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Some hydrologic characteristics and modelling aspects of a small catchment in southern India

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सार — इस शोध-पत्र में जिस क्षेत्र का अध्ययन किया गया है वह करंजा नामक एक छोटा-सा जलग्रहण क्षेत्र है, जिसका क्षेत्रफल लगभग 2025 वर्ग कि. मी. है जो कर्नाटक में और आंध्र-प्रदेश से लगा हुआ है। मृदा आवरण भूमिगत जल स्तर और भूविज्ञान इत्यादि के उपलब्ध आंकड़ों सहित 1964–84 में प्रेक्षित सरित प्रवाह के दैनिक आंकड़ों और 1980–84 की अवधि के दैनिक घंटेवार वर्षा के नदी प्रमापी आंकड़ों का उपयोग किया गया है। जलग्रहण क्षेत्र का लगभग 80 प्रतिशत भाग अत्याधिक उच्च अपवाह विभव वाली मृदाओं से ढका हुआ है। सामान्य मानसून वर्ष में जलग्रहण क्षेत्र की वर्षा का 5 प्रतिशत भाग भूमिगत जल से आधार प्रवाह के रूप में नदी में बह जाता है। 1964–1984 की अवधि के दौरान जुलाई से अक्तूबर के महीनों में मासिक वर्षा और अपवाह आपस में विशेषरूप से सम्बद्ध थे। इस सम्बन्ध का प्रयोग करते हुए अपवाह का अनुमान लगाने के लिये समाश्रयण समीकरण का विकास किया गया है। औसत रूप से जलग्रहण क्षेत्र में वर्षा का 33 प्रतिशत भाग अपवाह में परिवर्तित हो जाता है और अपवाह का प्रतिशत 1972 में न्यूनतम और 1983 में अधिकतम रहा। सात बाढ़ घटनाओं से संम्बधिन्त यूनिट जलारेख व्युत्पन्न किये गये हैं और उससे जलग्रहण क्षेत्र के लिये औसत यूनिट जलारेख प्राप्त किया गया है। इन उत्पन्न यूनिट जलारेखों की सार्थकता और अनुप्रयोग पहलुओं को बताया गया है। 1983 में जलग्रहण क्षेत्र में अभूतपूर्व भारी बाढ़ की भी संक्षेप में चर्चा की गई है।

ABSTRACT. The area under study is a small catchment called Karanja, having an area of about 2025 km² in Karnataka and adjoining Andhra Pradesh. Observed daily streamflow data and daily rainfall data for the period 1964-1984 and hourly rainfall and river gauge data for the period 1980-84, along with the available data on soil cover, groundwater levels and geology etc, have been utilised. About 80 per cent of the catchment area is covered by soils of considerably high runoff potential. About 5 per cent of the catchment rainfall is discharged into the river as base flow from the ground water in a normal monsoon year. Monthly rainfall and runoff were significantly correlated for the months of July to October during the period 1964-1984. Regression equations for estimating runoff have been developed using these relationships. On an average about 33 per cent of the rainfall in the catchment is converted into runoff and the percentage of runoff is maximum in the year 1983 and minimum in 1972. Unit hydrographs corresponding to the seven flood events have been derived and thereby an average unit hydrograph for the catchment is obtained. The validity and application aspects of the derived unit hydrographs are indicated. The unprecedented peak flood of 1983 in the catchment is also briefly discussed.

1. Introduction

A detailed study of the rainfall characteristics of Karanja catchment has been made by Ramana murthy *et al.* (1987) to estimate the design raindepths of different frequencies. It is, however, important to recognise the catchment response to the rainfall which depends upon various factors like time and space distribution of rainfall, soils, vegetation, topography, groundwater conditions, base flow conditions of the river etc. In the present study an attempt has been made to discuss some hydrologic characteristics of the basin and rainfall-runoff modelling processes which involve regression analysis, derivation of unit hydrographs and their application. The unprecedented peak flood which occurred in the catchment in September 1983 in association with a rainstorm of not unprecedented nature has been given special attention.

2. Data used

Thrice-daily observations of streamflows measured at Halhalli for the period 1964-1984, daily rainfall records of the three stations namely, Bidar, Humnabad and Zaheerabad in the catchment for the concurrent period of 1964-84, hourly rainfall records of Bidar, the only self-recording raingauge station in the catchment and hourly gauge data at Halhalli for the period 1980-84 have been used in the present study. Apart from these, all the available data on soils, geology, groundwater, basin maps, index maps, cross-section map of gauging site and topographic maps formed as data base for the present study. Most of these data are supplied by the Irrigation Department, Government of Karnataka.

