RUNOFF COMPUTATION IN A DATA SCARCE ENVIRONMENT FOR URBAN STORMWATER MANAGEMENT - A CASE STUDY

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Abstract

Most hydrological studies require short duration rainfall-runoff data and generally in developing countries, such short duration data are not available. However, daily data are available and efforts have been made to develop short duration data from daily data to aid in hydrological studies in general, and urban stormwater management in particular. In the present study, an attempt has been made to estimate the generated runoff from an urban watershed for design storms of different return periods. The fast growing city of Hyderabad in south India has been taken up for the study. A record of observed daily rainfall values, of length 17 years, was available. From each annual maximum value, corresponding values of 1-hr, 2-hr, 3-hr, 6-hr and 12-hr rainfall values were obtained using an Indian Meteorological Department (IMD) empirical reduction formula and this series is used in the absence of observed data (t-hour rainfall). Frequency analysis was then carried out to establish Intensity Duration Frequency (IDF) relationships. Design storm hyetographs for various return periods (2-yr, 5-yr, 10-yr and 20-yr) were derived from the IDF relation and assumed time profiles. Two approaches, viz., the Rational method and NRCS Curve Number method were used to estimate the generated runoff. The results obtained from the study can effectively be used to design storm sewers and detention facilities for urban stormwater management.

Introduction

The consequences of urbanization is widely known in hydrologic studies since there have been increasing problems in urban water management. One of the most important facilities in preserving and improving the urban environment is an adequate and properly functioning of stormwater drainage system, which includes stormwater conveyance and storage facilities. There is need for comprehensive planning, design of storm sewer systems and management of urban water resources (Adams and Papa,2000). Better stormwater management is possible only when the generated runoff from the suitable design storms on an urban watershed is known or estimated. The hydrologic methods frequently used in the runoff computation and design work can be separated into two groups: peak discharge methods and hydrograph methods. The former method is commonly used for design problems on small watershed where storage effects are unimportant; this would include design of street drainage, inlets and storm sewers. Hydrograph methods are most often applied to larger watersheds where effects of storage must be taken into account, such as in the design of regional detention facilities (ASCE, 1996). Rainfall information used in urban hydrologic analysis and design most often takes the two forms: i) a characteristic rainfall depth and intensity from IDF curves, and ii) a time distribution of the design storm. In the present study the Rational method and NRCS (Natural Resources Conservation Service) hydrograph method were used in computing the generated runoff from various design storms.

Objectives of the study

The following constitute the objectives of the present study.

- To fit a suitable frequency distribution to the rainfall data available for an urban watershed
- To develop a rainfall Intensity- Duration- Frequency relationship for the rainfall record and obtain a design storm for the study area in the urban catchment.
- To compare the flood hydrograph generated for various design storms using Rational method and software SMADA (Stormwater Management And Design Aid, Wanielista et al, 1997). This Software uses F.P.S units and the same units are retained in the present study.

Study area details and Data Availability

The study area selected for the study is the city of Hyderabad in South India. The city has been divided into many zones for administrative purposes and for the present study, zone 5 of the city has been chosen. 17 years of daily rainfall data were made available for the present study. A base map of the study area is shown in Figure 1. Table 1 gives the land use pattern of the area.

Table 1 Watershed Information

Watershed Total Area (acres)	822.00
Impervious Area (acres)	531.40
Time of Concentration (min)	85.9
% Impervious Directly Connected	0.00
Additional Abstraction	
Over Pervious Area (inches)	0.00
Over Impervious Area (inches)	0.00
Infiltration Characteristics	
Max Infiltration Capacity (in)	999.00
SCS Curve Number for Pervious	65
Initial Abstraction Factor	0.20

