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NETWORK DESIGN OF RAINGAUGES IN RAJASTHAN STATE

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ABSTRACT

Hydrological and meteorological data are collected mainly to provide information for assessing,developing and managing the water resources. The aim of a hydrological network is to provide a density and distribution of stations in a region such that by interpolation between data sets at different stations, it should be possible to determine with sufficient accuracy, the characteristics of meteorological and hydrological elements anywhere in the region.

A network of raingauges are intended to serve general as well as specific purposes such as water supply, hydro-power generation, irrigation and flood control. For planning, a network to meet these requirements, scientific approach is necessary. Several authors have suggested simple and rigorous statistical techniques like estimation of error in the computed areal rainfall and optimum interpolation techniques like objective analysis and Kriging.

Rajasthan State with a total geographical area of 3,42, 271 km^2 is having a network of 521 raingauge stations. Though the state is semiarid and arid climatically, from hydrological considerations,however, the state has experienced both extremes: floods and droughts. A good network of raingauge stations at the block level is, therefore, necessary for planning relief measures and future drought management schemes Also, an adequate network of ordinary and self-recording raingauges is necessary for providing good data base for

project planning, design of rail and road bridges, drainage schemes in cities and operational flood forecasting and river management. The State Irrigation Department had indicated interest in scientific assessment of present network and to determine need for the augmentation of the raingauge network for water resources assessment and flood forecasting purposes in 59 important watersheds and other areas.

A network design study of the raingauges in the State has been undertaken keeping in view the requirements of raingauges in the district as an administrative unit and the 59 watersheds as the hydrological units. Besides the WMO standard and simple well known formula $N = (C_v/P)^2$, the Kagan's technique involving the interstation correlation has also been used to determine the number of raingauges required from climatological and hydrological considerations in the different districts of the Rajasthan State.

The results indicate that in general the existing network seems to be adequate from the climatological point of view but needs to be augmented for hydrological purposes. Both the $(C_v/P)^2$ and Kagan's techniques have yielded comparable results.

This case study has also indicated that for designing the raingauge network for hydrological purposes appropriate accuracy criteria needs to be laid down and the area based WMO criteria need not be the only guideline.

1.0 INTRODUCTION

Hydrological and meteorological data are collected mainly to provide information for assessing, developing and managing water resources. Rainfall is one of the most important factors for correct assessment of water resources. It is,therefore, necessary to ensure that the raingauge network is adequate, so that by interpolation between data at different point locations, it should be possible to determine with sufficient accuracy the rainfall depths in the region.

A network of raingauge stations is intended to serve one or more of the purposes such as water supply, hydropower generation, irrigation, flood control etc. The setting up of raingauge networks is a long term process. The purpose of data collection and the level of information required changes as the level of development of the region changes. For example, the information required for design and construction purposes would be more than that for mere inventory purpose; and would be certainly much more for operation and management purposes such as reservoir regulation, flood control and flood forecasting.

Rajasthan State with a total geographical area of 342271 sq.km. has a network of 521 raingauges. The State Irrigation Department has indicated its interest in the augmentation of the raingauge network for providing better estimates of areal rainfall for operational purposes during the flood and other hydrological purposes. A study to design the network of raingauges in the Rajasthan State has accordingly been undertaken by considering the available rainfall data from the existing raingauges upto date i.e. 1985, provided by Rajasthan Irrigation Department.

2.0 REVIEW

Rainbird(1965) had discussed the problem of network design of precipitation stations and suggested an overview of the problem by assessing the accuracy of data required, the relative importance of precipitation data for the project and the time intervals for which such records need be maintained for a given region.

The World Meteorological Organisation(1974) has recommended the following as minimum network densities for general hydrometeorological practices.

(i) For flat regions of temperate, mediterranean and tropical zones-one station for 600- 900 km^2.

(ii) For mountainous regions of temperate, mediterranean and tropical zones-one station for 100-250 km^2.

(iii) For arid and polar regions - one station for 1500-10000 km^2 depending on feasibility.

The Indian Standards Institute(ISI 4987-1968) suggested that one raingauge upto 500 km^2 might be sufficient in non-orographic regions. In regions of moderate elevation(upto 1000 m a.s.l.) the network density might be one raingauge for 250 km^2 to 400 km^2. In predominantly hilly areas and areas of heavy rainfall, the density recommended was one for 130 km^2

The ISI standard and India Meteorological Deptt(1972) had recommended a simple formula based on Rycroft(1949)

$$N = \left(\frac{C_v}{p}\right)^2 \qquad \ldots(1)$$

where N is the number of raingauges, C_v is the coefficient of variation of the rainfall of the existing raingauges and p is the percentage permissible or desired error of accuracy.

Interesting and valuable studies using very dense raingauge networks have been conducted to determine the standard error of average precipitation estimates over various size drainage areas with various raingauge network densities. Linsley et al (1947) had presented a U S weather Bureau graph which suggested that the standard error of estimate of storm rainfall over Muskingum basin in Chicago, USA (CA=8000 mi^2) was about 6 percent for a density of one raingauge per 100 mi^2 (about 250 km^2) and about 14% for a density of one gauge per 500 mi^2 (about 1250 km^2).

Huff and Neill (1957) carried out a study of areal variability of rainfall in a region characterised by thunder storm activity in Illinois State, USA. Mooley and Mohammed Ismail (1981) determined the network for estimation of areal rainfall. They used the method of optimum estimation to determine the network density required for various limits of tolerable error in the areal estimates of monthly, seasonal and annual rainfall for different size areas in Vidarbha.

Kagan (1966) had suggested a procedure for computing the error in estimation of areal rainfall which could be used as a criteria for determining the optimum network density of raingauges.

The technique of harmonic analysis and the concepts of distributed linear systems had been applied by Eagleson (1967) to the problem of optimum density of rainfall networks for flood forecasting purposes. Specifications of network density for the study of long term catchment average rainfall was accomplished by considering the long term point rainfall as a homogeneous random variable to be sampled spatially. The author concluded that the incorporation of catchment dynamics into the design of flood forecasting networks reduces the number of gauges needed when compared with those obtained by mere consideration of precipitation variability.

Jones et al.(1979) used the optimal estimation procedure for preparation of maps of root mean square error of point interpolation for suggesting procedures for determining the accuracy of estimation of areal rainfall for any shape of area and any configuration of gauges.

Based on optimal estimation procedures,O'Connell et al (1979) had assessed the accuracy requirements for point and areal rainfall estimates using the data from existing network in the Wessex Water Authority of Southwest England. Root mean square errors of interpolation were calculated using the estimates of spatial auto correlation of daily and monthly rainfall.

