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Design of representative and key raingauge stations network for flood forecasting in Yamuna and Damodar rivers

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ABSTRACT. Representative raingauge networks have been determined for two selected catchments in India and regression equations for working out estimates of areal rainfall over the catchment from the rainfall data recorded at these stations have been developed. A few alternate key station networks have also been indicated for yielding representative estimates of areal rainfall when data for some station in the representative network may be missing. The stability of the various selected networks has also been tested with different sets of rainfall data. It has been possible to determine a small number of stations giving a multiple correlation coefficient of 96 and 98 and the regression explains about 92 and 97 per cent of the variation in areal rainfall respectively for the two catchments.

1. Introduction

Network design has been one of the most discussed topics in hydrology. Much of the impetus for hydrological network design was provided by the Symposium on Network Design held in Quebec (WMO/IASH 1965). Langbein and others (1969) have also laid solid foundations to this very important and fascinating problem of network design. More recently a collection of various methods appears in the case-book of network design (WMO 1972), wherein norms for the adequacy of network for general purposes, and for special hydrometeorological studies have been indicated.

1.1. *Meaning of 'adequate' network for operational flood forecasting* — From the references given above one would see that the emphasis so far has been towards augmenting the precipitation network. In flood forecasting, for instance, reasonably accurate and very quick determination of average rainfall that has fallen in the catchment is very essential. Adequate attention does not seem to have been given to this important aspect of hydrological forecasting. During a given flood situation, it is not always feasible to collect rainfall from a large number of raingauges where obviously the time factor does not permit such an exercise. Hence, for flood forecasting information on a representative value of rainfall has to be collected in the least possible time and a method should be available to make use of this data for getting a quick areal estimation of rainfall. The success of any scientific flood forecasting depends to a very great extent, on the ability to design a small operational raingauge network, which will be sufficient to define the areal rainfall with comparable accuracy attainable from a large number of raingauges for the same area. It is usually referred to as representative network or key station network. For operational flood forecasting, this then is the adequate network. It is, therefore, desirable to orient the approach to the design of a network, even for other water resources problems, from purely theoretical considerations towards a practical design. Furthermore, a flood forecasting system may consist of estimation of parameters like rainfall, run-off soil moisture, evapotranspiration etc, it is not sufficient and necessary if a very accurate determination of one of the parameters is made, in this case rainfall, but one has to visualise the possibility of having to relate this rainfall to the other parameters such as soil moisture, evaporation etc, which are either not accurately estimated or require extrapolation at the cost of overall accuracy. A third consideration is how the error in estimating the areal rainfall gets reflected in the estimated run-off and finally the river-stage that is forecast. One need not, therefore, insist on having the areal estimation of rainfall to a high degree of accuracy. Even in the conventional methods used in rainfall estimation there are considerable sources of errors, as for instance in the isohyetal method of estimating the areal rainfall, the subjective error introduced due to drawing of isopleths, can be of the order of about 20 per cent. Of course, conceptually, one has to have an idea of these errors and their effect in run-off forecasts in comparison to other errors in the parameter used in a flood forecasting model.

Having proposed now that for operational purposes the number of raingauges may be reduced to a very small number, we should make use of a method which renders a simple objective determination of areal rainfall. The multiple regression analysis has been in the past applied in many areas successfully, and in this case, this method has been made use of. The multiple regression method for hydrological purposes is discussed in detail by Yevdjevick (1964). This has been also discussed by Body (1966) and later tried by Hall (1972) for Australian rainfall.

1.2. *The procedure used for determination of key station network* — Let P_a be the areal rainfall required to be estimated from the observed records at selected stations $X_1, X_2, X_3, X_4, \ldots, X_n$ then P_a can be determined by

$$P_a = C + A_1X_1 + A_2X_2 + A_3X_3 + \ldots + A_nX_n \quad (1)$$

where $A_1, A_2, A_3 \ldots\ldots A_n$ are called the regression coefficients derived from a sample observed data and C is constant which is called the 'intercept'. The expression given by Body (1966) and Hall (1972) are much the same as above, and is given as

$$P_{\text{areal}} = a_1x_1 + a_2x_2 + a_3x_3 + \ldots + a_nx_n \quad (2)$$

who suggest that the intercept be taken as zero, in order to satisfy a condition stipulated by them that regression expression should give zero average rainfall when all the individual stations report zero rainfall. In the present paper Eqn. (1) above has been used.

The method involves a gradual process of elimination of stations. For this purpose, the following steps would illustrate the method followed.

At first correlation coefficients between the average of the storm rainfall and the individual station rainfall are found. The stations are then arranged in order of their decreasing correlation cofficients and the stations exhibiting higher correlation coefficient are considered for further analysis. The next step is to determine the independent order of correlation. For this, the station showing the highest correlation coefficient among the stations considered is called the first key station and its data is removed for the determination of the second key station, which gets the second preference is significance in the determination of key station network and this procedure is repeated by considering the average rainfall of the remaining stations. The station showing the highest correlation coefficient, after removing the data of first station is called the second key station in the representative network design. Similarly, the third key station will be the one having the highest correlation with the two key stations already selected and their data removed out of consideration.

