ESTABLISHMENT OF RAINFALL INTENSITY-DURATION-FREQUENCY (IDF) CURVES FOR MAMPONG-ASHANTI MUNICIPAL AREA OF THE ASHANTI REGION IN GHANA

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ABSTRACT

The paper presents intensity-duration-frequency (IDF) curves developed for the Mampong-Ashanti Municipal area using autographic rainfall data. The intensity-duration-frequency relationship is a mathematical relationship between the rainfall intensity, the duration and the return period commonly required for planning and designing of various hydrological resource projects. Many sets of relationships have been developed and used in several parts of the world. This relationship is determined through statistical analysis of samples of records collected from the catchment's meteorological station. Mampong-Ashanti Municipal area in the Ashanti Region of Ghana has a daily rainfall recording rain gauge. A total of six different durations ranging from 5 minutes to 60 minutes for return periods of 1, 2, 3, 4, 6, 7, 11 and 22 years were analyzed. The IDF curves for the area were developed using the available rainfall data, Weibull plotting position and empiricism.

Keywords: rainfall, intensity-duration-frequency, hydro climatology, return period, exceedence proability.

1. INTRODUCTION

The principal characteristics of a storm are its intensity, duration, total amount and frequency or recurrence interval. Rainfall intensity is expressed as the rate of rainfall in millimetres per hour (Okonkwo and Mbajiorgu, 2010). (Dupont *et al.* 2000) defined rainfall intensity-duration-frequency (IDF) relationships as graphical representations of the amount of water that falls within a given period of time. These graphs can be used to determine when an area will be flooded and when a certain rainfall rate or a specific volume of flow will re-occur in the future. The intensity is an important characteristic of rainfall because, other things being equal, more soil erosion can be caused by one rainstorm of high intensity than by several storms of low intensity. Similarly, rainfall duration is the period of time that rain falls at a particular rate or intensity. For every storm, the rainfall intensity may vary from high to very low; hence, the duration is how long time rainfall intensity lasts at a particular rate. Generally, the high-intensity portion of a storm has a shorter duration than the low-intensity portion. Frequency is how often a storm of specified intensity and duration may be expected to occur (Rick, 2007). According to him IDF can be reported in two ways; probability (p) that an event of specified depth and duration will be exceeded in a year and the average length of time (T) between events of a given depth and duration.

Rainfall is an integral component in the hydrologic cycle. Engineers must be able to quantify rainfall in order to design structures impacted by or dealing with the collection, conveyance, and storage of excess rainfall. Quantification of rainfall is generally done using isopluvial maps and intensity-duration-frequency (IDF) curves. These two tools are used by engineers to design safe and cost effective structures for certain return periods, thus accepting a certain amount of risk that the capacity may be exceeded (Raiford *et al*., 2007). According to Easterling *et al*., (2000) an important effect of warming of the climate system is intensification of the hydrologic cycle that leads to shifts in temperature and rainfall patterns and that the timing and frequency of extreme rainfall events are influenced by changing climate conditions which have the potential of destroying engineering design standards. They further opined that design of municipal water management infrastructure (sewers, storm water management ponds or detention basins, etc.) are typically based on the use of local extreme rainfall characteristics captured through intensity duration frequency (IDF) analysis. Such curves are developed using historically observed rainfall time series data, where annual extreme rainfall for each duration is extracted and fitted to a theoretical probability distribution, they added.

The 2000-2009 decade has shown an increasing evidence of more extreme rainfall at different places around the world and these, according to the 4thAssessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), have been linked to global warming due to an increase in atmospheric vapour and air temperature. Kotei *et al*., (2013) examined the annual time series rainfall magnitudes in the Mampong-Ashanti Municipal catchment and emphasized that the rainfall regime is characterized by strong inter-annual variability without any significant trend in the extremes for the period 1980-2009. And that, between 1990-1999 and 2000-2009, water loss by actual evapotranspiration (ET_a) increased by 5.26%.

According to Brian *et al.* (2006), rainfall frequency analyses are used extensively in designing hydraulic systems to handle storm runoff, including roads, culverts and drainage systems. Smith (1993), states that "the rainfall frequency analysis problem is to compute the amount of rainfall falling over a given area in a duration of *x* minutes with a given probability of occurrence in any given year." For engineering design applications, it is necessary to specify the temporal distribution of rainfall for a given frequency, or return interval. IDF or Depth-Duration-Frequency (DDF) curves "allow calculation of the average design rainfall intensity (or depth) for a given exceedence probability over a range of durations" and is the result of the rainfall frequency analysis. IDF estimates are important statistical summaries of rainfall records used for hydrologic engineering design (Gerold and Watkins, 2005).