3. Geographical features

The Karanja catchment is located in the northern parts of Karnataka and adjoining Andhra Pradesh (Fig. 2). The catchment area up to the dam site, Halhalli is about 2025 km² of which 72% lies in Karnataka and 28% in Andhra Pradesh. The length and gradient of the mainstream of the river are 77 km and about 1 km respectively. The mean annual rainfall is about 898 mm and nearly 80% of it is contributed by the southwest monsoon (June-September) period.

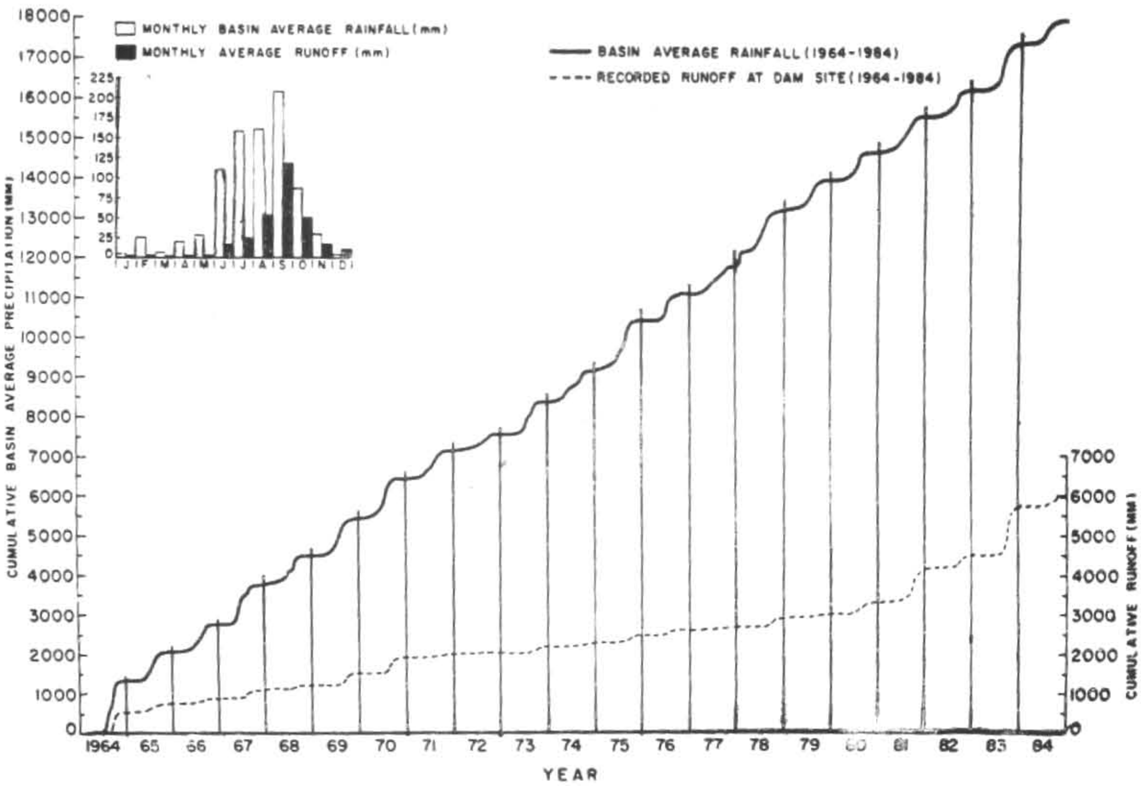


Fig. 1. Recorded average monthly catchment rainfall and recorded cumulative rainfall and runoff

TABLE 1

Soil types occurring over the catchment

Soil type	Mean profile depth (cm)	Infiltra-tion	Permeabi-lity	Hydro-logic soil group	Runoff po-tential	% area of the catch-ment
Moderately fine textured, moderately deep red laterite soils	37	Medium	Moderately rapid	C	Moderately high	40.6
Fine textured very deep black soil	75	Do.	Slow	C	Do.	26.7
Moderately deep, moderately fine textured gravelly red soil	37	Do.	Rapid	B	Moderately low	19.4
Fine textured moderately deep black soil	75	Do.	Moderately rapid	C	Moderately high	12.5
Moderately fine textured shallow dark grey soil	15	Do.	Do.	B	Moderately low	0.8