As each station gets added to the key station network, the total amount of variance which is accounted for by the network at that stage is determined. This would provide a basis for determining the number of stations required for achieving an acceptable degree of error in the areal estimate.

The multiple correlation coefficient increases with the increase of the number of stations in the combination and the sum of the squares of the deviations of the estimated values of average rainfall from actual as wall as the maximum deviation decreases. A stage will then be reached when improvement in either the multiple correlation coefficient or the sum of the squares of deviation will be little. The corresponding number of raingauges at that stage will be taken as the representative network for the purpose of determining areal estimate of rainfall. The next step is to test several combinations of the number of key stations which give a satisfactory estimate of the areal rainfall. Thus a number of alternative key station networks are determined which may be employed to give estimates of areal rainfall taking into account, the possibility of any of the stations in the best combination not reporting the rainfall data .

It should be once again stressed at this stage that for flood forecasting purposes, it would be futile in any event to try and obtain rainfall data from a conventional network, because in a flood situation, it is open to doubt if the full data required for spatial averaging will at all be forthcoming within the short time available for issue of forecasts. Hence, the need for a new and practical approach to the design of network for operational purposes.

2. Method applied to Yamuna catchment upto Kalanaur

2.1. *The catchment area considered* — The *Yamuna* river rises in the Tehri Garhwal district of Uttar Pradesh from the Yamnotri glacier at an elevation of about 6,320 m at Lat. 30°58′ N and Long. 78° 27′ E. It is joined by a number of tributaries in the lessor Himalayan ranges and ridges. The combined stream forces its way through Siwalik range of hills and into the plains of Uttar Pradesh in the Saharanpur district. The entire *Yamuna* basin extends over an area of 2,26,755 sq. km.

The present study is confined to *Yamuna* catchment having area of 12,800 sq. km upto Kalanaur (Fig. 1) for the purpose of determination of representative network for flood forecasting. The catchment above Paonta is rugged terrain with ridges extending to heights of about 5,000 m and the area is close to the snowline. Some of the stations like Chakrata, Chopal, etc experience seasonal snowfall. Most of the contribution of flow in this river is contributed by rainfall in these areas. The catchment below Paonta and Tajewala is a plains area and is a narrow one whose total contribution to the flood discharge in the river may be of the order of 20 per cent only.

The seasonal rainfall from June to September which are the monsoon months which give the main flood producing rains, is shown in Fig. 2. There is a concentration of seasonal rainfall in the area around Dehra Dun-Mussoorie. Seasonal rainfall decreases further to the north and south of Dehra Dun. The outer isohyet of 70 cm covers practically all the three sub-catchment areas and one could see easily the reasons for 80 per cent of flood contribution made by rainspells occurring over the areas above Paonta. In the plains area rainfall gradually decreases southwards. The rainfall that occurs in the sub-catchments of the *Giri, Tons,* etc above Paonta is of sufficient importance for downstream flood and hence the necessity to quickly know the areal rainfall in this area. The catchment upto Kalanaur has been selected for this reason.

2.2. *Raingauge network and data used for the analysis* — A network of 35 raingauge stations (Fig. 1) are functioning within the upper Yamuna cachment upto Kalanaur. On examination of past rainfall records of these stations, it was found that rainfall data for 16 stations (Table 1) were available without breaks. The data of each station is represented by a symbol shown in this table. The data at these 16 stations for the period from 1951 to 1967 were made use of for the study. Daily rainfall averages for various storm dates of these 16 stations were computed and all occasions when the average rainfall was above 10 mm were further considered for treatment and analysis. In the present study one-day storm rainfall has been used.

2.3. *Determination of representative raingauges for Yamuna catchment* — The details of the method adopted were given in earlier sections. The computations give the sum of squares of deviations of the estimated values of average rainfall employing the regression equation from the actual rainfall as well as the maximum deviation between them. As the number of representative raingauge stations increases, it is natural to expect that the sum of the squares of deviation as well as the maximum deviation of any single estimated value from the actual will decrease. A stage will reach when little improvement is noticeable either in the multiple correlation coefficient or in the sum of squares of deviations by any further increase in the number of representative raingauges in the network. List of the 10 representative raingauge stations selected on this basis is given in Table 2(a). Beyond this stage, therefore, any further increase in the representative raingauges is not likely to bring any marked increase in the efficacy and at that level the network is taken as the representative network for the area under consideration.

2.4. *Results of application of regression analysis for determining the key station network* — It has been seen that as the data of an additional key station is introduced into the regression equation, the estimated value of catchment rainfall generally improves and the maximum deviation and the sum of squares of deviations generally falls rapidly at first and less rapidly after about 5 raingauge stations. The maximum deviation and sum of the squares of the deviation are shown in Fig. 3(a) & 3(b). Since the curves show a tendency to get flattened after 5 stations, it was decided to take up the solution for regression equation for 5 stations and above. The regression equations for 5, 6, 7 and 8 key stations network were worked out accordingly.

2.5. *Test results of appliation of two regression equations for Yamuna catchment rainfall* — The test results for 5, 6, 7 and 8 key station networks based on a sample of 50 observations may be seen in Table 3. The test was carried out on a fresh set of 100 observations.