Frequency Analysis of Rainfall

Information on the frequency of heavy rainfall is often required by engineers and hydrologists involved in the water management and design of drainage systems. Though many frequency distributions are reported in the literature, for the present study, it was decided to test the applicability of Extreme Value Type 1 (EV1) distribution to the available rainfall data. A brief description of the EV1 distribution follows (Chow et al 1988, Cunnane, 1989). The probability distribution function for EV1 is given by

$$F(q) = P \quad (Q \le q) = e^{-e^{-(Q-u)/\alpha}} \tag{1}$$

where u and α are location and scale parameters of the distribution and q is the threshold value. The parameters of u and α are given by α

$$u = P_m - 0.5772\alpha \tag{2}$$

$$\alpha = \frac{\sqrt{6}}{\pi} s \tag{3}$$

where P_m and s are sample mean precipitation and sample standard deviation respectively. The plotting position for the EV1 distribution as proposed by Gringorten (1963) and used in the present study is

$$F_i = \frac{i - 0.44}{N + 0.12} \tag{4}$$

where, F_i is the plotting position, N is the sample size and i is the rank with i=1, indicating the smallest sample member. The reduced variate of EV1 can be defined as

$$Y_i = -\ln(-\ln(F_i) \tag{5a}$$

$$Y_T = -\ln(-\ln(1 - \frac{1}{Tr})) \tag{5b}$$

where T_r is the return period. Using the method of frequency factors, the expected value of P can be obtained from the relation

$$P_{T_r} = P_m + K_{T_r} s \tag{6}$$

where K_{Tr} is the frequency factor given by

$$K_{T_r} = -\frac{\sqrt{6}}{\pi}[0.5772 + \ln\{-\ln(1 - \frac{1}{T_r})\}] \tag{7}$$

Analysis

Daily rainfall data for the study area were available for a period of 17 years (1982-1998). From this data base, the maximum values were extracted for each year wee converted into shorter duration (1-, 2-, 3-, 6- and 12-hr) values using the reduction formula suggested by the Indian Meteorological Department(IMD, Ramaseshan, 1996), which is

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

where, P_i 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 . It should be noted that application of this reduction formula (Eqn. 8) to calculate t-hour values from 24-hour values does not give the actual series of t-hour annual maximum rainfalls but rather provides a series of pseudo values of t-hour annual maximum rainfall depths. In the absence of observed t-hour data, the developed pseudo series is used for further analysis. For each duration, the sample mean and standard deviation are calculated and presented in Table 2. The plotting positions (F_i) and reduced variate (Y_i) were calculated by after arranging the values in descending order of magnitude, vide Eqn. (4) and (5). Using the mean and standard deviation of the generated series for different durations, the location and scale parameter values of EV1 distribution are calculated using the Eqn (2) and (3) and shown in the Table 3. The frequency factor K_T, the reduced variate Y_T and the depth of rainfall P_T for different frequencies are then calculated. Fig. 2 shows the plot of fitted and observed values of maximum precipitation depth for different duration. It is seen from the figure that there is an excellent match between observed and fitted values indicating that EV1 distribution fits well to the annual maximum precipitation data series (Venkata Rathnam, 2000).

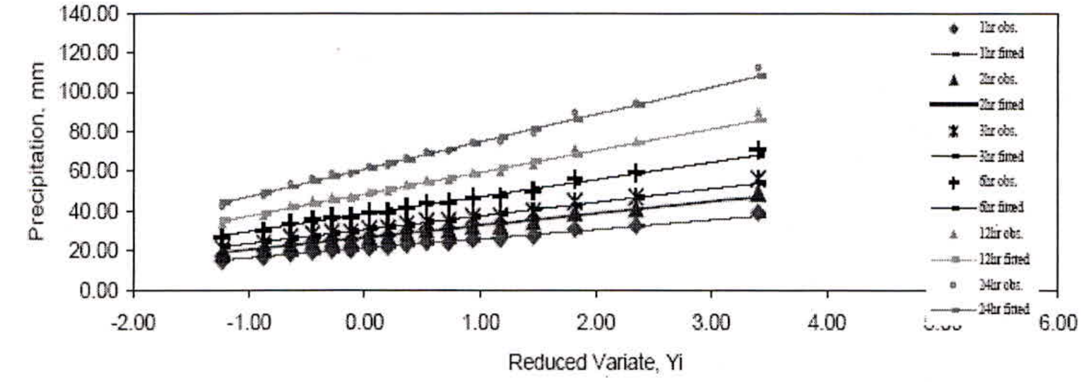
Table 2 Statistics of Rainfall Values for Various Time Durations