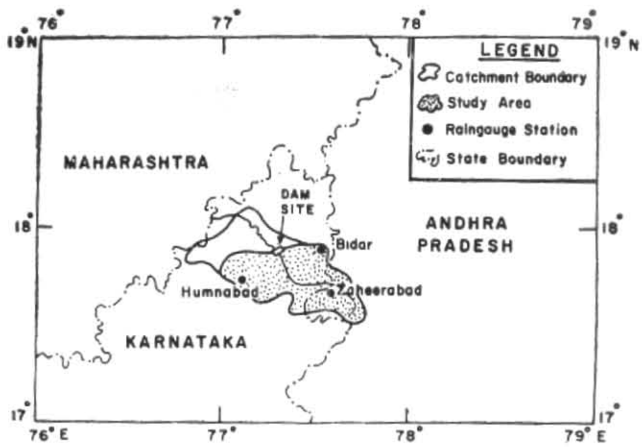


Fig. 2. Location map of Karanja catchment

4. Soils

The soil profiles occurring on the catchment can be categorised into five broad types and they are shown in Table 1. The qualitative hydrologic properties for the soils in the catchment are obtained by correlating the soil descriptions with those of standard published tables (Schwab *et al.* 1971).

5. Geology and groundwater

The catchment is underlain by Deccan basalts of late cretaceous period and stratigraphically they overlie precambrian granitic gneisses. The Deccan basaltic outcrops are prominent along the valley sections of the trunk stream and the principal tributaries.

The average depth to the water table during the recharge period varies spatially from 1.06 m to 13.82 m below ground level and during discharge season they vary from 3.38 m to 20.83 m. Atmospheric precipitation in the form of rainfall is the principal source of recharge to the groundwater body. In a normal monsoon year 5.1% of the total precipitation is discharged from the aquifers to the river streams as baseflow. There are eight reported natural springs in the catchment and five out of them drain their water into the channel network of the basin. Hence the groundwater outflow from these springs forms an integral component of measured or estimated baseflow. Most of the groundwater occurs in the laterite and decomposed traps under unconfined watertable conditions. Piezometric (confined) conditions of groundwater are reported from Humnabad taluka.

6. Streamflow statistics

The maximum recorded discharge so far at Halhalli was 120000 cusecs and the minimum recorded is zero. The observed annual peak flows varies from 120000 cusecs (1983) to 3010 cusecs (1972) and the mean annual peak flood is about 26730 cusecs. Most of the major floods occurred in the month of September. It may be mentioned here that the number of rainy days and rainfall per day are highest in the month of September (Ramanamurthy *et al.* 1987). The mean monthly volumes of water yield in the form of runoff and their percentages of annual are given in Table 2 and it is seen that more than 40% of the annual volume of water is yielded in the last month of the monsoon season, *i.e.*, in September. The 21-year period average monthly catchment rainfall histogram is shown in Fig. 1.

7. Correlation and regression analysis

The daily streamflow data at Halhalli were available for the period 1964-84. From the observed daily streamflows, mean monthly flows were computed for the period and converted into millimetres. Rainfall data for the concurrent period, *i.e.*, 1964-84 of the three stations namely, Bihar, Humnabad and Zaheerabad within the catchment were utilized to obtain the weighted monthly catchment rainfall by Thiessen Polygon method. Linear regression equations relating monthly rainfall-runoff have been developed which showed significant correlations for individual months July through october as well as entire period (Table 3). Annual total catchment rainfall, runoff and percentages of runoff for all the years 1964 to 1984 are presented in Table 4. During the drought year of 1972, only 2.7% of the rainfall was converted into runoff. In 1983 the percentage runoff was above 100% and the probable reasons for this could be either the substantial contribution of baseflow from groundwater or errors in discharge measurements. On an average during the period of study 33.3% of the catchment rainfall was converted into runoff. Utilizing monthly catchment rainfall and runoff, cumulative rainfall together with cumulative runoff for the period 1964-1984 is plotted in Fig. 1. The runoff curve shows almost similar trend with that of rainfall for entire period of study except during 1981-83 where a slight deviation is seen.

