Rainfall-runoff analysis of a compacted area

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Abstract: Ongoing droughts and water scarcity problems indicate the significance of conservation of natural water resources. Rainwater harvesting is going to be the most applicable method to eliminate water scarcity and to meet the escalating demand. Hydrological analysis is unavoidable in any water harvesting structural designing. A study was conducted to analyze the rainfall-runoff characteristics by selecting an area of 1.23 ha as the study area, where prominent runoff occurred during the rainy season. Runoff for seven storms were measured using a rectangular notch and a relation between discharge and corresponding head for the notch at the downstream end of the study area was calculated. The R^2 value obtained was 0.98 and the runoff coefficient for the study area was 0.12. Unit hydrograph from various storm hydrographs were derived and the unit hydrograph for the storms P_1 and P_7 were considered for the derivation of representative unit hydrograph for the studied area. A relation between rainfall and runoff was found out as $Y = 0.2X^{-0.85}$ and the R^2 value was 0.98. From rainfall mass curve analysis, a relation between maximum intensity and duration was obtained as $Y = 9X^{-0.69}$. The R^2 value was 0.95. The results showed that the rainwater recharge structures constructed based on the rainfall-runoff analyses in the study area enhanced the water table level. The derived rainfall-runoff relation and representative unit hydrograph will be helpful at any time to design the rainwater harvesting and recharge structures in the studied area.

Key words: water scarcity, rainwater harvesting, hydrological analysis, unit hydrograph

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1 Introduction

Kerala is one of the states in India with abundance of water resources. Krishnakumar et al. (2009) conducted a study to investigate the rainfall trend in Kerala and they found out that there is a decrease in South-West monsoon, even though rainfall received in Kerala is much above the national average. Small amount of this water is used for productive purposes due to the lack of water harvesting facilities, especially in rural areas. The undulating topography is the main reason for water loss to the sea immediately after the rainy season. Over the years Kerala has progressively moved towards a man made water management crisis. In 2001, national census figures indicate that only 21% Keralites have access to safe public water supplies. Water scarcity leads to the degradation of human health, ecosystems, agricultural and industrial output (Postel et al., 1996).

Runoff is the total surface flow from a given drainage area. Before runoff can occur, precipitation must satisfy the demands of evaporation, interception, infiltration, surface storage, and surface detention and channel detention. Rainfall duration, intensity and aerial distribution influence the rate and volume of runoff. Total runoff of a storm is clearly related to the precipitation intensity. The amount of runoff from a given drainage area depends on many inter related factors. Watershed characteristics such as slope, shape and size, cover of soil and duration of rainfall have a direct effect on the peak flow and volume of runoff from any area (Chandler and Walker, 1998). Intensity of rainfall has

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dominating effect on the runoff yield. If the intensity is greater than the infiltration rate of the soil, then surface runoff is generated rapidly, while in case of low intensity rainfall, a reverse trend is found. Fernandez (1996) conducted a study to investigate the impacts of long-term trends and fluctuations in rainfall characteristics as runoff from the Little Washita River watershed. The land use pattern or land management practices used have great effect on the runoff. There are a few studies conducted to evaluate the influence of climatic and catchment characteristics on runoff generation (Faucette et al. (2004), Gilley et al. (1998), Zhang (1998). Savabi (2004) conducted a study to find out the influence of soil type on runoff generation.

Rain water recharge pits can improve the field availability of water and hence replenishment of the groundwater table. Runoff harvesting is going to be the most applicable method for meeting the water demand in the future. Hydrological analysis is unavoidable in any water harvesting structure design, and hence the present study was intended to analyze the rainfall-runoff characteristics and to derive a representative unit hydrograph for the selected rural region for future runoff calculations to design water harvesting structures. There are different methods for runoff estimation (Mc Cool et al., 1995), but these sophisticated methodologies are not suitable for rural areas with limited data. Most of the rainfall-runoff models need historical data for the calibration to get efficient results. Therefore it is significant to develop simple methodology for the efficient hydrological analysis for regions with limited data set. Hence, the specific objectives of the study were runoff estimation, determination of runoff coefficient of the study area, derivation of intensity-duration relationship of rainfall, to derive a relation between the rainfall and runoff measured, and finally the derivation of unit hydrograph (representative hydrograph for the region) from the obtained storm hydrograph.