Statistics	1-hour	2-hour	3-hour	6-hour	12-hour	24-hour
Mean	23.9	30.1	34.5	43.4	54.7	68.9
St.dev	6.13	7.72	8.84	11.14	14.03	17.68

Table 3 EV1 Parameters for Various Durations

Parameter	1-hour	2-hour	3-hour	6-hour	12-hour	24-hour
u	21.13	26.63	30.48	38.40	48.38	60.96
alpha	4.78	6.02	6.89	8.69	10.94	13.79

Fig. 2 Plots of EV1 fitted and Observed Annual Precipitation values



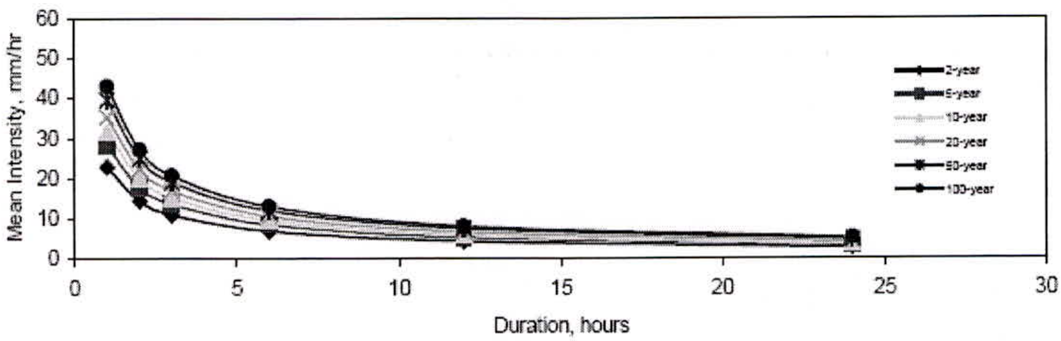
Development of IDF Relation/Curves

In previous section EV1 distribution has been fitted to the hourly record of annual maximum series. By Substitution of frequency factor (K_{Tr}) and mean precipitation (P_m) and standard deviation (s) in Eqn. (6), 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). The IDF curves, now could be obtained by plotting, on a graph, the mean intensity (I_m) against the duration (T_d). Using the multiple regression technique, a common equation for IDF curves is fitted as given in Eqn. (9).

$$i = \frac{21.49T^{0.16}}{T_d^{0.66}} \tag{9}$$

where is rainfall intensity in mm/hr, T is return period in years and is duration in hours. The fitted IDF relation has a correlation coefficient of 0.999 and coefficient of determination of 0.998 with a standard error of 0.012. This indicates that the IDF relationship is fairly describing the rainfall pattern of the Hyderabad region/watershed. The developed IDF curves for various return periods are shown in Fig.3.

Fig.3 Rainfall Intensity Duration Frequency Curves



Design Storm Hyetograph Estimation from IDF Relationships-Alternating Block method

The alternating block method is 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 $T_d = n\Delta t$. After selecting the design return period, the intensity is read from the IDF curve/relation for each of the durations, $\Delta t, 2\Delta t, 3\Delta t, ...$ and the corresponding precipitation depth found as the product of the intensity and duration. Differences between successive precipitation depth 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 center 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). Table 4 shows the values design storm hyetographs derived from IDF relations using the alternating block method for various return periods and which are used in runoff computation.

