. The basin forms a principal resource in Kenya and is critical in water resources supply, irrigation, hydro-power generation and rain-fed agriculture. Due to its importance in Kenyan economy, its crucial to understand rainfall characteristics such as the rainfall intensity-duration-frequency (IDF) relationship [17]. Rainfall intensity-duration-frequency (IDF) curves refer to graphical representation of the quantity of water falling on the basin area. The curve may also be defined as a mathematical relationship of rainfall intensity, duration and return period [3]. The curves are used to link the amount of rainfall per unit time (intensity) to the time (duration) taken for a defined event and its rate of occurrence (frequency). An IDF curve is a very important index in water resources engineering [1], [6], [21]. The IDF is used for planning, design operation and vulnerability assessment of water resource systems. The IDF can be estimated to represent rainfall characteristics of any region [15], [5], [18]. Although IDF curves have been developed for river basins across the world, they have not been adequately formulated for most basins in developing countries. Upper Tana River Basin is such a basin that requires IDF formulation and its subsequent application in offering solutions for water resources. A number of methods have been used for IDF development and frequency analysis. The theoretical probability distribution functions have been extensively used for frequency analysis. Some of the common methods include the log-normal distribution, Log—Pearson Type III distribution and the Gumbel distribution functions [16], [10].

2. Applications of IDF Curves

The IDF curves are very useful in planning, design and operation of hydraulic structures. IDF involves extreme rainfall statistical analysis. The curves may be used for planning and design of urban drainage systems [23] and in determination of capacity of other hydraulic structures such as channels [2]. The curves form bases upon which floods can be controlled [9]. A useful procedure for design of artificial hydraulic structure may involve the following steps.

(i) Computation of river basin area (A): This require the use of a topographic map which is first delineated and then area is estimated

(ii) Determination of flow length (L) and slope (S): The longest runoff flow path is established on a river basin map and its average slope determined. A digital elevation model (DEM) of the study area can be used to establish the two variables.

(iii) Computation of time of concentration (T_c): The longest time taken by rainwater falling at the farthest point with reference to the outlet, to flow downslope and reach the outlet is called T_c. It may be computed using the following formula of the form:

$$T_c = 0.0195 \times L^{0.77} \times S^{-0.385} \quad (1)$$

Where, T_c=time of concentration (min), L=slope length (m) S=average slope (m/m) and

(iv) Determination of rainfall intensity (I) and the IDF curves: The T_c equation is processed via taking logarithms, and then ant-logarithm. The logarithm value is slotted on the intensity on the intensity (y) axis. For a selected design return period. The antilogarithm value of T_c is considered as intensity (I).

(v) Estimation of runoff coefficient: The runoff coefficient may be established for the entire basin for generally uniform land use. However, if the river basin exhibit different land use practices, a composite runoff coefficient can be computed from the relation:

$$C_c = \frac{C_1 A_1 + C_2 A_2 + \dots + C_n A_n}{A_T} \quad (2)$$

Where, C_c=composite runoff coefficient (dimensionless), A_1, A_2,…A_n and C_1, C_2, …C_n are areas and runoff coefficient for each land use within the river basin respectively.

(vi) Computation of peak runoff rate (Q): calculation of peak runoff may be based on the rational method defined by equation (3);

$$Q = \frac{C_c I A}{360} \qquad (3)$$

Where, Q=peak runoff rate (m^3/s), C_c=composite runoff coefficient for the entire river basin (dimensionless) and A= river basin area contributing to runoff (ha)

(vii) Average velocity of runoff: The average velocity of runoff flowing from the remotest point to the outlet can be computed based on either Manning's or Chezy equations presented respectively as:

$$V = \frac{1}{n} \times R^{\frac{2}{3}} \times S^{\frac{1}{2}} \qquad (4)$$

$$V = C\left(RS\right)^{\frac{1}{2}} \qquad (5)$$

Where, Where, V=velocity of flow (m/s), C=Chezy coefficient of flow (dimensionless), R=hydraulic radius of flow (m), S=the slope of channel (m/m)

(viii)Computation of the capacity of hydraulic structure: The design hydraulic structure may be for a high, medium or short return periods and may be computed from the continuity relation:

$$Q = V \times A \qquad (6)$$

Where, A==the area of hydraulic structure (m^2), Q=Peak runoff rate (m^3/s), V=velocity of flow (m^2/s)

Due to the need to have a reference indices for planning and design of water resources engineering systems, this research was conducted to formulate the intensity-duration-frequency (IDF) curves for rainfall characterization using empirical function for Upper Tana River Basin in Kenya.