8. Unprecedented flood of 1983

A record peak flood of 120000 cusecs occurred on 22 September 1983 breaking the previous records of 119685 cusecs on 15 September 1983 and 92550 cusecs on 19 September 1969. The project authorities of the dam are contemplating for improvements in the spillway design capacity after the experience of 1983 flood. The annual peak discharges with dates of occurrence for the period 1964-84 and their return periods are given in Table 5. The one-day catchment rainfall preceding the peak flood day of each year for the period is given in Table 6 along with the average monthly flow of the preceding month of the peak flood month. It is seen that the rainstorm of 22 September 1983 was not of an unprecedented nature. Obiously the temporal distribution of rainfall and the favourable baseflow conditions have contributed to a large extent in producing this peak flood. It is a known fact that the shape and magnitude of the flood hydrograph is very much dependent upon the distribution of rainfall within the storm period. Rakhecha *et al.* (1985) have analysed the hourly rainfall data of Bidar station for the period 1974-1981. They have studied six intense rainstorms of 24-hour duration of Bidar station in the catchment and found that during one hour 56% and in two hours 73% of one-day rainfall of Bidar occurred on 19 August 1980 which are the highest percentages and magnitudes amongst the analysed intense storms. The total catchment rainfall of the day was 34.3 mm, out of which 19.2 mm occurred in one hour and 25 mm in two hours. In the present study, the author has analysed

TABLE 2

Mean monthly and annual volumes of water of Karanja catchment up to the dam site

	Monthly volumes of water (Mcft)	% of annual
January	149.739	0.73
February	106.533	0.52
March	46.075	0.23
April	12.232	0.06
May	8.852	0.04
June	1136.109	5.58
July	1657.626	8.15
August	3656.780	17.97
September	8358.920	41.07
October	3596.393	17.67
November	1086.594	5.34
December	536.920	2.64
Monsoon (Jun-Sep)	14809.435	72.77
Annual	20352.713	

TABLE 3

Regression analysis results of monthly rainfall-runoff

Month/period	Regression constant	Regression coefficient (mm)	Correlation coefficient	Significance level (%)
Jul	—0.3821	0.1412	0.4822	5
Aug	—17.4041	0.4068	0.6812	1
Sep	—100.8996	1.0458	0.7611	1
Oct	18.7100	0.3637	0.5055	2
Entire period 1964-1984	—5.5287	0.4132	0.6253	1

TABLE 4

Annual rainfall-runoff statistics

Year	Total annual rainfall (mm)	Total annual runoff (mm)	Percentage runoff
1964	1326.6	562.9	42.4
1965	730.2	199.9	27.4
1966	755.4	147.2	19.5
1967	931.2	239.3	25.7
1989	736.4	103.4	14.0
1999	949.9	302.2	31.8
1970	1008.8	396.7	39.3
1971	679.9	82.4	12.1
1972	429.7	11.8	2.7
1973	800.7	168.5	21.0
1974	781.8	66.5	8.5
1975	1217.7	227.7	18.7
1976	727.8	114.0	15.7
1977	673.4	77.0	11.4
1978	1410.2	233.2	16.5
1979	745.4	105.2	14.1
1980	699.4	282.8	40.4
1981	930.2	826.4	88.8
1982	679.7	368.3	52.8
1983	1096.1	1204.3	109.9
1984	562.2	246.3	43.8

TABLE 5

Annual peak discharge data and their return periods

Year	Date of flood	Peak discharge (Q_p) cusecs	Return period [$T_R = (n+1)/m$] (yr)	Ratio : Q_p/(Mean peak flood)
1964	16 Sep	30375	5.5	1.14
1965	15 Jul	26700	2.75	0.99
1966	4 Sep	19800	2.0	0.74
1967	27 Sep	24950	2.44	0.93
1968	5 Sep	7150	1.22	0.27
1969	19 Sep	92550	11.0	3.46
1970	18 Aug	35460	7.33	1.33
1971	24 Aug	11490	1.37	0.43
1972	4 Nov	3010	1.05	0.11
1973	26 Oct	13075	1.47	0.49
1974	16 Jun	6040	1.16	0.23
1975	10 Oct	15350	1.69	0.57
1976	25 Aug	7855	1.29	0.29
1977	17 Sep	4365	1.1	0.16
1978	15 Aug	21875	2.22	0.82
1979	23 Sep	17895	1.83	0.67
1980	20 Aug	28955	3.66	1.08
1981	22 Sep	30310	4.4	1.13
1982	24 Sep	15235	1.57	0.57
1983	22 Sep	120000	22.0	4.48
1984	1 Aug	28895	3.14	1.08