Table 4. Design Storms for various return periods

Time (minutes)	2-yr return storm (inches)	5-yr return storm (inches)	10-yr return storm (inches)	20-yr return storm (inches)
0-20	0.082	0.096	0.110	0.124
20-40	0.121	0.144	0.163	0.185
40-60	0.666	0.788	0.895	1.017
60-80	0.173	0.205	0.232	0.264
80-100	0.097	0.114	0.130	0.147
100-120	0.071	0.084	0.096	0.109

Runoff Hydrograph Computation

Contributing Area Method

The contribution area method, which is based on Rational method (Urbonas and Roesner, 1992) which is given by

$$Q_T = kCi_T A \qquad (10)$$

has been applied to study area. In this equation, Q_T is the peak flow rate in m^3/s for a return period T years, C is the runoff coefficient depending on land use, i_T is the design rainfall intensity in cm/hr for return period of T years and duration equal to the time of concentration for the basin, A is the drainage area in hectares and k=0.0278. The value of k depends on the units adopted.

The study area has been divided into sub-areas such that each is drained by a single channel to the outfall where the hydrograph is required. Using the planimeter, the area of each of the sub-areas were found and rational coefficients of 0.85 and 0.36 were chosen respectively for the commercial and residential portions. A composite rational coefficient has been determined as a weighted average. Time of concentration (T_c) for each sub area and also for the entire zone was estimated using the Federal Aviation Agency (FAA) formula (ASCE, 1996), which is

$$T_c = \frac{1.8(1.1 - C)L^{0.50}}{S^{0.333}} \qquad (11)$$

where C is the Rational coefficient, L is the length of overland slope in ft, S is the average overland slope in ft/ft.

Sub-area-1 begins contributing to the flow first, to be followed sequentially by the remaining sub-areas. The individual time-area curves are drawn and a composite curve for whole zone is drawn by summing the sub-area contributions at time intervals of 5 minutes. The incremental contributing areas after each interval are then read from the composite curves prepared. Then storms of various return periods (2 to 20 years) have been applied to the urban watershed and discharge rates for each time interval are estimated using the rational method. The routed discharge hydrographs for storms of 2-yr return period for various assumed time profile are shown in the Figs. 4, 5 and 6.

NRCS Hydrograph Method

The software SMADA has been used to estimate the runoff generated from different storms. SMADA is a windows program designed to generate watershed hydrographs and route hydrographs through ponds using inventory routing. There are four main windows in SMADA corresponding to watershed, rainfall, hydrograph, and pond (Wanielista et al, 1997). To meet the desired objective of getting runoff hydrographs due to storms of various return periods, the information available in the Tables 1 and 4 are entered in the watershed file and the rainfall properties file respectively. The chosen method for hydrograph generation was Soil Conservation Service (SCS-484) Curve number technique. Details of Curve Number technique can be obtained from references (SCS, 1986, Chow et al, 1988, Wanielista et al, 1997). The generated runoff resulting from storms of 2-yr return period for various assumed time profile are shown in the Figs. 4, 5 and 6.

Discussion on Computed Runoff

Fig. 4 reveals that for the generated runoff for 2-yr return period storm using Rational method, the total duration of flow is 3.33 hours (200-min) and peak flow of 146 cusecs (4.13 m^3/s) occurs at time 2 hours; and using SMADA (with the option of SCS hydrograph generation) the total flow duration is 5.33 hours (320-min) and peak flow is 90 cusecs (2.55 m^3/s) at time 2.66 hours for the same storm. The same trend is observed for 5-yr, 10-yr return period storms also but for 20-yr return period storm the NRCS hydrograph method has given slightly higher peak than the Rational Method. For all the storms (2-yr, 5-yr, 10-yr and 20-yr return periods) the NRCS hydrograph method has longer runoff duration than the Rational method. Runoff was also computed for an early peak of 2-yr storm and constant intensity 2-yr storm. The Rational method gives higher peak runoff for early peak type rain while the NRCS hydrograph method gives delayed higher peak for constant rainfall pattern (Venkata Rathnam, 2000).

