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ESTABLISHMENT OF RAINFALL INTENSITY-DURATION-FREQUENCY EQUATIONS AND CURVES USED TO DESIGN AN APPROPRIATE AND SUSTAINABLE HYDRAULIC STRUCTURE FOR CONTROLLING FLOOD IN NYABUGOGO CATCHMENT-RWANDA.

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ABSTRACT

Intensity Duration Frequency curves describe the connection between rainfall intensity, rainfall duration and return period. Intensity-Duration-Frequency (IDF) curves are one of the most often applied implements in water resource engineering in areas aimed at controlling floods. In particular, IDF curves for precipitation answer problems of improper drainage systems or conditions and extreme characters of precipitation which are the main cause of floods in Nyabugogo catchment. This study aims to establish Rainfall IDF empirical equations, curves and predicted peak rate of runoff (Q_{logy}) equations that will be used for designing appropriate and sustainable hydraulic structures for controlling flood in Nyabugogo catchment. Goodness of Fit tests revealed that Gumbel's Extreme-Value

Distribution method appears to have the most appropriate fit compared with Pearson type III distribution for validating the Intensity-Duration-Frequency curves and equations through the use of daily annual for each meteorological station. The findings of the study show that the intensity of rainfall increases with a decrease in rainfall duration. Additionally, a rainfall of every known duration will have a higher intensity if its return period is high, while the predicted peak rate of runoff (Q_{logy}) increases also with an increase in the intensity of rainfall.

KEYWORDS: Adequate drainage structures; Rainfall IDF Curve relationship; predicted peak rate of runoff (Q_{logy}); Gumbel's Extreme Value Distribution Method.

1. INTRODUCTION

Due to the increase in the emission of greenhouse gases, the hydrologic cycle is being altered on the daily basis. Rainfall is noticed to be one of the major determining factors in the hydrological cycle. When an area receives rainfall, the efflux of water at that area is known as stormwater. The categorization of a storm is mainly based on its Intensity, Duration and Frequency. Besides the occurrence of continuous heat, variations in extreme meteorological events such as cold waves, heavy rainfall and drought are results of modifications in climate. Modifications in the hydrological cycle owing to an increase in greenhouse gases lead to changes in the IDF of rainfall events. Curbing the adverse effects associated with climate change and adapting to them a technique to control some of the urban risk factors. As the result of the rainfall used in hydraulic design, assessment and updating of rainfall characteristics (mean: Intensity- Duration- Frequency (IDF) curves in the future are needed (Mirhosseini et al., 2013). Intensity-Duration-Frequency relationship is a mathematical interconnection between rainfall intensity I, the duration d, and the return period T (similarly, the annual frequency of exceedance, typically denoted to as 'Frequency' only) (Koutsoyiannis et al., 1998). Rwanda is a country which is located in one of the tropical regions of the earth. As projected by Engineers, it is challenging to construct Intensity-Duration-Frequency curves for rainfall in the above climatic region due to the lack of long–term extreme rainfall data. Careful planning is adopted in making an amalgamation of limited high-frequency information on rainfall maximum values with long-run daily data of rainfall. We should note due to climate change, precipitation increases at an alarming rate and that sudden increase in rainfall is the primary cause of flooding. Flood is known to be one of the ultimate natural disasters that affect people's health as well as the economies worldwide. As it relates to Rwanda, due to climatic profile and its relief (geographical features), Rwanda is among countries that are at risk of natural disasters in sub- Sahara Africa, most especially localized floods (Norbert, 2019). Rwanda experiences disasters such as landslides and flooding due to extreme rainfall. In those cases, lives and properties are lost due to erosion and other forms of environmental deprivation which are prevalent in the country. This problem has increased due to the poor management of high discharging runoffs which has provoked hydrological risks especially in urban areas (MIDIMAR, 2012). Nyabugogo catchment is considered among the catchments in Rwanda, where Kigali, the most populous city is located. Flood-related disasters are often reported in this catchment. This is mainly owing to its altitude which is low compared to other neighboring areas and its nature of the convergence zone of drainage systems especially in Kigali city which has been repetitively subjected to floods. Floods can occur when water accumulates above the soil surface (e.g. from rainfall) and cannot flow quickly (Rasel & Hossain, 2015) and also they are most likely to happen in city areas which have fast runoff processes and short response times because of a greater dominance of impermeable surfaces (Mishra et al., 2012). Flood damages property and endangers the lives of humans and other species. Moreover, its rapid water runoff causes simultaneous sediment deposition elsewhere and soil erosion (for instance: downstream). Also, the breeding grounds for fish and other wildlife habitats can be destroyed (Gaume et al., 2009; Hosseinzadehtalaei et al., 2020; Papagiannaki et al., 2015; Willner et al., 2018). Floods in Nyabugogo usually cause adverse effects that can be classified as follows: Primary effects: Physical destruction which can affect any type of structure including roadways, cars, houses, canals, bridges, and sewerage systems (Brammer, 1990); secondary effects: polluted water supplies, flooded farmland, destruction of vegetation, impede transportation; and Tertiary and long-term economic effects (Frumkin et al., 2008). Intensive flooding which occurs in the Nyabugogo River can be categorized as flash floods which generally result from intensity rainfall even over a relatively small area or if the area was before saturated from the last precipitation. Since the 2013 flood has been disturbing Nyabugogo wetland and has resulted in the loss of four human lives who got drawn in a car due to the flood, loss of properties and animal health and disturbance of socio-economic activities, disturbance of businesses in the region. Also, issues such as transport facilitation at times come to a halt because of flooding in the wetland during the rainy season (Munyaneza et al., 2011). For instance, stormy weather from 02nd to 03rd February 2020 brought thunderstorms and floodwaters that caused floods and landslides in the capital, Kigali, and other parts of the country. Referring to the ministry's provisional update of 03rd February, at least thirteen people died, two people injured and fifteen houses destroyed in Jali in Gasabo District including twelve households were damaged in Nyarugenge District.

Potential loss of life, degradation of water, air and soil quality and property damage due to flooding is caused by extreme rainfall events (Handmer, 2012). The major cause of the flood is rainfall runoff that cannot be channeled appropriately into the drainage systems forcing the water to flow overland. Clogged or lack of proper drainage system is usually the cause of this type of flooding (Abolade et al., 2013). Ancient rainfall events are used to design structures mostly hydraulic structures as well as many other flood protection structures relating to hydrologic flows (Nirupama & Simonovic, 2007). Previous studies have been established to investigate and assess factors affecting adaptation, the mitigation of climate change and to increase and sharpen the disaster controlling by various stakeholders (Burlando et al., 1996; Sane et al., 2018); but no study has assessed the question of waterlogging and flood which are a common problem during the raining period due to poor living condition of people and inadequate drainage system. To address this problem, a new drainage design with hydraulic discharge (**Q_{lics}**) should be designed that should be higher than the predicted peak rate of runoff (predicted hydrological discharge (**Q_{logy}**) (Engineers, 1969; Robert Manning, 1890)**.** This research was conducted to establish IDF Curves and equations for various duration of rainfall in eight Districts which are Nyarugenge, Gasabo, Kicukiro, Rulindo, Gicumbi, Rwamagana, Kayonza and Gatsibo with their meteorological stations such as Gitega, Kabuye sugar, Kigali Aero, Rulindo, Byumba Pref. , Rwamagana, Kayonza and Kiziguro respectively of Nyabugogo catchment. In this present research, Gumbel's Extreme value Distribution method (GEVDM) is applied to develop IDF curves and equations. In this background, a trial has been made to develop the precipitation for the different return periods and different durations of 'n' such as 10,20,30,60,120,180,360,720 and 1440 min adopting GEVDM for generation of IDF relationship with eight Districts of Nyabugogo catchment-Rwanda (de Paola et al., 2014; Nhat et al., 2006).

Model performance indicators such as correlation coefficient (R) is used to examine the performance of the established Intensity-Duration-Frequency relationships by GEVDM for the design of rainfall intensity for the areas under study. Rainfall is normally calculated using Intensity-duration-frequency (IDF) Curves (Kotei et al., 2013). This study aims to establish Rainfall IDF empirical equations, curves, and hydrological discharge equation for eight Districts that will be used for designing an appropriate and sustainable hydraulic structure for controlling flood to reduce human and economic losses and improve infrastructure planning and design in Nyabugogo catchment. This study will help to design hydraulic structures for a long period especially in this study area of Nyabugogo catchment. The information generated can be used for water resource projects, sewer systems design, or water quality management projects in large urban areas such as Kigali (Van de Vyver & Demarée, 2010).

2. Data Collection and Methodology

2.1. Description of the Study Area

Nyabugogo catchment is located in the central-eastern part of Rwanda and consists of both rural and urban areas which including Kigali, as Rwanda's capital city (Fig. 1). Nyabugogo catchment cuts across 8 districts, Rulindo and Gicumbi Districts in Northern Province, Gasabo, Kicukiro, and Nyarugenge districts of Kigali city and Gatsibo, Kayonza and Rwamagana Districts of Eastern Province. The study area contains an approximate population of about 1.135.428 inhabitants. It covers a total surface area of about 1,647 km^2 with the main activity of its inhabitants being agriculture. 897 km^2, which is about 54 percent of the total land space of the study area are used for agricultural activities.

