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Rainfall Analysis for multipurpose water power projects in India *

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CONTENTS

1. *Introduction.*

1.1 India has a big plan of development of her water resources in the shape of " multipurpose waterpower projects " with a view to increase the standard of living of her people. The main objects of the contemplated programme are (i) to increase food production by conserving the surplus water of the rainy season which goes to waste for use in the dry season, thereby increasing the area under irrigation and (ii) to produce and distribute cheap electric power for industrialising the country. If the programme is completed certain ancillary benefits such as flood control, increase in inland water transport, freedom from risk of famines etc. will also accrue which will contribute to the increase in the standard of living of the people. This is why these are called " multipurpose projects ". The United States of America, Canada, Sweden and U.S.S.R. are cited as examples of large-scale achievements in this respect and it has been ascertained from a broadbased preliminary survey that similar development is possible in India[1]. To help speedy completion of the programme a Central Waterpower Irrigation and Navigation Commission is in existence since 1945 with expert staff to advise the Government of India on the soundness of various projects to be undertaken. Several hundreds of crores of rupees will have to be invested in these projects during the next twenty years or so before the programme is completed.

1.2. The aim of this article is, in the above-mentioned context, to examine what kind of analysis of available rainfall data should be undertaken and carried out for providing adequate technical information on rainfall for the proposed projects in India.

* In this article, the author presents some ideas and principles governing the preparation of technical data of rainfall for use in the design of water-power projects. He also gives some suggestions for items of rainfall analysis which, if carried out with available data in India, will prove useful in designing the projects. Although the ideas discussed in the article are well known among meteorologists and climatologists, their re-statement here in a collected form might be useful to students of these problems and perhaps also to Engineers and Hydrologists. Those engaged in the planning of water-power projects in India may derive from the article some information about the type of rainfall data on which to base their designs. Readers will also get an idea of what data of rainfall are already available in India and what items of analysis can be undertaken. Coming, as it does, at a time when there is a widespread planning for tapping the water resources of the country it is hoped that the article will be read with interest. Views or comments, from Engineers and Hydrologists on the suggestions made in the article will be welcome.

—*EDITOR*

2. *Nature of Technical Surveys for the Projects.*

The structural designing and operational planning of these projects depend to a large extent upon the data of various kinds covering wide field of knowledge which are collected by preliminary technical surveys and investigations relating to the catchment area concerned. These preliminary surveys include topographical, agricultural, economical, geological, hydrological, seismological surveys of the area. In fact everything that is to be known about the catchment and its surroundings will be of use in the planning of the multipurpose projects. Considering the huge amount of investment involved in undertaking each project no amount of caution will prove superfluous in marshalling the technical surveys in such a manner that they yield accurate technical information of a high order for the planning of these projects. Very often, when a project is undertaken and want of data of a particular kind is discovered, the tendency is to estimate the factor involved and complete the design rather than wait for the collection of the data. It is needless to point out here that such a procedure is shortsighted and risky. For, designs and plans based on inaccurate and inadequate technical data run the risk of either proving insufficient for the tasks which they are expected to perform or becoming unjustifiably costly, resulting in either case in avoidable expenditure. It is, therefore, clear that utmost care has to be bestowed in the collection of technical information for the projects in order to ensure their correctness by planning for the collection and analysis of data in advance. Wherever quantitative measures are involved, it will be better to obtain values of the factors by more than one set of independent observational data or method. It will be a sound working principle to follow that a quantitative measure derived once, should at best be accepted only as a fair estimate of the factor involved and should not be accepted as the final working value unless checked up by say, three independent determinations or methods. It is also highly desirable to test all the technical data for mutual consistency at various stages of planning and designing so that any error lurking will be eradicated before it is too late.

3. *Scope of Rainfall Data for the Projects.*

Rainfall and its variation with respect to time and space in the catchment area concerned forms one of the important items of technical data that are to be assembled before preparing the plans and designs for any waterpower project. For, these data enable the designer to construct the *water budget* for the catchment for various units of time such as a day, a month or a year which helps him to formulate his proposals regarding the size of the reservoir and the operational planning such as storage and release of water. For catchments where precipitation occurs not only in the form of rain but also as snow etc., the collection and study of precipitation data to yield the water account becomes more complex because of the time lag involved in the conversion of solid precipitation into water which again depends upon other weather conditions. Considerable attention has been paid in U.S.A. to snow-surveying methods and run-off forecasting therefrom for catchments. 2 But these methods which have been developed for extra-tropical conditions would require suitable modifications before they can be made applicable to mountainous catchments in India in the north which differ from the catchments of U.S.A. both in orography and meteorological conditions. Confining ourselves to the catchments where precipitation occurs in the form of rain only, the following are the technical data on rainfall and its variation that are to be collected for the structural designing and operational planning of any multipurpose waterpower project. Under each item, which is put in the form of a query to be more explicit, the particular aspect of the project where the answer to the question enters as a factor as well as the method of obtaining the data have been indicated briefly.

(*i*) What is the normal annual water-catch over the catchment area and how is it distributed during the various months ?

These data would give the total quantity of water that falls normally over the catchment as a whole during different months of the year, which information is essential to determine the amount of water that will be available for conservation at the end of the rainy season, so as to be used for irrigation purposes during the dry season until the arrival of the next seasonal rains. The magnitude of the project depends upon this factor.

There are two ways of obtaining this information. If reliable normal monthly and annual isohyetal maps on a fairly open scale are available for the region the mean precipitation values for the catchment area can be determined from such maps by measuring areas within various isohyets. The values can otherwise be arrived at by taking the arithmetical average of the monthly and annual rainfall at the various raingauge stations in the catchment. For this purpose there should be a fairly well distributed density of raingauge stations and the data of a common period of years preferably not less than 30 or 35 years should be used for all stations. For accurate work it will be desirable to get the values by both the methods and arrive at checked values.