Bastin et al.(1984) used a similar approach of optimal estimation for real time estimation of the areal average rainfall. For this purpose, the rainfall has been modelled as a two dimensional random variable. The variance was minimised by using the Kriging technique. It was shown that the method could be used for the optimal selection of the raingauge locations in a basin.

Sreedharan and James (1983) used the spatial correlation technique proposed by Kagan for design of raingauge network in the Chaliyar basin in Kerala. Using monthly data of 31 raingauge stations for seven years, the number of raingauge stations required for estimating the areal rainfall with a given accuracy were derived by stipulating two criteria.

(i) the accuracy with which the average rainfall may be obtained over a given area and

(ii) the accuracy of spatial interpolation

Mehra(1986) had also used the Kagan's technique for determining the raingauge network using the same accuracy criteria as above. A case study for ' Purna catchment' in Tapi basin has been presented by the author.

3.0 PROBLEM DEFINITION

Raingauge networks are generally set up for

i) climatological or water balance studies

ii) flood forecasting and

iii) weather modification evaluation

The networks are seldom planned or designed. The development of raingauge networks, more often than not, has been haphazard and adhoc, generally catering to the immediate local needs of time specific problems. Such networks though adequate in numbers, generally do not meet even the minimum requirements of water resources assessment and flood forecasting For planning and management of water resources systems, therefore, the criteria used for design of hydrological network must be appropriate to the targets to be achieved by such planning. Several factors influence the design of a raingauge network. Problems of network design can be summed up as

i) number of data acquisition points required,

ii) location of data acquisition points,

iii) duration of data collection from a network.

Rodda (1969) has suggested the use of two types of network- (i) primary and (ii) secondary or auxiliary stations. A small number of long term primary stations supported by a large number of secondary stations are to be installed so that a statistical relationship can be developed between the primary and secondary stations. Data from the secondary or special stations is generally used for specific purposes such as project planning and forecasting of floods in the flood season etc.

Rajasthan State is climatologically classified under semi-arid and arid. However, extreme hydrological events like floods and droughts are not uncommon. Large scale flooding due to severe storms as in the case of 1924 and 1981 around Jaipur 1944 and 1978 in Sahibi Catchment and 1979 in Luni basin, indicates the need for revamping the raingauge network, especially the self-recording raingauge network in Rajasthan. Besides, for purposes of planning and design of new irrigation schemes, rail and road bridges and urban drainage schemes, it is very much essential to have a dense network of ordinary and self recording raingauges.

Also, the recurring phenomenon of drought is still fresh in the memory as the State is currently going through one of the worst droughts. For organising relief measures and remission of revenue, the administration needs blockwise information on rainfall deficiency which is only possible by considering this aspect while **designing** the raingauge network and locating them.

There are 521 raingauge stations in the State of Rajasthan. These are being maintained by three different organisations namely, the India Meteorological Department, the Revenue Department of Rajasthan State and the Rajasthan State Irrigation Department. The State Irrigation Department has identified

59 watersheds in the State for Irrigation development and desired designing of a suitable raingauge network for operational purposes such as project planning and flood forecasting during the monsoon season.

4.0 DESCRIPTION OF THE STUDY AREA

The Rajasthan state has a total geographical area of 342271 sq.km and is the third largest state in the country areawise.34610 sq.km area is under forests. The area has wide ranging geographical features with the sand dunes of the Thar desert in the west,Chambal ravines in the east, and the Aravalis running south-north. The highest point is Mt.Abu in the Sirohi district, at an elevation of 1195 m.

Meteorologically, the state has been divided into two sub-divisions, West Rajasthan and East Rajasthan. The districts covered in these divisions are

West Rajasthan	Barmer,Bikaner,Churu,Sri Ganganagar,Jalore Jaisalmer,Jodhpur and Nagaur.
East Rajasthan	Alwar,Ajmer,Banswara,Bharatpur,Bhilwara, Bundi,Chittorgarh,Dholpur,Dungarpur, Jaipur,Jhunjhunu,Jhalawar,Kota,Pali, Sawai Madhopur,Sikar,Sirohi,Tonk and Udaipur.

Southwest monsoon season from July to September is the principal rainy season contributing about 90% of the annual rainfall. The state has a normal annual rainfall of 586.4 mm. East Rajasthan has an average annual rainfall of 704.1 mm and West Rajasthan 311.4 mm(Based on 1950 normals). The coefficient of variability of annual rainfall ranges from 30 to 40% in the east to 60 to 80% in the west.

At present there are 521 raingauge stations in the State being maintained by the India Meteorological Department, The State revenue department and the State irrigation department.

The break up is given below :

i)	India Meteorological Department	30
ii)	State Revenue Department	268
iii)	State Irrigation Department	223
	Total	521

Some of these raingauge stations are shown in the locator map at figure 1. The districtwise break up of these raingauge stations is given in table 1.

The major river systems in the State are, the Chambal, Mahi and Luni. Other smaller rivers are Som and Sahibi.

FIGURE 1 - INDEX MAP OF RAJASTHAN

TABLE 1 - DISTRICTWISE LIST OF RAINGAUGE STATIONS IN RAJASTHAN

Sl.No.	District	Revenue R.G.	Irrigation R.G.	IMD R.G.	Total R.G.
1.	Alwar	16	3	1	20
2.	Ajmer	19	nil	1	20
3.	Banswara	15	3	1	19
4.	Barmer	6	3	1	10
5.	Bharatpur	9	9	nil	18
6.	Bhilwara	12	12	1	25
7.	Bikaner	5	nil	1	6
8.	Bundi	5	1	nil	6
9.	Chittorgarh	14	13	nil	27
10.	Churu	7	nil	1	8
11.	Dholpur	7	1	1	9
12.	Dungarpur	12	nil	1	13
13.	Ganganagar	12	38	1	51
14.	Jaipur	20	13	2	35
15.	Jaisalmer	6	nil	1	7
16.	Jalore	5	3	-	8
17.	Jhunjhunu	4	-	1	5
18.	Jhalawar	11	3	1	15
19.	Jodhpur	5	6	2	13
20.	Kota	15	17	3	35
21.	Nagaur	8	1	1	10
22.	Pali	7	39	1	47
23.	S.Madhopur	11	8	nil	19
24.	Sikar	7	nil	1	8
25.	Sirohi	6	19	1	26
26.	Tonk	6	13	1	20
27.	Udaipur	18	18	5	41
	Total	268	223	30	521

5.0 DATA

The rainfall data of all the raingauge stations in the State is being published by the State Irrigation department since the formation of Rajasthan State in 1956.The data for the earlier years was published by the respective princely states. The India Meteorological Department has published the monthly and annual rainfall data of raingauge stations in the State for the period 1901 to 1950(India Meteorological Department,1970). The State irrigation department has made available the daily rainfall data for some years and the monthly and annual rainfall data for other years for the period 1957 to 1985. Rainfall data for the period 1901 to 1950 has been taken from the I.M.D. publication(1970). For the period 1951 to 1956, the data has been collected from the rainfall volumes of Rajasthan available in the Hydrology Directorate of Central Water Commission.

