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Hydrological Analysis For Planning Rooftop Rainwater Harvesting of Urban Area

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Abstract: *Increase in the impervious surface in general increases the volume of stormwater runoff, and there is a reduction in groundwater recharge to the aquifer below. In India, about 310 administrative blocks are over-exploited where groundwater is withdrawn more than its replenishment from rainfall. The groundwater levels have declined by more than 4 meters in 40 districts of 16 states in the country during the last decade, and urban areas are most vulnerable. Roof water harvesting and artificial recharge can be a better action plan in urban areas to control rainwater, surface water and groundwater interaction and towards conservation of quantity and quality of water resources. Practices such as roof water harvesting and artificial recharge need to be evaluated as alternate interventions to undertake such restoration of natural conditions in urban areas. For planning water harvesting systems, the long term daily as wells as short term sub-hourly data are equally important. Long term data on normal rainfall and number of rainy days is important to plan roof water harvesting potential and design of harvesting systems requires information on sub-hourly rainfall intensity. Information on the intensity of rainfall over an urban watershed and the resulting stormwater runoff is needed to design the size of any artificial recharge structure for proper restoration of declining groundwater levels.*

Keywords: *Roof water harvesting, artificial recharge, groundwater and rainfall*

INTRODUCTION: Rapid industrialisation and urbanisation, coupled with a continuous decline in per capita water availability, is putting a lot of pressure on the available water resources in the country. In India, about 310 blocks in India are over-exploited, where groundwater is withdrawn more than its replenishment from rainfall (CWC, 2005). The groundwater levels have declined by more than 4 m in 40 districts of 16 states in the country over a decade. As per the report of standing Sub-Committee for Assessment of Availability and requirements of water for diverse uses in the country, the future water requirements for meeting the demands of various purposes in the country for the year 2025 and 2050 have been estimated to be 1093and 1447 Billion Cubic Meters (BCM) respectively. The increasing gap between water availability and demand highlights the need for conservation of water.

In Madhya Pradesh, the urban population has increased from 8.14 % to 32% in the last century. The growth up to the year 2011 is more than the national average of 31%. The population of about 26.35 million out of a total of 73.35 million lives in urban areas in the state as of 2011. Whereas, this was only 5.95 million people in the state during 1961. Thus, in the last half a century, the urban population increased by about 21 million. Thus urbanisation is taking place at a brisk pace and has a striking impact on the natural resources and especially on the hydrology of the urban areas. Schwartz and Smith (2014) analysed hydrological data along the rural to the urban land-use gradient. They demonstrated the multi-metric slow flow analysis that quantifies distinct differences in urban slow-flow response to elucidate the dominant processes driving the slow flows in the urban hydrology.

Study Area: Bhopal is popularly known as the city of Lakes. Bhopal gets this distinction because of a large number of lakes, tanks and ponds in the city shown in Figure 1. The city is relatively away from a dependable perennial lotic water source; hence the administrators had to construct ponds and reservoirs to cater to the needs of the city. Presently the city occupies a geographical area of about 285.88 km^{2,} and According to the 2011 census, the population of the Bhopal city (the area under Bhopal Municipal Corporation) is 1,798,218, with 936,168 males and 862,050 females.

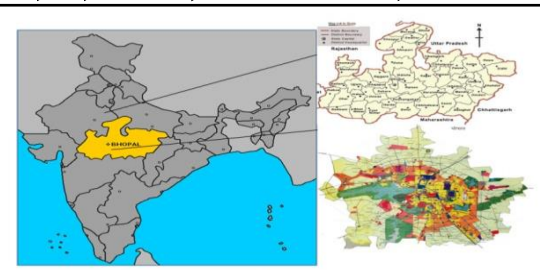

Figure 1 - Inventorization of electronic waste from selected target area of Bhopal city

Rainfall: This study is undertaken to understand the urban hydrology and its rainfall-runoff relationship during urbanisation and its impact on groundwater recharge to the aquifer of a typical coastal city of Bhopal. Rainfall is monitored using digital rain gauge to measure short-duration rainfall, which is the key input in the estimation of runoff in an urban watershed. The stable isotopes of hydrogen and oxygen can be used to characterise the precipitation and other sources of water in a region or area. Spatial distribution of rainfall of Bhopal is shown in Figure 2.

Hydrological Analysis: In this chapter hydrological analysis of data on sub-hourly rainfall, runoff and groundwater recharge and their interaction are presented for Bhopal city. The results from the hydrologic budget to understand the impact of rainfall on groundwater recharge during various stages of urbanisation have been discussed. In this study, a procedure to understand the impact of urban development on the hydrological budget of an urban watershed is demonstrated.