3. Materials and Methods

3.1 Study Area

This study was conducted in upper Tana River basin which has an area of 17,420 km^2 (Figure 1). The upper Tana River basin is part of the larger Tana River basin, the largest river system in Kenya covering an area of 100,000 km^2 [22]. It has forest and land resources within the eastern slopes of Mount Kenya and Aberdares range. According to [22] these resources are key to the regulation of the hydrology of the entire basin. The river basin is also very important in hydro-power generation, water resources and supply, agricultural production and food security hub in the area.

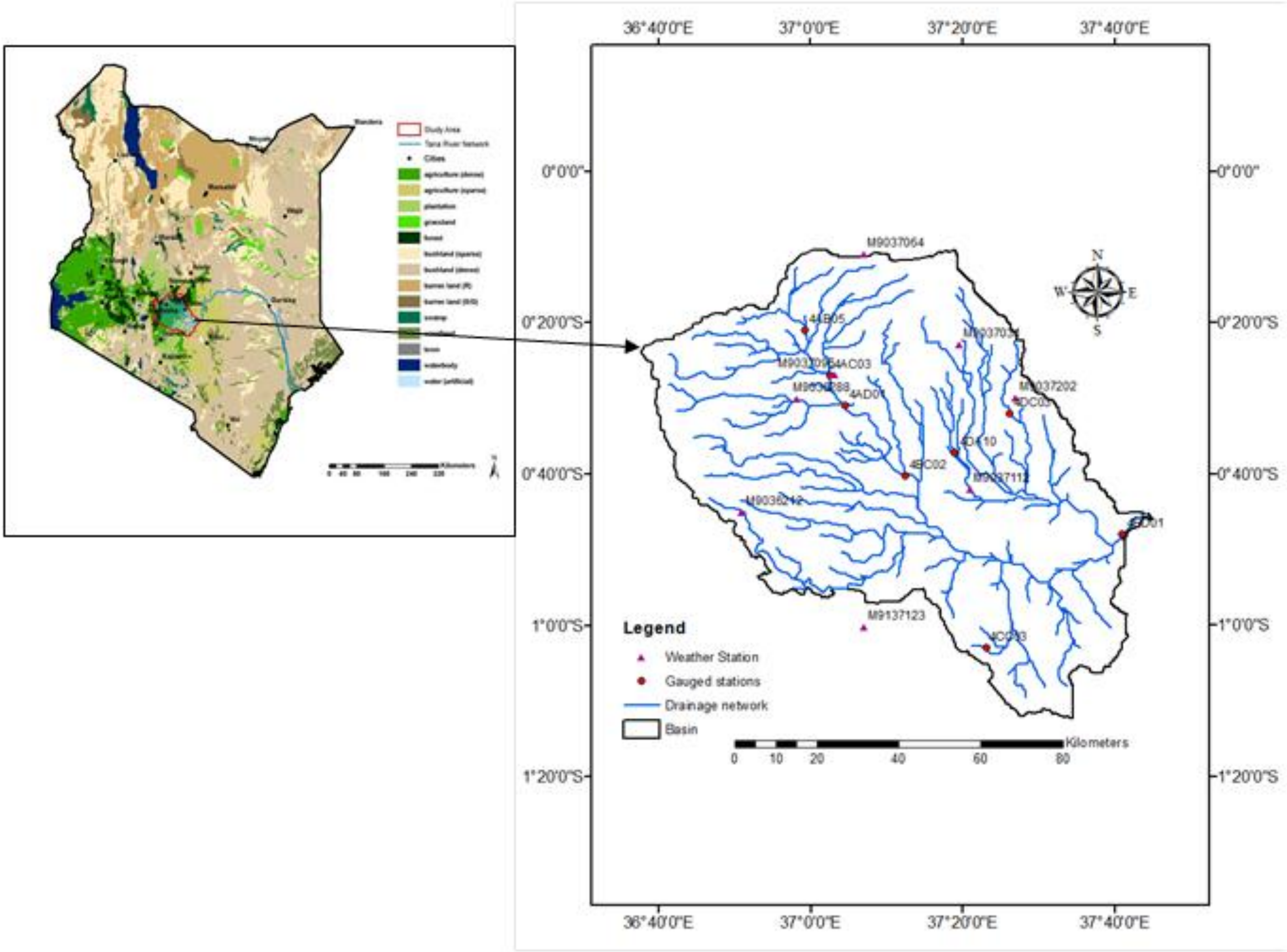

Figure 1: The study area

The upper Tana River basin lies between latitudes 00^0 05' and 01^0 30' south and longitudes 36^0 20' and 37^0 60' east. This river basin is plays an important role of influencing the environment downstream [22]. The river basin drains nine counties namely; Muranga, Nyandarua, Kiambu, Kirinyaga, Laikipia, Machakos, Nyeri, Embu and Kitui. Its elevation ranges between 4,700 m and 730 m above mean sea level (a.m.s.l.). These elevations found at Mount Kenya and Kindaruma hydropower dam. The area has heterogeneous soil types, and Andosols are the soil types which are predominant at high elevations, Nitosols are found in the mid elevations while Ferrasols and Vertisols fall in lower elevations. The study area experiences varying precipitation and temperature. For instance, Mount Kenya and Aberdares ranges receive annual rainfall of approximately 1800 mm. Within the middle elevation of 1200 to 1800 m a.m.s.l., the annual rainfall ranges between 1000 and 1800 mm, while the lower elevations of 1000 m, receive annual rainfall of around 700 mm. Although the basin receives significantly high rainfall amounts, its seasonality keep on fluctuate over time. This leads to seasonal variation of the generated stream flow in Tana River. The basin experiences bimodal rainfall pattern as a result of inter-tropical convergence zone. The main rain seasons are distributed in the months of March to June, and September to December. The precipitation of the area is extremely influenced by the orographic forces. The temperatures in the study area vary across the year. The maximum and minimum mean