(*ii*) What are the maximum and minimum values of annual as well as the monthly water-catches for the catchment ?

The maximum values will be helpful in determining the capacity of the reservoir from the point of view of flood control while the minimum values might guide the operational planning such as the release of water for irrigation purposes after keeping the minimum head in the reservoir required for production of electric power etc.

The maximum and the minimum values can be picked out from the series of monthly and annual rainfall over the catchment for individual years computed from data as far as available. If necessary, isohyetal maps may be drawn for particular years or months and the arithmetical average checked against the values obtained from the maps.

(*iii*) Are the maximum and minimum values mentioned under (*ii*) above the absolute extremes that are ever likely to occur for the catchment ? If not, what are their chances of occurrence again ? What are the extreme values that will occur once in 10 years, 20 years, 50 years, 100 years etc. ?

These data are essential for two reasons. The values derived under (*ii*) may be based on a comparatively short period and may not serve the purpose well. The relationship between the extreme values and the period will enable us to derive the extreme values for longer periods from those of shorter periods. Secondly, even if the extremes are derived from proper long series of data, it may happen in some cases that provision in the project for an absolute maximum or minimum may make the project prohibitive from the point of view of cost. In such a case a knowledge of the amount of risk involved in adopting extremes of a lower order is essential to know whether a project of lower denomination can be accepted. In practice it would seem to be always desirable to study the cost-risk function for each project before finalising the plans.

Extraction of the information required under this head from the basic rainfall data would involve the preparation of necessary rainfall frequency tables and rainfall probability maps from them together with curves of time—extreme values of precipitation. Chapters VIA and VIB of Parker's "*control of water*" will give an idea of the methods involved*.

(*iv*) What are the normal and abnormal features of the rain-yielding storms in the catchment area and its neighbourhood ?

(*v*) What is the maximum rainfall that has occurred over the catchment as a whole in durations of 1 day, 2 days, etc..... upto 7 days, and what are the probabilities of occurrence of values of slightly lower order than the maxima ?

(*vi*) What is the duration-depth-area relationship of maximum precipitation in the neighbourhood of the catchment ?

The data required under (*iv*) to (*vi*) above are essential in calculating the maximum likely accumulation of water at the reservoir site or sites during very severe storms in the catchment and the duration of time for which such accumulation is likely to remain. This information would be useful in determining the required capacity of the reservoir for flood control purposes. These data are extremely important and may be arrived at by a detailed analysis of rainfall during various storms that have occurred in the neighbourhood of the catchment on the basis of a storm as a Unit. This aspect will be explained in greater detail later in this article.

(*vii*) What is the intensity-duration relationship of rainfall for short periods *i.e.*, less than 24 hours ?

This information will be helpful in the planning of the operational stages of the project in estimating the time of arrival of flood water and its amount at the point of outlet from the catchment when intense rain falls in some part of the catchment. The data should be derived from records of self-recording raingauges during some of the severe storms in the catchments. If records are not available already, arrangements should be made to install such instruments at some stations in the catchment to provide material for analysis.

4. *Rainfall data of India.*

4.1. We are fortunate in having a fairly reliable, uninterrupted and long series of daily rainfall records of a large number of raingauge stations spread over the country for over 50 years for making a rainfall survey for any project, except for mountainous catchments in the north. Table 1 shows the number of raingauge stations in each meteorological sub-division in India classified

TABLE

Frequencies of raingauge stations classified according to the length of period for which rainfall

Provinces Years. ..	6–10	11–15	16–20	21–25	26–30	31–35	36–40	41–45	46–50
Assam	10	10	6	4	5	12	10	9	25
West Bengal ..	6	4	8	13	8	15	4	4	5
Orissa	4	2	3	9	9	4	7	3	2
Bihar	20	9	13	11	37	23	21	21	31
Eastern states ..	5	9	3	2	3	4	27	3	5
United Provinces (Uttar Pradesh) ..	10	4	5	2	2	5	3	8	23
East Punjab & Delhi ..	2	1	2	0	5	1	1	1	5
Kashmir	6	0	4	1	5	0	9	15	5
Rajputana (Rajasthan) ..	21	39	7	4	20	25	9	17	61
Bombay	9	0	1	0	2	5	3	4	6
States in Bombay area..	14	11	1	0	0	2	1	1	23
States in Central India.. (Madhyabharat)	30	16	33	5	6	31	8	10	21
C.P & Berar (Madhya Pradesh) ..	12	50	3	10	12	29	13	3	17
Hyderabad ..	23	15	3	0	4	1	2	3	5
Mysore	1	1	1	0	0	0	0	4	4
Madras	26	24	9	23	17	25	49	23	80
TOTAL (India) ..	199	195	102	84	135	182	167	129	318
Eastern Pakistan ..	1	14	8	10	5	15	7	15	10
West Punjab ..	3	5	5	4	2	3	4	9	2
N.W. Frontier Province	3	3	2	0	6	2	7	2	0
Baluchistan ..	17	9	5	5	23	8	3	7	13
Sind	9	6	1	0	46	0	0	1	4
TOTAL (Pakistan) ..	33	37	21	19	82	28	21	34	29
Total (India & Pakistan)	232	232	123	103	217	210	188	163	347

1.

data are available upto the end of 1940 (compiled from Memoirs of I.M.D. XXVII Part V).