For the present study of network design of raingauges in Rajasthan state, the annual rainfall data of all the raingauge stations, long term as well as short term has been considered.

6.0 METHODOLOGY

The network design of raingauges has been attempted by considering two contingencies namely the requirement of gauges from (i) climatological and (ii) hydrological considerations. For this purpose, besides the criteria laid down by the World Meteorological Organisation(1974) on the basis of area, other techniques like $(C_v/p)^2$ and cross correlation of the rainfall on the basis of data available from the existing network of raingauge stations have also been used.

A stepwise procedure for the computation of the number of raingauges required(N) using the Coefficient of Variability(C_v) of the rainfall in space and some required accuracy criteria(P) is indicated in Appendix-I.

The procedure of estimating the number of raingauges required on the basis of the error of estimation of areal rainfall as recommended by Kagan(1966) is described in Appendix II.

7.0 ANALYSIS

The analysis of the annual rainfall data has been carried out for estimation of the number of raingauges required using the WMO criteria with geographical area as a basis; and the $(C_v/p)^2$ and the Kagan's technique considering the spatial variation of rainfall and the expected error in the estimation of areal rainfall as the criteria. The analysis has been carried out using (i) the district as a unit and(ii) the river sub-basins(59 in number) as the other unit. For the purpose of the analysis, Dholpur district has been considered as a part of Bharatpur district.

7.1 Computation of Long Term Means of Rainfall

Because of gaps in the rainfall data of some months in some years and for the whole year in some other years, data filling has been carried out wherever possible. Where data gaps were more than two years either continuously or otherwise, the data has not been filled up. As such, the long term means worked out on the basis of the data for the period 1901 to 1985 are based on the data of rainfall of less than 85 years in case of many stations either because of the late date of commissioning of the station or because of discontinuities in the data.

7.2 Computation of Short Period Means

Since data of many of the raingauge stations operated by the irrigation department is available only after 1956,short term means for the period 1957 to 1985 have also been computed.

The normal annual rainfall(1901-1950), the long term means and the short period means of the raingauge stations in each district are given in table 2.

7.3 Analysis of Network Design

Analysis for determining the number of raingauges required for the climatological and hydrological purposes have been carried out using the following alternatives and criteria.

7.3.1 Climatological considerations

For climatological purposes, generally, it is adequate if the information on rainfall becomes available from a representative network of raingauges such that the spatial variation of rainfall is represented by the observations. The WMO recommended one raingauge per 600 to 900 km^2 in tropical areas and 1500 to 10000 km^2 in arid areas. Rajasthan being a State with climate ranging from semi-arid to arid,a criteria of one raingauge per 900 km^2 has been considered appropriate for the present study. For this purpose, the district has been considered as an unit.

The India Meteorological Dept(1972) has recommended the use of an error criteria of 10% for estimation of the number of raingauges using the $(C_v/p)^2$ formula. However, raingauge networks for specific purposes may require the use of a lesser error criterion. The requirement of the number of raingauges has,therefore, been estimated for 5% and 10% error criteria. In table 3, the number of raingauges required in each district of Rajasthan are indicated with the

TABLE 2 - NORMAL ANNUAL RAINFALL AND LONGTERM AND SHORTTERM MEANS(UNIT : mm)

District Station	Normal Annual Rainfall (1901-50)	No of years	Long-term mean (1901-85)	No of years	Short-term mean (1957-85)	No of years
1	2	3	4	5	6	7
AJMER DISTT.						
1. Ajmer(obsy)	520.0	50	542.9	85		
2. Sawar	531.9	50	511.0	83		
3. Kekri	607.1	50	571.7	85		
4. Pisangan	398.5	50	400.8	82		
5. Goela	451.7	50	423.0	83		
6. Beawar	468.5	50	492.5	85		
7. Jawaja	456.9	50	566.3	83		
8. Tatgarh	592.1	50	562.5	83		
9. Nasirabad					371.3	29
10. Pushkar					423.5	29
11. Srinagar					455.8	29
12. Mangliawas					281.7	29
13. Kishangarh					480.6	29
14. Bhinai					368.4	29
15. Sarwar					573.2	29
16. Arain					455.4	29
17. Ajmer					576.0	29
ALWAR DISTT.						
1. Alwar	639.7	50	656.2	85		
2. Kishangarh	606.3	50	622.8	85		
3. Mundawar	572.0	50	597.0	85		
4. Laxmangarh	570.1	50	568.0	85		
5. Tijara	590.2	50	608.6	85		
6. Nimrana	555.9	50	624.6	85		
7. Govindgarh	586.6	41	568.9	76		
8. Kotkasim	749.9	21	595.7	56		
9. Ramgarh	633.7	40	635.7	75		
10. Malakhera					624.1	29
11. Kathumber					586.8	29