The regression equation for 8 key stations in this case gave the best results. The regression coefficients and constants for 5, 6, 7 and 8 stations based on a sample of 50 observations used in the derivation of regression equations may be seen in Table 4. The multiple correlation coefficient for 8 stations is 0·95 and the regression accounts for 91 per cent of total variation in average rainfall.

Further to see if the regression coefficients are significant in the second case, Student's t value for each regression equation were worked out. Based upon the Student's t values a set of 8 key stations was selected as shown in Table 2(b). Regression equations for 5, 6, 7 and 8 of these stations were worked out and tested on a fresh set of data. The results of this test are shown in Table 3, and the regression coefficients and constants in Table 4. The multiple correlation coefficient for

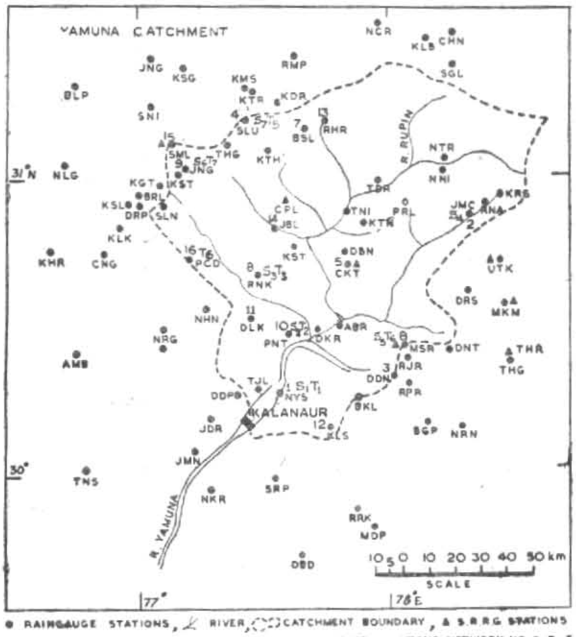


Fig. 1. Raingauge stations in Yamuna catchment upto Kalanaur

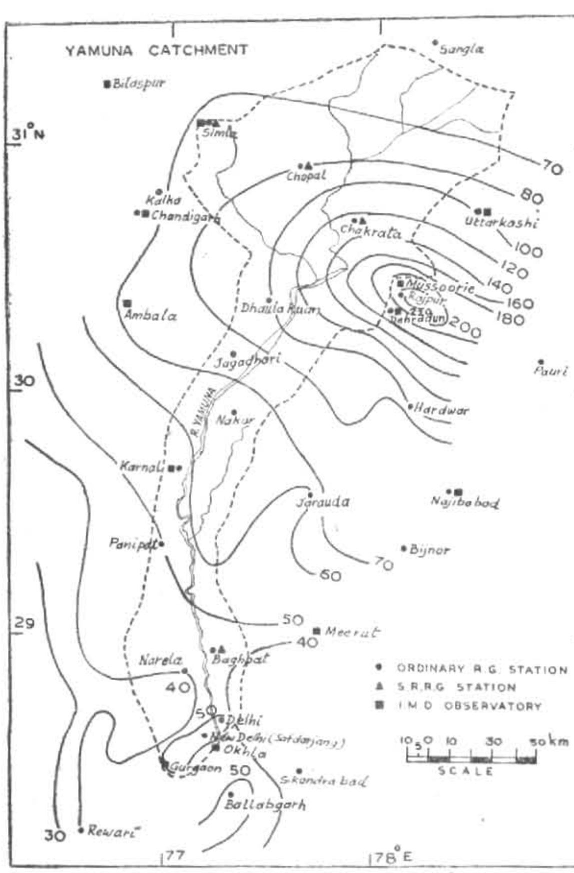


Fig. 2. Normal seasonal map (Jan-Sep) for Yamuna catchment

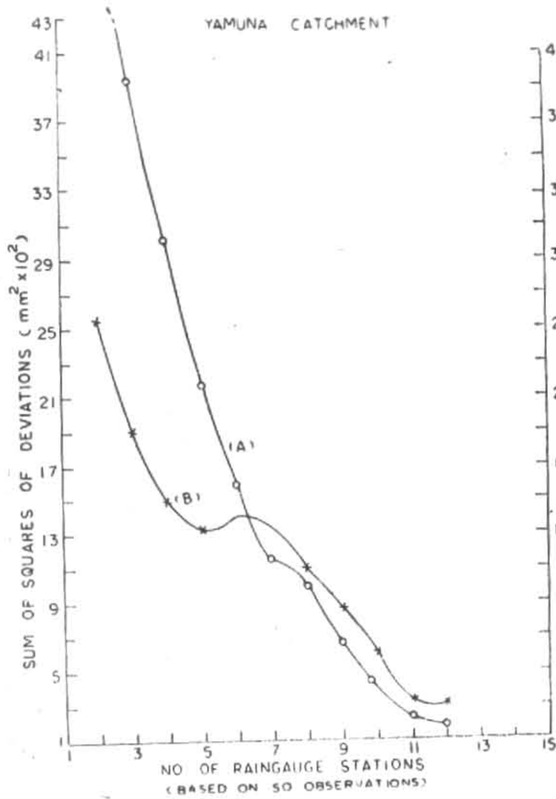


Fig. 3. Graph showing the variation in (A) sum of square of difference of calculated values from actual and (B) maximum difference with increase in number of key stations