51–55	56–60	61–65	66–70	71–75	76–80	81–85	86–90	Total No. of raingauge stations.	Total closed stations.	No. of current stations.
25	5	5	8	4	1			139	24	115
13	22	9	8	13				132	3	129
2	15	5	5	12				82	2	80
15	33	3	13	17				267	22	245
1	8	5	0	1				76	2	74
5	15	30	8	39	147	3		309	26	283
10	14	8	3	60				113	6	107
0	1							46	7	39
4	19	5	5	1	1	2		240	43	197
69	10	111	0	1				221	4	217
21	3	8						85	1	84
0	8	3	1	2	1			175	45	130
4	15	3	9	47	4	1		232	24	208
2	0	8	0	2				68	3	65
6	14	15	9	26				81	1	80
12	43	55	12	165	0	0	1	564	32	532
189	225	273	81	390	154	6	1	2830	245	2585
19	16	13	12	13				158	11	147
5	10	6	3	40	1			102	11	91
3	3	1	2	9				43	5	38
15	2							107	26	81
0	4	5						76	1	75
42	35	25	17	62	1			486	54	432
231	260	298	98	452	155	6	1	3316	299	3017

according to the length of data available up to the end of 1940. The rainfall data of years 1891 onwards have been published in the volumes of *Daily Rainfall of India* compiled and issued by the India Meteorological Department each year and the data for the periods prior to 1891 are available in MSS records in the India Meteorological Department. The details of storms and depressions that have affected the weather in India and the neighbouring seas are found in the *Monthly Weather Reviews* and *Annual Summaries* of the respective years issued by the India Meteorological Department. Also records of self-recording raingauges giving continuous records of rainfall for over 20 stations in India for a fairly long series of years are available.

4.2. The above constitute the basic data of rainfall required for analysis for the projects. It will be seen that most of the information that will be required as explained in section 3 above can be obtained from these basic data by a planned analysis. Some analysis has been done with these data in the past but such items of analysis have mostly been, apart from a few which were conceived and compiled on a comprehensive basis, on a limited aspect of the rainfall feature with an emphasis on climatology or long-range forecasting and hence are not directly utilisable as technical data required for these projects. Mention should be made here of the brief but very illuminating chapter on "Rainfall in relation to water supply and drainage; evaporation and wind pressure," by Blanford in his "*Climates of India, Burma and Ceylon*"[4]. Written in 1886, it gives a succinct but clear statement of the problem with a broad-based review of the rainfall characteristics of the water-sheds in the plains of India.

4.3. During recent years, however, there have been some investigations which have focussed their attention on the hydrological aspect of rainfall analysis, anticipatory as it were, of the current large scale demand for hydrological data. For example, Mahalanobis has carried out rainfall analysis for the Mahanadi Catchment[5]. The Central Board of Irrigation passed a comprehensive resolution in 1947 emphasising the need for systematic collection and analysis of hydrological data[6]. Gulhati[7] and Sohoni[8] have discussed the hydrological and hydrometeorological requirements in India in two papers. Satakopan has carried out analyses of rainfall data for the Damodar Catchment to provide the technical data on rainfall for the Damodar Development Scheme[9, 10].

4.4 With the large amount of basic data available and with the proposed large-scale development of waterpower envisaged by the Government's policy, it would perhaps be not only advantageous from the technical point of view but also economical in the long run to plan for a comprehensive analysis of these rainfall data to yield the required technical information for these projects so that when any project is undertaken the required data can be extracted readily from the analysed information without waiting for a fresh analysis. Such an analysis will also yield much useful information for other user interests such as Agriculture, Soil Conservation, Communications, Forestry, Industry, Townplanning etc. whose requirements are now being met with by small pieces of investigations done from time to time as and when occasions arise. The huge development of waterpower in the U.S.A. has been preceded by a very detailed and comprehensive analysis of precipitation data as seen from various publications received from that country. The scope of such analysis and the valuable nature of the technical data that result will be seen from Chapter 11 of *Drainage and Flood Control Engineering* by Pickels[11] and the list of rainfall maps included in *Climate and Man*—Year Book of Agriculture 1941[12].

4.5. The following items of analysis of available rainfall data will prove, therefore, very useful for the waterpower projects in India:—

(*i*) Isohyetal maps on as open a scale as practicable showing the normal monthly and annual rainfall may be prepared.

(*ii*) Frequency tables of rainfall amounts during short durations such as 1-day, 2-days, etc. up to 7 days, as well as for the durations of months and the year may be compiled from daily rainfall data for as many raingauge stations as possible.

(*iii*) Maps of rainfall probability of different amounts during different durations with isolines wherever feasible may be got prepared from data of (*ii*) above.

(*iv*) Maps showing track of storms with areas of rainfall accompanying each storm may be prepared by plotting the rainfall data of all raingauge stations on a fairly large-sized map for all storms that have affected the weather of the Indian area.

(*v*) A detailed study of selected important storms may be made so as to get time-depth-area relation curves of Maximum precipitation for various areas of the country.

(*vi*) Values of maximum possible precipitation for various catchments may be computed on the basis of meteorological conditions as illustrated in studies made in U.S.A. and these values will be useful as checks against the values obtained actually from the data under (*iii*) and (*v*) above. Such studies would however require more extensive and frequent *Radiosonde* observations in the field of storms.

(*vii*) An analysis may be made of all available self-recording raingauge charts for finding the intensity duration relationship of rainfall for different areas for heavy rainfall during very short periods. Arrangements may be made to install self-recording raingauges at unrepresented areas to get more detailed information of rainfall data for these areas.

4.6. We shall now consider the above items, one by one, and review the general principles and considerations that are to be remembered in carrying out the suggestions for each item so that useful and reliable statistical material may become available for the projects.