Rainfall is the limiting factor in the forest-savannah transitional zones. It governs the crop yields and determines the choice of the crops that can be grown and the required technologies. Therefore, a detailed knowledge of rainfall regime is an important prerequisite for agricultural planning. The analysis of rainfall for agricultural purposes must include information concerning the trends or changes of precipitation, the start end and length of the rainy season, the distribution of rainfall amounts throughout the year, and the risk of dry and wet spells (Pashiardis, 2004).

Inspite of having a good rainfall average, the Mampong Municipality intermittently experiences acute problem of water shortage during the dry season. Since the economy of the area depends solely on agriculture which, in turn, relies on rainfall, the study of changes in rainfall magnitudes and trends is very important for agro-ecological planning in the area. To understand the problem of rainfall and particularly for identification of any trend or persistence in the rainfall series, a climatological study of rainfall in the catchment is undertaken. The Municipal catchment does not have IDCs for hydrological designs and urban development. On the other hand, rainfall variations lasting decades or longer have the potential to greatly surpass short-term variations in their societal, economic, and political impacts (Woodhouse and Overpeck, 1998). Even though decade-scale precipitation variations are subtler, it is the cumulative effects of sustained departures from average conditions that may lead to the greater impacts.

The main water sources in the catchment, rainfall, surface and groundwater, have been affected by climate change, deforestation, exploitation of sand and gravel deposits and increasing drought periods and occurrence. Generally, however, much of the catchment receives sufficient rain, but the full potential of this condition has not been exploited. Further municipal resource development is constrained by fear of increasing erosion risk levels and ecological degradation, technical inadequacy, and budgetary limits. Water demand is on an ever-increasing spree due to the formidable effects of population expansion, economic development, and changing life-style as the catchment plays host to one University, two Colleges of Education and six Senior High Schools whose annual enrollments keep increasing and putting variable annual and intra-annual pressure on the resources as students go down and come back.

Six major effects of urbanization have been identified in the catchment: a higher proportion of rainfall appears as surface runoff, catchment's response to rainfall is becoming flashy with a decreasing lag time, increasing peak flow magnitudes, decreasing low flow magnitudes perceived to be due to reduced contributions from ground storage, increasing abstraction, increasing effluent discharges, intensified exploitation of sand (near the gauge station) and gravel deposits (near the Sumampa-Offinso divide) for urban and rural development.

The Municipal area has undergone major anthropogenic changes affecting its land cover for over five decades. These changes, however, have not been quantified in a manner to allow wider scale understanding of the causative factors, their effects and show hot spots that required immediate intervention. The Mampong-Ashanti Municipality has experienced series of drought since 1980 caused by rainfall failure, rain coming rather late causing short agriculture season or excessive rains which cause damage to properties and affect valley bottom and wetland agriculture. Since the economy of the area depends solely on agriculture which, in turn, relies on rainfall, the study looks at quantification of rainfall through the establishment of local intensity-duration-frequency curves for designing safe and cost efficient hydraulic structures for certain return periods. No Intensity-Duration-Frequency curves have been generated in the area. The objective of this study was to establish intensity-duration-frequency curves for planning and designing of hydraulic structures in the Municipality. This will help in better interpretation of the catchment hydrological conditions and their socio-economic and ecological impact on the catchment. The paper looks at the establishment of intensity-duration frequency (IDF) and rainfall probability curves for the 1980-2009 by the analytical method.

2. MATERIALS AND METHODS

2.1. Study area

The Municipal area is located within longitudes 0.05^o and 1.30^o west and latitudes 6.55^o and 7.30^o north, covering a total land area of $2346km^2$. It has about 220 settlements with about 70% being rural. The rural areas are mostly found in the Afram Plains portion of the Municipality where communities with less than fifty (50) people are scattered here and there. The Sumampa stream catchment, ($07^o04^'$N and $010^o024^'$W) is located within the forest-savannah transitional zone, Mampong-Ashanti, Ghana, with a population of 44,380 at a growth rate of 4.2% (MLGRD, 2006). The land surface elevation varies from 457m above sea level at the summit of the highland, near Daaman, on the Eastern side of the Sumampa stream to 290 m above sea level at the confluence of the stream (Sumampa) to the Kyirimfa River near the Ghana Water Company Limited'sreservoir.