1	2	3	4	5	6	7
12. Thanagazi					733.7	29
13. Behror					615.2	29
14. Bansur					688.3	29
15. Tapukara					654.7	29
16. Rajgarh					656.5	29
BANSWARA DISTT.						
1. Banswara	929.2	50	969.1	85.		
2. Garhi	856.1	40	727.8	75		
3. Kushalgarh	1017.9	50	985.1	85		
4. Danpur	1006.5	22	989.0	56		
5. Shergarh	859.2	22	814.0	57		
6. Khandu	840.0	22	853.6	57		
7. Arthuna	886.8	22	825.9	57		
8. Loharia	866.2	12	750.6	47		
9. Jagpura	882.9	22	819.8	57		
10. Sallopat	947.7	22	927.0	57		
11. Bhungra	1010.5	22	927.8	57		
12. Sajjangarh	915.0	23	847.6	51		
13. Ghatol					919.4	29
BARMER DISTT.						
1. Barmer(obsy)	314.0	21	281.1	52		
2. Barmer	261.4	50	265.9	85		
3. Sheo	207.6	50	212.3	85		
4. Siwana	343.5	50	341.8	85		
5. Pachpadra	270.1	50	254.2	85		
6. Balotra	293.7	22				
7. Chohtan	238.5	50				
8. Gudha			254.7	58		
BHARATPUR DISTT.						
1. Bharatpur	673.5	50	666.7	85		
2. Kaman	646.5	50	656.4	85		
3. Nadbai	618.5	43	680.6	78		
4. Bayana	644.4	50	669.2	85		
5. Dholpur	722.8	50	713.9	85		
6. Bari	721.9	47	745.2	85		
7. Rajakhera	691.6	50	698.4	85		
8. Baseri	631.3	47	645.1	83		
9. Sepao	702.9	46	689.1	82		
10. Sir Mathura	662.3	46	671.1	82		
11. Angai	-	-	652.1	65		
BHILWARA DISTT.						
1. Bhilwara	748.5	9	684.4	44		
2. Shahpura	657.0	50	630.1	85		
3. Jahajpur	835.3	9	725.2	44		
4. Sahada	555.8	44	540.6	60		

1	2	3	4	5	6	7
5. Mandal					550.0	29
6. Banera					624.1	29
7. Raipur					547.5	29
8. Hurda					524.0	29
9. Kotri					713.2	29
10. Asind					481.2	29
BIKANER DISTT.						
1. Bikaner(obsy)	306.1	50	287.8	85		
2. Lunkaranser	233.3	45	244.6	80		
3. Magra	227.0	9	228.1	44		
4. Palana	286.6	45	283.4	78		
5. Surpura(Nokha)	265.8	45	242.4	70		
BUNDI DISTT.						
1. Bundi	758.6	50	743.1	85		
2. Hindoli	754.0	20	724.8	55		
3. Keshavarai Patan	779.4	20	763.0	55		
CHITTORGARH DISTT.						
1. Chittorgarh	1008.8	9	833.4	44		
2. Kapasan	781.6	9	693.1	44		
3. Pratapgarh	908.9	50	865.2	85		
4. Nimbahera	709.5	20	806.5	55		
CHURU DISTT.						
1. Churu	367.6	45	384.7	79		
2. Ratangarh	353.9	45	382.9	78		
3. Sujangarh	372.3	45	390.4	77		
4. Sardarshahr	280.5	45	326.1	77		
5. Rajgarh	342.4	45	380.4	80		
6. Taranagar	301.8	45	328.0	78		
7. Dungargarh	261.2	45	300.0	75		
8. Churu(obsy)					398.5	29
DUNGARPUR DISTT.						
1. Dungarpur	732.6	50	734.6	85		
2. Sagwara	700.9	42	694.9	77		
3. Dhambola	825.3	20	723.8	55		
4. Nithawa	788.7	20	688.6	55		
GANGANAGAR DISTT.						
1. Sri Ganganagar	303.3	14	331.1	46		
2. Ganganagar	237.9	25	276.7	59		
3. Karanpur	190.8	23	224.2	56		
4. Padampur	201.2	23	215.5	56		
5. Raisingnagar	206.6	23	226.1	56		
6. Anupgarh	191.4	45	198.1	79		
7. Suratgarh	227.1	45	219.2	79		

1	2	3	4	5	6	7
8. Hanumangarh	288.5	45	270.4	78		
9. Nohar	307.8	45	317.2	79		
10. Bhadra	384.5	45	359.6	79		
JAIPUR DISTT.						
1. Jaipur	597.9	50	618.2	85		
2. Chatsu	536.7	50	589.9	85		
3. Amber	636.8	35	647.1	69		
4. Jamwa Ramgarh	576.7	18	595.4	53		
5. Bairath	569.0	22	590.2	57		
6. Kotputli	516.2	50	530.7	85		
7. Dausa	554.9	50	606.0	85		
8. Lalsot	633.3	50	649.7	85		
9. Sanganer	557.9	50	573.4	85		
10. Baswa	474.6	20	665.8	55		
11. Sambhar	494.4	50	509.3	78		
12. Naraina	468.0	11	499.4	38		
13. Mozamabad			519.3	43		
14. Samodh	534.2	50	529.7	74		
15. Pawata	484.0	15	566.1	40		
16. Chomu	522.3	50	545.8	76		
JAISALMER DISTT.						
1. Jaisalmer	178.5	50	189.8	83		
2. Lathi(Nachna)			149.9	33		
3. Fatehgarh	182.6	22	176.9	52		
4. Nokh			167.6	41		
5. Ramgarh	136.4	50	132.7	78		
JALORE DISTT.						
1. Jalore	363.0	50	383.8	85		
2. Sanchore	380.5	50	401.9	85		
3. Jaswantpura	471.4	50	467.2	85		
4. Bhinmal	470.2	22	413.8	57		
JHALAWAR DISTT.						
1. Jhalawar	1089.3	21	948.2	56		
2. Dug	941.6	50	926.1	85		
3. Pirawa	847.8	15	969.2	49		
4. Bakani	989.6	50	955.2	85		
5. Iklera	960.2	50	926.2	84		
6. Manoharthana	1128.4	50	1111.2	84		
7. Khanpur	985.7	50	927.1	84		
8. Bhawaniganj			875.7	47		
JHUNJHUNU DISTT.						
1. Jhunjhunu	387.4	50	404.5	85		
2. Chirawa	408.9	50	418.8	85		
3. Khetri	560.6	50	552.3	85		