5. *Isohyetal Maps.*

5.1. Although the method of preparation of an isohyetal map may be explained as a simple process of plotting rainfall values and drawing lines joining equal values of rainfall at suitable intervals of rainfall amounts, it is a very complicated process in practice, in the accomplishment of which it calls for a keen sense of judgment, an expert knowledge of the laws of variation of rainfall, an understanding of the general climatology of the area concerned and a general knowledge of the meteorology of the storms of the areas. This is the reason why the Climatological Commission of the International Meteorological Organisation emphasised the fact that " isoline charts should be prepared only by experts after careful consideration of the relation of topography to the meteorological element represented. " (*vide* Resolution XIX —Toronto Session—August, 1947—Publication No. 67 of I.M.O.). [13]

5.2. Considerable amount of literature is available on the principles governing the construction of isohyetal maps. Considerations have been given to points such as the most suitable scale of the map to be chosen consistent with the density of recording stations in different areas etc. For any one who has the task of constructing isohyetal maps the collection[14] of 36 articles presented by the Editor of the *Monthly Weather Review, Washington* in April 1902 will be found to be invaluable. A discussion of the various aspects of the problem from eminent climatologists is presented in this collection. The background with which monthly and annual isohyetal maps have been prepared for U.S.A. will be found in Washington Monthly Weather Review[15] of May 1917. The method of reducing the averages to a common period of years where they are not based on the same periods is described in this paper. The discussion in the Quarterly Journal of Royal Meteorological Society in 1914[16] and 1921[17] describe the principles on which the British Isohyetal maps were prepared. The special feature of this method is the use of " isomeric " maps as an intermediate step for the construction of the monthly isohyetal maps. The method has one advantage, namely, it permits a smaller number of control stations being used for the preparation of the monthly charts and minimises the discrepancies between the monthly and annual charts. It will be worth while to examine, whenever the preparation of the monthly and annual normal isohyetal maps are undertaken, whether this use of isomeric maps will be advantageous. The monthly and annual isohyetal maps for the British Isles have been published in " Rainfall Atlas of the British Isles "[18].

5.3. On examining the elaborate literature mentioned above, the following are the main considerations and principles that emerge to serve as a guidance for any one who is engaged on the construction of isohyetal maps.

(*i*) All values, normals or averages, plotted on the map should be comparable. Especially in the case of isohyets of normals, the figures plotted should be based on data of same length of period. If they are not, some common period should be fixed and all averages which are not for the standard period fixed should be converted to that period as explained by Reed and Kincer [15].

(*ii*) It is essential to use maps with contour lines preferably layered in different shades or colours as the base map, so that the influence of orography can be taken into consideration when drawing the isohyets.

(*iii*) In drawing isohyetal maps for small areas such as a catchment area, a district, a province etc. it should be remembered that it is not enough to plot only the rainfall data of the stations inside the area concerned for drawing isohyets but some more area surrounding the one in which we are interested should be taken on the map and isohyets drawn for the bigger area enveloping the area in which we are interested. It should be remembered that weather phenomena are often very extensive and extend beyond topographic boundaries.

(*iv*) If isohyetal maps are to be drawn on a large scale for the country as a whole it is better to draw them on different sections for convenience of handling. But the projection of the map chosen should be such that the sections can be conveniently put together to get a complete map for the country.

The scale of the map should be so chosen that a fairly good number of recording stations fall within each section of the map so that reliable isolines can be drawn. In planning isohyetal maps for the country as a whole the density of recording stations in different regions should be examined and a scale of map chosen should be such that in the region with rarest density of stations the section of the map contains a fairly good number of stations. For example in an area where the density of raingauge stations is one in 4900 sq. miles a section of map containing 2° lat. by 2° long. will contain only 4 stations with which no useful isohyetal maps can be drawn. Whereas, if the density of stations is 1 in 400 sq. miles the same section of the map will contain 49 stations which will be quite adequate for drawing isohyets. Convenience of handling decides the scale of the map sections to be chosen.

When drawing isohyetal maps in sections continuity of the lines from section to section should be ensured.

(*v*) In drawing the monthly and annual isohyetal maps for any area, the consistency of the monthly maps with the annual map should be checked by taking a certain number of points on the maps and calculating the spot values. The total of twelve monthly values should agree with the annual value. If not, the isohyetal lines should be adjusted suitably. This is a difficult task no doubt and has to be done by trial and adjustment. For, in drawing the annual isohyetal charts the general ideas of the meteorologist regarding the variation of rainfall with orography, the location of the area concerned with reference to the normal track of storms etc. will play a large part in shaping the isohyets, especially in parts where data are scanty. In the monthly maps the above effects are not so determinable and moreover, the spatial variation of monthly normals are likely to be more erratic because of a few abnormal values than that of the annual normals. To overcome this difficulty Salter has suggested the use of isomeric maps at an intermediate stage in drawing the monthly maps as already mentioned in para. 5.2 above.

(*vi*) While drawing isohyets careful attention should be given to fit in all available values as far as possible or to reject doubtful values after suitable examination. The following extract from the article by Reed and Kincer[15] explains this process very clearly :

" *Inconsistencies*—In drawing the isohyets the data for a small number of the stations appeared erratic. These cases were examined with great care, and the averages recomputed to detect possible arithmetical errors, but in most cases the original computations were found to be correct. The record was then examined in detail, and this examination usually showed particular years whose records seriously affected the average. In most cases the averages were evidently correct for the data as recorded and as all the original records had been carefully checked both by the section directors and at the central office, the explanation had to be sought elsewhere. In practically all these cases strictly local causes were found, which indicated that these records were not truly representative of large areas, and it became necessary either to disregard them, or to show small areas of precipitation different from the surrounding regions......"

(*vii*) Choice of intervals of isohyetal lines is another matter that requires careful consideration. Isohyetal lines drawn at uniform intervals of rainfall values such as 1″ or 5″ for all parts of the map and for all months will not be suitable. For a region or a month where the general rainfall varies from 0 to 2 inches or so, a 5″ interval for isohyetals will be too wide and will not depict any variation of rainfall at all on the map. On the other hand isohyetals at intervals of 1″ for a monsoon month map will result in far too many lines and a number of small pockets around individual stations for which there may not be any justification or need. The choice of intervals of isohyets should be such that they separate out as clearly and successfully as possible regions of different rainfall on the map so that average rainfall over any area of the map may be obtainable as accurately as possible by following these isohyets. Yet another consideration demands that the intervals adopted for drawing isohyets should not be different for different maps of the same series because then the maps will not be comparable with one another.