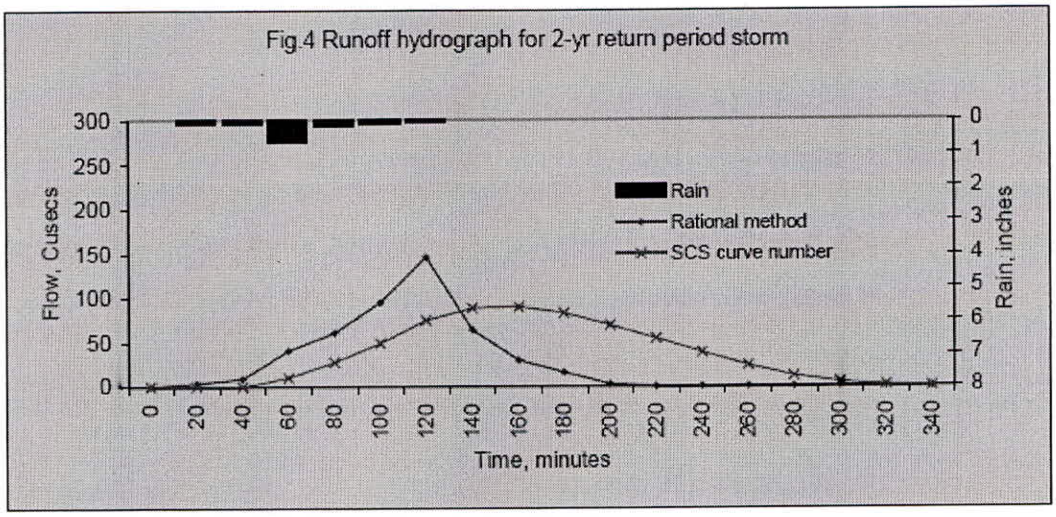
Conclusions

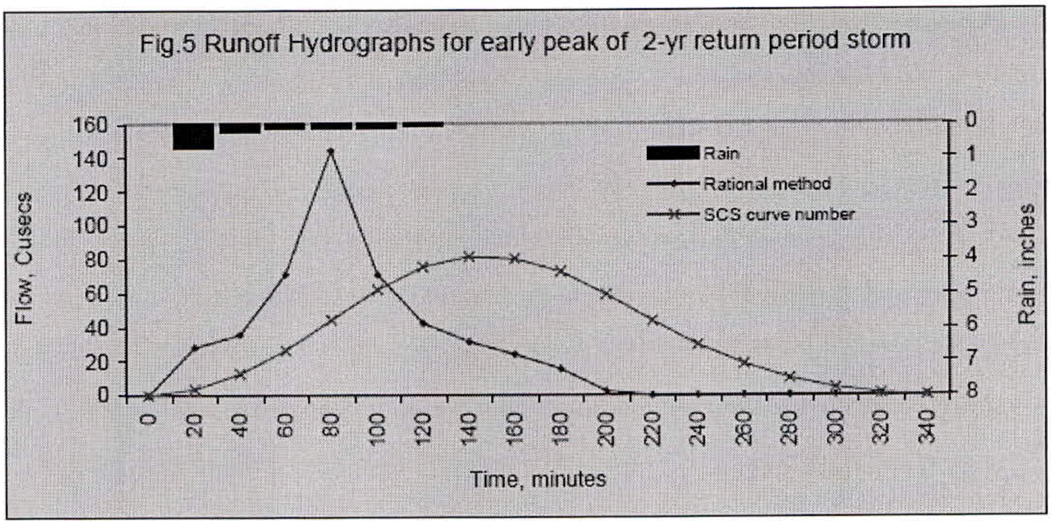
- The Extreme Value Type-1 (EV1) distribution is found to be suitable for the annual maximum rainfall series of the Hyderabad urban watershed .