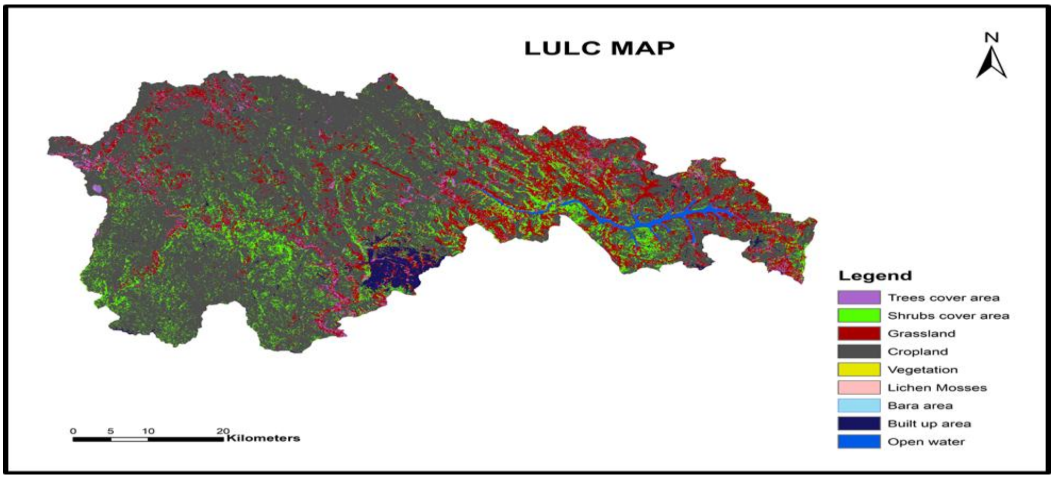

Fig. 1: Land use and land cover (LULC) map of Nyabugogo catchment.

The catchment has an equatorial and a moderate climate which has a temperature varying between 16 Celsius degree and 23 Celsius degree, depend on the altitude of the region. In Rwanda, the annual precipitation ranging from 800 millimeters to 1,600 millimeters. Rwanda has four normal seasons. The first season, which is a long dry season starts from June to September, the second season spans from October to December, this is a short rainy season that received 30% to 40% of the yearly rainfall with the highest rains falling in November. The third season is a short dry season which spans from December and ends in January. The fourth season which starts from February up to the end of May is the rainy season. It receives around 60% of annual rainfall (Nhapi, 2011).

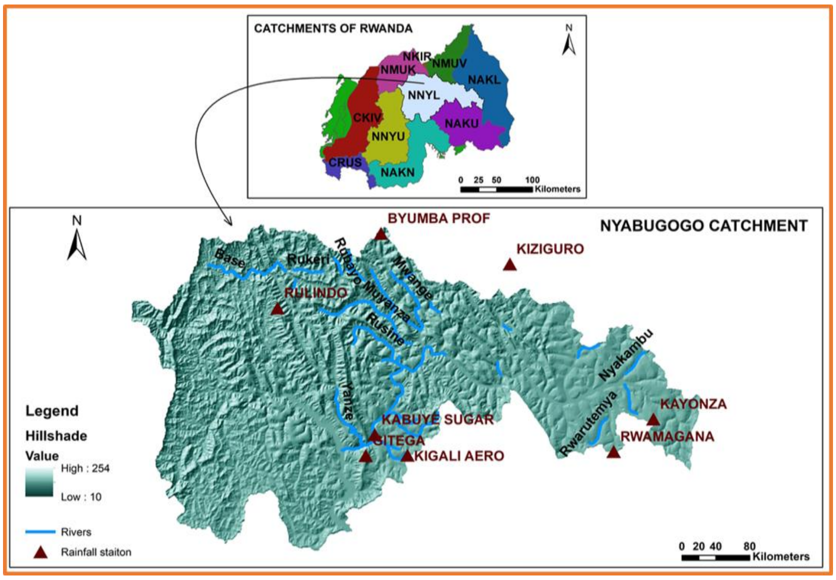

Fig. 2: Location of case study area: Nyabugogo catchment.

The study area has experienced environmental degradations such as erosion of soil due largely to factors such as deforestation, lack of proper agricultural technological practices and illegal mining activities. These activities lead to a large deposit of heavy sediments in the River of Nyabugogo and its tributaries. This reduces the volume of water intake of the river and hydraulic structures thus causing spillover which leads to flooding. The River Nyabugogo which is fed by its tributaries, such as Marenge, Mwange and Rusine Rivers on its upstream area crosses Kigali City as the main source of flooding in Kigali City. It is also supplied by other Rivers from the urbanized area of Kigali City such as the Mpazi, Ruganwa, Rwanzekuma and Yanze Rivers.

2.2. Data Collection

The data used in this research have been obtained from METEO-RWANDA which has the responsibility of gauging, analyzing and keeping meteorological data and forecasting the meteorological conditions in Rwanda. The data consisted of daily annual maximum series (AMS) of rainfall depth for 37 years for all eight meteorological stations (1981-2017) found in Nyabugogo catchment for durations of time: 10min, 20min, 30min, 60min, 120min, 180min, 360min, 720min and 1440min. Meteorological conditions in Nyabugogo catchment has relatively never stopped activity over 37 years for all Districts so that sufficient data were available to calculate a frequency analysis of extreme rainfall. There were some Daily AMS that has been digitized for the period 1993-1994 because of the genocide that happened in Rwanda against the Tutsi ethnic group in that period; these have been included in this work. The gaps were filled based on previously recorded data that were recorded in the meteorological books. These books were filled by the meteorological agents at the station regularly but only ceased in the period of instability. Data together with daily weather changes such as the rainfall depth obtained from a rain gauge every day, the beginning and ending time of rainfall are regularly recorded. 8 stations which include, Gitega, Kabuye sugar, Kigali Aero., Rulindo, Byumba Pref., Rwamagana, Kiziguro, and Kayonza with one metrological station representing each District.

2.3. Fitting for Gumbel distribution to the sample data

To compute the exceedance probability (**p**), the Gringorten and Weibull equation could be applied for approximating the cumulative probability distribution. The most problem of the Weibull formula is that it is asymptotically exact (as the number of observations approaches infinity) only for a population with an underlying uniform distribution, which is relatively rare in nature. To address this shortcoming, Gringorten proposed that the exceedance probability of observed. Data be estimated using the relation:

$$p = \frac{m - 0.44}{N + 0.12} \quad (1)$$

Where **m:** Rank of AMS values from highest to lowest. It is the most recommended formula for calculating the cumulative probability distribution from measured data, for the Extreme Value type I distribution. Calculate the reduced variable **u** from p by the equation:

$$u = -\ln[-\ln(1 - p)] \quad (2)$$

Then, to calculate the sample mean $\boldsymbol{\mu_S}$ and standard deviation $\boldsymbol{\sigma_S}$ by using an Excel program and we found the position parameter $\mathbf{x_0}$ and the scale parameter **S** of the Gumbel distribution with the following formulae:

$$X_0 = \mu_S - \frac{\mu N}{\sigma N}\sigma_S \quad (3)$$

$$S = \frac{\sigma S}{\sigma N} \quad (4)$$

where**:** μ_{N}: the mean of reduced variable, σ_{N}: the standard deviation of the reduced variable. μ_N and σ_N are shown in the table of Parameters of reduced Gumbel Distribution. They both depend on the number of sample points. They use the formulae below which are the Gumbel mean (μ_G) and Standard deviation (σ_G) and finally for each rank, the Gumbel variable is obtained by the use of the formula. They constitute the expected data.

$$\mu_G = X_0 + 0.5772 * S \quad (5)$$

$$\sigma_G = 1.2825 * S \quad (6)$$

$$X_G = \left(X_0 + (u * S)\right) \quad (7)$$

2.3.1. Preparation of short-duration rainfall data

To estimate the short duration rainfall from daily rainfall data, many researches like (Choi et al., 2019; Ghanmi et al., 2016; Skahill et al., 2016; Yilmaz et al., 2017) used an empirical reduction formula to estimate different hourly durations from daily precipitation values. Based on (Lee & Dang, 2020), the empirical reduction formula in Eq. 3.8 gives the best estimation of short-duration rainfall. In this research, Eq.3.8 was applied to estimate short duration rainfall in Nyabugogo catchment (e.g.10 min, 20 min, 30 min, 1, 2, 3, 4, 6 and 8 h):

$$P_t = P_{24}\left({}^{t}/_{24}\right)^{1/3} \quad (8)$$

Where: P_t = Precipitation in mm for a given duration **t** hours, P_{24} = Daily Precipitation data in mm, and **t** = Shorter duration in hours. This equation has been chosen because it gives the best estimation of short-duration rainfall.