5.4. Taking the above-mentioned principles into consideration, the following suggestions are made for getting a standard set of monthly and annual isohyetal maps showing normal rainfall for India prepared.

(i) A base map of raingauge stations with contours and layered in colour may be got prepared in scale 1″ = 16 miles. The series of maps already printed by Survey of India known as HIND 5000 (Sixth edition) seems to be suitable for this purpose. Locations of various raingauge stations may be indicated on the map. For the portion of area of Indian Union, there will be 25 sections of the map. This base map apart from being used for the normal isohyetal maps, will also be found to be very useful for other rainfall studies such as storm studies etc., to be mentioned later in this article in Section 8 and therefore sufficient number of copies of the base map may be got printed.

This scale is suitable and will contain from 120 to 150 raingauge stations in each section except for some sections where sea area covers a part of the section. Even on these there will be sufficient number of stations to enable isohyets to be drawn. Fig. 1 shows the various sections of the map as suggested above. The boundaries of various meteorological sub-divisions are also shown in the map together with the number of raingauge stations in each subdivision.

(ii) The period 1891—1940 may be chosen as the standard period for the normal isohyetal maps. From Table 1 it will be seen that there are 1,319 stations for which data are available for more than 50 years. All these normals which are not exactly for a period of 50 years should be converted to a period of 50 years. Normals of stations with data for 20 years or more will be converted to normals of 50 years. These will be 1015 stations making in all 2334 stations for an area of 12,20,000 sq. miles, giving an average density of 523 sq. miles per station. The data of

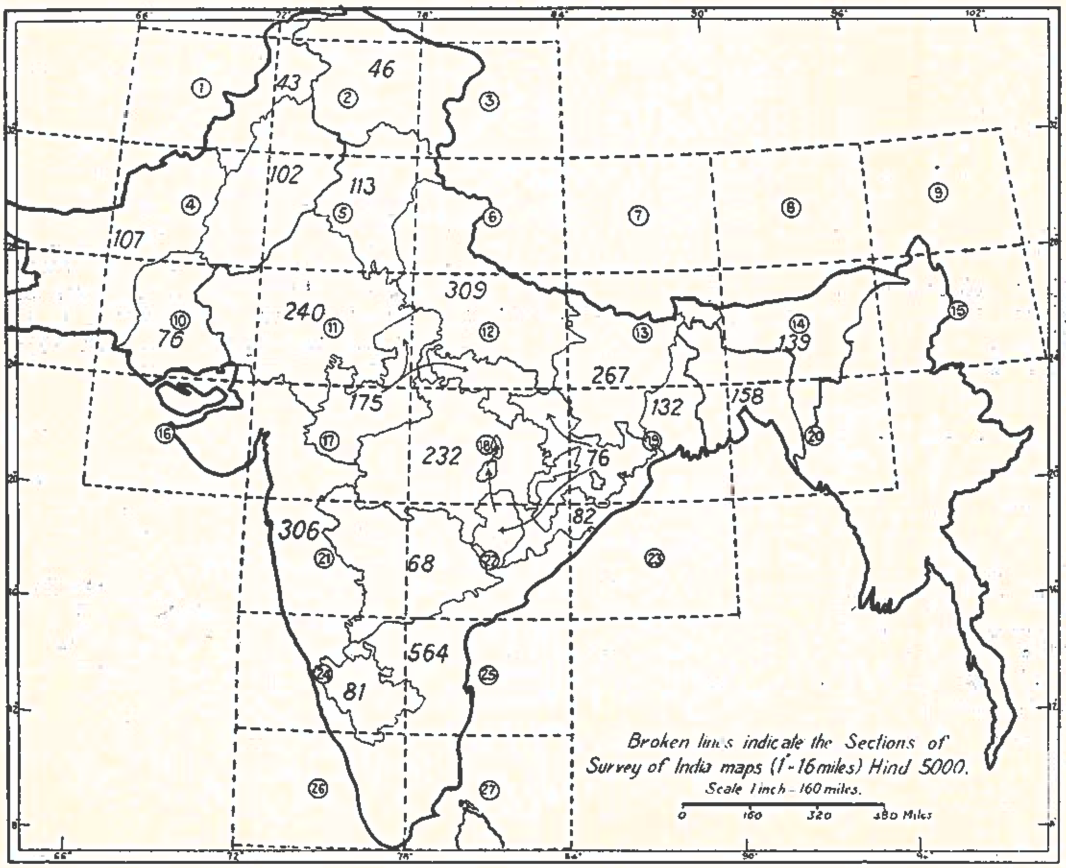

FIG. 1. MAP OF INDIA SHOWING NUMBER OF RAINGAUGE STATIONS.

stations less than 20 years *i.e.* 496 stations and of closed stations 245 will also be converted to 50 years but these will not be used as control stations but will be plotted on maps in distinct colours and will be used to guide the isohyets wherever necessary but will not be relied upon.*

(iii) Eliot has adopted the following values for drawing isohyets for India in his Climatological Atlas of India. 10 cents, 50 cents, 1″, 2″, 5″, 10″, 15″, 20″, 25″ (some times) 30″, 40″, 50″, 75″ and 100″. In certain intervals these values are not close enough. The following intervals of rainfall amounts may be adopted for drawing isohyetal lines on the maps for different ranges of rainfall values for India:

Range of rainfall values	Isohyetals to be drawn for values
0 to 1 inch	At 10 cents, 50 cents, 1 inch
1 to 5 inches	At 1 inch, 1.5″, 2.0″, 3.0″, 4.0″, 5.0″
5 to 10 inches	Lines to be drawn for 6″, 8″ and 10″
10 to 20 inches	At 12,″, 16″, 20″
20 to 50 inches	At intervals of 5 inches
50 to 100 inches	At intervals of 10 inches
100 to 200 inches	At intervals of 20 inches
Over 200 inches	At intervals of 50 inches