Analysis for Planning Rooftop Rainwater Harvesting: To overcome the problem of reduced groundwater recharge while urbanisation continues, planning appropriate rainwater harvesting techniques and adopting artificial recharge methods is very important. In a watershed, the type of structures to store and recharge rooftop rainfall-runoff depends on the size of harvesting area, useful rainfall, IDF of short duration or sub-hourly rainfall, the available space and its cost apart from natural drainage, soils and hydro-geological setup of the aquifer system below.

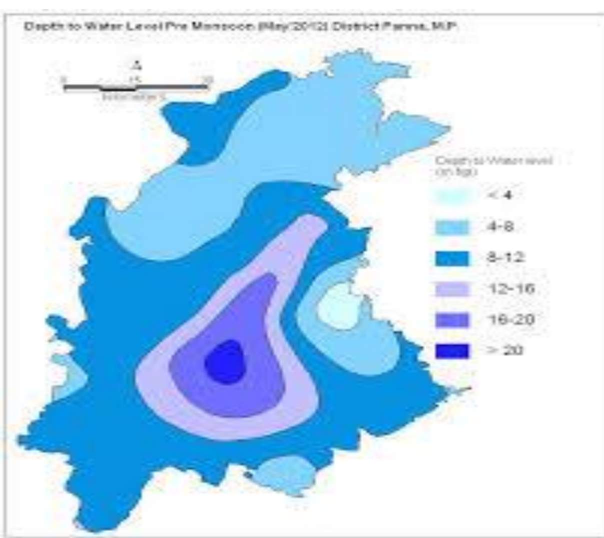

Fig. 2: Spatial distribution of rainfall of Bhopal

The impact of the progress of urbanisation or level of urbanisation is to be evaluated to account for important hydrologic components. Such evaluation is required to understand the quantities of excess surface runoff, which becomes an input to the water harvesting system to be designed. Next stage is to evaluate the quantities using a rainfall-runoff model to establish hydrographs which facilitate in understanding the effects of urbanisation and to know the storage volumes to be disposed of.

Short Duration Rainfall Analysis: Rainfall is an important observed input data and necessary to estimate runoff from any hydrological model. However, the temporal resolution over which rainfall data is to be input depends on the size of watershed. For urban hydrological models dealing with the design of rooftop rain harvesting, rainfall data is required over 5 to 30 minutes or sub-hourly and is rarely available. Thus, providing sub-hourly rainfall is the key to rainfall-runoff model and is an important observed input data required in the design of roof water harvesting and design of artificial recharge structures. As observed rainfall over such short durations is scarcely available, it can be estimated from daily or hourly observed rainfall data using typical temporal disaggregating techniques (Ramaseshan, 1996). In this study, using the observed short duration rainfall of several events over five years at Bhopal, a sub-hourly disaggregating relationship from hourly rainfall is developed. The procedure of the same was dealt with in detail in the previous chapter. Using the developed sub-hourly disaggregating relationship and combing the same with disaggregating daily rainfall to hourly rainfall, frequency analysis of the short duration rainfall is undertaken from the procedure of Ramaseshan (1996) by estimating hourly rainfall for over 30 years using corresponding observed annual peak daily rainfall. Using such estimated sub-hourly rainfall at Bhopal for 30 years in frequency analysis, intensity-duration-frequency relationship or IDF relationship is developed following the EV I distribution.

Frequency Analysis of Rainfall: Information on the frequency of heavy rainfall is often required for water management and design of drainage systems. For the present study, EV I distribution has been applied to the available short duration rainfall data. A brief description of the EV1 distribution follows (Chow et al., 1988 and Cunnane, 1989). The probability distribution function for EV I is given by

$$F(q) = P(Q<=q) = {}_{e}\text{-}e^{-(Q-u)/\alpha}$$

where u and α are the location and scale parameters of the distribution and q is the threshold value for the excellence of which probability P is assessed. The parameters of u and α are given by α

$$u = P_m - 0.5772\,\alpha$$
$$\alpha = (\sqrt{6}\,S)/\Pi$$

where P_m and *S* are the samples, mean precipitation and sample standard deviation, respectively. The plotting position for the EV I distribution as proposed by Gringorten (1963) and used in the present study is

$$F_i = (i - 0.44)/(N+0.12)$$

where F_i is the plotting position, N is the sample size, and 'i' is the rank with i=l, indicating the smallest sample member. The reduced variate of EV I can be defined as

$$Y_i = -\ln(-\ln(F_i))$$
$$Y_T = -\ln(-\ln(1 - (\tfrac{1}{Tr})))$$

where T_r is the return period. Using the method of frequency factors, the expected value of precipitation for a given return period, 'P_{Tr}' can be obtained from the relation