2.3.2. Goodness of Fit tests

These tests can be applied reliably in climate statistics to assist to find the best distribution to use to fit the given data. Goodness of fit tests determine test-statistics, which are applied to investigate how well the data fits the given distribution. They describe also how the observed data values and the expected values are different when the distribution is being tested

2.3.2.1. The chi-square test $x^2(v)$

The Chi-Squared test is applied to find out if a sample comes from a provided distribution. Chi-Squared test should be well-known that the statistical test is not considered to have a high power. By putting the observed data and the expected values into intervals to determine the frequencies of both variables in each class. This can be well expressed by a histogram of frequencies (Fig. 2b) and rearrange the classification so that the minimum expected frequency in each class becomes 5 or great. The classes with low frequency should be merged to this end. Then after compute the chi-square value for all intervals.

$$X^2(V) = \sum_i^n \frac{(Oi - Ei)}{Ei} \quad (9)$$

Where V is the degree of freedom and equals n-k-1, here n symbolize the number of intervals and k is the distribution number of parameters obtained from the sample statistics; the constraints imposed on the fitting process. Compare the value so obtained to the tabulated Chi-square value $X^2_{0.95}$ (Chi-Square Distribution Table); the null hypothesis will be accepted if $\mathbf{X^2 < X^2_{0.95}}$ **(Eq.3.10)** and rejected otherwise.

2.3.2.2. Kolmogorov-Smirnov Test

The Kolmogorov-Smirnov test statistic is built on the greatest vertical distance from the empirical and theoretical cumulative distribution function. A hypothesis is rejected if the critical value at a chosen significance level is lesser than the test statistic (D), otherwise accepted. The samples are supposed to be from a cumulative distribution function.

$$D = max|F0(x) - Ft(x)| \qquad (11)$$

Where D: maximum deviation, F0 (x) be the sample cumulative distribution function based on N observations. For any observed x, F0 (x) $=\frac{j}{N}$, where j is the number of observations less than or equal to x and Ft(x) be the specified theoretical cumulative distribution function under the hypothesis.

2.3.3. The IDF curve designing procedures

Tabulation of yearly rainfall data, regular daily rain data from the long term is used to get current trends in the rainfall intensity followed by the formulation of short-duration rainfall data. Applying the Indian Meteorological Department expression, a short duration rainfall series is obtained from Daily Precipitation data (table 1) and then determine Probability Distribution. In this research, Gumbel's Extreme. The value distribution method is applied for probability distribution for each picked out duration data series. (Rashid et al., 2012) showed that hydrological studies can be expressed by the expression below depicting hydrologic Frequency analysis: The precipitation (PT) comparable to an estimated return period (T) applying the GEVDM is given by:

$$\mathrm{PT} = \sigma + \mathrm{K.S} \qquad (12)$$

Where: σ: Average annual daily maximum rainfall (AADMR), S: Standard deviation of (AADMR) and K: Frequency Factor given by:

$$\mathrm{K} = -\frac{\sqrt{6}}{\pi}\left[0.5772 + \ln\left[\ln\left[\frac{\mathrm{T}}{\mathrm{T}-1}\right]\right]\right] \qquad (13)$$

Using the above equation, Frequency Factors for the return periods of 2, 5,10,25,50 and 100 years are calculated and the values are of Frequency factor should be obtained respectively.

Those parameters of frequency factor are applied to get precipitation (PT) matching to return periods of 2 years to 100 years for durations of 10 min to 1440min.

At this point, the rainfall intensity (I_T) is obtained for the return period T from the following equation:

$$I_{T}=\frac{P_t}{T_d} \tag{14}$$

Where T_d is the duration in hours. The frequency of the precipitation is well-defined by reference to the AMS, which contains the highest values observed in every year. The using the Least Square method, Orange software, or Excel sheet to find parameters x and y for different return periods. Equation **(Eq.3.15)** in the formation of the IDF empirical formula which is applied in this research (Haddad & Rahman, 2011).

$$I = X * (td)^{-y} \tag{15}$$

Where td: is the rainfall duration in a minute, I: is the rainfall intensity in millimeter per hour. **X** and **y** are fitting parameters. These empirical formulas are commonly applied in different hydrological uses. This formula indicates that for a given return period, the rainfall duration increases with a decrease in rainfall intensity. Finally finding the correlation coefficient by using the Excel sheet. The correlation coefficient (R) was established to obtain the best-fit IDF empirical equation. For any particular return period, the formula that allows the correlation coefficient value nearer to one has the best fit. So after all these steps, we found peak flow (hydrological discharge (**Q_{logy}**)) which was compared with a hydraulic discharge (**Q_{lics}**) (Engineers, 1969).

$$Q_{logy} = (ARF)\, C_f * CIA$$

$$Q_{logy} = (ARF) * C_f * C * (X * (td)^{-y}) * A \tag{16}$$

$$ARF = [1.343 - 0.09 ln(A)] T_d \tag{17}$$

$$C=\frac{Q}{P} \tag{18}$$

$$Q_{lics} = \frac{1}{n} * R^{2/3} * \sqrt{S} * Ac \tag{19}$$

Where: **Q_{logy}** = predicted peak rate of runoff (m^3/sec), **Q_{lics}** =Hydraulic discharge (m^3/sec),

C = runoff coefficient, **Q**=Runoff volume (m^3) and **P**=Rainfall volume (m^3) **I=X*(td)$^{-y}$** = Rainfall intensity (mm/hr.), (**ARF**)= Area Reduction Factor, **A** = drainage area (in ha), **C_f =** Frequency Factors for Rational Formula, **A_c=** Cross section Area of hydraulic structure (m^2), **n** = Manning roughness coefficient, **S** = Channel bottom slope, in meters per meter and **R** = Hydraulic Radius in (m), in meters, x and y are the parameters to fit the IDF curve.

Least Square method is applied to get parameters **x** and **y** for various return periods and the outcomes are shown in the table of rainfall Intensity-Duration-Frequency empirical equation for corresponding return period and their correlation coefficients for all meteorological stations.

3. RESULT AND DISCUSSION

To reduce the risk of failure of hydraulic structures and to design a reliable and durable construction, hydraulic structures should be designed and constructed with resilience to withstand future climate change. To build such a future climate-resistant infrastructure, the design storms estimated from the IDF curves should be reviewed to adapt the infrastructure to a changing climate through fulfilling adaptation actions (Hosseinzadehtalaei et al., 2020). As the non-performance of different categories of hydraulic structures occurs at different rainfall thresholds (Nissen & Ulbrich, 2017), the predicted changes in common return periods for hydraulic structure design (means: a storm with heavy rain of 2,5,10,50 and 100 years of return periods) are studied.

3.1. Application of Procedures for Gitega Meteorological station

3.1.1. Daily Annual Maxima Series (AMS) analysis

As from the table of parameters of reduced Gumbel Distribution, here μN and σN are found to be equal to 0.54180 and 1.13390 respectively for N =37. Here sampled extreme rainfall depth, in millimeter are arranged in descendent order, the exceedance probabilities got with Gringorten formula, the reduced valuable u is calculated using the expression Eq.3.2 and the expected values as were generated by Gumbel distribution were computed in the (Table S1).

The frequencies of the observed values and expected values for the given ranges are calculated.

This enables us to plot into a diagram frequency as expressed in terms of ranges; furthermore, to make tests of best fit, the histograms in (Fig. 2b) give an idea of the distribution of data and (Fig. 2a) showed the Annual Maximum Daily Rainfall.

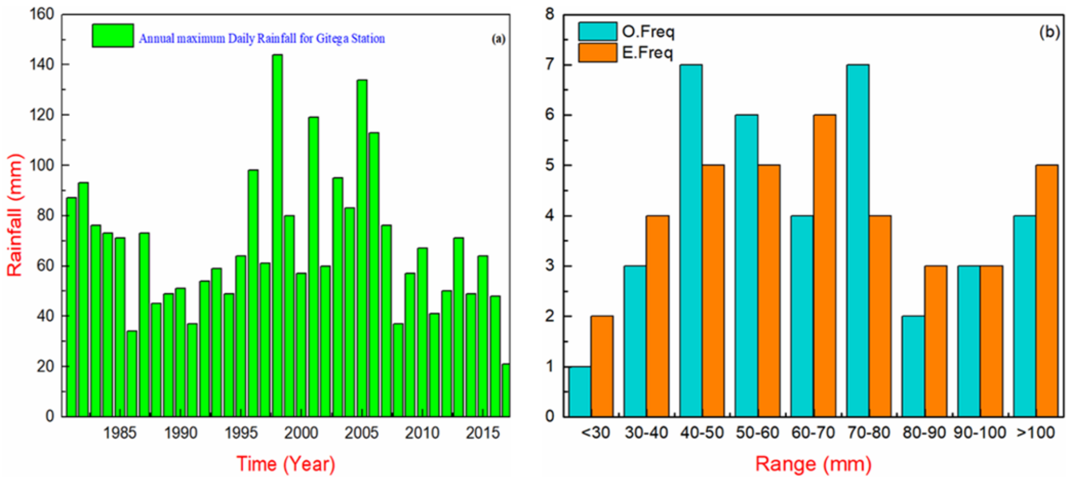

Fig. 3: (a) Annual Maximum Daily Rainfall for Gitega station and (b) Distribution of observed and expected frequencies.

In Figure 3a, the results showed that the annual maximum daily rainfall (AMDR) of 144 mm has been observed in Gitega station, Nyarugenge District but for the whole catchment AMDR of 270 mm was observed also at Rwamagana station, Rwamagana District for the last 37 years. This is because maybe in Rwamagana District, we are found grassland, open water, and some trees as we have seen in Figure 1; these made transpiration from vegetation and soil and also evaporation from open water which leads much condensation into atmosphere (Cycle & Properties, n.d.; Porto de Carvalho et al., 2014).