TABLE 6

One day catchment raindepths, resulting peak floods and baseflow conditions

S. No.	Year	One-day catchment rainfall preceding peak flood day (mm)	Mean discharge of the month preceding the peak flood month (cusecs)
1	1964	27.5	37.4
2	1965	70.7	22.7
3	1966	46.1	14.3
4	1967	14.3	16.8
5	1968	30.9	1.2
6	1969	67.9	21.4
7	1970	39.1	7.6
8	1971	76.6	0.6
9	1972	30.8	0.2
10	1973	27.0	27.8
11	1974	2.9	0.1
12	1975	14.4	16.2
13	1976	23.8	21.7
14	1977	18.5	11.2
15	1978	27.1	42.9
16	1979	30.6	4.0
17	1980	34.3	1.2
18	1981	15.2	80.8
19	1982	11.2	24.5
20	1983	58.5	139.5
21	1984	41.4	20.4

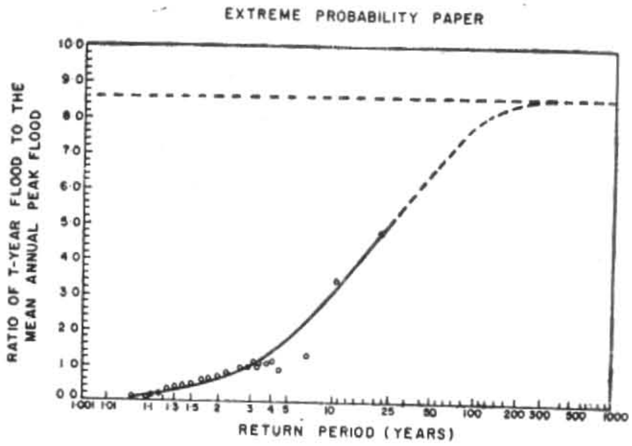


Fig. 3. Probable peak discharges for different return periods

TABLE 7

Estimated peak-flood for different return periods

S. No.	Return period (yr)	Ratio	Esimated peak flood (cusecs)
1	10	3.1	82863
2	25	5.1	136323
3	50	6.6	176418
4	100	7.8	208494
5	200	8.6	229878

the major rainstorms of 1983 and 1984 in a similar way. It is seen from Table 6 that the 1 August 1984 storm produced peak flood almost equivalent to that of 1980 though the one day catchment rainfall of 1984 storm is relatively more. The probable reason could be the temporal distribution on that day. A maximum of 22.6% (9.34 mm) of the one-day rainfall on 1 August 1984 occurred in one hour, 41.9% (17.35 mm) in two hours and 54.8% (22.7 mm) in three hours; which indicate considerably less intense than that of the 1980 storm. Coming to the 22 September 1983 rainstorm the total one-day catchment rainfall is 58.5 mm, preceded by another intense rainstorm by 7 days, *i.e.*, on 15 September 1983 which yielded an areal raindepth of 64.4 mm. The peak flood resulted by the 15 September 1983 rainstorm was 119685 cusecs which is almost equal to that of 22 September 1983.

In the case of 22 September 1983 rainstorm 55.5% (32.5 mm) of rainfall occurred in one hour, 73.4% (42.9 mm) in two hours and 85.3% (49.9 mm) in three consecutive hours. These percentages are similar to those of August 1980 rainstorm. On 15 September 1983, 41.9% (27.0 mm) occurred in one hour, 69.8% (44.9 mm) in two hours and 77.2% (49.7 mm) in three consecutive hours. Hence, it may be concluded that the rainstorm of 22 September 1983 was not of unprecedented nature and that the resulting peak flood of 120000 cusecs at 2 PM on this day may be due to conducive antecedent conditions in the catchment.

The hourly catchment rainfalls are computed by taking the one-day weighted precipitation utilizing daily rainfall of the three stations and distributed into hourly according to the observed hourly distribution at Bidar. Since the catchment size is small and the spatial variations are very less in the catchment, it is believed that the assumption may not lead to any erroneous results.

