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Probable maximum precipitation for the catchment of Koyna dam

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सार — कोयना नदी पर बने कोयना बाँध के जलग्रहण क्षेत्र में विभिन्न अवधियों में होने वाली अधिकतम संभावित वर्षा (पी.एम.पी.) का आकलन किया गया है। 892 वर्ग किमी. के विस्तृत जलग्रहण क्षेत्र के लिए 1 से 3 दिन की अवधि की अधिकतम संभावित वर्षा का आकलन किया गया है। कोयना बाँध के लिए भौतिक विधि द्वारा किए गए आकलन से1,2 और 3 दिन में क्रमशः 48 सेंमी., 87 सेंमी. और 117 सेंमी. अधिकतम संभावित वर्षा का पता चला है जबकि सांख्यिकीय विधि द्वारा किए गए आकलन से इसी अवधि में क्रमशः 54 सेंमी., 89 सें. मी. और 124 सेंमी. वर्षा होने का आकलन किया गया है। इन आकलनों का उपयोग कोयना बाँध के मौजूदा बाढ़ उत्प्लव मार्ग (स्पिलवे) की डिजाइन की जाँच के लिए किया जा सकता है।

ABSTRACT. Estimates of Probable Maximum Precipitation (PMP) for different durations were made for the catchment above Koyna dam on the Koyna river. The catchment spans an area of 892 km^2 and the PMP estimates were made for a range of durations of 1 to 3 days. The PMP estimates for Koyna dam were found to be 48,87 and 117 cm by the physical method and 54,89 and 124 cm by statistical method for 1, 2 and 3 day respectively. These estimates can be used to check the existing spillway design flood of Koyna dam.

Key words — Probable maximum precipitation (PMP), Spillway design flood.

1. Introduction

The Probable Maximum Precipitation (PMP) study over the catchment of the Koyna river above Koyna dam (see Fig.1) with a total area of 892 km^2 has been carried out. The objective of this study is to provide estimates of PMP depths for durations of 1 to 3 days over the catchment so that these values can be used to check the adequacy of the current spillway design flood (SDF) of Koyna dam.

2. Koyna dam and need for review of SDF

Koyna dam on the river Koyna for hydropower generation was built near Helwak village in Satara district of Maharashtra state during 1956-64. The project supplies electric energy to Bombay - Pune area and the adjoining districts. The dam is approximately 103 m high with a capacity of 2796 $\times 10^6$ m^3. The spillway is designed to discharge 7845 m^3/s which was computed using empirical formula. The Koyna catchment though has a comparatively small drainage area but large national economic importance.

Since the Koyna dam was designed in 1960's, the method used to estimate SDF has greatly changed with the advent of hydrometeorological techniques. The CWC (1972) has given guidelines that all large dams with storages more than $60\times 10^6 m^3$ and hydraulic heads greater than 30m should be designed for the Probable Maximum Flood (PMF) resulting from the PMP and dams with storages less than $60\times 10^6 m^3$ for standard project flood. The PMP denotes the estimated largest possible rainfall that will occur for a given duration over a given area. It is derived by a physically based method using daily rainfall records over a long period of time at several stations in and around the catchment, supplemented with meteorological conditions. Keeping in view the fact that the existing spillway capacity of Koyna dam is not in accordance with the hydrometeorological method, the dam design authorities as also the CWC have felt the need to carry out comprehensive investigations into the adequacy of the current spillway capacity of Koyna dam. The purpose of the investigation is to incorporate a spillway capable of passing the PMF.