The frequencies of the observed values and expected values for the given ranges are calculated before leading to the chi-square test. Intervals of low frequencies have been put together so that the minimum frequency becomes greater than or equal to five. The computed chi-square showed that X^2=4.6. For n = 5 number of interval and k = 2 number of constraints, the degree of freedom is equal to v= 5 – 2 -1 = 2. The 5% non-acceptance limit would be the ninety-fifth percentile of the Chi-Square distribution (CSD) having 2 degrees of freedom, which is equal to 0.103 from the Chi-Square Distribution Table S8. The level of significance, α=0.05 gives rise to a critical value of 0.103 which is applied in this research. Also, if the test statistic is lesser than the critical value (0.103<4.6), the hypothesis is accepted. (Davies, 2008), used this method and after making his calculations, he found that the test statistic was greater than the critical value because the significant level, produced a critical value of 12.592 which is applied in his report.

The Kolmogorov test showed that the highest difference is equal to 0.0692 and the critical value for Kolmogorov-Smirnov given in the Critical values of Kolmogorov-Smirnov test table Table S9 for eight intervals and a 5% significant level, is 0.457. Since $0.0692 < 0.457$ the Hypothesis is accepted at 0.05 significant level. The number of intervals were considered here instead of the sample size (37) for the Gitega station. Processes used for this Gitega station (Kolmogorov test) are similar for all remaining seven stations such as Kanombe Aero, Kabuye sugar, Rulindo, Byumba Pref, Rwamagana, Kiziguro, and Kayonza station, and the Hypothesis is accepted at 0.05 significant level. This process has been used (Solaiman, T.A., and Simonovic, 2011), the same Hypothesis was accepted at a 0.05 significant level.

Here, the results for the goodness of fit tests are examined for the statistical distributions in question. Goodness of fit tests, for all storm durations the Gumbel's Extreme-Value Distribution method appears to have the most appropriate fit.

3.2. Preparation of short-duration rainfall data

The relationship of short-duration rainfall (SDR) with the daily rainfall value was calculated and represented to improve the model of regression. Related to the nature of curvature and to obtain reliable estimations, the proposed two equations were mentioned: the rainfall duration less or equal to 2 hours, and the second one starts from above 2 h up to 24 hours; means less than 1 day. Here, there are some opportunities of having little different estimation of rainfall values for changing the duration which is 2 hours, in this special research.

Table 1: Shorter Duration Rainfalls Derived from Max. Daily Rainfall using Indian Meteorological Department 1/3rd rule.

No	Years	AMDR	10 min	20 min	30 min	1hr	2hr	3hr	6hr	12hr	24hr
1	1981	87	16.6498	21.1426	24.2499	30.4824	38.3168	43.8026	55.0604	69.2117	87
2	1982	93	17.7981	22.6007	25.9223	32.5847	40.9594	46.8234	58.8577	73.9849	93
3	1983	76	14.5447	18.4694	21.1838	26.6283	33.4722	38.2643	48.0988	60.4608	76
4	1984	73	13.9705	17.7404	20.3476	25.5772	32.1509	36.7539	46.2001	58.0742	73
5	1985	71	13.5878	17.2543	19.7901	24.8765	31.27	35.7469	44.9344	56.4831	71
6	1986	34	6.50682	8.26264	9.47697	11.9127	14.9744	17.1182	21.5179	27.0482	34
7	1987	73	13.9705	17.7404	20.3476	25.5772	32.1509	36.7539	46.2001	58.0742	73
8	1988	45	8.61197	10.9358	12.543	15.7668	19.819	22.6565	28.4795	35.7991	45
9	1989	49	9.37748	11.9079	13.658	17.1683	21.5807	24.6704	31.011	38.9813	49
10	1990	51	9.76023	12.394	14.2154	17.869	22.4616	25.6774	32.2768	40.5724	51
11	1991	37	7.08095	8.9917	10.3132	12.9638	16.2957	18.6287	23.4165	29.4348	37
12	1992	54	10.3344	13.123	15.0517	18.9201	23.7829	27.1878	34.1754	42.959	54
13	1993	59	11.2912	14.3381	16.4453	20.672	25.985	29.7052	37.3398	46.9367	59
14	1994	49	9.37748	11.9079	13.658	17.1683	21.5807	24.6704	31.011	38.9813	49
15	1995	64	12.2481	15.5532	17.839	22.4239	28.1871	32.2226	40.5042	50.9143	64
16	1996	98	18.755	23.8158	27.316	34.3365	43.1615	49.3408	62.0221	77.9626	98
17	1997	61	11.674	14.8241	17.0028	21.3727	26.8658	30.7121	38.6056	48.5277	61
18	1998	144	27.5583	34.9947	40.1377	50.4537	63.4209	72.5008	91.1345	114.557	144
19	1999	80	15.3102	19.4415	22.2987	28.0298	35.2339	40.2782	50.6303	63.6429	80
20	2000	57	10.9085	13.8521	15.8879	19.9712	25.1041	28.6982	36.0741	45.3456	57
21	2001	119	22.7739	28.9192	33.1694	41.6944	52.4104	59.9139	75.3125	94.6688	119
22	2002	60	11.4826	14.5811	16.7241	21.0224	26.4254	30.2087	37.9727	47.7322	60
23	2003	95	18.1808	23.0868	26.4798	33.2854	41.8402	47.8304	60.1234	75.576	95
24	2004	83	15.8843	20.1706	23.1349	29.0809	36.5551	41.7887	52.5289	66.0295	83
25	2005	134	25.6445	32.5645	37.3504	46.9499	59.0167	67.466	84.8057	106.602	134
26	2006	113	21.6256	27.4611	31.497	39.5921	49.7678	56.893	71.5152	89.8956	113
27	2007	76	14.5447	18.4694	21.1838	26.6283	33.4722	38.2643	48.0988	60.4608	76
28	2008	37	7.08095	8.9917	10.3132	12.9638	16.2957	18.6287	23.4165	29.4348	37
29	2009	57	10.9085	13.8521	15.8879	19.9712	25.1041	28.6982	36.0741	45.3456	57
30	2010	67	12.8223	16.2823	18.6752	23.475	29.5084	33.733	42.4028	53.3009	67
31	2011	41	7.84646	9.96377	11.4281	14.3653	18.0574	20.6426	25.948	32.617	41
32	2012	50	9.56885	12.1509	13.9367	17.5186	22.0212	25.1739	31.6439	39.7768	50
33	2013	71	13.5878	17.2543	19.7901	24.8765	31.27	35.7469	44.9344	56.4831	71
34	2014	49	9.37748	11.9079	13.658	17.1683	21.5807	24.6704	31.011	38.9813	49
35	2015	64	12.2481	15.5532	17.839	22.4239	28.1871	32.2226	40.5042	50.9143	64
36	2016	48	9.1861	11.6649	13.3792	16.8179	21.1403	24.1669	30.3782	38.1858	48
37	2017	21	4.01892	5.1034	5.85342	7.35783	9.24889	10.573	13.2904	16.7063	21
	Mean (σ)		**13.1378**	**16.6829**	**19.1347**	**24.0526**	**30.2345**	**34.5631**	**43.4462**	**54.6125**	**68.6486**
	St.Dev. S		**5.2632**	**6.68344**	**7.66568**	**9.63586**	**12.1124**	**13.8465**	**17.4053**	**21.8786**	**27.5017**

The precipitation of any duration near to 2 hours should be determined by applying both equations and the higher value should be established for determining rainfall value. SDR data of the close to automatic meteorological station were checked out for testing the output design graphs (Al Mamun et al., 2018).

Processes used for this Gitega station (Table 1) are similar for all remaining seven stations such as Kanombe Aero, Kabuye sugar, Rulindo, Byumba Pref, Rwamagana, Kiziguro, and Kayonza station.

Estimated rainfall in mm and its intensities in mm/hr for all return periods and its corresponding durations were analyzed using the Gumbel technique. The application of the Gumbel frequency factor method is highly useful for estimating frequencies of rainfall and storm floods (Basumatary & Sil, 2017). From the raw data, the extreme rainfall (P_T), the average and standard deviation for the duration (10, 20, 30, 60,120,180,360,720 and 1440 minutes) were estimated from the annual maximum 24hrs rainfall IMERF (Indian Meteorological empirical Reduction Formula). In terms of frequency, as shown by the curves of growing factor variation KT, it's possible to note how the effect of climate change can be visualized in the eight established Districts through the increase in the frequency of extreme events KT is kept as constant, the equivalent return period value is reduced taking into account the flood projections (de Paola et al., 2014). The various projected duration data were applied in Gumbel's Extreme Probability Method to calculate precipitation (PT) values and intensities (I_T) for the Districts of Nyabugogo Catchment. (Table 2) shows rainfall frequency values, intensities (I_T) for diverse durations and return periods using the Gumbel distribution Method for Gitega station (represents Nyarugenge District) were computed.