2.2. Hydrology, climate and vegetation

The combined effects of climatic and geological conditions on the catchment's topography has yielded

 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

subdendritic drainage pattern characterized by a network of channels and 12 streams. The site experiences double maximum rainfall patterns with peak rainfall periods in May-June and September-October and dry periods between July-August and November-February. The climate is typically tropical, with total annual rainfall between 1270mm-1524mm (MSA, 2006), annual average of 1300mm. The mean monthly temperature is about 25-32^{o}C. The potential evapotranspiration (PET) is estimated at 1450mm per annum. The average humidity during the wet season is typically high (86%) and falls to about 57% in the dry period (MSA, 2006).

2.3. Data collection

The rainfall data used in this study were obtained from the Ghana Meteorological Service Agency (MSA), Accra. The catchment station is a standard agro-meteorological station in which most climatic data are measured. Continuous daily rainfall data for the station is available since 1980. This 30-year period of data is sufficient to establish a long-term climate (Aldabadh *et al*., 1982).

2.4. Establishing intensity-duration frequency (IDF) curves

There are three steps of establishing IDF curve of precipitation. The first consists of fitting a probability distribution function to the data for each duration. Secondly, quantiles for each duration and for a set of return periods are calculated using the probability function. Finally, the IDF Tables are obtained by a non-linear regression on the quantiles, given a criterion function (Demarée, 2004).

2.5. Procedure of data analysis (graphical method)

In this study, IDF curves were developed for the Mampong-Ashanti Municipality for 7 different durations (ranging from 5 to 60 minutes) and 8 different return periods. Data collection and verification was the first step in the process. The data series were obtained as annual maximum series and the following operations carried out: Every storm in a year, from 1980 to 2008, was analyzed to determine the maximum intensities for durations of 5, 10, 15, 20, 30, 45 and 60min. Thus each storm gave one value of maximum intensity for a given duration. The largest of all such values was taken to be the maximum intensity in that year for that duration. Likewise the annual maximum intensities were obtained for all durations in different years. Maximum intensities were computed from;

$$I = \frac{R}{t} \text{ (mm/h)} \quad (1)$$

Where I is the intensity in mm/h, R is the amount of rainfall in mm, and t is the duration of rainfall in hours. The maximum intensities determined were ranked in descending order of magnitude such that the largest value was assigned a rank number 1. Return period was then computed using the Weibull plotting position:

$$T = \frac{(n+1)}{m} \quad (2)$$

Where

T is the return period in years, n is the number of items in the sample, and m is the rank of the individual items in the sample array. Regression of the intensity values for all the durations against the return periods gave a curve model with *Easyfit* statistical software. Rainfall intensities for varying durations were plotted against the return periods on normal axes using the *Excel* programme. From the plots, data of intensity against return periods of 1, 2, 3, 4, 6, 7, 11 and 22 years were extracted for each duration. Intensity was then plotted against duration as a function of return period on normal log paper.

2.6. Analytical method

The analytical method was used to determine the IDF parameters (a, b c) values of the IDF equation of the general form as in Equation (3). The maximum intensities were determined from the equation. It varies inversely with the duration and generally an equation of the form given by Equation (1) can be fitted between the maximum intensity and duration.

$$I = \frac{C}{(t+a)^b} \quad (3)$$

That is,

$$I = \frac{C_1}{(t+a1)^{b_1}} ; = \frac{C_2}{(t+a2)^{b_2}} ; \text{ etc.} \quad (4)$$

Where C_1, a_1 and b_1 are applicable for one return period T_{r1}, C_2, a_2 and b_2 are applicable for another return period T_{r2} etc. Generally, it is observed that the constants a and b are approximately the same for all the return periods and only C is different for different return periods. In such a case one general equation may be developed for all the return periods as given by:

$$I = \frac{KT_r^d}{(t+a)^b} \quad (5)$$

Where

T_r is the return period in years and K and d are the regression constants for a given location. If a and b are not same for all the return periods, then an individual Equation for each return period may be used:

$$I = \frac{C}{(t+a)^b} \quad (6)$$

is assumed between *I* and *t*. The values of *C*, *a* and *b* are obtained through regression analysis. Where *t* is time (duration) in minutes, and *I* is intensity of rainfall (mm/h). The regression constants are different for different locations. Taking logarithms on both sides transforms the equation into a linear form.

$$\log I = \log C - b \log (t+a) \quad (7)$$

The best value of C, *a* and *b* are those for which the sum of the squared deviations is minimum. That is equation 8 should be minimum. Partial differentiation of S with respect to *C* and *b* yields equations (9) and (10).

$$S = \sum[\log I - \{\log C - b\log(t+a)\}]^2 \quad (8)$$

$$\sum \log I = n \log C - b \sum \log(t+a) \quad (9)$$

$$\sum[\log I \log(t+a)] = \log C \sum \log(t+a) - b\sum[\log(t+a)]^2 \quad (10)$$

Where *n* is the number of observations and all the summations are over all the observed values. After obtaining the required summations Equations (9) and (10) are solved simultaneously to provide the best values of *C* and *b* for any assumed value of *a* and the best value of *a* itself has to be found only by trial and error (Reddy, 2002).