9. Flood frequency analysis

Return periods (T_R) of annual peak floods observed at Halhalli have been computed using the formula :

$$T_R = (n+1)/m$$

where , n is the total number of years considered (21 in the present case) and m is the rank number. The ratios of each year peak flood with the mean annual peak floods have also been computed. Return periods *vs* these ratios are plotted on the extreme probability paper and the best fit curve has been drawn (Fig. 3). The curve has been extended to the higher return periods which is show as broken curve. In extending the fitted curve a tentative upper limit (horizontal dashed line) has been put which is equal to the peak of the storm hydrograph derived on the basis of PMP values and the unit hydrograph of the catchment which will be discussed in the following section. From the fitted curve 10, 25, 50, 100, 200-yr return period values of peak floods are estimated as 3.1, 5.1, 6.6, 7.8 & 8.6 times the mean annual peak flood respectively which are given in Table 7. Since the data set is only for 21 years, estimating return period values of more than 200 years may not be meaningful.

10. Derivation of unit hydrographs and their application

10.1. *Time of concentration of the catchment*

The foremost important aspect in the derivation of unit hydrograph is the unit duration of the unitgraph, which must be less than the time of concentration. The time of concentration for the Karanja catchment up to the dam site at Halhalli has been determined using the formula given by Hathaway (1945) :

$$T_c = 2.8\ (L/\sqrt{S}\ )^{0.47}$$

where,

T_c is the time of concentration in hours,

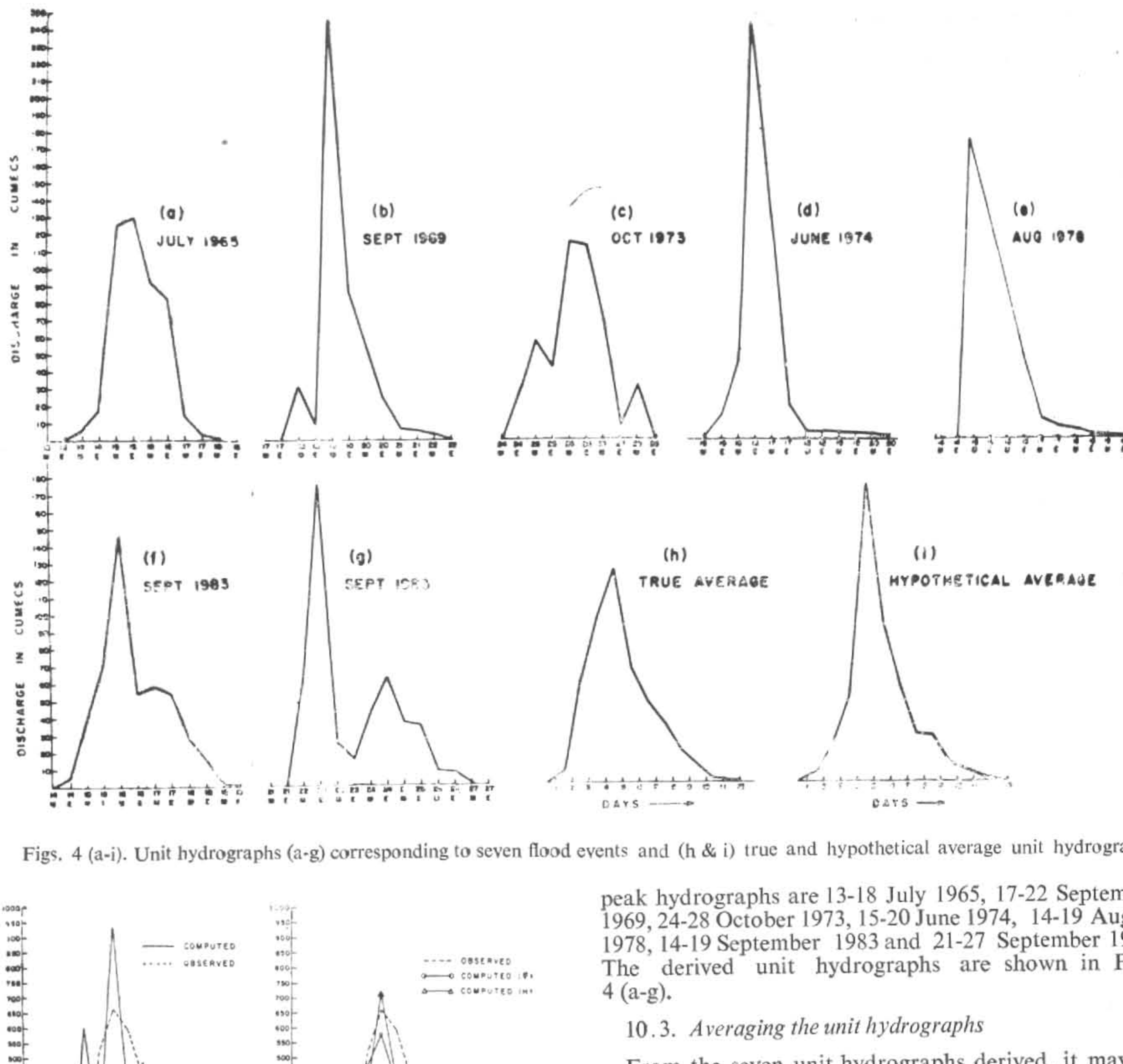
L is the mainstream length in km,

S is the mainstream slope in m km^{-1}.