Table 2: Computed frequency rainfall (PT) values and intensities (IT) for different durations and return periods using Gumbel Method for Gitega station (Nyarugenge District).

10 min				20 min				30 min			
Mean (σ)		13.13777673		Mean (σ)		16.68291292		Mean (σ)		19.13473201	
S		5.263200974		S		6.683438555		S		7.665676029	
Tr(Year)	**K**	**PT(mm)**	**IT(mm/hr)**	**Tr(Year)**	**K**	**PT(mm)**	**IT(mm/hr)**	**Tr(Year)**	**K**	**PT(mm)**	**IT(mm/hr)**
2	-0.164	12.27461177	76.71632358	**2**	-0.164	15.586829	47.2328	**2**	-0.164	17.8776	35.75512229
5	0.719	16.92201823	105.762614	**5**	0.719	21.488305	65.1161	**5**	0.719	24.6464	49.29270616
10	1.305	20.006254	125.0390875	**10**	1.305	25.4048	76.9842	**10**	1.305	29.1384	58.27687846
25	2.044	23.89575952	149.348497	**25**	2.044	30.343861	91.9511	**25**	2.044	34.8034	69.60674764
50	2.592	26.77999366	167.3749604	**50**	2.592	34.006386	103.05	**50**	2.592	39.0042	78.00832856
100	3.137	29.64843819	185.3027387	**100**	3.137	37.64886	114.087	**100**	3.137	43.182	86.36391544
60 min				**120 min**				**180 min**			
Mean (σ)		24.05261406		Mean (σ)		30.23445757		Mean (σ)		34.56306888	
S		9.635857294		S		12.11240149		S		13.84651159	
Tr(Year)	**K**	**PT(mm)**	**IT(mm/hr)**	**Tr(Year)**	**K**	**PT(mm)**	**IT(mm/hr)**	**Tr(Year)**	**K**	**PT(mm)**	**IT(mm/hr)**
2	-0.164	22.47233346	22.47233346	**2**	-0.164	28.248024	14.124	**2**	-0.164	32.2922	10.76408033
5	0.719	30.98079545	30.98079545	**5**	0.719	38.943274	19.4716	**5**	0.719	44.5187	14.83957024
10	1.305	36.62740783	36.62740783	**10**	1.305	46.041142	23.0206	**10**	1.305	52.6328	17.5442555
25	2.044	43.74830637	43.74830637	**25**	2.044	54.992206	27.4961	**25**	2.044	62.8653	20.95511286
50	2.592	49.02875616	49.02875616	**50**	2.592	61.629802	30.8149	**50**	2.592	70.4532	23.48440897
100	3.137	54.28029839	54.28029839	**100**	3.137	68.231061	34.1155	**100**	3.137	77.9996	25.99985858
360 min				**720 min**				**1440 min**			
Mean (σ)		43.44623985		Mean (σ)		54.61250456		Mean (σ)		68.64864865	
S		17.40525026		S		21.87863236		S		27.5017335	
Tr(Year)	**K**	**PT(mm)**	**IT(mm/hr)**	**Tr(Year)**	**K**	**PT(mm)**	**IT(mm/hr)**	**Tr(Year)**	**K**	**PT(mm)**	**IT(mm/hr)**
2	-0.164	40.5917788	6.765296467	**2**	-0.164	51.024409	4.25203	**2**	-0.164	64.1384	2.672431848
5	0.719	55.96061478	9.326769131	**5**	0.719	70.3432412	5.86194	**5**	0.719	88.4224	3.68426646
10	1.305	66.16009144	11.02668191	**10**	1.305	83.1641198	6.93034	**10**	1.305	104.5384	4.355767119
25	2.044	79.02257138	13.17042856	**25**	2.044	99.3324291	8.2777	**25**	2.044	124.8622	5.20259133
50	2.592	63.44349011	10.57391502	**50**	2.592	111.32192	9.27683	**50**	2.592	139.9331	5.830547578
100	3.137	98.04650991	16.34108499	**100**	3.137	123.245774	10.2705	**100**	3.137	154.9216	6.45506611

Results in table 2 show clearly that for those short duration, the rainfall intensity increases and also increase with increasing precipitation in the return period of 2,5,10 50 and 100 years. Similarly, for all other seven stations rainfall frequency (P_T) values and intensities (I_T) for different durations. The same results are found by (Carlier & Khattabi, 2016) when they computed IDF Curves before and after 1980 in Toronto (Canada) and their results were that the intensity decreases particularly with an increase of return period of 5,10,20 and 50 years. From the calculated rainfall (P_T) values and intensities (I_T) in (Fig.4 and 5), Rainfall IDF curves were developed for the eight Districts of Nyabugogo Catchment. As the curves show the rainfall intensity increases when rainfall duration reduces. Similar results were also obtained by (Nhat et al., 2006; Rasel & Hossain, 2015) in which an equation was designed where rainfall Intensity was developed in 10-minute increments for different return periods by using GEVDM.

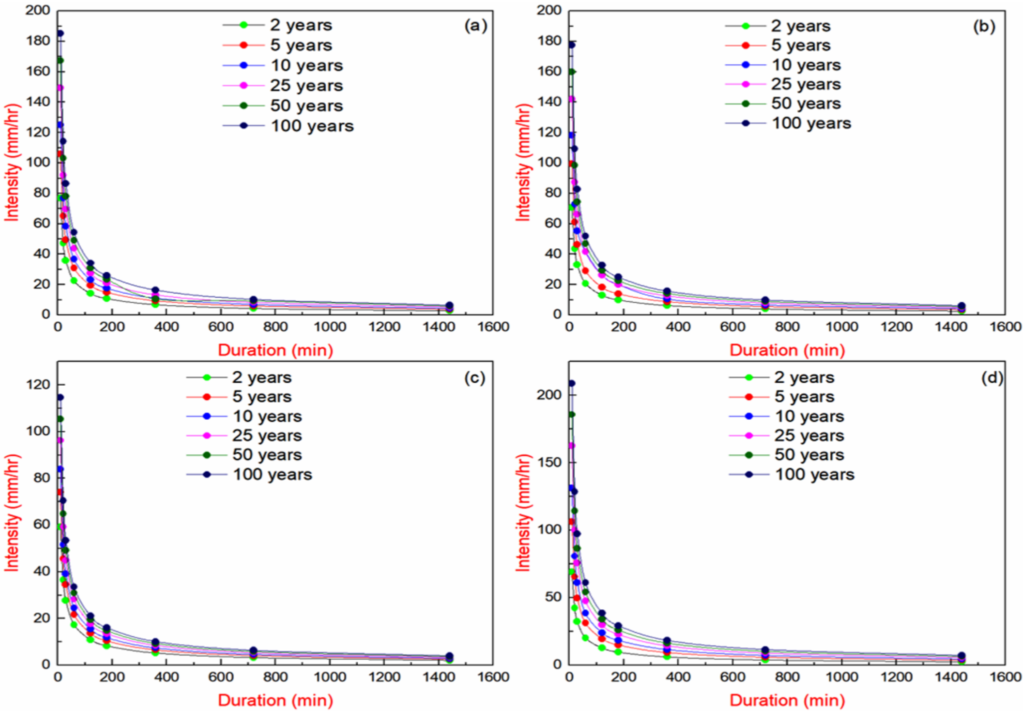

Fig. 4: Rainfall IDF curve for (a) Gitega station-Nyarugenge District, (b) Kigali Aero-Kicukiro District, (c) Byumba Pref. station-Gicumbi District and (d) Rwamagana station-Rwamagana District.

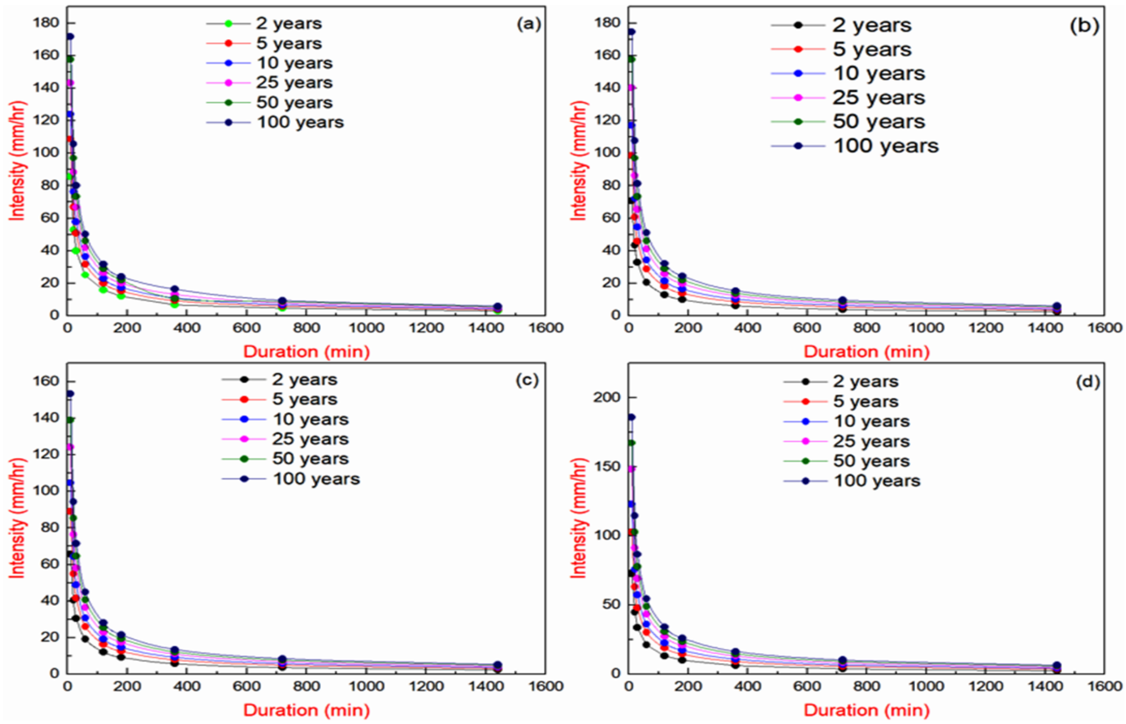

Fig. 5: Rainfall IDF curve for (a) Kabuye sugar station-Gasabo District, (b) Rulindo station-Rulindo District, (c) Kiziguro station-Gatsibo District and (d) Kayonza station-Kayonza District.