annual temperature lies between 25.5 and 31.0^0C and 21.0 to 24.0^0C respectively [22]. This temperature and other hydro-meteorological factors influence the evapotranspiration rates of the area. The average catchment evapo-transpiration is around 500 mm in the peak areas of the mountains. A number of land use types are found within the upper Tana River basin. The main land use types include forests, crop land, and agriculture and range land. The dominant land use types in high elevations of the basin are forests and tea plantations.

3.2 Precipitation Data

In the upper Tana River basin, data from eight meteorological stations which had reliable was obtained from the Ministry of Water and Irrigation. The meteorological data included precipitation, temperature and evaporation data. This available data contained less than 20% data gaps, and was used for intensity duration frequency (IDF) curves. The eight stations used in the study (Table 1) are located within the low (LE), lower middle (LME), middle (ME) and high (HE) elevations. The stations are located at different agro-ecological zones within the Upper Tana River basin.

Table 1: Meteorological stations

S. No	Station name	Station ID	Coordinates		Elevation (m)
			Longitude (Degrees)	Latitude (Degrees)	
1	MIAD	9037112	37.350	-0.700	1246
2	Embu	9037202	37.450	-0.500	1494
3	Kerugoya DWO	9037031	37.327	-0.382	1598
4	Sagana FCF	9037096	37.054	-0.448	1234
5	Nyeri	9036288	36.970	-0.500	1780
6	Maragua G. E. F.	9036212	36.850	-0.750	2296
7	Naro-moru F.G.P.	9037064	37.117	-0.183	2296
8	Mangu HS	9137123	37.033	-1.100	1630

3.3 Consistency Test of Hydro-meteorological Data

A double-mass curve was fitted for the collected hydro-meteorological data to test for consistency/homogeneity. The homogeneity of stream flow time series data was conducted to detect for any possible errors resulting from the data measurements. In addition, homogeneity was used to check for the fluctuations due to climate and weather changes. The cumulative total stream flow and precipitation were computed for each station and then plotted against the cumulative total of an adjacent station in the data. Although there were some changes at some points on the curves for some stations, it was considered insignificant for the present study.