3. Topography of the Koyna river catchment

The Koyna river catchment is situated in the Western Ghats approximately between the latitudes 17°20′ and 17°55′ N and longitudes 73°35′ and 73°55′ E (Fig.1). The

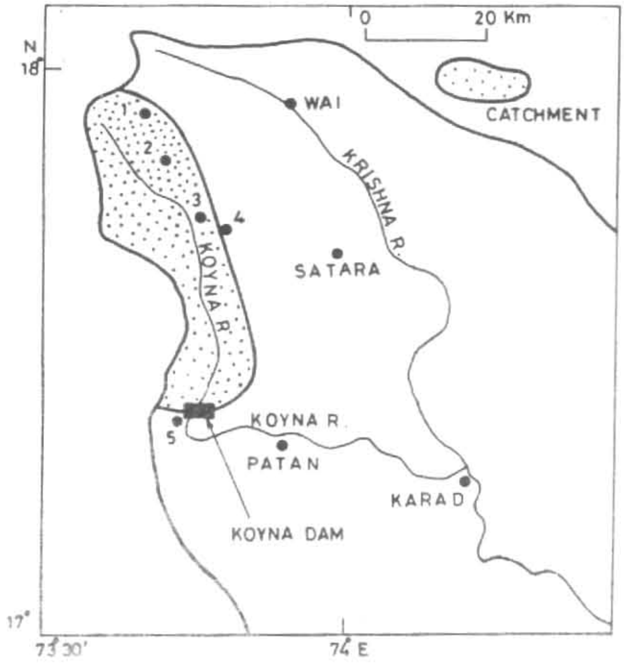

Fig.1. Koyna catchment above Koyna Dam and locations of five raingauge stations

catchment is parallel to the Western Ghats for about 70 km in length with about 12 to 13 km in width. Spurs of the Western Ghats stretch into the catchment from the west. The river Koyna on which Koyna dam is located rises from Mahabaleshwar hills of the Western Ghats at an elevation of about 1380 m. The river after flowing parallel to the Western Ghats in a southward direction for about 70 km turns sharply near Helwak and joins the Krishna river near Karad. The catchment is characterized topographically by steeply rising hills on both sides of the river bed and ranges in elevations from about 600 m to 1380 m above mean sea level. This feature is the major contributing factor for rapid rainfall-runoff response.

4. Data used

As stated earlier that the estimation of PMP for a catchment area by the hydrometeorological method needs long period daily rainfall and other meteorological data at a dense network of stations in and around the catchment. It has been found that there are only 5 stations in the catchment for which a long period of records is available. These are as follows:

1.	*Mahabaleshwar*	-	*Daily rainfall data since*	*1829*
2.	*Bamnoli*	-	*-do-*	*1907*
3.	*Helwak*	-	*-do-*	*1902*
4.	Kas	-	*-do-*	*1901*
5.	*Sonat*	-	*-do-*	*1902*

The locations of these stations are shown in Fig.1. Of these stations, Mahabaleshwar raingauge station is maintained by India Meteorological Department (IMD) while the other four stations are maintained by the Koyna dam maintenance authority. Mahabaleshwar is one of the oldest raingauge stations in the Maharashtra state and the data for the same is available since 1829. It may also be mentioned that all the raingaugae stations except Mahabaleshwar were discontinued from 1973 and restarted since 1979. Hence, the daily rainfall data for 4 stations is not available from the year 1973 to 1978.

5. Method and analysis

5.1. *Rainfall characteristics of the Koyna catchment*

The topography of the catchment plays a large part in the spatial distribution of rainfall. The average annual rainfall in the catchment is about 500 cm declining from 600 cm at Mahabaleshwar to about 300 cm at Bamnoli. About 95 percent of the annual rainfall is received with relatively high intensity during the southwest monsoon (SW) months of June to September. The SW monsoon normally sets in over the catchment in the first week of June and withdraws in the first week of October. The major weather systems that influence heavy rainfall over the catchment are the formation and subsequent movement of cyclonic storms and depressions from the Bay of Bengal. When these systems move across Madhya Pradesh, often the Arabian Sea monsoon currents are strengthened, and heavy rainfall occurs over the catchment. However, no storms or depressions from Bay of Bengal directly affect the project area.