In whole catchment, referring to the results from the figure 4 and figure 5, the highest intensities which are 208.77, 186.02, 185.3, 177.43, 174.69, 171.74, 153.24 and 114.57 mm/hour will occur at Rwamagana District, Kayonza District, Nyarugenge District, Kicukiro District, Rulindo District, Gasabo District, Gatsibo District and Gicumbi District respectively; these mean that the highest rainfall will happen after 100 years. Flood measures should be taken before and any hydraulic structures should be designed well with referring to these results. The same results are stated by (Al Mamun et al., 2018; Ghanmi et al., 2016; Skahill et al., 2016), they showed that the intensity increases with an increase of precipitation.

According to the intensity-duration- frequency curves, rainfall (PT) estimates increase with an increase in the return period as it can be seen from (Tables 3-6) and (Table S2 to Table S5) and also result showed that all rainfall intensities decrease with rainfall duration in all return's periods. Also, a rainfall in any given duration will have a higher intensity if its return period is high (Hosseinzadehtalaei et al., 2020). These tables indicate the design of Rainfall IDF empirical equation for respective return period and their correlation coefficient, R of all 8 Districts located in Nyabugogo Catchment using similar means. Those designed period equations can be used from 2017 to 2117 which means, the range of the design is 100 years as a designed period.

Table 2: Rainfall IDF empirical equation for respective return period and their correlation coefficient, R for Nyarugenge District.

Return Period(Year)	x	y	Equation	Correlation Coefficient (R)
2	356.25	0.67	$I=356.25(td)^{-0.67}$	R=1
5	491.13	0.67	$I=491.13(td)^{-0.67}$	R=1
10	580.64	0.67	$I=580.64(td)^{-0.67}$	R=1
25	693.53	0.67	$I=693.53(td)^{-0.67}$	R=1
50	812.46	0.67	$I=812.46(td)^{-0.67}$	R=1
100	860.49	0.67	$I=860.49(td)^{-0.67}$	R=1

Table 4: Rainfall IDF empirical equation for respective return period and their correlation coefficient, R for Kicukiri District.

Return Period(Year)	x	y	Equation	Correlation Coefficient (R)
2	328.62	0.67	$I=328.62(td)^{-0.67}$	R=1
5	461.11	0.67	$I=461.11(td)^{-0.67}$	R=1
10	585.93	0.67	$I=585.93(td)^{-0.67}$	R=1
25	659.93	0.67	$I=659.93(td)^{-0.67}$	R=1
50	742.15	0.67	$I=742.15(td)^{-0.67}$	R=1
100	823.93	0.67	$I=823.93(td)^{-0.67}$	R=1

Table 5: Rainfall IDF empirical equation for respective return period and their correlation coefficient for Gicumbi District.

Return Period(Year)	x	y	Equation	Correlation Coefficient (R)
2	275.32	0.67	$I=275.32(td)^{-0.67}$	R=1
5	343.99	0.67	$I=343.99(td)^{-0.67}$	R=1
10	389.57	0.67	$I=389.57(td)^{-0.67}$	R=1
25	447.04	0.67	$I=447.04(td)^{-0.67}$	R=1
50	489.66	0.67	$I=489.66(td)^{-0.67}$	R=1
100	532.05	0.67	$I=532.05(td)^{-0.67}$	R=1

Table 6: Rainfall IDF empirical equation for respective return period and their correlation coefficient, R for Rwamagana District.

Return Period(Year)	x	y	Equation	Correlation Coefficient (R)
2	320.69	0.67	$I=320.69(td)^{-0.67}$	R=1
5	494.24	0.67	$I=494.24(td)^{-0.67}$	R=1
10	609.24	0.67	$I=609.24(td)^{-0.67}$	R=1
25	754.67	0.67	$I=754.67(td)^{-0.67}$	R=1
50	862.38	0.67	$I=862.38(td)^{-0.67}$	R=1
100	969.5	0.67	$I=969.5(td)^{-0.67}$	R=1

In comparing with the value of correlation coefficients R to those found by (Agbazo et al., 2016) in Northern Oueme Valley, Benin Republic (West Africa), (Elsebaie, 2012) in Najran and Hafr Albatin regions in the kingdom of Saudi Arabia (KSA) and (Rasel & Hossain, 2015) in Bangladesh; we were found that the correlation coefficients R for all the eight stations are the same as their results, ranging between (0.997-1). This indicates that in all cases, the correlation coefficient R is very high demonstrating the goodness of fit of the equation to establish Intensity-Duration-Frequency curves in Nyabugogo catchment; mean that a correlation coefficient of 1 was found for each equation, which indicates a strong positive relationship in the IDF equation. Similar results have been obtained by (Kundwa, 2019). Evaluation of Figure 3 and Figure 4 and Tables 3-6, it shows that the highest rainfall will happen at the first rainfall durations (less than 1h), means that much floods will have occurred in this coming years but the effects of a flood happening in Nyabugogo catchment should be managed when Engineers make attention on these results when they were designing flood control and drainage structures in this catchment especially in urban areas. (Agarwal & Evaluation, 2020; Jokowinarno, 2020; Syarifudin & Destania, 2020); discussed the importance of rainfall IDF curves to flood control for future events.

Finally, the formulation of the new hydraulic structures was done with the consideration of the predicted peak rate of runoff for the whole Nyabugogo catchment. Here Manning equation was compared with the hydrological equation (using a rational method). All hydrological discharges established and carried out at Gitega station were simultaneously done for all seven remaining stations. As shown in (table 7), the predicted Q_{logy} (peak rate of runoff) was increased with the increase in the rainfall intensities. As suggested by (Munyaneza et al., 2011) on the rehabilitation and reconstruction of damaged or clogged drainage systems which cause floods in Nyabugogo catchment, it was found that the predicted peak rate of runoff (Q_{logy}) should be less than the hydraulic discharge (Q_{lics}) to overcome or to manage flooding when Engineers are designing any hydraulic structures in Nyabugogo catchment i.e: $\mathbf{Q_{logy} < Q_{lics}}$ (Bengtson, n.d.; DUDFC, 2016). Therefore, with the formulation of a formula for calculation on the maximum amount of water that can or should be permitted to pass through a waterway (drainage system) which is the main cause of flooding in Nyabugogo catchment as the prime objective of this study which has not been addressed in previous books and articles, through the design of a hydraulic structure based on peak rate of runoff in this study, the calculation of maximum water intake of a drainage or waterway is now possible. The Frequency factor or runoff Coefficient Adjustment Factor $\mathbf{(C_f)}$ values that can be used are listed in (Table S6). The product of the Frequency factor $\mathbf{C_f}$ and runoff coefficient **(C)** shall not exceed 1 means $0 < C \leq 1$. The runoff coefficient C is the ratio of the peak runoff rate to the rainfall intensity and is dimensionless. The runoff coefficient is defined as: The runoff coefficient, C, is an integrated value representing many factors influencing the rainfall-runoff relationship, i.e. Topography, vegetation cover and land use (Del Giudice et al., 2012). The coefficient must account for all factors affecting the relation of peak flow to average rainfall intensity other than area and response time. Design values are normally obtained from table S7 of suggested values.

It rarely happens, higher intensity of rainstorms may need a change of the coefficient because infiltration and other losses have a proportionally smaller effect. For adjustment of the Rational Method for use during major rainstorms, this can be done by multiplying the right side of the Rational Formula by a frequency factor C_f. Thus effect. Thus, the rational formula at this point becomes $\mathbf{Q_{logy} = (ARF) * C_f * C * I * A}$. Finally, by using the data from Tables 3 to 6 and Table S2 to S5, the IDF equation can be derived. Table 7 shows the results of the empirical equation of predicted peak rate of runoff (Q_{logy}) using Gumbel distribution and Ration methods respectively. The empirical IDF and The predicted peak rate of runoff (Q_{logy}) equation can be written as seen below:

$$\mathbf{I = X * (td)^{-0.67}}$$

$$Q_{logy} = (ARF) * C_f * C * (X * (td)^{-0.67}) * A$$

Where values of X and C_f are found in Table 3 to 6, Table S2 to S5 and Table S6 respectively.