1		2	3	4	5	6	7
JODHPUR DISTT.							
1.	Jodhpur	292.7	22	330.9	57		
2.	Jodhpur(Obsy)	366.0	50	366.2	85		
3.	Nilasa	434.4	50	430.7	85		
4.	Phalodi	235.8	50	245.1	85		
5.	Phalodi(Obsy)					247.2	29
6.	Shergarh	264.8	50	253.7	85		
7.	Osian					263.7	29
KOTA DISTT.							
1.	Kotah	785.6	50	751.3	85		
2.	Mangrol	834.0	47	808.5	80		
3.	Sangod	903.8	47	867.5	80		
4.	Indargarh	819.9	50	768.7	85		
5.	Atru	994.3	50	955.8	85		
6.	Baran	888.2	50	881.8	85		
7.	Itawah	739.4	50	684.8	85		
8.	Shahbad	864.3	50	863.5	85		
9.	Kishanganj	953.1	41	864.8	75		
10.	Chipabarod	1044.7	50	975.4	85		
11.	Chhabra	1075.0	20	962.7	55		
12.	Chechat			791.0	65		
13.	Antah	819.4	47	806.3	76		
14.	Sultanpur			787.5	43		
15.	Mandana			847.7	48		
16.	Ramganj Mandi					887.1	29
NAGAUR DISTT.							
1.	Nagaur	309.9	50	339.3	85		
2.	Didwana	356.8	50	371.5	85		
3.	Parbatsar	389.3	50	412.5	85		
4.	Merta City	419.3	50	406.8	85		
5.	Nawa	469.8	50	482.5	85		
6.	Jayal					381.3	29
7.	Degana					439.8	29
8.	Ladna					396.7	29
PALI DISTT.							
1.	Pali	411.0	50	418.4	85		
2.	Jaitaran	378.2	50	387.2	85		
3.	Desuri	626.1	50	623.9	85		
4.	Bali	564.3	50	556.2	85		
5.	Sojat	472.1	50	445.4	85		
6.	Raipur					466.1	29
SAWAI MADHOPUR DISTT.							
1.	Sawai Madhopur	887.6	50	854.8	85		
2.	Khandar	718.3	21	725.7	56		
3.	Gangapur	656.8	50	690.5	85		

1	2	3	4	5	6	7
4. Hindaun	660.4	50	657.9	85.		
5. Todabhim	589.4	20	646.5	55		
6. Mahua	579.4	50	598.2	85		
7. Karauli	708.4	50	728.7	85		
8. Sapotra	741.2	50	771.5	85		
9. Bamanwas					717.0	29
10. Nadhodi					639.0	29
11. Bauli					746.8	29
SIKAR DISTT.						
1. Sikar(obsy)	468.6	5				
2. Sikar	441.4	50	468.9			
3. Nim Ka Thana	504.7	50	515.9			
4. Danta Ramgarh	426.0	7	477.5			
5. Sri Madhopur	489.7	50	503.3			
6. Fatehpur					437.2	29
7. Laxmangarh					456.4	29
8. Ramgarh					389.2	29
SIROHI DISTT.						
1. Mount Abu (obsy)	1630.1	50	1636.2			
2. Sirohi	574.2	50	511.9			
3. Sheoganj	493.7	40	529.9			
4. Abu Road	847.4	28	766.1			
5. Pindwara					680.4	29
6. Reodhar					627.7	29
TONK DISTT.						
1. Tonk	667.2	50	666.2	85		
2. Malpura	513.6	50	543.8	85		
3. Niwai	602.1	23	633.5	56		
4. Toda Rai Singh	611.6	21	598.9	50		
5. Aligarh	651.3	20	642.5	55		
6. Deoli					595.3	29
UDAIPUR DISTT.						
1. Udaipur	638.1	50	635.5	85		
2. Sarara	702.7	9	569.9	44		
3. Bhim	570.5	50	532.6	85		
4. Kherwara	672.6	50	665.1	85		
5. Rajasamand	537.7	9	525.1	44		
6. Kumbalgarh					636.6	29
7. Amet					523.1	29
8. Devgarh					535.4	29
9. Vallabhnagar					610.5	29
10. Mavli					557.7	29
11. Salumber					689.9	29
12. Kotra					821.1	29
13. Railmagra					582.0	29
14. Nathedwara					526.4	29
15. Udaipur(obsy)					549.5	29

TABLE 3 - RAINGAUGE REQUIREMENT IN EACH DISTRICT OF RAJASTHAN

Sl.No.	District	Area in km^2	Existing No. of raingauges	Number of raingauges required on the basis of area $1/900km^2$	$N = (Cv/P)^2$ 1901-50 Normals		Long period mean		Short period mean	
					5%	10%	5%	10%	5%	10%
1	Ajmer	8504	20	9	8	2	7	2	12	3
2	Alwar	8394	20	9	4	1	1	1	2	1
3	Banswara	5042	19	6	2	1	4	1	4	1
4	Barmer	27373	10	30	17	4	10	3	16	4
5	Bharatpur*	8100	27	9	1	1	1	1	2	1
6	Bhilwara	10448	25	12	12	3	6	2	8	2
7	Bikaner	27118	6	30	7	2	4	1	**	**
8	Bundi	5564	6	6	1	1	1	1	1	1
9	Chittorgarh	10446	27	12	10	3	4	1	7	2
10	Churu	16866	8	19	7	2	3	1	3	1
11	Dungarpur	3781	13	4	2	1	1	1	3	1
12	Ganganagar	20696	51	23	25	6	18	5	14	4
13	Jaipur	13969	35	15	4	1	3	1	6	1
14	Jaisalmer	38445	7	42	10	2	8	2	**	**
15	Jalore	11699	8	13	8	2	3	1	2	1
16	Jhalawar	6229	15	7	4	1	2	1	3	1
17	Jhunjhunu	5913	5	7	18	4	10	2	6	2
18	Jodhpur	22716	13	25	26	6	23	6	25	6
19	Kota	12417	35	14	6	1	4	1	6	1
20	Nagaur	17828	10	20	10	2	7	2	6	1
21	Pali	12441	47	14	18	5	17	4	17	4
22	Sawai Madhopur	10541	19	11	8	2	5	1	3	1
23	Sikar	7889	8	9	2	1	1	1	5	1
24	Sirohi	5127	26	6	4+	1+			2	1
25	Tonk	7163	20	8	5	1	2	1	2	1
26	Udaipur	17642	41	20	5	1	4	1	9	2
	Total	342271	521	380	226	59				

* Including present Dholpur district **Data of additional stations incomplete

\+ Excluding the effect of Mt.Abu

following alternatives.

i) Criteria of area considering one raingauge per every 900 km^2.

ii) $(C_v/p)^2$ with an error criteria of 5% and 10% using means of rainfall(a) all stations having data during the period 1901-1985 and (b) all stations having data during the period 1957-1985.

Besides the $(C_v/p)^2$ formula, the Kagan's cross correlation technique has been used for the estimation of error in the areal rainfall to be expected for a given number of raingauges (n). In table 4, the values of the error in the areal rainfall to be expected are indicated corresponding to values of n = 2,5,8,10 and 15 for each district.

7.3.2 Hydrological considerations

The occurrence of floods and droughts in Rajasthan has clearly indicated the need for keeping in view the hydrological considerations while designing the raingauge network rather than going merely by climatological aspects.