2 Materials and methods

The study was undertaken in the KCAET campus Tavanur, Malappuram district, Kerala, India (10°52'30"N, 76°E). Agro climatically the study area falls within the boarder line of northern zone, central zone and kole zone and climatologically the area is in the low rainfall area (1 000–2 000 mm). The area receives the rainfall mainly from south-west monsoon and north-east monsoon. Laterite soil is the speciality in this region.

2.1 Experimental details

A compacted field having 1.23 ha area was selected for the study, because this was one of the major areas contributing very good surface runoff to the downstream. It has 0.6% slope in the north south direction and a cross slope of 0.27% with a cross section of 175 m × 70 m. Due to the sediment deposition; the southern and western sides were partially covered by vegetation during the study period. To stabilize the slopping side in the southern boundary of the study area, paving of the slope with stone pitching was adopted. The downstream portion of the study area consists of a cement concrete rectangular channel (average cross section of 0.625 m × 0.16 m and 0.2% bed slope). The total length of the channel is about 75 m. The runoff from the area is conveyed through this channel and is disposed to a recharge pit.

Figure 1 Cement plastering at the stone pitched area

2.2 Installation of notch

A rectangular notch of crest length 35 cm and height of 25 cm was installed to measure the runoff generated at the end of the channel. The notch was designed based on the peak runoff rate expecting from the study area. The peak runoff was estimated using rational formula given below (Suresh, 2004):

$$Q = CIA/36 \quad (1)$$

Where, Q = Peak runoff rate, m^3/s; C = Runoff coefficient; I = Rainfall intensity, cm/hr; A = Area, ha.

The discharge through the notch is obtained by (Bansal, 2005)

$$Q = 2/3(Cd\sqrt{2g}LH^{3/2}) \quad (2)$$

Where, Q = Discharge rate, m^3/s; Cd = coefficient of discharge of notch; g = acceleration due to gravity, m/s^2; L = Length of crest, m; H = Head over the crest, m.

The design dimensions of the notch are given in Figure 2 and the installed notch is shown in Figure 3.

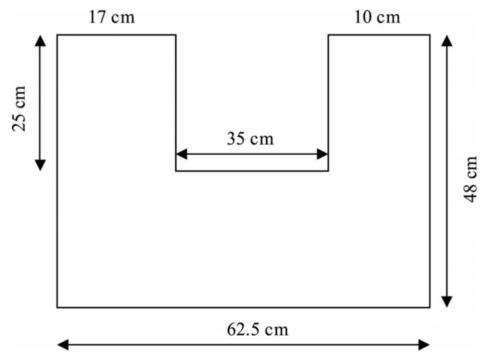

Figure 2 Dimensions of rectangular notch

Figure 3 Hook gauge at 4H distance from the crest

The calibration of notch was done during a high intensity storm. The initial depth of flow over the channel was measured using the hook gauge with respect to a stopwatch. Discharge from the notch was collected in the measuring tank, and then the time taken for filling the measuring tank and corresponding depth of flow from the hook gauge was noted.

2.3 Rainfall-runoff analysis

The discharge corresponding to the depth of flow taken at an interval of 30 s was calculated from the discharge-head relationship. Runoff hydrographs were plotted for each separate storm and the area under the hydrograph gave direct runoff volume. The channel needs water till the crest level for the initiation of runoff. So this initial amount of water needed to start the channel flow should be considered to get the total runoff volume. Also, the rainfall depth corresponding to the storm was obtained from the rainfall mass curve chart. The runoff depth was obtained by dividing the runoff volume with area. Rainfall – runoff relationship was obtained by plotting rainfall depth as abscissa and runoff depth as ordinate. The severity of runoff can be evaluated using runoff coefficient and is the ratio between runoff and rainfall. The runoff coefficient for various storms was calculated and the average value was taken as the runoff coefficient of the area. Runoff coefficient can give some information about the land cover and topography.