For Karanja catchment, we have L=77 km and S=1 m km^{-1} and using these values, the time of concentration for the catchment has been worked out to be 21.6 hr.

10.2. *Derivation of unit hydrographs*

The unit hydrograph is the very simple yet powerful tool for hydrological analysis. It is defined as the direct runoff hydrograph resulting from one unit of effective rainfall which is uniformly distributed over the basin at uniform rate during a specified period of time known as unit duration. The unit of effective rainfall taken here is



Figs. 4 (a-i). Unit hydrographs (a-g) corresponding to seven flood events and (h & i) true and hypothetical average unit hydrographs

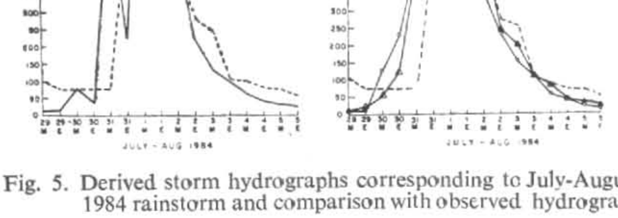


Fig. 5. Derived storm hydrographs corresponding to July-August 1984 rainstorm and comparison with observed hydrograph

1 cm and the outflow expressed by discharge is in cumecs (m^3 sec^{-1}). Streamflow observations of twice per day were utilized and the procedure outlined by Varshney (1979) has been followed in deriving unit hydrographs.

In order to develop unit hydrographs for the river *Karanja* at Halhalli site, several plotted flood hydrographs were examined and during seven major flood events, isolated flood hydrographs were selected taking into account of all monsoon months. The selected single peak hydrographs are 13-18 July 1965, 17-22 September 1969, 24-28 October 1973, 15-20 June 1974, 14-19 August 1978, 14-19 September 1983 and 21-27 September 1983. The derived unit hydrographs are shown in Figs. 4 (a-g).

10.3. *Averaging the unit hydrographs*

From the seven unit hydrographs derived, it may be seen that the peak of the unit graph as well as the total baselength vary. As a matter of fact it is not uncommon when various storms of different nature are considered for the development of unit graphs, that a marked variation may be observed especially in the peak as well as the time of peak occurrence. Therefore, it is necessary to obtain an average unit hydrograph for the catchment for practical use.

Two types of averages have been obtained here, called (*i*) True average and (*ii*) Hypothetical average. In the former type, the ordinates of all seven derived unit hydrographs have been added beginning from the first value of each unit graph and averaged. In the latter case, the peaks of all unit-graphs are superposed at one time and then their ordinates are averaged. These average unit hydrographs are shown in Figs. 4 (h & i).

10.4. *Application of the derived unit hydrographs*

Before discussing the application of the derived unit-graphs, it is desirable to examine their validity. Using