TAALE 1

Correlation coefficient between station rainfall and average rainfall

(Number of observation used 50)

Station	Parameter symbol	Correlation coefficient	Rank No.	Height a.m.s.l. (m)
Nayashahr	X_1	·623	I	319
Jamuna Chetty	X_2	·564	IV	1585
Dehra Dun	X_3	·299	XII	682
Shillaru	X_4	·157	XVI	2450
Chakrata	X_5	·355	IX	1905
Mussoorie	X_6	·571	III	2042
Bashla	X_7	·211	XIII	2250
Renuka	X_8	·403	VIII	2100
Junga	X_9	·341	X	2100
Paonta	X_{10}	·581	II	600
Dhaula Kuan	X_{11}	·489	VII	600
Kalsia	X_{12}	·503	VI	296
Rohru	X_{13}	·171	XIV	2100
Jubbal	X_{14}	·322	XI	2000
Simla	X_{15}	·165	XV	2202
Pachhad	X_{16}	·554	V	1200

TABLE 2

Yamuna Catchment

(a) Representative stations

1. Nayashahr	6. Renuka
2. Mussoorie	7. Junga
3. Pachhad	8. Dhaula Kuan
4. Jamuna Chetty	9. Shillaru
5. Paonta	10. Dehra Dun

(b) Key stations

1. Nayashahr	5. Shillaru
2. Paonta	6. Pachhad
3. Renuka	7. Junga
4. Mussoorie	8. Dehra Dun

*Selected on the basis of Student's t values of regression coefficients

TABLE 3

Departures of estimated rainfall averages from actual averages below the indicated percentage for Yamuna catchment

(Total number of cases tested : 100)

No. of stations		No. of cases lying withing 20%	30%	40%	Total number considered
5	A	33	42	57	100
	B	48	70	80	100
6	A	41	54	62	100
	B	54	67	81	100
7	A	47	65	75	100
	B	67	76	88	100
8	A	51	67	77	100
	B	67	83	93	100

NOTE A—Combination of key stations selected on the basis of independent order of correlation.

B—Combination of key stations selected on the basis of Student's t value of regression coefficients.

8 stations network is now 0·97 and the regression accounts for 94 per cent of the total variation in average rainfall.

A graph showing percentage of cases, for which values estimated employing the Student's t regression equations for 5, 6, 7 and 8 key stations were within ± 30 per cent of the average for a different set of 100 observations, is given in Fig. 4.

It was also seen that increasing the sample size from 50 to 70 observations did not bring in any appreciable improvements in the results.

2·6. *Standard error of estimate* — On a comparison of the results for a fresh set of data employing the equations based upon the various combinations of

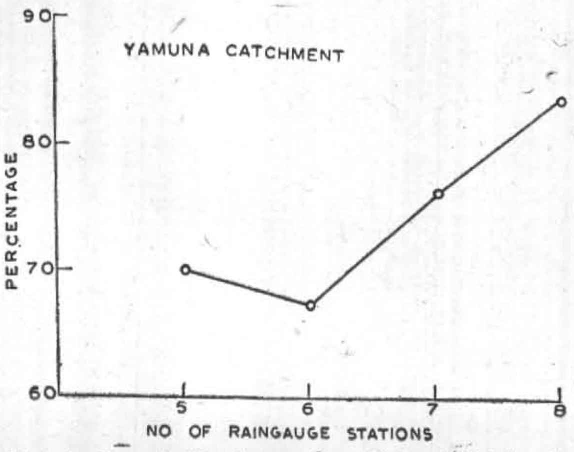


Fig. 4. Percentage of cases for which calculated values were within $\pm$ 30 per cent of the actual averages (Result of fresh set-B of Table 3)

number of stations, it was seen that the set of 8 key stations using Student's t values gave the best results. The values of the computed rainfall averages based on the regression coefficients for this set were used to work out the standard error of estimate yielded by this equation which works out to 3·7 mm or 11 per cent of the average. The standard errors of the estimates yielded by the two sets of regression equations for 5, 6, 7 and 8 stations and expressed as percentage of averages are shown in Table 4. In particular the regression equation developed on the basis of 50 observations as sample data, for 8 key stations yielded estimates which on 83 per cent of occasions were found to be within 30 per cent of actual with a standard error of estimate of 3·7 mm or 11 per cent of the average.

The regression equation based on 5 of the stations selected on Student's t basis yielded results which in 70 per cent of the cases lie between ± 30 per cent of actual, the corresponding multiple correlation coefficient was 0·94, and regression accounted for 88 per cent of the total variation. The standard error of estimate for the 5 stations network is 6·2 mm or 18 per cent of the average.