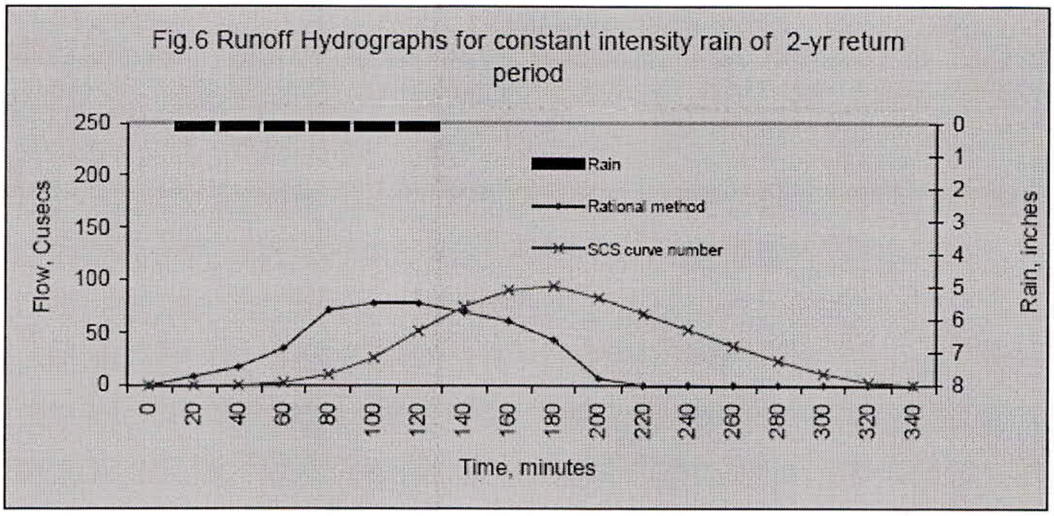
- The developed Intensity Duration Frequency (IDF) relation has R^2 (coefficient of determination) value equal to 0.998 and standard error of 0.012. This indicates that the IDF relationship is fairly describing the rainfall pattern of the Hyderabad region and hence a design storm hyetograph of any return period (≤100 years) can easily be derived from that IDF relation and from assumed time profile.

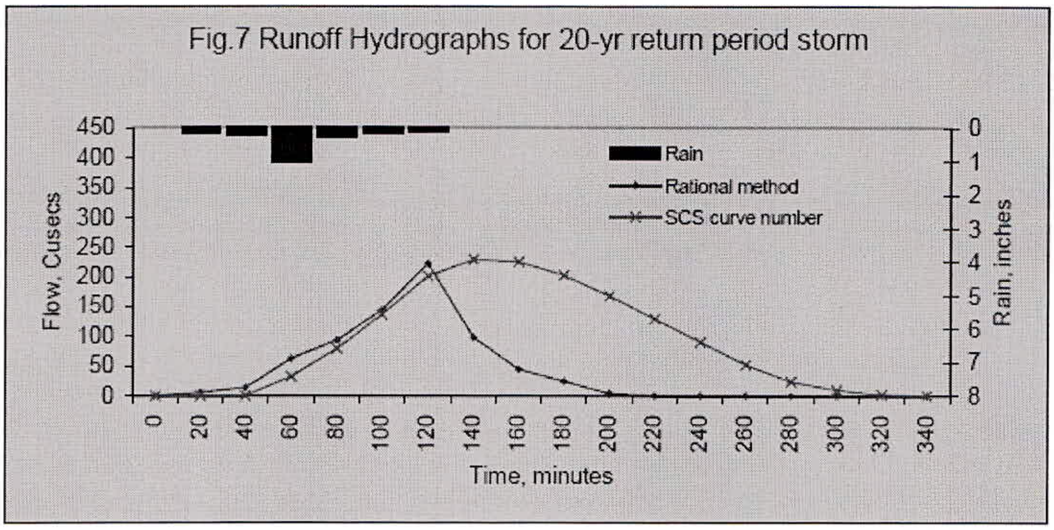
- The Contributing Area Method, based on the Rational formula, gives higher magnitudes of peak runoff than the NRCS Curve number technique for storm of return periods 2-yr, 5-yr and 10-yr. But the duration of runoff is more (by about 2 hours) in case of NRCS hydrograph.

- For larger return periods of storms such as 20-yr, the NRCS hydrograph has slightly higher peak runoff magnitude than the Rational method runoff hydrograph. It showed no change in duration of runoff in both the methods for all types of storms.









General Comments

The method proposed in the study can be used for design of conveyance elements and detention facilities for urban stormwater management, especially in developing countries where short duration rainfall data are not available.

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