Table 3: The predicted peak rate of runoff (Q_{logy}), equations for Gitega meteorological station (Nyarugenge District).

Return Period (Year)	x	y	Equation	Hydrological discharge equation (Q_{logy})
2	356.25	0.67	$I=356.25(td)^{-0.67}$	Q_{logy} = (ARF)*C*(356.25(td)$^{-0.67}$)*A
5	491.13	0.67	$I=491.13(td)^{-0.67}$	Q_{logy} = (ARF)*C*(491.13(td)$^{-0.67}$)*A
10	580.64	0.67	$I=580.64(td)^{-0.67}$	Q_{logy} = (ARF)*C*(580.64(td)$^{-0.67}$)*A
25	693.53	0.67	$I=693.53(td)^{-0.67}$	Q_{logy} = 1.1(ARF)*C*(693.53(td)$^{-0.67}$)*A
50	812.46	0.67	$I=812.46(td)^{-0.67}$	Q_{logy} = 1.2(ARF)*C*(812.46(td)$^{-0.67}$)*A
100	860.49	0.67	$I=860.49(td)^{-0.67}$	Q_{logy} = 1.25(ARF)* C*(860.49(td)$^{-0.67}$)*A

Frequency Factors for Rational Formula and its Recurrence Interval (years) are found in table S6. The assumptions associated with the rational method are: If the catchment area increases (>2km^2) the rational formula becomes less accurate (Veneziano & Langousis, 2005). In such a case the point area should be multiplied by ARF (Area Reduction Factor). To deal with this problem, and avoid overestimating flows from larger catchments, *areal reduction factors* (ARF) have been developed. The expression is valid for the storm durations of 5mins to 48h (Jaleel & Maha Atta Farawn, 2013). Processes used in Gitega station for establishing the predicted peak rate of runoff (**Q_{logy}**), equations for Gitega meteorological station (Nyarugenge District), are similar to all remaining seven stations such as Kanombe Aero, Kabuye sugar, Rulindo, Byumba Pref, Rwamagana, Kiziguro and Kayonza station. More precisely, this design can be applied to quantify flood and overflow frequencies of the catchment drainage systems and storage equipment and to design adaptation strategies.

CONCLUSIONS

This paper highlights insights into how the rainfall can be projected in the Nyabugogo catchment. Since the area of the catchment is big and has diverse climatic conditions that vary from one District to another, a relation for each District had gotten to establish the intensity of the rainfall for different duration and different return periods. These equations show that for a given return period a decrease in rainfall intensity leads to an increase in rainfall duration. We found that the results showed a good correlation between the rainfall intensity calculated by the way used and the values developed by the calibrated equations with a correlation coefficient above 0.987. This shows that the goodness of fit of the equations to establish Intensity-Duration-Frequency curves in the District's concern for a duration varying from 10-min to 1440-min and return periods of two years to a hundred years. The rational method estimates the peak rate of runoff at a specific location in a catchment was established. The results show that the peak rate of runoff (hydrological discharge) should be less than hydraulic discharge ($\mathbf{Q_{lics}}$) obtained by using the Manning formula; used for designing hydraulic structures. This will lessen the overflow of water in any designed hydraulic structure. This research will be applied in the designing of hydraulic structures (like culverts and bridges) conservation studies, management of municipal infrastructures and design of safe and economical structural flood control, storage and routing of stormwater, surface drainage and flood plain management. Each District had its presented station in the study. From the research results, the following recommendations have been proposed: Reconstructing the new hydraulic structures due to the incapacity of existing structures of carrying predicted peak discharges; evacuation of residents along the Mpazi channel to avoid flood-related risks and a part of the open channel after the Nyabugogo-Kinamba Bridge be dredged several times to remove all deposed sediments transported by the water along the whole channel. This research strongly agrees that ministry of infrastructures, the ministry of environment and the local community should take necessary means or measures to make sure that proper structures (drainage, bridge, house, etc.) are built and clear in the rainfall season. It is also advised that people should avoid constructing new buildings on waterways to reduce the continuing event of flooding and the government must make sure that constructing buildings in flood-prone areas should be stopped.

Supporting Information

Supplementary data associated with this article can be found in the online version.

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SUPPLEMENTARY INFORMATION

Table 4: Daily AMS Analysis with its Sample and distribution parameters for Gitega Meteorological station.

Year	X(Observed)	Rank	p	u	X(Gumb)
1998	144	1	0.015086207	4.186383451	157.0447707
2005	134	2	0.042025862	3.148079644	131.8616376
2001	119	3	0.068965517	2.638631924	119.5054374
2006	113	4	0.095905172	2.294408351	111.1566015
1996	98	5	0.122844828	2.03201332	104.792444
2003	95	6	0.149784483	1.818521939	99.61440094
1982	93	7	0.176724138	1.637508513	95.22408168
1981	87	8	0.203663793	1.479577824	91.39361363
2004	83	9	0.230603448	1.33884311	87.98021863
1999	80	10	0.257543103	1.211365188	84.88835529
1983	76	11	0.284482759	1.094372539	82.0508029
2007	76	12	0.311422414	0.985835689	79.41833837
1984	73	13	0.338362069	0.884218575	76.95370587
1987	73	14	0.365301724	0.788325161	74.62789662
1988	71	15	0.392241379	0.697200421	72.41774731
2013	71	16	0.419181034	0.610063878	70.30432815
2010	67	17	0.44612069	0.526263396	68.27182218
1995	64	18	0.473060345	0.445241956	66.30671939
2015	64	19	0.5	0.366512921	64.39721683
1997	61	20	0.526939655	0.289640897	62.53275443
2002	60	21	0.55387931	0.21422623	60.70363894
1993	59	22	0.580818966	0.139891703	58.90072126
2000	57	23	0.607758621	0.066270297	57.11509969
2009	57	24	0.634698276	-0.007007019	55.33782373
1992	54	25	0.661637931	-0.080324588	53.55957146
1990	51	26	0.688577586	-0.15409786	51.77026654
2012	50	27	0.715517241	-0.228793663	49.95858642
1989	49	28	0.742456897	-0.304958114	48.11128557
1994	49	29	0.769396552	-0.383257479	46.21220429
2014	49	30	0.796336207	-0.464541689	44.24072826
2016	48	31	0.823275862	-0.549949393	42.16924055
1988	45	32	0.850215517	-0.641094545	39.95859614
2011	41	33	0.877155172	-0.740428247	37.54934578
1991	37	34	0.904094828	-0.852027528	34.84260472
2008	37	35	0.931034483	-0.983631068	31.6506782
1986	34	36	0.957974138	-1.153564409	27.52909653
2017	21	37	0.984913793	-1.433648829	20.73589864
Sample Mean μ_s	68.64864865				
Sample st.Dev σ_s	27.5017335				
Position parameter **(x_0)**	55.50777273				
Scale parameter **(s)**	24.25410838				
Gumbel Mean **(μ_G)**	69.50724409				
Gumbel st.Dev σ_G	31.105894				

With **p**: Exceedance probability, **u**: Reduced variable, and **XG**: Gumbel variable .

Text 1 In the second column of Table S1; sampled extreme rainfall depth, in mm, is ordered in descendent order. In column four values are exceedance probabilities obtained with Gringorten formula. The reduced valuable u is computed using expression (Eq.3.2; Main manuscript). In the last column are given the expected values as were directed by generated by Gumbel distribution in accordance with formula (Eq.3.7; Main manuscript). The mean and standard deviation of the sample and the parameters of the distribution are computed as have seen in the above table.

Table 5: Rainfall IDF empirical equation for respective return period and their correlation coefficient, R for Gasabo District.

Return Period (Year)	x	y	Equation	Correlation Coefficient (R)
2	403.81	0.67	$I=403.81\ (td)^{-0.67}$	R=1
5	506.67	0.67	$I=506.67\ (td)^{-0.67}$	R=1
10	575.12	0.67	$I=575.12\ (td)^{-0.67}$	R=1
25	661.55	0.67	$I=661.55\ (td)^{-0.67}$	R=1
50	758.59	0.67	$I= 758.59(td)^{-0.67}$	R=1
100	789.54	0.67	$I=789.54\ (td)^{-0.67}$	R=1

Table 6: Rainfall IDF empirical equation for respective return period and their correlation coefficient, R for Rulindo District.

Return Period (Year)	x	y	Equation	Correlation Coefficient (R)
2	328.33	0.67	$I=328.33\ (td)^{-0.67}$	R=1
5	457.5	0.67	$I=457.5\ (td)^{-0.67}$	R=1
10	543.23	0.67	$I=543.23\ (td)^{-0.67}$	R=1
25	651.33	0.67	$I=651.33\ (td)^{-0.67}$	R=1
50	731.5	0.67	$I=731.5\ (td)^{-0.67}$	R=1
100	811.22	0.67	$I=811.22\ (td)^{-0.67}$	R=1

Table 7: Rainfall IDF empirical equation for respective return period and their correlation coefficient, R for Gatsibo District.