3. RESULTS AND DISCUSSIONS

Figure-1 shows maximum rainfall intensities at durations of 5, 10, 15, 20, 30, 45 and 60min at return periods of 1, 2, 3, 4, 6, 7, 11 and 22y. From the graph, rainfall intensities, their return periods at various durations can be determined. The ranked maximum annual rainfall intensities and their exeedence probabilities at the various durations were extracted. The rainfall-intensity-probability graphs for annual maximum, mean and minimum intensities have also been plotted (Figure-5). From Figure-1, return periods of given rainfall intensities could be determined and from Figure-2, rainfall durations of given maximum intensities could be determined. The exceedence probabilities of annual maximum mean and minimum intensities in the catchment respectively can be determined from the curves.

The median maximum rainfall (50% probability) is 195.2mm (Figure-4) with a return period of 2yrs. Normal maximum rainfall occured between 335.5mm (25% probability) and 81.9mm (75% probability). The assessment of extreme rainfall magnitudes is an important problem in hydrologic risk analysis and design. This is why the evaluation of rainfall extremes, as embodied in the IDF relationship, has been a major focus of both theoretical and applied hydrology (Andreas and Veneziano, 2006). The rainfall IDF curves are derived from the point agro-meteorological station; eight set of IDF curves at point were established. The results are shown in Figure-2. Then the relationship between the maximum rainfall intensities and the durations for every return period are determined by fitting general empirical function. The fitness of the desired regression equation for the return periods in the study area are presented in Table-1 and the values of the parameters at the various return periods in Table-2. The maximum rainfall intensities at various durations for a given return period can be estimated by the regression models developed for the catchment area.

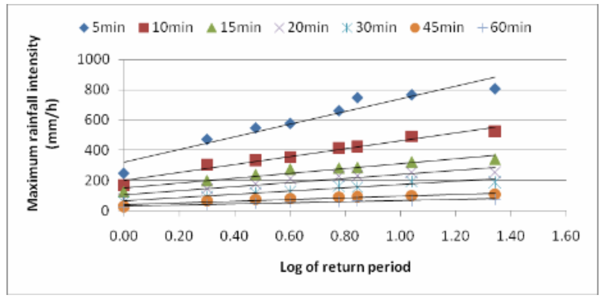

Figure-1. Rainfall intensity-frequency curve.

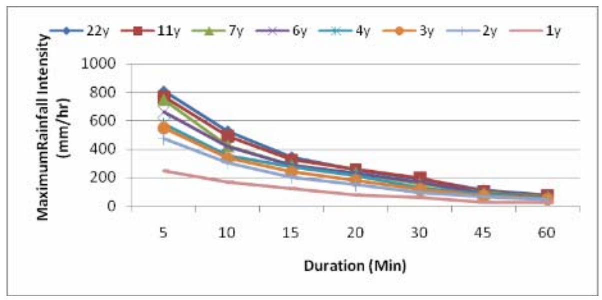

Figure-2. Rainfall intensity duration curve.

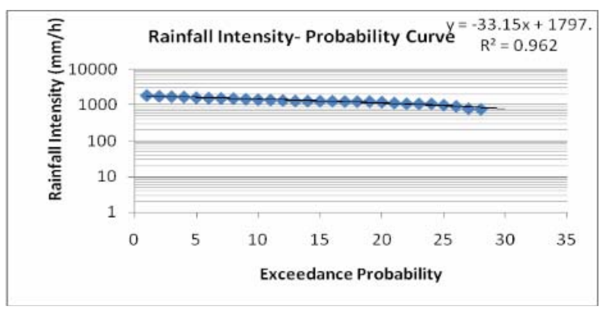

Figure-3. Rainfall intensity-duration curve.