5.2. *Highest observed 1,2 and 3-day point rainfalls*

The magnitude of the highest rainfall recorded at a point is useful in the assessment of design flood as well as in estimation of PMP. The highest recorded rainfall values of 1 to 3-day durations at 4 stations that occurred between their period of records are given in Table 1. This table shows that stations in the catchment have recorded the highest rainfall in the range of 40 to 50 cm in 1-day, 65 to 76 cm in 2-day and 86 to 106 cm in 3- day duration. The highest known measured rainfalls were associated with the storm of July 1912. The two greatest amounts of storm rainfall 106 cm and 100 cm were observed at Mahabaleshwar and Bamnoli respectively.

5.3. *Method of estimating design storm rainfalls*

A design storm of a catchment is an estimate of the highest rainfall over the catchment which is accepted for use in determining the spillway design flood. Design storms in common use for deriving design floods are the probable maximum storm (PMS) that is equal to the PMP and the standard project storm (SPS). The PMP provides an estimate

TABLE 1

Highest observed point rainfall (cm) for 1,2 and 3-day durations

Station	Highest 1-day	Date	Highest 2-day	Date	Highest 3-day	Date
Bamnoli	28	21 Jul 1912	55	21-22 Jul 1912	75	20-22 Jul 1912
Helwak	51	24 Jul 1921	76	24-25 Jul 1921	99	19-21 Jul 1912
Kas	45	4 Aug 1914	68	4-5 Aug 1914	86	3-5 Aug 1914
Mahabaleshwar	44	22 Jul 1912	76	22-23 Jul 1912	106	21-23 Jul 1912
Sonat	41	18 Jul 1914	77	21-22 Jul 1912	105	20-22 Jul 1912

TABLE 2

Rainstorms and associated daily areal rainfall averages over the catchment upto Koyna dam

S. No.	Date of rainstorms	Daily rainfalls (cm)			Highest rainfalls (cm)		
		1	2	3	1-day	2-day	3-day
1	23-25 Jul 1907	23.1	27.1	23.0	27.1	50.2	73.2
2	21-23 Jul 1912	29.4	36.2	26.4	36.2	65.6	92.0
3	18-20 Jul 1914	33.2	20.0	20.2	33.2	53.2	73.4
4	3-5 Aug 1914	13.3	23.5	23.6	23.6	47.1	60.4
5	23-25 Jul 1921	18.8	34.0	19.1	34.0	53.1	71.9
6	2-4 Aug 1956	25.3	30.3	26.0	30.3	56.3	81.6

of the upper limit of rainfall and the SPS is the most severe rainstorm which has actually occurred over the catchment during the period of available records. The PMP is used in the design of all hydraulic structures where the failure of structures will lead to significant economic loss or life or social damage. The SPS is used where the economic involvement is small and the risk of loss of life is either very small or does not exit.

The first requirement of estimating the PMP or SPS is the selection of major historical rainstorms that have occurred in and around the catchment under study. These rainstorms usually constitute the greatest rainfall depths for catchment or the surrounding region. Such rainstorms are the main source of floods in the catchment. After obtaining a suitable severe rainstorm database, three methods may be used for the estimation of SPS or PMS design storm rainfalls. First is the depth-duration (DD) or depth-area-duration (DAD) method starts with the analysis of the severe rainstorms occurring within the catchment, or in the neighbourhood from where the transposition of storm is carried out over the catchment area. The second method is the statistical approach which consists in analyzing the annual maximum rainfall series of small catchments only. The main object of these methods is to estimate the highest rainfall that might occur over the catchment. In evaluating the PMP, the highest observed rainfall is maximized for a moisture maximization factor (MMF). The marked topographic effects make it difficult to use the transposition method. As such the PMP depths for the Koyna catchment are determined by DD or DAD method.