As mentioned earlier, the important river systems in the State are the Chambal,Mahi,Luni and Sahibi rivers. The Irrigation Department of Rajasthan has identified 59 watersheds in the state for the purpose of assessing the adequacy of the raingauges. Because of the rather non-uniform raingauge distribution some of the sub-catchments are not covered by even a single raingauge, while some have only one or two raingauges.

Using a criterion of one raingauge per 500 km^2, the

TABLE 4 - RELATIVE ERROR OF MEAN AREAL RAINFALL FOR A GIVEN NUMBER OF RAINGAUGES IN DIFFERENT DISTRICTS(IN PERCENTAGE)

Sl. No.	District	Relative error of mean areal rainfall for				
		n=2	n=5	n=8	n=10	n=15
1.	Ajmer	6.52	3.77	2.88	2.53	2.02
2.	Alwar	2.96	1.77	1.37	1.21	0.977
3.	Banswara	2.95	1.76	1.36	1.21	0.971
4.	Barmer	4.67	2.47	1.80	1.55	1.19
5.	Bharatpur*	3.02	1.83	1.42	1.26	1.02
6.	Bhilwara	5.12	2.94	2.23	1.96	1.56
7.	Bikaner +					
8.	Bundi	1.97	1.12	0.85	0.75	0.59
9.	Chittorgarh	5.15	2.49	1.90	1.68	1.34
10.	Churu	3.27	1.91	1.48	1.29	1.035
11.	Dungarpur	3.51	2.15	1.68	1.50	1.21
12.	Ganganagar	7.09	3.85	2.84	2.47	1.93
13.	Jaipur	4.46	2.47	1.85	1.61	1.26
14.	Jaisalmer+					
15.	Jalore +					
16.	Jhalawar	2.67	1.55	1.19	1.05	0.84
17.	Jhunjhunu	4.04	2.30	1.74	1.53	1.21
18.	Jodhpur	7.44	4.09	3.04	2.65	2.07
19.	Kota	4.28	2.53	1.94	1.72	1.38
20.	Nagaur	3.35	1.91	1.45	1.27	1.01
21.	Pali	5.70	3.26	2.49	2.10	1.736
22.	Sawai Madhopur	3.27	1.89	1.44	1.27	1.01
23.	Sikar	3.94	2.28	1.74	1.53	1.218
24.	Sirohi #	1.63	0.87	0.62	0.54	0.414
25.	Tonk	2.19	1.23	0.917	0.80	0.631
26.	Udaipur	4.12	2.22	1.63	1.41	1.089

* Includes present Dholpur District

\+ Analysis not carried out because of less number of station's data

\# Excluding the effect of Mount Abu.

number of raingauges required in each of the 59 sub-basins has been estimated on the basis of geographical area. As the number of raingauges in a majority of the sub-basins was less than four, the cross correlation technique could not be applied and the requirement has been worked out using $(C_V/p)^2$ formula for accuracy requirements of 5% and 10%. The requirement in different sub-basins worked out by the above procedures is indicated in table 5.

7.3.2.1 self recording raingauges

The large scale flooding of Luni basin in 1979 and Jaipur City in 1981 had emphasized the need to have a better network of self recording raingauge stations in the river catchments. At present besides the sixteen SRRGs maintained by India Meteorological Department, only six of the irrigation department SRRGs are reported to be working. Since information on short duration rainfall is very essential for planning as well as operational purposes, it may be necessary to install some more SRRGs in the different watersheds of the State.

A criterion of one SRRG for each of those catchments with catchment area between 1000 sq.km. and 5000 sq.km. and two SRRGs for those above 5000 sq.km. has been adopted to work out the requirement of self recording raingauges. For those of the catchments with area less than 1000 sq km. the rainfall pattern at the nearest SRRG or group of SRRGs could be used.

TABLE 5 - CATCHMENT-WISE REQUIREMENT OF ORDINARY AND SELF RECORDING RAINGAUGES

Sl. No.	Name of Sub-basin	Catchment Area km^2	Existing No. of Raingauges					Total requirement of gauges		
			SRRG	ORG Inside	ORG Outside	Total	SRRG	WMO Standard 1/500 km^2	ORG $(C_v/P)^2$ 5%	10%
1.	Kantli	2810		1	6	7	1	6	11	3
2.	Dohan	993		1	1	2		2	1	1
3.	Navalgarh Nallah	479		1	-	1		1	-	-
4.	Krishanwati	322		-	1	1		1	-	-
5.	Ranoli	492		-	1	1		1	-	-
6.	Sabi	4566	1	13	1	14	1	9	2	1
7.	Barah	3146	1	11	1	12	1	6	3	1
8.	Bangana	6747		20	2	22	2	14	1	1
9.	Gambhir	4786		12	2	14	1	10	1	1
10.	Parbati	1898	1	6	2	8	1	4	1	1
11.	Menda	4235	1	11	2	13	1	9	3	1
12.	Mashi	7000		16	7	23	2	14	1	1
13.	Morel	5991	3	14	5	19	2	12	1	1
14.	Dhil	800		2	1	3		2	-	-
15.	Kalisil	751		2	1	3		2	-	-
16.	Sohodra	1541		5	3	8	1	3	-	-
17.	Dia	2991		5	8	13	1	6	3	1
18.	Khari	6760		19	7	26	2	14	2	1
19.	Kothari	2320	1	5	4	9	1	5	-	-
20.	Banas I	6089		11	2	13	2	12	1	1
21.	Banas II	6058	1	14	4	18	2	12	11	3
22.	Berach	8550	1	23	7	30	2	17	6	2
23.	Chambal	2103	2	7	9	14	1	4	1	1
24.	Chakan	891		2	3	5		2	-	-
25.	Nej	5672		10	7	17	2	12	-	-
26.	Eru	363		-	2	2		1	-	-
27.	Alnia	549		3	3	6		1	-	-
28.	Parbati'	5000		8	1	9	1	10	2	1
29.	Kuru	699		1	-	1		1	-	-
30.	Parwan	3051		5	5	10	1	6	-	-
31.	Kalisindh	7400		15	15	30	2	15	2	1