3.4 Generation of IDF Function

To generate the IDF curves, maximum rainfall quantity for each month corresponding to selected rainfall duration were sorted. The rainfall magnitude was then ranked in descending order and then the return periods computed using Weibull's equation as per the relation:

$$T = \frac{n+1}{m} \tag{7}$$

Where, T=return period (years)
N=number of data records (dimensionless)
M=rank of the rainfall magnitude (dimensionless)

The key constants for an empirical function were established through regression analysis. The regression was used to formulate an empirical function relating the rainfall intensity to return period and the duration. The rainfall intensity (I) was set as an independent variable while the rainfall duration (D) was set as an dependent variable. The regression technique was then applied to correlate the means of the two variables and was expressed as;

$$\bar{I} = a + b\overline{T_d} \tag{8}$$

The mean of the variables were expressed as

$$\bar{I} = \frac{\sum I}{n} \tag{9}$$

$$\overline{T_d} = \frac{\sum T_d}{n} \tag{10}$$

From Equation (8), the values of a and b were computed as per equations (11) and (12) respectively.

$$a = \bar{I} - b\overline{T_d} \tag{11}$$

And

$$b = \frac{\sum T_d I - \left(\sum T_d\right)\left(\sum I\right)/n}{\sum T_d^2 - \left(\sum T_d\right)^2 / n} \tag{12}$$

The complete regression analysis resulted into an empirical equation of the form;

$$I = \frac{C \times T^{k}}{T_{d}^{x}} \qquad (13)$$

Where, I=rainfall intensity (mm/hr)
T=return period (years) of a given event
T_d=rainfall duration (hours)
k and x are exponents that represent conceptual parameters (dimensionless) that depend upon the nature of the river basin.

Data for plotting IDF curves was generated by substituting the selected rainfall durations of 1 to 12 hours and return periods of 2, 5, 10, 25 and 50 years into the formulated function. Then Different rainfall intensities were computed. The summary of the procedure used in this research to generate IDF curves is as shown in Figure 2.

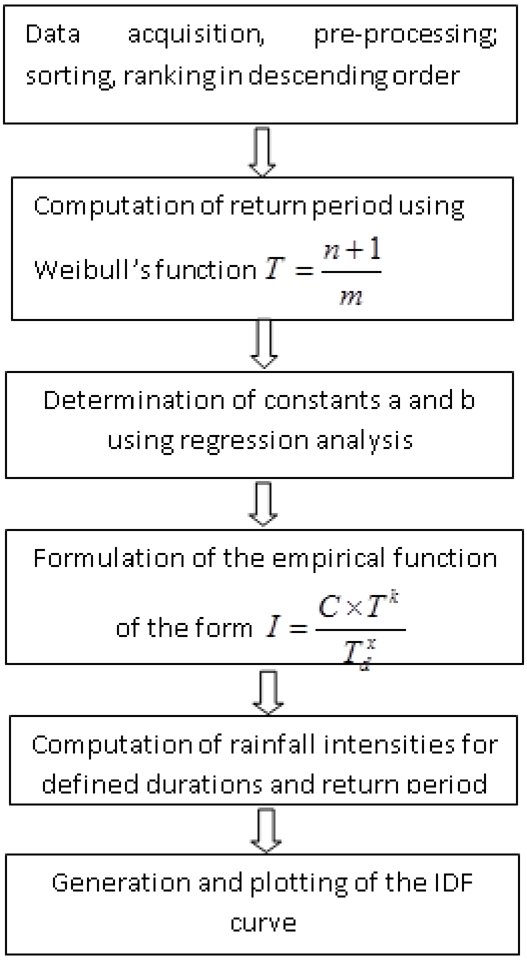

Figure 2: *Flow chart of the procedure used in development of IDF curve*

4. Results and Discussion

From the regression analysis, an empirical equation for generation of IDF curves for Upper Tana River basin was established as per equation (13). For each meteorological station within the river basin, different values of the constants were established as indicated in Table 2. The empirical function was found to be consistent with a similar expression established by [14] for Makurdi catchment in Nigeria. However, the values of the river basin constants indicate a slight difference from those established for the Makurdi catchment. Additionally, the basin constants significantly differ from similar variables of C=153, k=0.35 and x=0.82 for Riyadh region as formulated by [2].