5.4. *Analysis of severe rainstorms over the catchment*

There are only 5 stations within the catchment. However, around the catchment a good number of stations are being maintained whose daily rainfall data are available for several years. The data of these stations are useful in selecting the severe rainstorms over the catchment. A review of the daily rainfall data for the available period has revealed in the past 6 rainstorms gave maximum rainfalls over the catchment. The dates of occurrence of these rainstorms are as follows:

S.No.	*Date of rainstorm*	*S.No.*	*Date of rainstorm*
1.	*23-25 Jul 1907*	2.	*20-23 Jul 1912*
3.	*18-21 Jul 1914*	4.	*3-5 Aug 1914*
5.	*23-25 Jul 1921*	6.	*2-4 Aug 1956*

Heavy rainfall associated with the above rainstorms have been found to occur with durations from 3 to 4 days. The areal average rainfall upto the dam site for each day of the storm period was then computed by the thiessen polygon method. The daily areal rainfall averages of the six rainstorms are given in Table 2 along with the maximum rainfalls for 1 to 3-day durations.

The quantitative analysis of the 6 storms showed that the worst rainstorm over the catchment occurred during 21-23 July 1912 with its centre at Mahabaleshwar within the catchment. This storm contributed the highest rainfalls amounting to 36.2, 65.6 and 92.0 cm in 1,2 and 3-day durations over the catchment above the dam site. The July 1912 rainstorm had its heavy rain centre inside the catch-

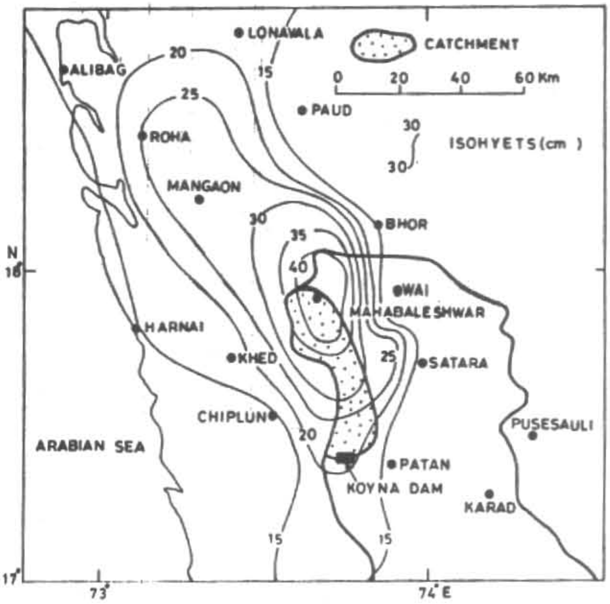

Fig.2. Isohyetal pattern of 1-day (22 July 1912) rainstorm over Koyna catchment

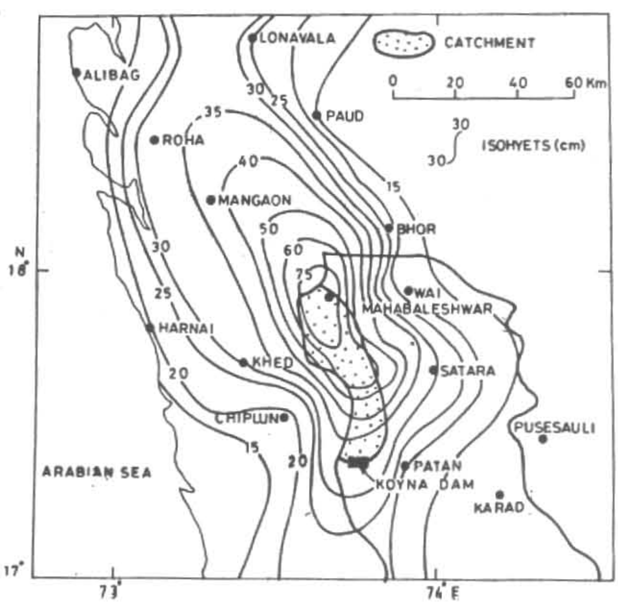

Fig.3. Isohyetal pattern of 2-day (22-23 July 1912) rainstorm over Koyna catchment

ment and as such a detailed analysis of this storm by DAD method is presented in the following section.