6. *Rainfall frequencies.*

6.1. Frequency of heavy rain, *i.e.* rainfall 3 inches and above in a day based upon 30 years' daily rainfall data ending 1920 for all raingauge stations in India have been published in ***Memoirs of the India Meteorological Department*** Vol. XXIII Part VIII[20]. Heavy rainfalls of 10″ and above in a day at all raingauge stations in India between the years 1891 and 1911 have been listed in Vol. XXI, Part III[21] of the Memoirs which have been brought up to 1926 in a subsequent Memoir Vol. XXV, Part III[22]. From 1927 onwards these data of heavy rainfalls for all raingauge stations are being published in the *Annual Summary*[23] of every year. An analysis of these data has been made and map of heaviest rainfall over India and also some maps of frequencies of heavy rain have been published in *Scientific Note* No. 77 of the India Meteorological Department[24].

6.2. While the above-mentioned compilations give some general information about heavy rainfalls in different regions of the country, they do not treat the rainfall distribution as a whole and consequently are inadequate to answer definite queries of a more detailed nature in respect of heavy rainfall that are required for the water power projects. It is therefore necessary to reduce the available daily rainfall data of all raingauge stations into complete frequency distributions. The longer the series of data, the more reliable and stable will be the resulting distribution.

6.3. In reducing the daily rainfall data into frequency distributions the question of choosing the class intervals requires some careful consideration. A class interval of one inch throughout the range of values of rainfall amounts may appear quite suitable at first sight especially because it will keep the number of classes within reasonable limits in most cases. It is, however, found that this classification does not give adequate information about the behaviour of rainfall in the lower ranges, say up to 2 inches. Moreover, it has been the experience of the writer of this article that while on a broad classification rainfall frequencies indicate L-shaped distribution, on a closer examination the rainfall distribution appeared to be a highly skew distribution with a mode somewhere within the first few cents. Another interesting feature that lends support to this view is that if the duration of time intervals for rainfall enumeration is increased the rainfall dis-

* The use of normals converted to a long period from too short a period of actual observations or by taking a reference station too far away is not advisable. Sir Alexander Binnie obtained a normal value of 36.66 inches for monsoon rainfall at Nagpur by comparing the actual records of the four years 1869-72 with those of Bombay long period data. The 1940 normal for monsoon rainfall at Nagpur is 42.85 inches[19].

tribution becomes unimodal skew distribution. Fig. 2 illustrates this transformation clearly. There seems therefore to be a law of transformation connecting time-interval and the frequency distribution of rainfall. Deter-

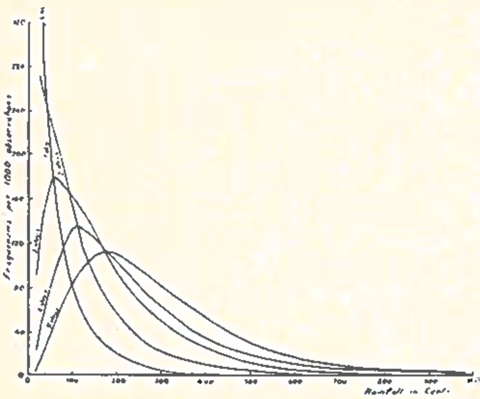

Fig. 2 Frequency distributions of rainfall amounts for different durations, 1 day, 2 days, etc.

mination of this law may lead to a very useful solution in practice for dealing with rainfall probabilities because if the basic distribution of rainfall amounts, say, for 24 hours, is known, the frequency distribution for other periods of any interval can be derived. This solution will enable one to answer the question as what is the chance of x inches of rain and above falling in t hours at any place for various values of x and t from the basic distribution of rainfall amounts in 24 hours. For such work a more detailed frequency table will be required than the one with one inch class interval. On the other hand choosing the class interval at the smallest unit of say one cent throughout the range is also unnecessary as it will make the number of class intervals unwieldy.

6.4. Considering the above requirements the following scheme of class intervals is suggested for classification of rainfall amounts of the raingauge stations for 24 hours.

TABLE 2.

Range of rainfall amounts in cents	Class interval in cents	No. of class intervals
1 to 10	1	10
11 to 50	5	8
51 to 100	10	5
101 to 200	20	5
201 to 500	50	6
Above 500 (*i.e.* 5 inches)	1 inch	20
Total		54

It is expected that the frequencies resulting from this classification will yield, by suitable combinations, the required data for all practical purposes and to a certain extent for theoretical discussions also.

6.5. Frequency tables of rainfall amounts for durations of 2 days, 3 days etc. upto 7 days may also be compiled in the same manner at least for a few stations in each district. For these durations the class intervals may be chosen suitably governed by considerations similar to those enunciated above for the one day period.

6.6. Frequency tables of monthly and annual rainfalls will also be useful for all raingauge stations. These are much simpler for compilation because monthly and annual totals are already available. Frequencies of seasonal rainfall such as monsoon rainfall, winter rainfall etc. may also be found useful but these can be compiled as and when required for various catchments.

7. *Maps of Rainfall Probabilities.*

The frequency tables suggested for compilation in the previous sections will enable one to obtain roughly the probabilities of rainfall at a particular location. Such frequencies if plotted on a map and iso-lines drawn will yield very interesting information on rainfall probabilities for areas such as catchments. But before plotting the frequencies on maps and drawing lines, one thing should be remembered. If the frequencies are compiled from different lengths of rainfall data they have to be converted to some standard period by proportionate evaluation. All frequencies may be converted as number of occasions for 50 years. The following set of 40 maps, will, it is hoped, meet the requirements if prepared from the data. The list is a provisional suggestion and may require some modifications depending upon the actual frequencies that result for different ranges in the frequency tables.