***Table 2**: Constants for empirical functions for each meteorological station*

S.No	Station name	Station constants			Corresponding Equation
		C	k	x	
1	MIAD	21.523	0.723	0.2271	$I = \dfrac{21.523 \times T^{0.723}}{T_d^{0.2271}}$
2	Embu	21.482	0.681	0.2133	$I = \dfrac{21.482 \times T^{0.681}}{T_d^{0.2133}}$
3	Kerugoya DWO	20.209	0.592	0.2367	$I = \dfrac{20.209 \times T^{0.592}}{T_d^{0.2367}}$
4	Sagana FCF	22.114	0.694	0.2089	$I = \dfrac{22.114 \times T^{0.694}}{T_d^{0.2089}}$
5	Nyeri	20.391	0.748	0.2172	$I = \dfrac{20.391 \times T^{0.748}}{T_d^{0.2172}}$
6	Maragua G. E. F.	21.230	0.675	0.2066	$I = \dfrac{21.230 \times T^{0.675}}{T_d^{0.2066}}$
7	Naro-moru F.G.P.	22.728	0.589	0.2180	$I = \dfrac{22.728 \times T^{0.589}}{T_d^{0.2180}}$
8	Mangu HS	21.826	0.697	0.2138	$I = \dfrac{21.826 \times T^{0.697}}{T_d^{0.2138}}$
Average values for the entire river basin		21.438	0.675	0.2177	$I = \dfrac{21.438 \times T^{0.675}}{T_d^{0.2177}}$

This is attributed to the fact that Makurdi area is in the same geographical location/continent with Upper Tana River basin while Riyadh region is on a different geographical area, thus exhibit different characteristics. The IDF curves generated for individual meteorological stations and for the entire river basin are presented in Figures 3 to 11.