1	2	3	4	5	6	7	8	9	10	11
32	Choti Kalisindh	389		1	1	2		1	-	-
33	Jakham	2458	1	6	6	12	1	5	-	-
34	Som	6130	1	16	15	31	2	13	1	1
35	Moran	1012		1	1	2	1	2	-	-
36	Anas	1436		4	4	8	1	3	3	1
37	Mahi	5918	1	18	17	35	2	12	5	1
38	Bhadar Vartak	1049		2	2	4	1	2	-	-
39	Wakal	2023		1	3	4	1	4	-	-
40	Sei	799		1	6	7	1	2	-	-
41	Sabarmati	425		3	1	4		1	-	-
42	Jojri	4864		4	4	8	1	10	-	-
43	Luni I	3911		5	6	11	1	8	11	4
44	Luni II	4260		3	1	4	1	9	-	-
45	Luni III	1738		-	-	-	1	4	-	-
46	Guhiya	3841		8	7	15	1	8	7	2
47	Sukri Hemawas	1269		5	5	10	1	3	-	-
48	Bandi Hemawas	1502		2	2	4	1	3	-	-
49	Sukri	1347		1	3	4	1	3	-	-
50	Sukri	1715		7	2	9	1	4	-	-
51	Milhri	1305		6	6	12	1	3	-	-
52	Jawai	3248	1	18	17	35	1	7	-	-
53	Khari	2507		4	4	8	1	5	-	-
54	Sukri	1214		-	-	-	1	3	-	-
55	Bandi	943		2	1	3		2	-	-
56	Sagi	948		1	1	2		2	-	-
57	West Banas	1870	1	12	2	14	1	4	-	-
58	Sukli	945		5	3	8		2	-	-
59	Other Nallahs of Jalore Distt.	471		-	1	-		1	-	-

8.0 RESULTS

From an examination of the normals upto 1950 and long term means upto 1985 it may be seen that they are comparable in case of a number of stations. Where differences are noticed, they are due to the short period data on which their normals for the period upto 1950 have been based.

It could be seen from table 3 that excepting Bikaner, Churu,Jalore,Jaisalmer,Jhunjhunu,Jodhpur and Nagaur, the requirement of additional raingauges is nil. However, of these districts except Jhunjhunu all are arid in nature and the areal criteria has little relevance in deciding the raingauge network.

The relative error of mean areal rainfall given in table4 shows that it is less than 10% for even 2 raingauges in case of all the districts. In case of only five districts namely Ajmer,Chittorgarh,Ganganagar,Jodhpur, and Pali, where the spatial variability of rainfall is more, the error is more than 5% for two raingauges.

In the 59 watersheds, six sub-basins do not have a single raingauge station while four sub-basins have more than 20 raingauges and 12 sub-basins have 10-20 gauges.

In majority of the 59 sub-basins, the existing number of raingauges is adequate even considering an accuracy requirement of 5% error as may be seen from table 5.

In the case of 21 sub-basins, there is requirement of additional raingauges which varies from 1 to 5 **totaling** to about 50 raingauges.

8.1 Self Recording Raingauges

The requirement of self recording raingauges is worked out as 53 whereas at present there are only 11 IMD and 6 irrigation SRRGs in the 59 sub-basins. In case of Morel (sub-basin 13), all the three SRRGs are located in and around Jaipur City. Thus, there is a net requirement of atleast 40 self recording raingauges in the different sub-basins.

9.0 CONCLUSIONS AND RECOMMENDATIONS

The results have broadly indicated that there is not much change in the rainfall regime of the state. The study has indicated the need to have appropriate criteria for designing the network for hydrological purposes. Thus, in case of Rajasthan, though the existing raingauge network is adequate from the climatological considerations some additional raingauges are required from the hydrological consideration.

A better network of raingauge stations and self-recording raingauge stations in the river catchments and major cities is necessary.

Because of the rather non-uniform distribution of raingauges many of the sub-catchments are not covered by even a single raingauge and naturally, need to be equipped with one to five gauges as per the requirement totalling to about 50 raingauges.

At present besides the sixteen SRRGs maintained by India Meteorological Department, only six of the irrigation department SRRGs are reported to be working. Out of these only 17 are located in the various sub-basins. There is thus a need for setting up of at least 40 more self recording raingauges in the 59 sub-basins.

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APPENDIX- I

Network Design Using Mean Rainfall

Indian Standards Institute(1968) and India Meteorological Deptt.(1972) had recommended the use of the following formula for the determination of the number of raingauges required using information of the mean(normal) rainfall at each of the raingauges located in a given catchment.

$$N = (C_v/p)^2 \qquad (I.1)$$

where P is the desired degree of percentage error.

C_v is the coefficient of variability of rainfall estimated from the rainfall data at the existing gauges.

In the case of Alwar district considered for the purpose of example, there are sixteen raingauges data of which is available during the period 1957-85. The mean rainfall of these stations is listed below. Units are in millimeters.

Alwar.....	691.7	Kishnagarh..	662.6	Mandawar..	652.5
Tijara....	644.0	Laxmangarh..	544.9	Nimrana..	609.6
Behror....	615.2	Govindgarh..	621.1	Kotkasim..	567.6
Bansur....	688.3	Ramgarh ...	599.3	Malakhera..	624.1
Kathumer..	586.8	Rajgarh ...	656.5	Tapukara..	654.7
		Thanagazi..	733.7		

The coefficient of variation of rainfall C_v=7.9%

The number of raingauges required to estimate the average rainfall with a percentage error of 10% or less is given by

$$N = (7.9/10)^2 = 0.6241 \text{ say } 1 \ldots\ldots \qquad (I.2)$$

APPENDIX II

Methodology of Cross Correlation Technique

Kagan(1966) introduced a correlation function, $\rho(d)$ as a function of the distance between raingauge stations. The form of the function **depends** on the spatial variability of the rainfall and can be expressed as

$$\rho(d) = \rho(o)\, e^{-d/d_o} \qquad \ldots(II.1)$$

where $\rho(d)$ is the correlation function of the distance between raingauge stations

$\rho(o)$ is the correlation corresponding to zero distance

d_o

Theoretically, $\rho(o)$ must be equal to 1 as it is the correlation corresponding to zero distance. However, the microclimatic variations and the random errors in measurement of rainfall make $\rho(o)$ as being less than unity and the variance of these random errors is given by

$$\sigma_1^2 = [1 - \rho(o)]\, \sigma_n^2 \qquad \ldots(II.2)$$

where σ_n is the variance of precipitation time series at a fixed point. The two parameters $\rho(o)$ and d_o provide the necessary for assessing the accuracy of a given raingauge network.

Kagan has given the relative root mean square error in the average rainfall over an area S as

$$Z_1 = C_v \sqrt{\frac{1 - \rho(o) + 0.23 \frac{\sqrt{S}}{d_o \sqrt{n}}}{n}} \qquad \ldots(II.3)$$

Equation(II.3) can be used to obtain the permissible value of error z_1 for a given number of raingauges n provided $\rho(o)$ and d_o are known. Alternatively, the number of raingauges required for a desired percentage of error can be estimated. Thus Z_1 can be used as a criteria for deciding the desired network.