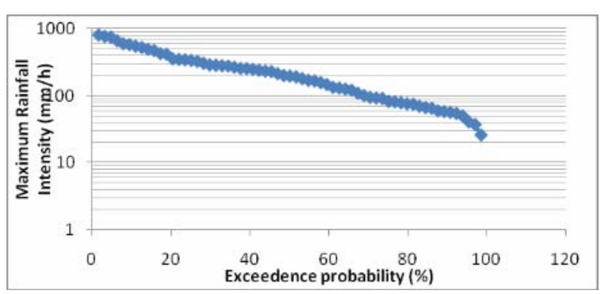

Figure-4. Maximum rainfall intensity probability curve.

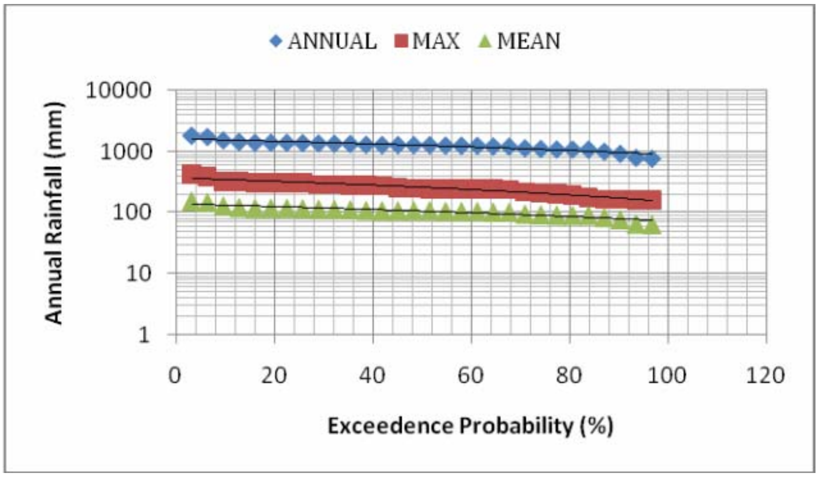

Figure-5. Annual maximum, mean and minimum rainfall probability curves.

Table-1. Empirical models determined from analytical methods for various return periods from 1980-2009 rainfall data.

Return period (y)	**Desired rainfall intensity regresion model** (mm/h)	**Return period** (y)	**Desired rainfall intensity regresion model** (mm/h)
22	$I = \frac{3505.88}{(t+2)^{0.8514}}$	4	$I = \frac{2716.06}{(t+2)^{0.8668}}$
11	$I = \frac{1684.74}{(t+2)^{0.69812}}$	3	$I = \frac{2376.96}{(t+2)^{0.855}}$
7	$I = \frac{2139.54}{(t+2)^{0.51859}}$	2	$I = \frac{1803.13}{(t+2)^{0.8223}}$
6	$I = \frac{3003.5}{(t+2)^{0.96054}}$	1	$I = \frac{1405.79}{(t+2)^{0.9180}}$

Table-2. Empirical parameters for mampong-ashanti Agro-meteorological station (1980-2009).

Return period (Y)	**Agro-meteorological station IDF curve parameters**		
	C	***a***	***b***
1	1,405.79	2	0.9180
2	1,803.13	2	0.8322
3	2,376.96	2	0.8550
4	2,716.06	2	0.8668
6	3,003.5	2	0.9605
7	2,139.54	2	0.5185
11	1,684.74	2	0.6981
22	3,505.88	2	0.8514

4. CONCLUSIONS

The Municipal IDF formula parameters have been generated to estimate rainfall intensity for various return periods and rainfall durations. The parameters *C*, a, and *b* (Table-2) were determined through regression analysis using the analytical method. Then, the IDF curves at the site were established by extracting annual maximum rainfall intensities and using the empirical equation (Table-1) developed from the relationship between the maximum rainfall intensity and duration. The observed maximum rainfall intensities for the durations of 5, 10, 15, 20, 30, 45 and 60min were plotted against the respective durations to obtain the intensity-duration graphs. The IDF curves were generated using data from the agro-meteorological station by using empirical equation to represent IDF relationship for the Mampong-Ashanti Municipal area in the forest-savannah-transitional zone of the Ashanti region. The three parameters function has shown acceptable fitting to the rainfall intensity quartiles. Accordingly the IDF curves are constructed for the area to estimate rainfall intensity for various return periods and rainfall durations. An increase in rainfall intensity as a result of climate change may impact the design of hydraulic infrastructure because the 1980-2009 rainfall data series indicates an increasing trend in the rainfall magnitudes (Kotei *et al*., 2013). With the catchment empirical models and the IDFs hydraulic infrastructure could be designed to accommodate future runoff extremes augmented by urbanization.

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