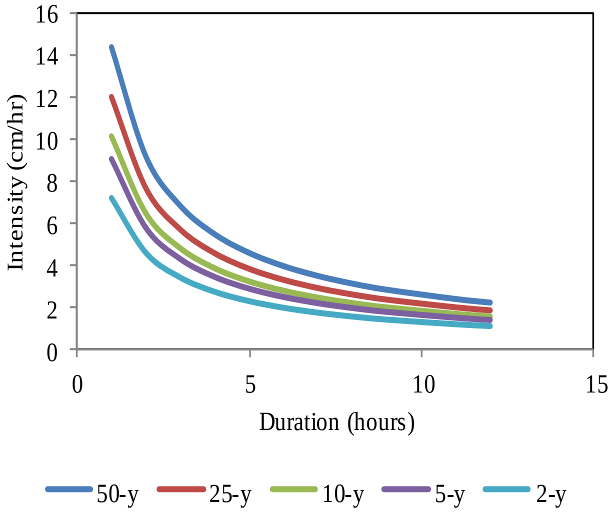

***Figure 3:** The IDF curves for MIAD meteorological stations*

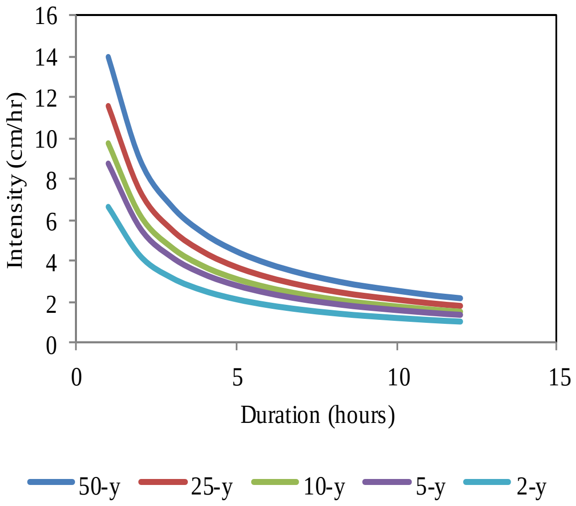

***Figure 4**: The IDF curves for Embu meteorological stations*

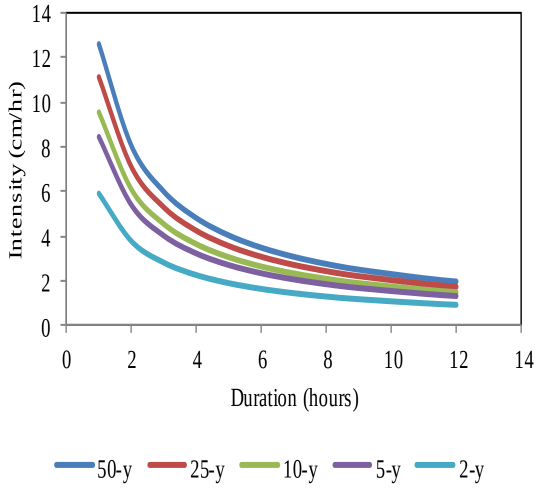

Figure 5*: The IDF curves for Mangu meteorological stations.*

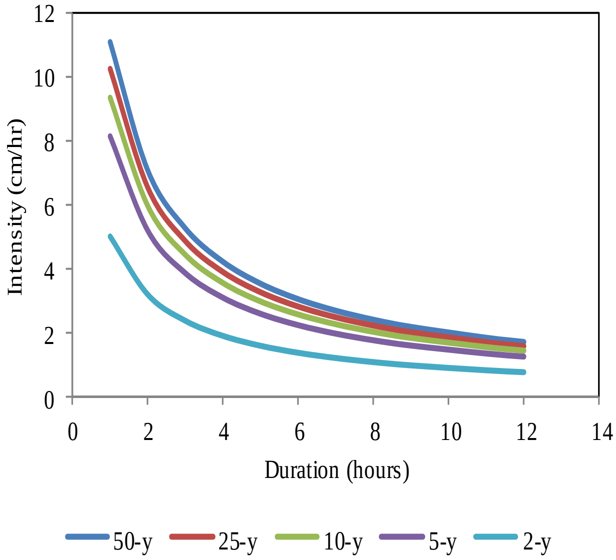

***Figure 6:** The IDF curves for, Kerugoya meteorological stations*

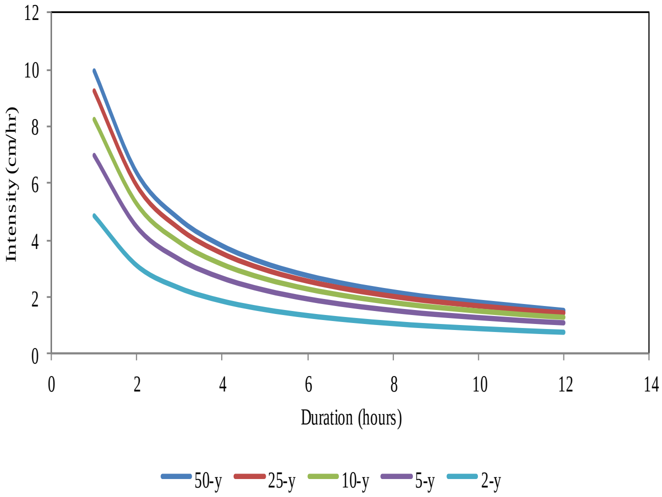

***Figure 7:** The IDF curves for Sagana meteorological stations.*

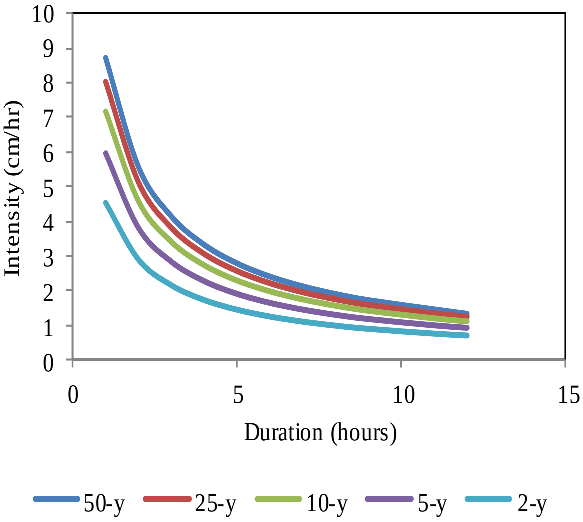

Figure 8*: The IDF curves for, Maragua meteorological stations*

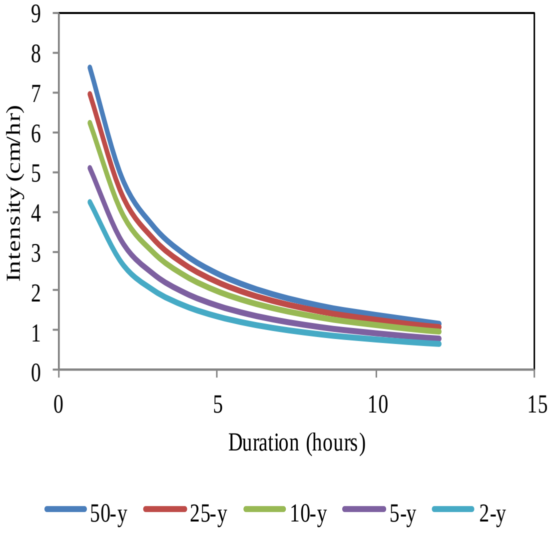

***Figure 9:** The IDF curves for Nyeri meteorological stations*

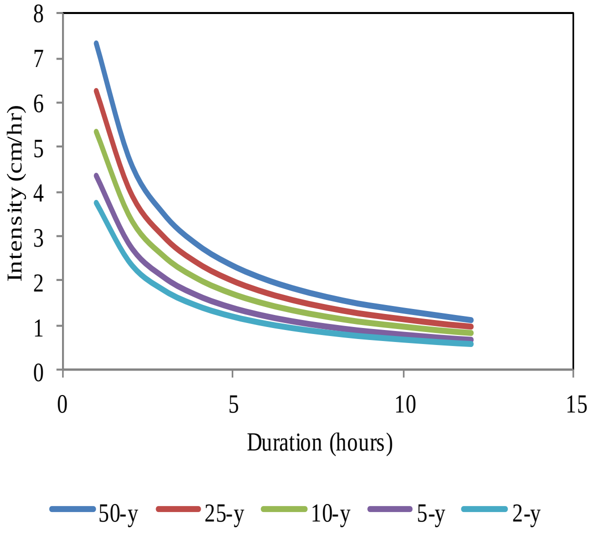

Figure 10*: The IDF curves for Naro-Moru meteorological stations.*

Based on average rainfall amounts-the following IDF curve is developed to represent overall rainfall characteristics for the entire river basin.

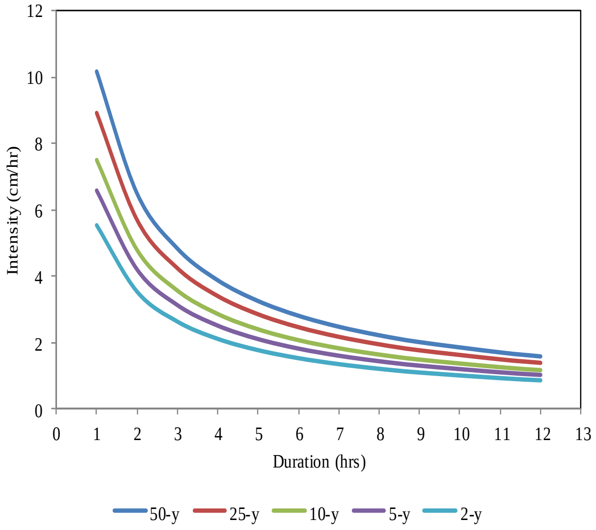

***Figure 11**: The IDF curves for upper Tana River Basin*

From figures 3 to 11, and the empirical function, the rainfall intensity is directly and inversely proportional to the return period and rainfall duration respectively. From the rainfall plots, the rainfall intensities decrease with increase in rainfall duration for a defined return period. On the other hand, for defined rainfall duration, the rainfall intensities increase with increase in return period. For a certain return period, rainfall intensities decrease with increase in rainfall duration. This means that rainfall of low intensity and long duration give rise to small quantities of runoff within a river basin. On the other hand, high intensity and short duration generate large quantities of runoff into natural and