5.5. DAD analysis of 21-23 July 1912 rainstorm

The July 1912 storm system brought extremely heavy rainfall to an area that extended from the north of Koyna catchment to the south of the catchment. Rainfall from the storm started on 20 July and continued over most areas until 23 July. The catchment recorded 1- day maximum rainfall on 22 July 1912, 2-day maximum rainfall for 22 and 23 July 1912 and 3-day maximum rainfall for 21, 22 and 23 July

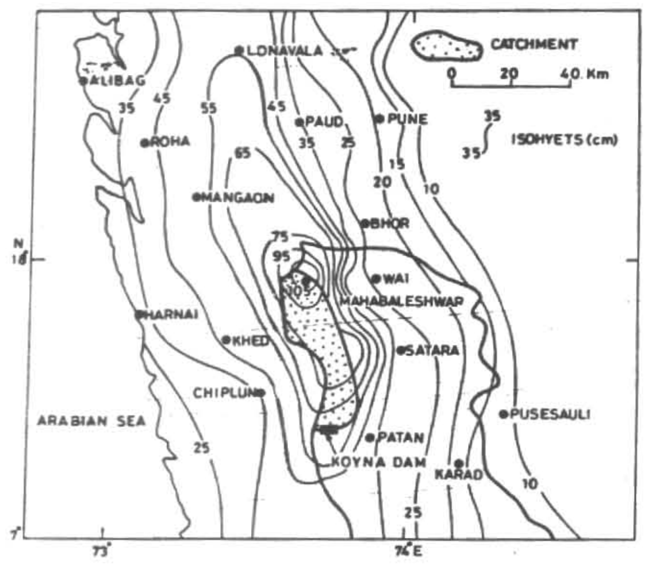

Fig.4. Isohyetal pattern of 3-day (21-23 July 1912) rainstorm over Koyna catchment

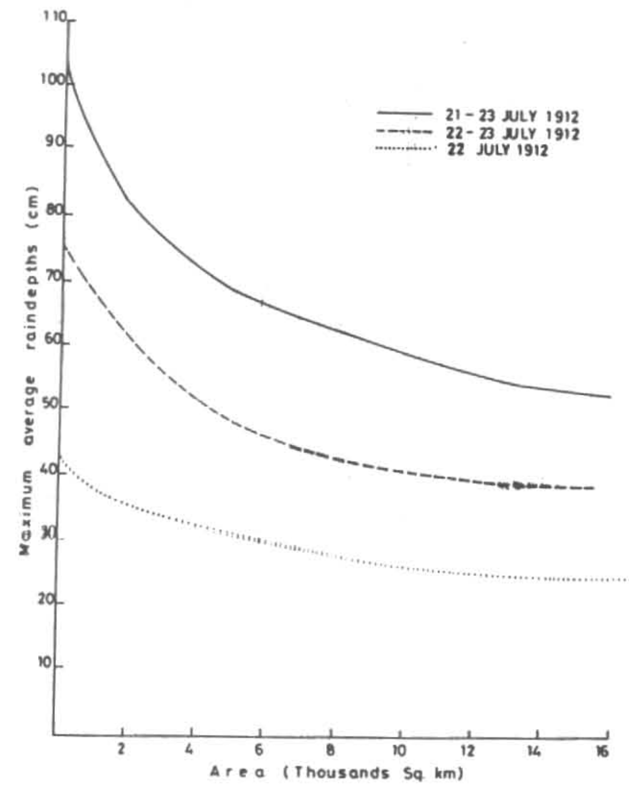

Fig.5. Depth-Area-Duration (DAD) curve

1912. The isohyetal patterns for this rainstorm for 1,2 and 3-day durations are shown in Figs.2-4 respectively. These figures show that the storm and orographic effects combined to cause extremely high rainfall in the mountainous head waters of rivers of the Koyna catchment. The maps show that the centre of the rainstorm was located at Mahabaleshwar which recorded rainfalls of 44, 76 and 106 cm in 1,2 and