2.4 Derivation of unit hydrograph

Unit hydrograph is defined as the direct runoff hydrograph, produced by a storm of specific duration, resulting from an excess rainfall depth (runoff depth) of 1 cm which is uniformly distributed over the entire watershed area. The unit hydrographs were derived from the individual storm hydrographs and then we derived the representative unit hydrograph by averaging the individual unit hydrographs. For more details about the derivation of unit hydrographs, please refer Suresh (2004).

2.5 Maximum intensity – duration relationship

Rainfall data from 17th June, 2005 to 19th November, 2006 was used to calculate the maximum intensity for the study period. During this period 88 mass curves were obtained. As we know the rainfall chart covers a period of 25 hrs and hence the smallest division of the chart is 15 min. The maximum intensities were calculated for some selected durations like 5 min, 10 min, 15 min, 30 min, 1 hr, 2, 4, 6, and 12 h.

The simple method to find the maximum intensity for a given duration in any storm is to use a transparent scale with vertical lines drawn on it at a distance equal to the required duration and to measure the maximum vertical intercept of the mass curve by sliding it over the chart. Transparent scales for the required durations were prepared using Auto CAD. The procedure was repeated for the 88 charts. From the 88 charts, highest value of maximum rainfall depth for each duration was found out. The maximum intensity was obtained by dividing the highest value of maximum rainfall depth by the corresponding duration. Rainfall intensity-duration relation was obtained by plotting intensity along the *X* axis and duration along the *Y* axis.

3 Results and discussion

3.1 Calibration of notch

The highest discharge of 31.43 lps was recorded corresponding to a head of 12.20 cm. The Figure 4 shows the relation between discharge and head. The R^2 value was found to be 0.98. A power relation was obtained as $Q = 0.7661H^{1.4503}$.

3.2 Mass curve analysis

The results of the mass curve analysis were presented in Table 1. Among the seven storms except the storm P_3, all were isolated. For the storm P_3, the total rainfall and durations were 45.25 mm and 225 min respectively. For the other storms the rainfall depth varied from 7.5 mm to 17.5 mm and rainfall duration ranged from 15 min to 55 min. Maximum intensities of these storms were with the range of 30-89 mm/h.

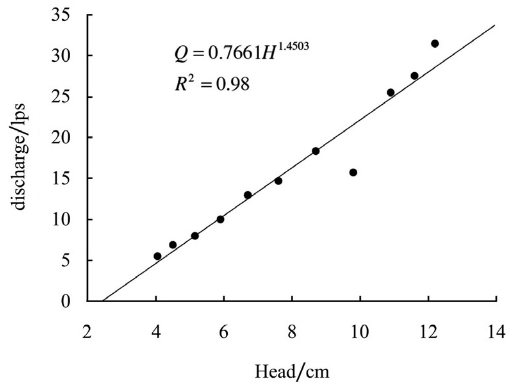

Figure 4 Head – discharge relationship

3.3 Discharge estimation

The discharge corresponding to the depth of flow measured over the notch for various storms was calculated from the equation $Q = 0.7661H^{1.4503}$. The corresponding hydrographs were also plotted.

The results obtained by analyzing mass curves and hydrographs of storms under consideration were summarized in Table 1.