$$P_{Tr} = P_m + K_{Tr}.S$$

where K_{Tr} is the frequency factor given by

$$K_{Tr} = (-\sqrt{6}/\Pi)[0.5772 + l_n\{-l_n(1-(1/Tr)\}]$$

Rainfall Analysis for Bhopal: The availability of observed hourly rainfall data is limited due to very poor network of such rain gauges. By analysing data at some locations where both hourly and daily rainfall data is available Ramaseshan (1996) proposed a relationship to disaggregate daily rainfall to a given 't' hour rainfall as

$$P_t = P_{24}(\sqrt[3]{t/24})$$

where P_t is required precipitation depth for the duration t-hour in mm, P_{24} is daily precipitation in mm and t is the time duration for which precipitation depth is required in hours.

Using this relationship, daily rainfall data can be disaggregated or converted to peak one-hour rainfall. Accordingly, from the annual maximum daily rainfall data for the Bhopal city available for a period of 36 years, i.e., 1980-2015 peak hourly rainfall was extracted using eq. 4.9. The hourly rainfall thus estimated can be further disaggregated using the observed 't' minute rainfall data over 120 events at Bhopal, as shown in Table 1, where rainfall fractions were established to disaggregate hourly rainfall to average t-minute sub-hourly rainfall. These fractions were used to convert the maximum hourly rainfall extracted for 36 years as above to average 't' minute, i.e. 60, 30, 15, 10, 5 and 1-minute annual maximum rainfall data. This sub-hourly data were used in the statistical analysis here. It should be noted that application of this disaggregation procedure as above to calculate t-minute rainfall values from daily annual maximum series does not give the actual series of t-minute annual maximum rainfall but rather provides a series of pseudo values of t-minute annual maximum rainfall series. In the absence of the observed t-minute data over the long term, the developed pseudo series as per disaggregation procedure as above is used for further analysis.

For the given duration of rainfall, the sample mean and standard deviation are calculated and presented in Table 1. The plotting position (F_i) and reduced variate (Y_i) for EV I distribution were calculated after arranging the values in descending order of magnitude using the above equation. Using the mean and standard deviation of the generated series for different durations, the location and scale parameter values of EV I distribution are calculated and are shown in Table 2. The frequency factor K_T, the reduced variate Y_T and the depth of rainfall P_T for different frequencies are then calculated. A graph plot for observed and EV I distribution fitted values of maximum precipitation for a different short duration between reduced variate Yi and corresponding P_T is shown in Fig. 4.1. From this figure, it can be observed that there is a good match between observed and fitted values indicating that EV I distribution fits the annual maximum sub-hourly precipitation data series. By substitution of frequency factor 'K_{Tr}' and mean precipitation 'P_m' and standard deviation 'S', the extreme rainfall depths would be obtained. Once the extreme rainfall depth (P) for a specified return period (T_r) is calculated, its mean intensity (I_m) is obtained by dividing it by the duration (T_d).

Table. 1: Statistics of sub-hourly duration annual maximum rainfall

Rainfall duration in minutes → / **Statistics**	**1**	**5**	**10**	**15**	**30**	**60**
Mean in mm	45.5	38.2	27.8	21.9	13.2	3.6
Standard deviation in mm	22.6	19	13.8	10.9	6.6	1.8

Table 2 Parameters μ (Mean) and α (Standard deviation) of EV I distribution for sub-hourly duration annual maximum rainfall

Rainfall duration in minutes → Parameter	1	5	10	15	30	60
mu, 'μ' in mm	35.3	29.7	21.6	17	10.2	*2.8*
alpha, 'α' in mm	17.6	14.8	10.7	8.47	5.12	1.41

The IDF curves for sub-hourly rainfall now could be obtained by plotting, on a graph, the mean intensity (I_m) against the duration (T_d). The IDF curves for rainfall intensity for 1, 5 10, 15, 30, 60-minute duration and different return periods using the fitted EV I distribution is shown in Fig. 3&4.