3. Alternativer key station network for Yamuna catchment upto Kalanaur

In order to take into account the possibility of data for any of the key stations in the network of 8 key stations mentioned above, being not available on some occasion, it was considered necessary to have a few alternative key station networks which will be equally acceptable for computing areal rainfall. Out of 10 representative key stations mentioned earlier, alternative key station networks consisting of 7 stations in each network have been considered. Table 5 indicates the serial number of the various key stations selected for various alternate networks together with their multiple correlation coefficient, the percentage of variance accounted for by the network and the standard error of

TABLE 4
Regression coefficients and standard error for Yamuna Catchment

No. of stations		Regression coefficients for station number								Cons-tant 'C'	Standard error of the estimate	
		1	2	3	4	5	6	7	8		S.E. (mm)	% of mean
5	I	·071	·049	·126	·185	·081	—	—	—	14·312	6·0	17·7
	II	·144	·093	·173	·118	·180	—	—	—	5·405	6·2	18·2
6	I	·085	·055	·095	·132	·090	·125	—	—	11·036	5·6	16·5
	II	·129	·090	·160	·113	·162	·043	—	—	5·947	5·7	16·8
7	I	·098	·086	·059	·081	·085	·135	·118	—	8·266	5·3	15·6
	II	·127	·086	·156	·121	·118	·029	·295	—	5·080	3·8	11·2
8	I	·092	·082	·060	·068	·077	·117	·132	·045	7·828	5·0	14·7
	II	·121	·082	·165	·108	·113	·041	·082	·052	3·233	3·7	11·0

Note : I—Key stations selected on the basis of independent order of correlation coefficients
II—Key stations selected on the basis of Student's t values of regression coefficients

TABLE 5
Serial numbers of parameters* for the various alternate networks for Yamuna Catchment

	S. No.	Alternate Network Number							
		1	2	3	4	5	6	7	8
	1	1	1	1	1	1	1	1	1
	2	6	10	10	10	16	16	11	10
	3	16	16	8	6	6	2	3	8
	4	2	6	2	16	2	6	16	6
	5	10	4	6	2	4	9	2	4
	6	8	2	9	4	10	10	4	16
	7	9	9	4	9	9	8	9	9
M.C.C. for the network		·946	·925	·955	·925	·925	·946	·908	·957
% variance in av. rainfall accounted for by regression		89·6	85·6	91·3	85·6	85·6	89·6	82·4	91·6
Standard Error (S.E.)		5·3	5·2	5·4	5·2	5·2	5·3	5·1	5·4

*For corresponding station of the number indicated in this table please see Table 1.

TABLE 6
Alternative key station networks for Yamuna Catchment

Set No.	Regression constants for various parameters							Intercept
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	
I	·098	·086	·059	·081	·085	·135	·118	8·2661
II	·098	·078	·083	·088	·096	·125	·072	9·9213
III	·132	·088	·158	·032	·114	·099	·122	4·8876
IV	·098	·078	·088	·083	·125	·096	·072	9·9213
V	·098	·083	·088	·125	·096	·078	·072	9·9213
VI	·098	·059	·081	·086	·118	·085	·135	8·2661
VII	·111	·086	·062	·118	·161	·077	·061	9·4899
VIII	·127	·086	·156	·121	·118	·029	·095	5·0800

TABLE 7
Test results of 8 alternative key station networks for Yamuna Catchment

Set No.	M.C.C.	First Set			Second Set		
		20%	30%	40%	20%	30%	40%
1	·946	19	31	35	29	34	41
2	·925	21	27	33	20	32	36
3	·955	29	36	43	30	40	45
4	·925	21	27	33	20	32	36
5	·925	21	27	33	20	32	36
6	·946	19	31	35	29	34	41
7	·908	25	30	32	24	34	37
8	·957	26	35	42	31	41	45

NOTE : No. of occasions for which estimated rainfall averages differ from actual are shown below the indicated percentage

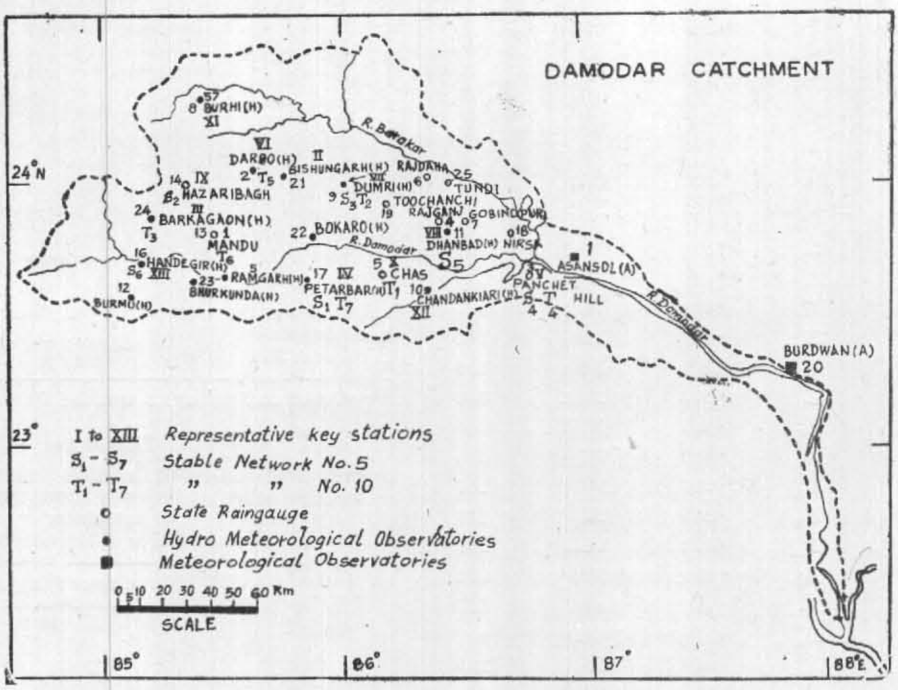


Fig. 5. Damodar catchment showing raingauge stations selected for key station network study

the estimate. The values of regression coefficients and intercepts for the various alternative key station networks are given in Table 6.