Table 1 Results of analysis of mass curves and hydrographs of various storms

Storm	Rainfall depth /mm	Duration of Rainfall/min	Runoff volume /m^3	Runoff duration /min	Max. Intensity /mm · hr^{-1}	Average intensity /mm · hr^{-1}	Peak rate /lps	Time to peak /min	Antecedent Rainfallin/24hr
P_1	7.50	15.00	9.13	9.00	30.00	30.00	0.61	5.50	10.75
P_2	8.00	17.00	10.55	20.50	48.00	28.20	2.64	7.00	16.25
P_3	45.25	225.00	102.01	167.00	45.60	12.01	31.43	78.00	33.50
P_4	8.00	55.00	9.71	14.00	24.00	8.70	1.72	5.00	66.00
P_5	17.50	35.00	37.32	41.00	44.00	30.00	27.8	9.00	73.75
P_6	8.75	35.00	11.45	26.00	81.00	15.30	3.70	6.00	36.00
P_7	11.50	30.00	9.22	13.00	57.00	23.00	0.71	4.00	0

3.4 Rainfall- runoff depth relation

The relation obtained can be used for finding out runoff corresponding to any rainfall occurring in the area. For the study area, the relation was found to be linear. The relation obtained was $Y= 0.2012X-0.8467$ and the R^2 value was 0.9851.

3.5 Determination of runoff coefficient

The runoff coefficient is the ratio between runoff and rainfall. Runoff coefficient obtained with different storms was given in Table 2.

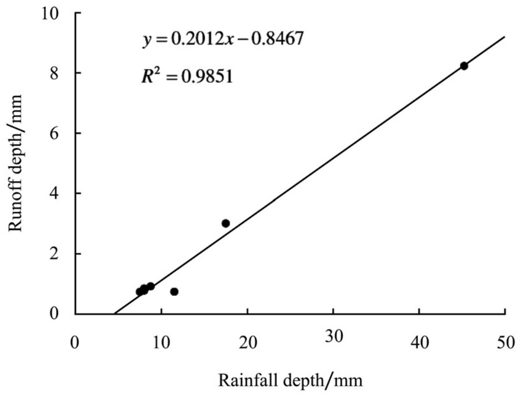

Figure 5 Rainfall- runoff relation

Table 2 Runoff coefficient for various storms

Storm	Rainfall depth/mm	Runoff depth/mm	Runoff coefficient
P_1	7.50	0.738	0.09
P_2	8.00	0.852	0.10
P_3	45.25	8.243	0.18
P_4	8.00	0.785	0.09
P_5	17.50	3.015	0.17
P_6	7.75	0.925	0.11
P_7	11.50	0.745	0.04

Runoff coefficient of the area was obtained as 0.12. There was percolation loss through the stone pitched area through which the water was conveyed to the channel. As one side of the channel was the stone pitched area, a portion of the runoff was also lost during ponding in the channel. So time taken for concentrating flow was high and time taken to drain the channel was less. As the downstream part of the ground was vegetated more water was infiltrated. The lower part of the study area was almost flat compared to the upper part, hence appreciable amount of water was lost due to ponding (standing water at the downstream part of the study area). These various reasons affected the derived runoff coefficient.

3.6 Derivation of unit hydrograph

The unit hydrograph obtained for six storms were vary in durations. The durations for various unit hydrographs were 9, 20.5, 14, 41, 26, and 13 min. The duration for the unit hydrograph for the storm P_1 and P_7 was found to be nearly equal. So the average of ordinates of these two was taken as the ordinate of representative unit hydrograph for the area. Unit hydrograph obtained for the area can be used for obtaining storm hydrograph for any duration and any rainfall depth. The ordinate of representative unit hydrograph derived was given in Table 3 and corresponding data was given in Figure 6.

Table 3 Ordinates of representative unit hydrograph

Time/min	Ordinate of unit hydrograph/$m^3.s^{-1}$
0	0
2	1.53
4	1.88
6	0.99
8	0.25
10	0.02
12	0

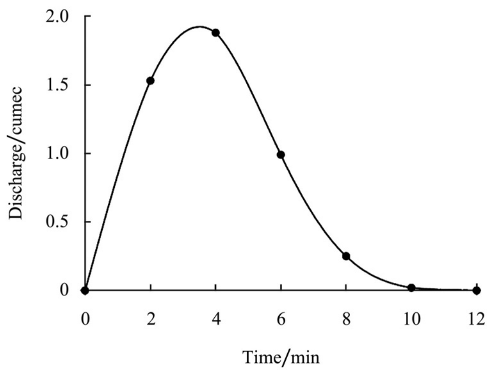

Figure 6 Representative unit hydrograph

In this study, the rising limb of hydrographs skewed to the left and it can give a brief idea about the shape of the watershed. The shape of the field more resembles to a fan shaped watershed. Hence the time to peak runoff was less and the rising limb was steeper than the falling limb. Time taken to reach peak for the six isolated storms was between 4 to 9 min. Even though there was wide variation in the runoff duration, the mainly varying part was the falling limb rather than rising limb.