Return Period (Year)	x	y	Equation	Correlation Coefficient (R)
2	304.95	0.67	$I=304.95\ (td)^{-0.67}$	R=1
5	413.73	0.67	$I=413.73\ (td)^{-0.67}$	R=1
10	485.92	0.67	$I= 485.92(td)^{-0.67}$	R=1
25	576.96	0.67	$I=576.96\ (td)^{-0.67}$	R=1
50	644.47	0.67	$I=644.47\ (td)^{-0.67}$	R=1
100	711.6	0.67	$I=711.6\ (td)^{-0.67}$	R=1

Table 8: Rainfall IDF empirical equation for respective return period and their correlation coefficient, R for Kayonza District.

Return Period(Year)	x	y	Equation	Correlation Coefficient (R)
2	337.43	0.67	$I=337.43\ (td)^{-0.67}$	R=1
5	478.25	0.67	$I=478.25\ (td)^{-0.67}$	R=1
10	571.7	0.67	$I=571.7\ (td)^{-0.67}$	R=1
25	687.55	0.67	$I=687.55\ (td)^{-0.67}$	R=1
50	776.94	0.67	$I=776.94\ (td)^{-0.67}$	R=1
100	863.86	0.67	$I=863.86\ (td)^{-0.67}$	R=1

Table 9: Frequency Factors or Coefficient Adjustment Factor for Rational Formula and its Recurrence Interval (years).

Recurrence Interval (years)	Frequency factor (C_f)
10 or less	1.0
25	1.1
50	1.2
100	1.25

Text 2 All these Rainfall IDF empirical equations for respective return period and their correlation coefficient tables, from the table, S2 up to table S5, their IDF Curve's figures are in the main manuscript (Figure 4a to 4d): Rainfall IDF curve for **(a)** Kabuye sugar station-Gasabo District, **(b)** Rulindo station-Rulindo District, **(c)** Kiziguro station-Gatsibo District and **(d)** Kayonza station-Kayonza District.

Text 3: The runoff coefficient (C) is coefficient which has no unity (dimensionless) connect with the runoff of volume to the precipitation volume received. It is not small value for areas with high runoff (steep gradient and pavement), lower permeability and low infiltration, well vegetated areas (flat land and forest). The runoff coefficient is highly used to construct channels for controlling flood and to figure out possible flood zone risk. A high runoff coefficient (C) value may show flash flooding zones during rainstorms as water moves fast overland on its way to a river channel or a valley floor. It is determined by measuring the permeability, soil type, land use and gradient. The higher runoff correspond with larger values and lower infiltration. The values are given to the table 7.

Table 7: Rational Method Runoff coefficient.

Land use	C	Land use	C
Business:		***Lawns***	
Downtown area	0.70 -0.95	Sandy soil, flat, 2%	0.05-0.10
Neighborhood areas	0.5 - 0.70	Sandy soil, avg.,2-7%	0.10-0.15
		Sandy soil, steep,7%	0.15-0.20
		Heavy soil, flat, 2%	0.13- 0.17
		Heavy soil, avg., 2-7%	0.18-0.22
		Heavy soil, steep, 7%	0.25-0.35
Residential:		***Agricultural land***	
Single-family areas	0.30-0.50	*Bare packed soil*	
Multi-units, detached	0.40-0.60	Smooth	0.30-0.60
Munti-units,	0.60-0.75	Rough	0.20-0.50
detached	0.25-0.40	*Cultivated rows*	
Suburban		Heavy soil, no crop	0.30-0.60
		Heavy soil, with crop	0.20-0.50
		Sandy soil, no crop	0.20-0.40
		Sandy soil, with crop	0.10-0.25
		Pasture	
		Heavy soil	0.15-0.45
		Sandy soil	0.05-0.25
		Woodlands	0.05-0.25
Industrial:		**Streets:**	
Light areas	0.50-0.80	Asphaltic	0.70-0.95
Heavy areas	0.60-0.90	Concrete	0.80-0.95
		Bricks	0.70-0.85
Parks, cemeteries	0.10-0.25	Unimproved areas	0.10-0.30
Playgrounds	0.20-0.35	Drives and walks	0.75-0.85
Railroad yard areas	0.20-0.40	Roofs	0.75-0.95

Table 8: Chi-Square Distribution Table.

df	$X^2(0.995)$	$X^2(0.99)$	$X^2(0.975)$	$X^2(0.95)$	$X^2(0.05)$	$X^2(0.025)$	$X^2(0.01)$	$X^2(0.005)$
1	0.000	0.000	0.001	0.004	3.841	5.024	6.635	7.880
2	0.10	0.20	0.051	0.103	5.991	7.378	9.210	10.597
3	0.072	0.115	0.216	0.352	7.815	9.348	11.345	12.838
4	0.207	0.297	0.484	0.711	9.488	11.143	13.277	14.861
5	0.412	0.554	0.831	1.145	11.071	12.833	15.086	16.750
6	0.676	0.872	1.237	1.635	12.592	14.449	16.812	18.548
7	0.989	1.239	1.690	2.167	14.067	16.013	18.476	20.279
8	1.344	1.646	2.180	2.733	15.507	17.535	20.090	21.956
9	1.735	2.088	2.700	3.325	16.919	19.023	21.666	23.590
10	2.156	2.558	3.247	3.940	18.307	20.483	23.210	25.189
11	2.603	3.053	3.816	4.575	19.675	21.920	24.725	26.757
12	3.074	3.571	4.404	5.226	21.026	23.337	26.217	28.300
13	3.565	4.107	5.009	5.892	22.362	24.736	27.688	29.819
14	4.075	4.660	5.629	6.571	23.685	26.119	29.141	31.319
15	4.601	5.229	6.262	7.261	24.996	27.488	30.578	32.801
16	5.142	5.812	6.908	7.962	26.296	28.845	32.000	34.267
17	5.697	6.408	7.564	8.672	27.587	30.191	33.409	35.718
18	6.265	7.015	8.231	9.390	28.869	31.526	34.805	37.156
19	6.844	7.633	8.907	10.117	30.144	32.852	36.191	38.582
20	7.434	8.260	9.591	10.851	31.410	34.170	37.566	39.997
21	8.034	8.897	10.283	11.591	32.671	35.479	38.932	41.401
22	8.643	9.542	10.982	12.338	33.924	36.781	40.289	42.796
23	9.260	10.196	11.689	13.091	35.172	38.076	41.638	44.181
24	9.886	10.856	12.401	13.848	36.415	39.364	42.980	45.559
25	10.520	11.524	13.120	14.611	37.652	40.646	44.314	46.928
26	11.160	12.196	13.844	15.379	38.885	41.923	45.642	48.290
27	11.808	12.879	14.573	16.151	40.113	43.195	46.963	49.645
28	12.461	13.565	15.308	16.928	41.337	44.461	48.278	50.993
29	13.121	14.256	16.047	17.708	42.557	45.722	49.588	52.336
30	13.787	14.953	16.791	18.493	43.773	46.979	50.892	53.672
40	20.707	22.164	24.433	26.509	55.758	59.342	63.691	66.766
50	27.991	29.707	32.357	34.764	67.505	71.420	76.154	79.490
60	35.534	37.485	40.482	43.188	79.082	83.298	88.379	91.952
70	43.275	45.442	48.758	51.739	90.531	95.023	100.425	104.215
80	51.172	53.540	57.153	60.391	101.879	106.629	112.329	116.321
90	59.196	61.754	65.647	69.126	113.145	118.136	124.116	128.299
100	67.328	70.065	74.222	77.929	124.342	129.561	135.807	140.170

With df: degree of freedom.

Table 9: Critical values of Kolmogorov-Smirnov test.

Sample size(n)	α=0.20	α= 0.15	α =0.10	α =0.05	α =0.01
1	0.900	0.925	0.950	0.975	0.995
2	0.684	0.726	0.776	0.842	0.929
3	0.585	0.597	0.642	0.708	0.829
4	0.494	0.525	0.564	0.624	0.734
5	0.446	0.474	0.510	0.563	0.669
6	0.410	0.436	0.470	0.521	0.618
7	0.381	0.405	0.438	0.486	0.577
8	0.358	0.381	0.411	0.457	0.543
9	0.339	0.360	0.388	0.432	0.514
10	0.322	0.342	0.368	0.409	0.486
11	0.307	0.326	0.352	0.391	0.468
12	0.295	0.313	0.338	0.375	0.450
13	0.284	0.302	0.325	0.361	0.433
14	0.274	0.292	0.314	0.349	0.418
15	0.266	0.283	0.304	0.338	0.404
16	0.258	0.274	0.295	0.328	0.391
17	0.250	0.266	0.286	0.318	0.370
18	0.244	0.259	0.278	0.309	0.370
19	0.237	0.252	0.272	0.301	0.361
20	0.231	0.246	0.264	0.294	0.352
25	0.210	0.220	0.240	0.264	0.320
30	0.190	0.200	0.220	0.242	0.290
35	0.180	0.190	0.210	0.230	0.270
40				0.210	0.250
50				0.190	0.230
60				0.170	0.210
70				0.160	0.190
80				0.150	0.180
90				0.140	
100				0.140	
Asymptotic F.	$1.07/\sqrt{n}$	$1.14/\sqrt{n}$	$1.22/\sqrt{n}$	$1.36/\sqrt{n}$	$1.63/\sqrt{n}$

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