Test results of the 7 alternative key station networks on two fresh sets of 50 observations each are presented in Table 7. It is seen that alternate key station networks numbere 3 to 8 have given fairly stable and consistent result.. These two key station networks are shown in Fig. 1. From Table 5 the numbers of stations for alternate set No. 3 are 1, 10, 8, 2, 6, 9 and 4 which correspond to the stations Nayashahr, Paonta, Renuka, Jamuna Chetty, Mussoorie, Junga and Shillaru. From Table 6, the corresponding regression equation is as follows :

$$P_a = \cdot 132\ X_1 + \cdot 088\ X_{10} + \cdot 158\ X_8 + + \cdot 032\ X_2 + \cdot 114\ X_6 + \cdot 099\ X_9 + + \cdot 122\ X_4 + 4 \cdot 8876$$

4. Determination of key station network for Damodar catchment

The *Damodar* river rises in the Palamau hills of Chotanagpur at an elevation of about 600 m above mean sea level. The river has a general flow in the southeasterly direction and meets the *Hooghly* river in the deltaic plains of West Bengal. The drainage basin of the *Damodar* river is of the order 22,000 sq. km. There are at present five dams across this river. A map showing the D.V.C. catchment is given in Fig. 5. Damodar is one of the catchments in India which has a very derse network of raingauges. The total number of raingauges in Damodar catchment is about 75.

4·1. *Key station network for D.V.C. and alternative key station networks* — The procedure outlined in 1·2 above has been applied to the Damodar catchment area and a key station network has been determined. It is found that the data of 25 stations (Table 8) are available continuously in the catchment during the period 1957-1969 and have, therefore, been considered for the key station network design. The data of each station is represented by a symbol. Following the procedure enumerated for Yamuna catchment in Sec 2·3 above, 13 key stations have been determined for the Damodar catchment. The representative raingauge stations selected on the basis of independent order of correlation using the data of 50 observations. These are given in Table 9 (a). The analysis as before gives the sum of squares of differences between the estimated and actual average rainfall, as well as the maximum deviation from the actual. A graph showing these two values may be seen in Fig. 7. From this figure it could be noticed that beyond 10 stations there is no significant change either in the sum of squares of differences or

TABLE 8

Raingauge stations (in order of rank) lying within Damodar catchment

(No. of observations used 50)

Name of the station	Para-meter symbol	Corr. coeff.	Rank No.	Height a.m.s.l. (m)
Asansol	X_1	·558	XVI	126
Daroo	X_2	·698	X	564
Panchet Hill	X_3	·720	VI	119
Rajganj	X_4	·121	XXV	241
Chas	X_5	·574	XIV	300
Rajdaha	X_6	·577	XIII	300
Gobindpur	X_7	·405	XXIII	200
Barhi	X_8	·699	IX	350
Dumri	X_9	·726	V	287
Chandan Kiary	X_{10}	·671	XI	117
Dhanbad (Obsy.)	X_{11}	·708	VIII	256
Burmu	X_{12}	·468	XX	622
Mandu (H)	X_{13}	·817	I	427
Hazaribagh (H)	X_{14}	·718	VII	611
Ramgarh	X_{15}	·524	XIX	335
Hendirgir	X_{16}	·587	XII	352
Petarbar	X_{17}	·769	IV	375
Nirsha	X_{18}	·569	XV	150
Topchanchi	X_{19}	·462	XXI	300
Burdwan	X_{20}	·543	XVII	32
Bishnugarh	X_{21}	·783	III	442
Bokaro	X_{22}	·386	XXIV	242
Bhurkunda	X_{33}	·526	XVIII	354
Barkagaon	X_{34}	·788	II	405
Tundi	X_{25}	·458	XXII	350

TABLE 9

Damodar catchment

(a) Representative stations

1. Mandu
2. Bishnugarh
3. Barkagaon
4. Peterbar
5. Panchet Hill
6. Daroo
7. Dumri
8. Dhanbad
9. Hazaribagh
10. Chas
11. Barhi
12. Chandan Kiary
13. Bendigir

(b) Key stations*

1. Chas
2. Dumri
3. Barkagaon
4. Panchet Hill
5. Daroo
6. Mandu
7. Peterbar

*Based on Student's *t* test for Damodar Catchment

TABLE 10

Departures of estimated rainfall averages from actual averages below the indicated precentage for Damodar catchment

(Total number of cases tested 50)

No. of stations		No. of cases lying within 20%	30%	40%	Total number considered
5	A	27	33	33	50
	B	32	40	43	50
6	A	23	36	41	50
	B	32	40	47	50
7	A	23	36	46	50
	B	31	42	47	50

NOTE A — Combination of key stations selected on the basis of independent order of correlation.