artificial water resources systems. This IDF scenario is paramount in design of hydraulic structures. Large hydraulic structures such as dams and its spillways are usually designed for high return periods; otherwise the risk of failure when subjected to rainfall events of certain intensities would be high. Additionally, small hydraulic structures such as culverts and drainage channels are designed for low return period.

5. Conclusion

An empirical function for rainfall intensity-duration-frequency was formulated for generation of IDF curves, rainfall characterization in the upper Tana River basin. The IDF curves can be adopted for water resources engineering and related structures. An empirical equation relating intensity, duration and frequency was formulated. The overall river basin constants for the empirical equation denoted as C, k and q are 21.438, .675and 0.218 respectively.

Acknowledgement

The author of this paper thanks the African Development Bank (AfDB) for resources support for the PhD research which yielded field data used for development of this text.

References

[1]. Alemaw, B. F. and Chaoka, R.T. (2016) Regionalization of Rainfall Intensity-Duration-Frequency (IDF) curves in Botswana, Journal of Water Resource and Protection, 8 (12): 1128-1144.

[2]. Alhassoun, S. A. (2011). Developing empirical formulae to estimate rainfall intensity in Riyadh region, Journal of King Saud university-engineering sciences, 23: 81-88.

[3]. Antigha R E and Ogarekpe N B. (2013). Development of intensity duration frequency curves for Calabar Metropolis, South Nigeria, The international journal of engineering and science, 2(3): 39-42

[4]. Basumatary, V. and Sil, B. S. (2017). Generation of rainfall intensity duration frequency curves for the Barak river basin, Journal of Meteorology hydrology and water management, 6: 1-12.