The maximum intensities obtained for various durations were given in Table 4 and the corresponding graph is shown in Figure 7. The obtained relation was $Y = 9.0029X^{-0.6986}$ with an R^2 value of 0.9506.

Table 4 Maximum intensities for different duration

Duration	Intensity/mm · h^{-1}
5 min	120
10min	96
15 min	87
30 min	07.8
1 h	44.4
2 h	22.2
4 h	11.4
6 h	7.2
12 h	4.8

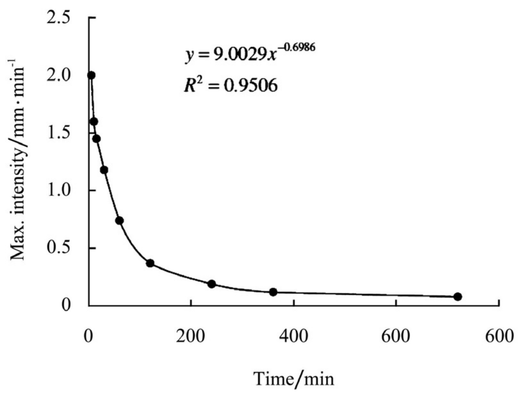

Figure 7 Maximum Intensity –Duration relationship

Maximum I h intensity obtained was 44.4 mm/h. An inverse relation was indicated between maximum intensity and duration. The relation gives an idea about the maximum intensity rain occurring for different durations in the study area. This is essential while designing any rainwater harvesting or soil conservation structures.

4 Conclusions

Rainwater harvesting appears to be one of the most promising alternatives for the escalating demand of fresh water. Hydrological analysis is the basic criteria for the design of rainwater harvesting structure. The study was undertaken to do the rainfall-runoff analysis. The study included runoff estimation from the area, determination of runoff coefficient and to find out a relation between maximum intensity and duration and a relation between rainfall and corresponding runoff.

Runoff rate from the ground was measured for seven storms. (P_1, P_2, P_3, P_4, P_5, P_6, P_7)

A relation between head and discharge was obtained for the calibration of notch. The relation was $Q = 0.77H^{1.45}$ with an R^2 value of 0.98.

Runoff volume estimated for various storms were 9.13 m^3, 10.55 m^3, 102.01 m^3, 9.71 m^3, 37.32 m^3, 11.45 m^3 and 9.22 m^3 respectively.

A relation between rainfall and runoff was found out as $Y = 0.2X - 0.85$ and the R^2 value obtained was 0.98.

Runoff coefficient for the area was obtained as 0.12

Maximum intensity for durations of 5 min, 10 min, 15 min, 30 min, 1 hr, 2 hr, 4 hr, 6 hr and 12 hr for the monsoon season was found out by the rainfall chart analysis.

A relation connecting maximum intensity and duration was obtained as

$Y = 9X^{-0.69}$. The R^2 value was 0.95.

Unit hydrograph for various storm hydrograph was derived and unit hydrograph with relatively same duration was taken as the representative unit hydrograph of the study area.

The runoff measurement for more number of isolated storms was possible if measuring was done using a stage level recorder. The stone pitched area through which water flowing to the channel was not fully lined. The unit hydrograph obtained from the storm hydrograph can be used as a representative unit hydrograph for the area for future runoff volume and peak runoff rate estimation. The maximum intensity for different duration can be considered for designing any water harvesting structures for the studied area. The representative unit hydrograph can be used to generate runoff and based on that water managers can develop efficient field water management programs and hence considerable reduction in soil erosion.

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