B — Combination of key stations selected on the basis of Student's *t* value of regression coefficient

TABLE 11

Serial number of parameters* used for various alternate network for Damodar catchment

	S. No.	Alternate network number 1	2	3	4	5	6	7	8	9	10
	1	13	13	13	24	17	5	5	13	13	5
	2	21	21	21	21	14	9	9	24	24	9
	3	24	17	17	9	9	24	4	17	17	24
	4	17	3	3	3	3	3	3	3	3	3
	5	3	11	11	11	11	2	2	2	2	2
	6	2	14	10	5	16	13	13	9	9	13
	7	9	8	8	8	8	8	11	8	11	17
M.C.C. for the network		·967	·949	·948	·974	·958	·983	·980	·968	·969	·983
% of variance in av. rainfall accounted for by regression		93·6	93·0	89·9	95·1	91·9	96·6	96·1	93·8	93·9	96·7
Standard Error (S.E.)		6·4	6·3	6·3	6·4	6·3	6·5	6·5	6·4	6·4	6·5

*For corresponding station of the number indicated in this table please see Table 1

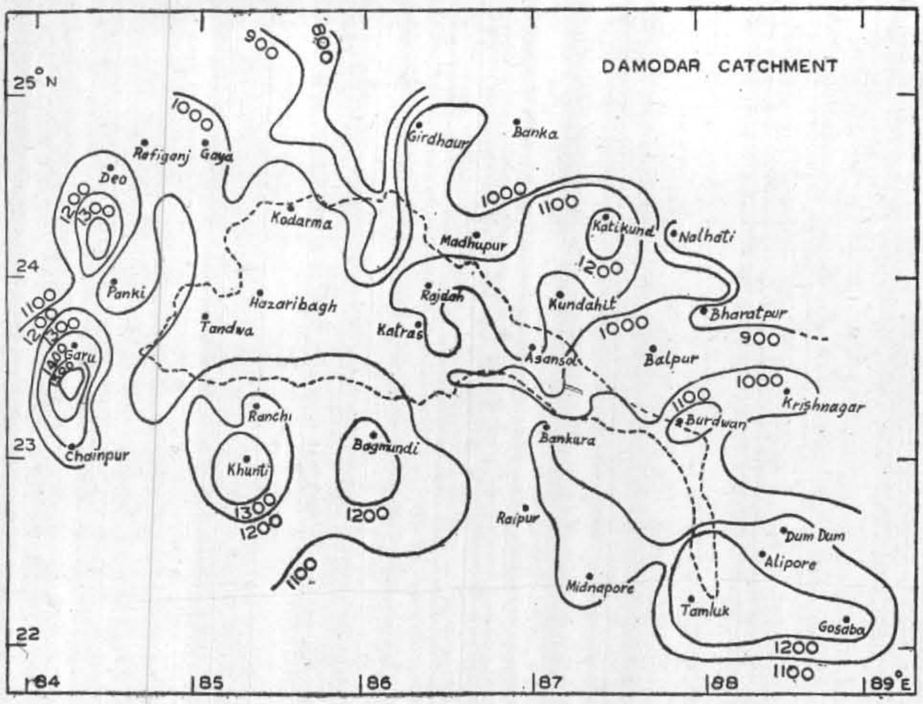


Fig. 6. Isohyetal map of Damodar catchment showing normal seasonal rainfall (June—September)

TABLE 12

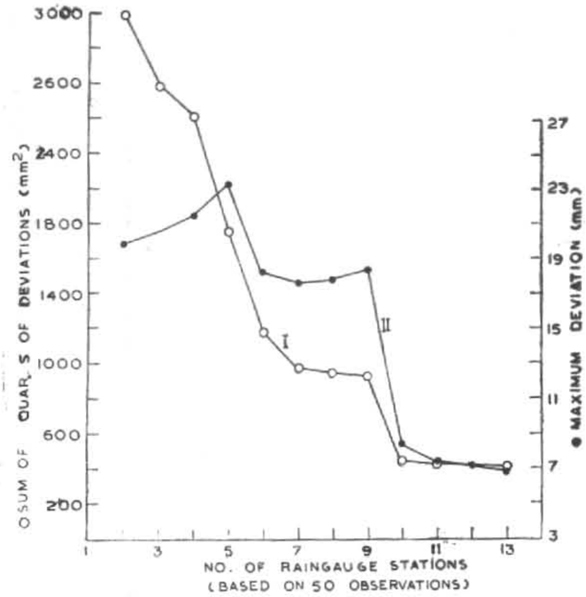
Key station network for Damodar Catchment