TABLE 3

DAD values (cm) for 21-23 July 1912 storm over Koyna catchment

Area (km^2)	1-day (22 July 1912)	2-day (22-23 July 1912)	3-day (21-23 July 1912)
10	44	76	106
500	40	72	97
892	38	69	93
1000	38	69	91
2000	35	61	82
5000	31	48	69
10,000	26	41	59
15,000	24	38	53

TABLE 4

Maximum raindepths (cm) by DAD and DD methods for 892 km^2 area of Koyna dam

Duration	DAD method	DD method	Ratio DAD/DD
1-day	38	36	1.06
2-day	69	66	1.05
3-day	93	92	1.01

3-day respectively. It is mentioned that the 106 cm of rainfall within a 3-day period measured at Mahabaleshwar set a new record. The depth-area- duration (Fig.5) values obtained for areas upto 15000 km^2 during the rainstorm are given in Table 3.

The maximum DAD rainfalls obtained in 1,2 and 3-days for an area of 892 km^2 of the Koyna river catchment above Koyna dam has been found to be 38, 69 and 93 cm respectively. The maximum DAD values along with DD values obtained in the previous section are given in Table 4 which shows that the ratios of DAD raindepths to DD raindepths for durations of 1 to 3 days obtained for July 1912 rainstorm typically fall in the range of 1.01 to 1.06.

6. Results and discussions

6.1. *Estimation of PMP by the physical method*

In the section, estimates of PMP, the theoretical upper limit of precipitation which might be expected to occur over the Koyna river catchment, has been made.

The PMP is defined as the theoretical greatest depth of precipitation for a given duration that is meteorologically possible over a drainage area (WMO 1986). This upper limit of precipitation is developed utilizing present day knowledge of the precipitation process. The main assumption in the method is that the PMP will result from a storm in which there is the optimum combination of the available moisture in the atmosphere and the efficiency of the storm mechanism. Factors which influence the storm efficiency include horizontal mass convergence, topographically induced lifting, vertical motion and the rate of condensation. The extreme observed rainfall values are then maximized by the moisture maximization factor (MMF) to estimate PMP. When the record of storm rainfalls over the catchment is inadequate, outstanding storms are transposed from other areas which are meteorologically homogeneous. In an orographic area, such as the Koyna catchment, the storm transposition has not been considered. As such in evaluating the PMP for the Koyna catchment, the maximum areal average rainfalls obtained by the DD or DAD method are adjusted for the MMF.

It has been found in the preceding section that the 21-23 July 1912 rainstorm centered over the Koyna catchment above the dam site produced the maximum areal rainfalls over the catchment. This rainstorm, therefore, has been considered as the design storm for the Koyna catchment. In view of its centering over the catchment, it was appropriately thought that the realistic estimates of PMP for Koyna dam could best be determined by moisture adjustment of observed areal rainfalls obtained by DAD method for an area of 892 km^2. For moisture adjustment, the observed areal rainfall values are multiplied by the ratio of the highest amount of moisture recorded in the Koyna catchment to that recorded during the storm period. The moisture in an air mass from which large precipitation occurs can be estimated from the surface dew points decreasing with height at the saturated pseudo-adiabatic lapse rate (Rietan 1963).