[5]. Bougadis, J. and Adamowski, K. (2006). Scaling model of a rainfall intensity duration frequency relationship, Hydrological processes, 20(17): 3747-3757.

[6]. Carlier, E. and Khattabi, J. E. (2016). Impact of global warming on Intensity-Duration-Frequency (IDF) relationship of precipitation, a case study of Toronto, Canada, Open Journal of Modern Hydrology, 6 (1): 1-7.

[7]. Chow, V. T. (1988). Handbook of applied hydrology, McGraw Hill

[8]. Dakheel, A. A. (2017). Drawing curves of the rainfall intensity duration frequency and assessment equation for Nasiriyah City, Iraq, Journal of Thi-Qar University, 12(2): 63-78.

[9]. Dar, A.Q. and Maqbool, H. (2016). Rainfall Intensity-Duration-Frequency relationship for different regions of Kashmir Valley (J&K) India, International Journal of Advance Research in Science and Engineering, 5 (1): 113-125.

[10]. Das, R., Goswami, D. and Sharma, B. (2016). Generation of Intensity Duration Frequency curve using short duration rainfall data for different return period for Guwahati city, International Journal of Scientific and Engineering Research, 7 (7): 908-911.

[11]. Devkota, S, Shakya, N. M., Sudmeier-Rieux, K, Jaboyedoff, M., Van Western, C. J., Mcadoo B. G and Adhikari, A. (2018). Development of a monsoonal rainfall intensity-duration-frequency (IDF) relationship and empirical model for data-scarce situations, the case of central western hills of Nepal, hydrology journal, 5(27):1-27.

[12]. Ewea, H. A., Elfeki, A. M. and Al-Amri, N (2016). Development of intensity-duration-frequency curves for the kingdom of Saudi Arabia, Geomatics, natural hazards and risk, DOI: 10.1080/19475705.2016.1250113

[13]. Fadhel, S, Rico-Kamirez, M. A, and Han, D. (2017). Uncertainty of Intensity-duration-frequency (IDF) curves due to varied climate baseline periods, Journal of Hydrology, 547: 600-612.

[14]. Isikwue, M. O, Onoja, S. B., Laudan, K (2012). Establishment of an empirical model that correlates

rainfall-intensity-duration-frequency for Makurdi area, Nigeria, International journal of advances in engineering and technology, 5(1): 40-46.

[15]. Koutsoyiannis, D. Kozonnis, D. and Manetas, A. (1998). A mathematical framework for studying rainfall intensity duration frequency relationship, Journal of hydrology, 206(1&2): 118-135.

[16]. Kumar, R. and Bhardwaj, A.(2015). Probability analysis of return period of daily maximum rainfall in annual data set of Ludhiana, Punjab, Indian Journal of Agricultural Research, 49 (2): 160-164.

[17]. Rasel, M. M. and Hossain, S. M. (2015). Development of Rainfall Intensity Duration Frequency Equations and curves for seven divisions in Bangladesh, International journal of scientific and engineering research, 6(5): 96-101.

[18]. Sharma, R. Choudhury, N., Alam, R., Seleyi, V. and Sangtam Y.(2016). Development of Intensity-Duration-Frequency curves for precipitation in western watershed of Guwahati (Assam), International Journal of Latest Trends in Engineering and Technology, 6 (4): 575-579.

[19]. Subyani, A. M. and Al-Amri, N. S. (2015). IDF and daily rainfall generation for Al-Madinah city, western Saudi Arabia, Arabian Journal of Geosciences, 8 (12): 11107-11119.

[20]. Vu, M. T., Raghavan, S. V., Liu, J, and Liong, S. Y. (2018). Constructing short-duration IDF cirves using coupled dynamical-statistical approach to assess climate change impacts, international Journal of Climatology, 38: 2662-2671.

[21]. Wagesho, N. and Claire, M. (2016). Analysis of rainfall Intensity- Duration-Frequency relationship for Rwanda, Journal of Water Resource and Protection, 8 (7): 706-723.

[22]. Wambua, R. M. (2016). Drought assessment and forecasting using indices and artificial neural networks for upper Tana River Basin, Kenya, PhD Thesis Egerton University.

[23]. Zope, P. E., Eldho, T .I. and Jothiprakash ,V. (2016). Development of rainfall Intensity Duration Frequency curves for Mumbai city, India, Journal of Water Resource and Protection, 8: 756- 765.