Set No.	Regression constant for various parameters							Intercept
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	
I	·054	·010	·180	·083	·127	·190	·086	6·2828
II	·133	·079	·054	·103	·122	·120	·082	6·1267
III	·154	·114	·025	·079	·091	·093	·131	6·8986
IV	·272	·067	·075	·044	·086	·238	·110	3·6746
V	·094	·161	·060	·132	·116	·165	·074	4·0328
VI	·197	·098	·197	·084	·094	·096	·071	4·4781
VII	·193	·107	·206	·077	·110	·102	·029	4·6079
VIII	·056	·173	·073	·125	·174	·076	·047	6·1209
IX	·049	·179	·082	·106	·175	·080	·054	5·8873
X	·182	·102	·203	·082	·118	·063	·059	4·6622

the maximum deviation. Therefore, the number could thus be brought down to 10 from 13. This was further brought down to 7 by a process of efficient combinations amongst the key stations. Multiple correlation coefficient (MCC) for these 7 stations was ·967 and it accounts for 94 per cent of variance. Testing of the regression equation on 100 observations showed that in 78 cases the estimated value was within 30 per cent of the actual. Next based upon the Student's t values of regression coefficients another set of 7 key stations was selected. These stations are given in Table 9 (b). The multiple correlation coefficient for this set was ·983 and it accounts for 97 per cent of variance. Testing the equation on 100 observations showed that in 87 cases the estimated values were within 30 per cent of the actual.

Test results for 5, 6 and 7 key stations network based on a fresh set of 50 observations for the two sets of regression equations are presented in Table 10. Fig. 8 shows the percentage of cases for which values of rainfall estimated employing the Student's t regression equations for 5, 6 and 7 key stations were within 30 per cent of the actual.

4.2. *Alternative key station networks for Damodar catchment* — Out of the 13 key stations, the analysis shows that from about 7 stations onwards the



Fig, 7. Key station network for Damodar. Variation in (I) sum of square of differences of calculated values for actual and (ii) the max. differences with incerease in No. of key stations

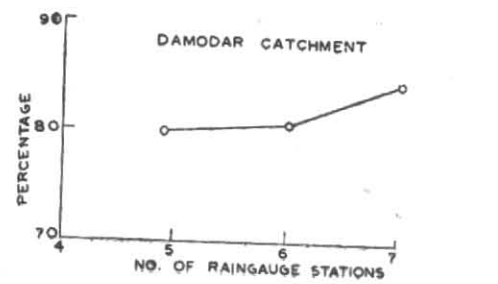


Fig. 8. Percentage cases for which the calculated values were within ±30 per cent of actaul averages (Result of fresh set-B of Table 9)

TABLE 13

Test result of 10 alternate key station networks for Damodar Catchment

Set No.	M.C.C.	First Set			Second Set		
		20%	30%	40%	20%	30%	40%
1	·967	23	36	46	36	42	47
2	·949	33	41	46	31	39	42
3	·948	27	41	47	29	37	42
4	·947	26	36	42	35	43	46
5	·958	35	43	48	35	39	44
6	·983	33	39	47	38	44	49
7	·980	34	42	47	36	43	49
8	·968	20	37	44	35	42	47
9	·969	25	41	46	38	43	46
10	·393	31	42	47	37	45	47

Note : No. of occasions for which estimated rainfall averages differ from actual are shown below the indicated percentage

improvement achieved in the multiple correlation coefficient as well as the percentage which the regression accounts for is marginal. Hence, the key station network is tried for an efficient combinations of 7 key station networks. For this purpose, by altering one or two stations in each of the earlier of key station network it was possible to get about 10 alternative key station network of 7 key stations each, which can estimate average catchment rainfall with comparable accuracy. This alternative network is of great practical significance because it takes into account the possibility of any of the stations in a particular key station network not reporting in a given operational situation. In such circumstances that alternative key station network which can make use of the reported data from among the 10 key station is used. 10 alternative key stations have been provided which should be sufficient to meet the contingency of data of any of the key stations not being received in time. Serial numbers of the ten alternative key station networks for estimating average rainfall for the Damodar catchment, together with their coefficient of multiple correlation, the percentage of variance accounted for by the network and the standard error of the estimate is indicated in Table 11. Values of the regression coefficient and intercepts for the various alternative key station networks are given in Table 12. Test results of the 10 alternative key station networks on two sets of 50 observations each are presented in Table 13. It is seen that alternate key station networks number 5 and 10 give fairly stable and consistent results. These two key station networks are shown in Fig. 5. From Table 11, the number of stations for alternate set 5 are 17, 14, 9, 3, 11, 16 and 8 which correspond to stations Petarbar, Hazaribagh, Dumri, Panchet Hill, Dhanabad, Hendigir and Barhi. The corresponding regression equation is as follows :

$$P_a = \cdot 094\ X_{17} + \cdot 161\ X_{14} + \cdot 060\ X_9 + \cdot 132\ X_3 + \cdot 116\ X_{11} + \cdot 165\ X_{16} + \cdot 074\ X_8 + 4 \cdot 033$$

5. Conclusion

Using the multiple regression analysis, representative networks and several alternative key station networks have been determined for two catchments, *viz.*, Yamuna and Damodar.

In the case of Yamuna catchment 10 representative raingauges have been determined and 8 alternative key station networks consisting of 7 key stations in each network have been given. The results have been tested on fresh sets of data. Similarly, for Damodar catchment, a representative raingauge network of 13 raingauges was determined and 10 alternative key station networks consisting of 7 stations in each were found out. The idea is that even if any one of the representative raingauge stations does not report data, the next alternative key station network can be pressed into service which will be of great practical use to an operational flood forecaster.

The stability of all these alternative key station networks has been tested with different sets of rainfall data for the above catchments. On the basis of this, two priority key station networks have been indicated for each catchment.

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