TABLE 3.

Duration of rainfall.	Probability of rain exceeding	Number of maps
1 day	1″, 3″, 5″, 10″, 15″, 20″	6
2 days	2″, 5″, 10″, 15″, 20″	5
3 days	3″, 5″, 10″, 15″, 20″	5
4 days	4″, 5″, 10″, 15″, 20″, 25″	6
5 days	5″, 10″, 15″, 25″, 30″	6
6 days	6″, 10″, 15″, 20″, 25″, 30″	6
7 days	7″, 10″, 15″, 20″, 25″, 30″	6

8. *Storm rainfall analysis.*

8.1. The characteristics of peak discharges at any point on the river, such as the rate of discharges during floods, their duration and their frequency over a long period of years enter as factors in designing a reservoir for flood control. The specific questions on heavy rainfall that are to be answered in determining these characteristics have already been mentioned under (*iv*) to (*vi*) in Section 3 above. The determination of the characteristics of these peak discharges referred to depend to a large extent on the analysis of rainfall data of the catchment for specific periods of continuous heavy rainfall and using the results in the "Unit hydrograph" method[2] in which knowing the characteristics of actual discharges observed for a unit of precipitation the characteristics of higher values of precipitation are derived. The method is particularly valuable when discharge observations on the river are meagre when compared with precipitation data, which are generally more extensive and cover a longer period.

8.2. Except for occasional severe thunderstorms which may give locally heavy rain at a few locations, widespread heavy rainfall covering an area such as a catchment or its part generally occurs more frequently in association with disturbed weather such as cyclonic storms than due to normal seasonal weather. Blanford[4] says that "excessive falls are always the result of cyclonic storms, not indeed such as are of destructive violence as regards the wind, but the long-lived cyclonic storms which occur chiefly in the rains, storms in which the barometer is not greatly depressed, and only recognisable in their true character when the barometric readings and the winds are laid down on charts". Any study of the characteristics of heavy precipitation should therefore, mainly involve the study of rainfall during storms but to cover all possibilities of heavy rain the data should be carefully examined for other occasions of heavy rainfall also. Moreover, not only the heaviest rainfall that has occured actually should be considered but also the maximum that is likely to occur for the catchment should be determined. The following three kinds of studies will be found helpful for this purpose.

8.3. The heaviest precipitation that has been observed so far at each recording station inside the catchment in, say, 24 hours may be plotted on a map and isohyets may be drawn at suitable intervals. The mean precipitation for the catchment or a part of it determined from these isohyets will give an absolute maximum of mean precipitation for the catchment in most cases because it will be evident from the Law of Probability that the chance of the highest value occurring at all stations simultaneously, which is implied in this method, will be considerably less than the chance of the highest value occurring at one station. More often than not, the value of this absolute maximum will be so high that it will not be useful from the point of view of practical considerations in designing, but it will serve as a useful check against the maximum precipitation values derived by other methods to be mentioned below. Such maximum precipitation maps for periods, 2 days, 3 days etc. will also be useful.

8.4. A study of all storms and depressions from the point of their rain-yields may also be made. In storm rainfall analysis it is important to remember that the analysis should be by storms as units instead of by catchments as units. Because the heavy rainfall area for any storm will cover more than one catchment and any study of the effects of these storms confined to within the boundaries of the catchments will not enable one to know the full rain-yielding capacity of the storm. Large scale maps with storm tracks marked thereon together with values of rainfall at raingauge stations plotted on them may be prepared for all storms and depressions. Table 4 below gives the number of storms and depressions that have affected the weather of India and the neighbouring seas during a period of 50 years 1891—1940 classified according to different seasons and the region of their tracks.*

Out of these we may omit 26 storms and depressions which crossed the Burma coast. A majority of the 146 storms which filled up in the Bay of Bengal and the Arabian Sea would not have affected the weather inland seriously. Only such of those which have affected the weather inland need be considered for this study. It is expected that nearly 630 storms have to be studied. It is needless to emphasise here that a systematic study of such a large number of storms for which the basic data are available, will yield much information about the spatial distribution of rainfall during storms with respect to the movement of the storms and yield much statistical material for correlation among themselves of the various features of the storms such as the pressure effect, total amount of rain, direction of the storm tracks, winds etc. In addition to being useful for the designing of waterpower projects such studies will also be of considerable help to the forecasting meteorologist. Such a comprehensive study of these storms has not been so far attempted for Indian storms. What kind of valuable information will become available if such an analysis is completed can be judged from the results of analysis of some typical individual storms in the *Memoirs* and *Scientific Notes* of the India Meteorological Department.[26-31]

8.5. Next, a selection of the storms which have been conspicuous for their rain-yields should be made out of these mentioned in the previous paragraph for studying the characteristics of maximum precipitation during 2 days, 3 days etc. for various regions. For each storm selected, maps of precipitation in 1 day, 2 days, 3 days etc. up to 7 days may be prepared and the mean precipitation values over different sizes of area, should be found. From these relationship between area and maximum precipitation can be derived. As a next step Duration-Depth-Area curves of maximum precipitation for each storm may be prepared. The method has been illustrated by the author for the Damodar Area taking the storm of 16th to 19th June 1898.[10]

8.6. In U.S.A. the maximum possible precipitation for catchments has also been derived from certain assumptions regarding the meteorological conditions during storms (*vide* Hydrometeorological Reports Nos. 6—33). The values computed by this method from actual observations during

TABLE 4.*

Season	Crossed Bay of Bengal coast including Burma coast	Filled up in Bay of Bengal	Crossed coast of Arabian Sea	Filled up in Arabian Sea	Total
Jan.—March.	11	5	4	4	24
April.—May.	49	8	4	11	72
June.—Sept.	347	15	18	22	402
Oct.—Dec.	169	40	20	41	270
Total ..	576	68	46	78	768