The moisture adjustment has, therefore, been worked out on the basis of maximum persisting storm and the maximum persisting dew point for the catchment. For long duration storms, the maximum 24-hr persisting dew point value is used. The 24-hr persisting dew point temperature for July 1912 storm has been worked out to be 22.8°C. The highest 24-hr persisting dew point temperature representing July month for the Koyna catchment has been obtained from the generalized map of 24-hr maximum persisting dew point prepared by Rakhecha *et al.* (1995) for the Krishna catchment. From this map, the highest 24-hr persisting dew point temperature for the Koyna catchment above Koyna dam for July month has been found to be 25.5°C. The calculation of MMF for the catchment to Koyna dam is given below:

Maximum persisting storm dew point	= 22.8°C
Precipitable water	= 66.7 mm
Highest persisting dew point for Koyna catcment	= 25.5°C
Precipitable water	= 84.3 mm

Moisture maximization factor = 84.3/66.7 ~1.26

The highest areal rainfalls obtained from July 1912 rainstorm by DAD method have been maximized to a factor of 1.26 to obtain PMP values which are as follows:

1-day PMP = 38×1.26 ~ 48cm

2-day PMP = 69×1.26 ~ 87cm

3-day PMP = 93 × 1.26 ~ 117 cm

The estimates of PMP for 1,2 and 3-day durations for the Koyna catchment above Koyna dam have been found to be 48, 87 and 117 cm respectively. These PMP raindepths can be used for calculation of the PMF hydrograph for Koyna dam.

6.2. *Estimation of PMP by the statistical method*

As the area of the Koyna catchment is less than 1000 km^2, an attempt has also been made to estimate PMP depths for different durations by the statistical method. Horton (1924) observed that in many storms there was an exponential relationship of point rainfall to areal rainfall in the form of

$$\bar{p} = P_m \, e^{-kA^n} \tag{1}$$

where $\bar{p}$ is the average rainfall for an area A, P_m is the maximum point rainfall at the centre of the storm and k and n are coefficients determined from storm depth-area statistics.

In this study depth-area statistics are available during 21-23 July 1912 storm over the Koyna catchment. The statistics for this storm are given in Table 3. This storm data have been used to derive a generalized relationship between depth-area values for 1-day duration as

$$\bar{p} = P_m \, e^{-0.00511 \, A^{0.5}} \tag{2}$$

The above equation can be used to convert point PMP rainfall to areal PMP rainfall for areas upto 1000 km^2 for 1-day duration. Estimates of PMP for other durations can be computed from 1-day value through the use of depth duration relations.

The estimate for 1-day point PMP by Hershfield statistical method for Mahabaleshwar staion has been obained as 65 cm. The 1-day PMP for an area of 892 km^2 has been worked out to be 54 cm by applying the areal reduction factor obtained from Eqn. (2). The 1-day PMP estimate for Koyna dam by the statistical method was found to be 54 cm, which is slightly on the higher side of the 1- day value obtained by physical method.

7. Conclusions

The estimates of PMP for 1,2 and 3-day durations for the Koyna catchment above Koyna dam were found to be 48, 87 and 117 cm respectively. As the catchment area is about 892 km^2, the statistical method has also been used to estimate PMP depths for 1-day so as to check results found by the physical method. The statistical method gave slightly higher estimate of PMP value.

Acknowledgement

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References

Central Water Commission, 1972, "Estimation of design flood recommended procedures", N. Delhi, 130p.

Horton, R.E., 1924, "Discussion of the distribution of intense rainfall and some other factors in the design of storm water drains", *Proc. Amer. Meteor. Civil Engineers*, **50**, 660-667.

Rakhecha, P.R., Deshpande, N.R., Kulkarni, A.K., Mandal, B.N. and Sangam, R.B., 1995, "Design storm studies for the Upper Krishna river catchment upstream of the Almatti dam site", *Theor. Appl. Climatol.*, **52**, 219-229.

Reitan, C.H., 1963, "Surface dew point and water vapour aloft", *J. Appl.Meteor.*, **2**, 776-779.

World Meteorological Organization, 1986, "Manual for estimation of probable maximum precipitation, "*World Meteorological Organization Operational Hydrology Report No.1*, WMO No. 232 (Second Edition).