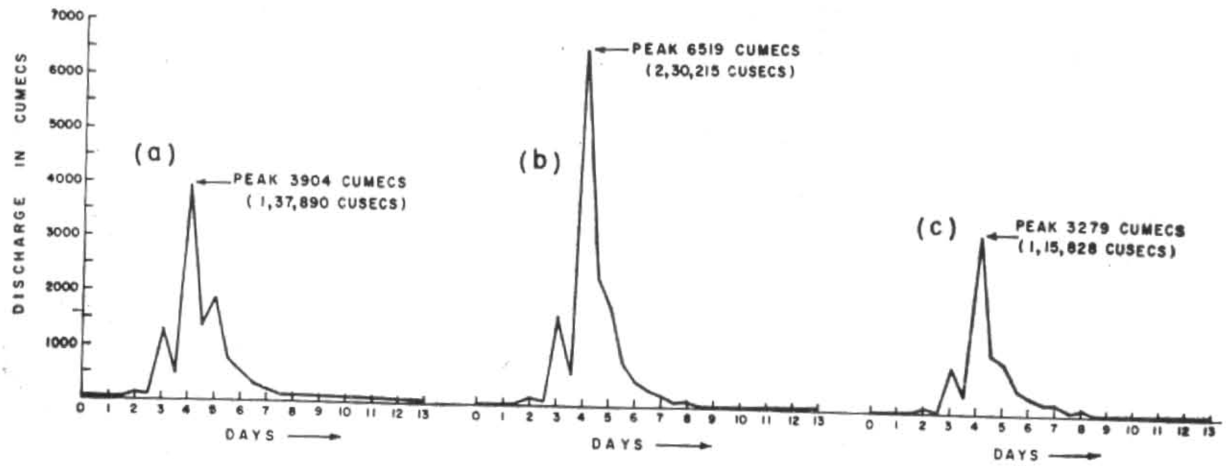


Fig. 6. Storm hydrographs derived utilizing 1, 2, 3-day highest observed rainfalls, estimated PMP values and SPS values

the unit hydrograph derived from 1969 flood event (Fig. 4 b); a storm hydrograph of direct runoff for the 3-day rainfall sequence of July-August 1984 rainstorm was obtained by following the computational procedure given by Viessman (1977) and the storm hydrograph is shown on left side of Fig. 5. The peak of this storm hydrograph is much above the observed, which is not unexpected. By utilising the true and hypothetical average unit hydrographs, storm hydrographs have been derived which are designated as computed (*T*) and computed (*H*) respectively and plotted on the right side of Fig. 5 together with the observed hydrographs. It may be seen from this figure that they are not much away from the observed one. Here, the excess or effective rainfalls are taken as 50%, 75% and 75% of observed first, second and third day rainfall sequence.

In a similar way, using the observed highest 1-day, 2-day and 3-day raindepths over the catchment (Ramanamurthy *et al.* 1987) and average unit hydrograph: storm hydrograph has been derived (Fig. 6 a). The maximum 1-day rainfall has been taken in the middle day of the 3-day rainstorm sequence. Based on the estimated probable maximum precipitation (PMP) values for 1, 2 and 3-day durations (Ramanamurthy *et al.* 1987), the corresponding storm hydrograph has been derivd in the same way (Fig. 6 b) and the peak of this is found to be 230215 cusecs which is nearly twice to that of the highest recorded so far. The highest observed raindepths experienced by the catchment are 193 mm (1949), 258 mm (1983) and 312 mm (1949) and the estimated PMP values are 339 mm, 406 mm and 424 mm for 1, 2 and 3-day durations respectively.

Generally, the standard project storm (SPS) rainfall is approximately half of the PMP (Viessman *et al.* 1977) and the storm hydrograph corresponding to this also been derived (Fig. 6 c).

11. Summary

(*i*) A major portion of the catchment area is covered by the soils of moderately high runoff potential.

(*ii*) About 5% of the total runoff measured at the dam site is contributed by the groundwater as baseflow and rainfall is the principal source of the recharge to the groundwater.

(*iii*) (a) Most of the major floods occurred in the catchment are in the month of September.

(b) The unprecedented peak flood of 120000 cusecs occurred on 22 September 1983 is the highest recorded so far.

(c) The mean annual peak flood is about 27000 cusecs.

(*iv*) (a) On an average about 33% of the catchment rainfall was converted into runoff during the period of study.

(b) Significant correlations between rainfall and runoff for individual months July through October as well as the entire period are observed.

(*v*) Peak floods in the catchment are mostly resulted by the events of intense short duration rainfalls and favourable baseflow conditions, as was reflected prominently in September 1983.

(*vi*) Peak floods of 10, 25, 50, 100, 200 years return periods are estimated as 3.1, 5.1, 6.6, 7.8 and 8.6 times the mean annual peak flood respectively.

(*vii*) (a) The time of concentration for the catchment has been worked out to be 21.6 hours.

(b) The unit hydrographs derived for various storm periods vary from one to another in shape and magnitude and thus an average unit hydrograph for the catchment has been obtained.

(c) Storm hydrograph corresponding to the highest observed 1-day, 2-day and 3-day rainfall sequence is obtained and the peak of the same is about 138000 cusecs which is little higher than the record flood of 1983.

(d) The storm hydrograph using estimated PMP values has also been derived and peak of the same is found to be 230215 cusecs which is approximately twice to that the highest recorded flood.

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