A typical example for Alwar district is worked out here. Alwar district has data of sixteen raingauges available during the period 1957 to 1985. As was worked out earlier in Appendix I, the Coefficient of variation(C) is 7.9% Table II.1 gives the average distance and the average correlation for stations falling within each interval. Figure II.1 shows the relationship between the distance and the correlation on semi-log paper. The value of $\rho(o)$ is read off the logarthmic ordinate which is intercepted by the extrapolated straight line fitted by eye to the plotted points.

Table II.1 Average Distance and Average Correlation Coefficient for Raingauge stations in Alwar District

Distance Class km	Mean distance km	Number of cases	Mean correlation coefficient
0-5	-	Nil	-
6-10	-	Nil	-
11-15	14.75	4	0.7390
16-20	18.40	5	0.6805
21-25	23.20	7	0.7191
26-30	27.50	8	0.6862
31-35	33.66	12	0.6601
36-40	38.59	11	0.6269
41-45	43.11	9	0.6451
46-50	48.50	3	0.5359
51-55	53.91	15	0.5708
56-60	57.50	2	0.5890
61-65	64.08	12	0.6750

66-70	67.59	7	0.6488
71-75	73.59	7	0.5770
76-80	80.00	6	0.5000
81-85	83.40	5	0.5200
86-90	88.25	4	0.5665
91-95	95.00	1	0.3179
96-100	100.00	3	0.4411
101-105	105.00	1	0.4638

From figure II.1 it may be seen that the straight line intercepts the Y axis at 0.80 which is the value of $\rho(o)$
The value of $\frac{\rho(0)}{e}$ is calculated as 0.2943 and the corresponding value of d_o is 185 km.(e=2.718)

Substituting the values of C_v, $\rho(o)$ and d_o the value of Z_1 is computed for different values of n, the number of rain gauges. The area of Alwar district is **8394** km^2.

$$Z_1 = 7.9 \sqrt{\frac{0.20 + 0.23 \times \frac{\sqrt{8394}}{185.0\sqrt{n}}}{n}} \qquad \text{...(II.4)}$$

The following table gives the values of Z_1 for a given n.

n	Z_1%	n	Z_1%
2	2.96	3	2.35
5	1.77	8	1.37
10	1.21	15	0.977

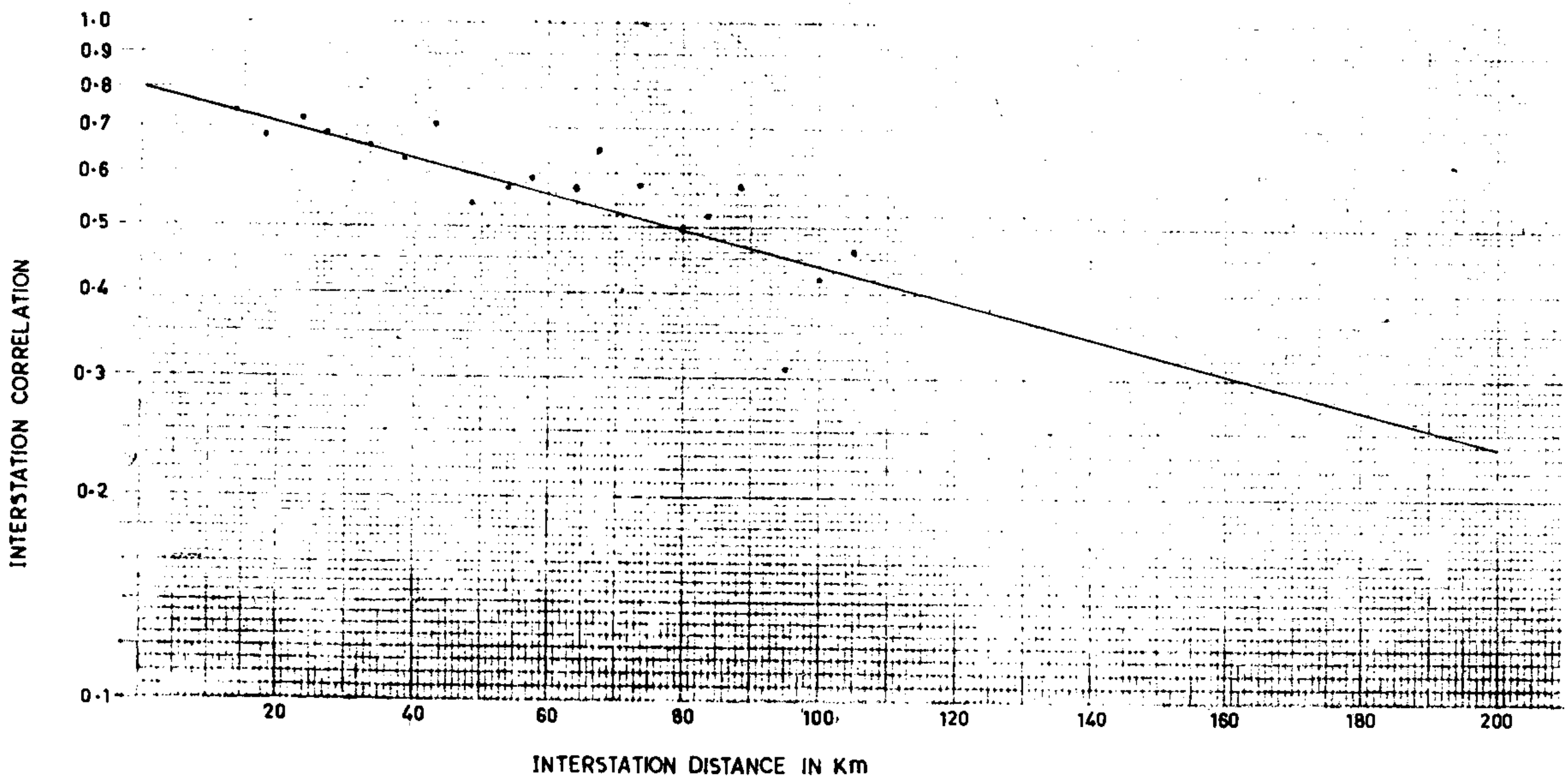

FIGURE II.1 - RELATIONSHIP BETWEEN INTERSTATION DISTANCE AND INTERSTATION CORRELATION