*The numbers of the storms indicated here have been compiled from Climatological Atlas for Airmen[25].

some storms using radiosonde meteorological observations have been compared favourably with the actual precipitation, thereby establishing the validity of the method. Assuming certain limiting conditions regarding wind movement, dew point, temperature etc. in the surface and upper layers of atmosphere, the maximum possible precipitation for various catchments have been derived. Also generalised maps of maximum possible precipitation during storms have been prepared for the whole country by integrating these results. The studies are very interesting and may lend themselves as applicable to tropical conditions with certain modifications. But such studies involve more extensive use of the radiosonde meteorological observations at frequent intervals such as 2 hours or 3 hours during storms at a certain number of selected locations near the storm. It will be worthwhile to arrange for these special observations for a few storms in the first instance and study the results. If they are encouraging then a more extensive use of the method may be taken up for various catchments in India. There is no doubt that the characteristics of maximum precipitation derived from this method which goes into the Physics of Storm precipitation will prove a valuable check on the data obtained from statistical methods mentioned in para. 8.5 above.

9. *Intensity of rainfall for short durations less than 24 hours.*

9.1. Intensity of rainfall varies inversely as the duration but the law of such variation is not uniform and varies with geographical location, nature of the rain etc. the relationship between intensity and duration may, therefore, be investigated for as many locations as possible. The general expression suggested for rainfall intensity is

$$I = KF^x / (t+b)^n \quad .. \quad .. \quad (1)$$

where K, b, x and n are coefficients and exponents varying in value with geographic location and F is the frequency in years with which average intensities are reached or exceeded. I is the intensity in time t [2]. For British rainfall Parker [3] has discussed the use of the formula

$$I = A/(t+30) \quad .. \quad .. \quad (2)$$

where A is a constant and varies with geographic location or a particular series of observation etc. and t the period of years.

Lacey[19] has indicated that a much simpler formula

$$I_t = 30/\sqrt{t} \quad .. \quad .. \quad (3)$$

where I_t is the intensity of rainfall in inches per hour and t is the duration of rainfall in minutes, gives a fair fit for intensities of rainfall for a greater part of India (except the hills). Other forms of formulae have also been discussed elsewhere. It will however be seen that formulae 2 and 3 above are only particular cases of the general formula (1).

9.2. Self-recording raingauge records of more than 20 stations are available for a series of years in India. From these records a large number of occasions, not less than 100, of continuous rainfall should be chosen for each station and the rainfall should be tabulated for intervals of 5 minutes. In the self-recording raingauge charts in use, about 1 centimeter represents an hour and hence it will be difficult to read out values of rainfall for intervals less than 5 minutes . For a few occasions however where the records are clear a photographic enlargement may enable us to read the data for shorter periods. The formula (1) indicated above may be fitted to the tabulated data for each location. The values of the constants obtained will indicate whether any simplification of the formula as in (2) and (3) can be accepted for use.

9.3. An extension of the above analysis to cover areas such as 100 sq. miles, 1000 sq. miles etc. will have to be taken up next. The existing records are not sufficient for this purpose. It may be necessary to set up more self-recording raingauges in certain catchments or areas. With such data and comparison of the short duration records of a few stations with the corresponding 24 hours rainfall which are available for a larger number of stations in the area, methods can be devised for deriving intensity-duration-area-frequency curves for short durations of heavy rainfall which will be useful at the operational stages of the reservoir schemes.

10. *Adequacy of observational data on rainfall.*

10.1. In what has been discussed above the extent of technical information for water power projects that can be obtained from available observational data by a comprehensive analysis has been indicated. It is quite likely to be found during the course of such analysis that available data are inadequate for certain areas. For, it will be seen from Table 1. that the density of the raingauge stations varies from 1 in 200 square miles in West Bengal to 1 in 1200 square miles in Hyderabad. In Kashmir the density works out to 1 in 1800 square miles. In catchments lying in areas with a sparse distribution of rain-recording stations, the available recorded data may not yield technical information of the desired degree of accuracy, especially if the area is susceptible to high variability of rainfall in space. The question of adequacy of existing rainfall organisation from the point of view of rainfall data for water-power projects has, therefore, to be investigated by making a systematic study of the variations and correlations of rainfall between raingauge stations in different areas.

10.2. It should be mentioned here that the existing rain-recording organisation in India was developed and is being maintained mainly for general climatological purposes and for providing information to help the Administration and to a certain extent to help Agricultural planning. For these purposes the monthly and annual totals of rainfall only are generally required. It will be found that the existing density of raingauge stations will be found adequate in most areas from this point of view because they will yield monthly and annual means of rainfall of a fairly high degree of accuracy for all administrative divisions. But the requirements of rainfall data for water power projects are more exacting because (*i*) the areas of catchments and sub-catchments that will be considered as units of areas are generally smaller than administrative divisions and (*ii*) the estimation of water-catches is required for smaller units of time, such as a day, 2 days etc. than the month. Hence to ensure the degree of accuracy of these data it will be necessary to extend and improve the rainfall registering organisation, as pointed by Sohoni[8]. The extent to which this is to be done may be determined for different areas by making a systematic study of the spatial variation of rainfall for different units of time in different areas. A reference is invited in this connection to Resolution No. 2 adopted at a combined meeting of Engineers and Meteorologists on 10th August, 1946, where such a study has been recommended[33].

10.3. A statement of the problem envisaged in such an investigation and a preliminary method of attack under some broad assumptions, which have yet to be tested, has been attempted by Satakopan[34] and later Ramamurthi[35, 3] has suggested a different approach to the same. These, however, touch only the fringe of the problem which has to be tackled by more extensive and thorough calculations to get a satisfactory solution.

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