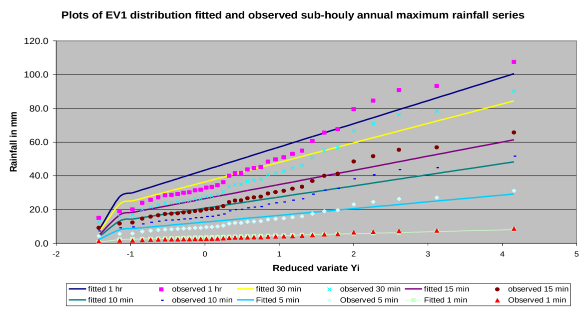

Figure 3: Plots of EV I distribution fitted and observed sub-hourly annual maximum rainfall series

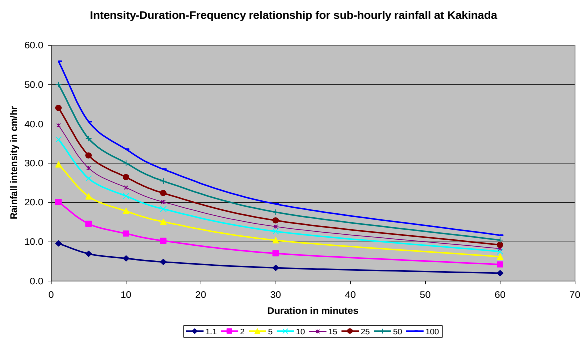

Figure 4: Intensity-Duration-Frequency relationship for sub-hourly rainfall at Bhopal

Design storm hyetograph: a simple way of developing a design hyetograph from an intensity-duration-frequency curve. The design hyetograph produced by this method specifies the precipitation depth occurring in *n* successive time intervals of duration Δt over a total duration T_d= n Δt. After selecting the design return period, the intensity is read from the IDF curve relation for each of the durations, Δt, 2Δt, 3Δt… and the corresponding precipitation depth found as the production values give the amount of precipitation to be added for each additional unit of time is found. These increments, or blocks, are recorded into a time sequence with the maximum intensity occurring at the centre of the required duration and the remaining blocks arranged in descending order alternately to the right and left of the central block to form the design hyetograph (Chow et al., 1988). Ten-minute duration rainfall hyetographs for a one hour storm of two and ten year return period are derived from IDF relation developed using the alternating blocks.

To compute design flood of two years or ten year return period, as shown in Fig 5 and Fig. 6, a peak 10-minute duration rainfall of 21.9 or 32.9 mm can be used while designing any roof water harvesting or urban drainage structure. The hyetographs, as shown in these figures, can also be used to derive respective flood hydrographs.

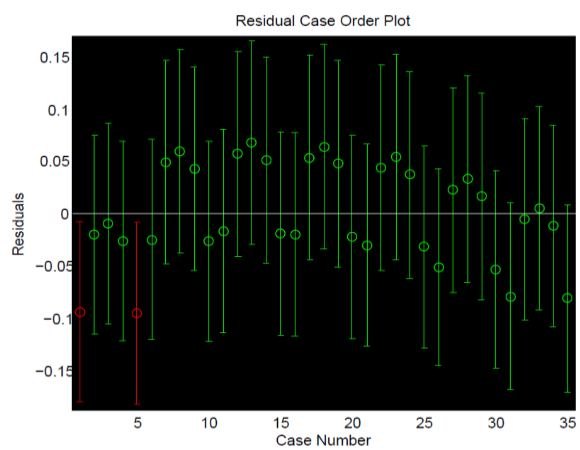

Figure 5: Residual Case Order Plot multiple for regression analysis from MATLAB

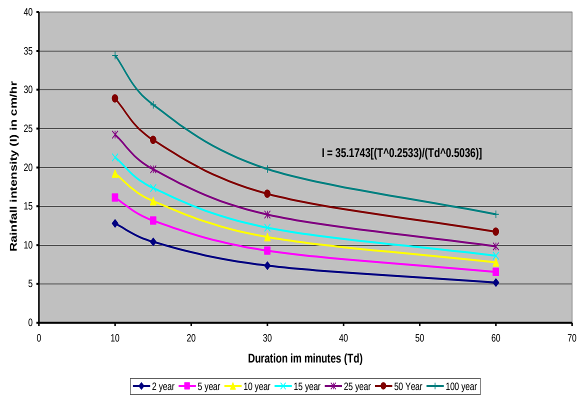

Figure 6: IDF curves for a given return period T in years for sub-hourly rainfall data of Bhopal

Conclusions: In this study, the sizing of the infiltration structure is designed considering an average daily rainfall of 20 mm on over a completely impervious individual plot area of 500 m^2 that results in a runoff of 9.5 m^3, which the infiltration structure can accommodate. During the initial phase of urbanisation ponds or basins may be preferred as previous vacant land is available, and the cost of the land is also not high. But, trenches may have opted at individual plot level during the final stages of urbanisation. As the land rates are high in the city provision of a surface area of about 10 to 20 m^2 for a recharge trench and 5 to 15 m^2 for a recharge pond in each plot of 500 m^2 may be reasonable as found in the study. Since the region gets rainfall over 50 rainy days on an average and with trench designed to recharge the runoff stored in half a day to two days; and pond designed to recharge the runoff stored in a day to three days the studied infiltration structures should operate efficiently.

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