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Probable maximum precipitation estimation and its spatio-temporal analysis

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सार — **संभावित अधिकतम वर्षा (पीएमपी) किसी डिज़ाइन वाटरशेड या दिए गए तूफान क्षेत्र के लिए मौसम विज्ञान की दृष्टि से दी गई अवधि के लिए वर्षा की सबसे बड़ी गहराई है। इसे किसी क्षेत्र में अनुमानित वर्षा की उचित ऊपरी सीमा के रूप में सोचा जा सकता है।**

संशोधित हर्शफील्ड तकनीक का उपयोग करते हुए 113 **वर्षों की लंबी अवधि के दैनिक वर्षा डेटा का उपयोग करके महाराष्ट्र में** 173 **वर्षा निगरानी स्टेशनों के लिए पीएमपी मूल्यों का अनुमान लगाया गया है। स्टेशन डेटा ग्रिड वर्षा डेटा सेट की तुलना में वर्षा के चरम व्यवहार को बेहतर तरीके से पकड़ता है क्योंकि यह सामान्यीकृत संस्करणों का प्रतिनिधित्व करता है। यह विधि आच्छादित आवृत्ति कारक विश्लेषण और इस धारणा पर आधारित है कि दीर्घकालिक वर्षा रिकॉर्ड किसी क्षेत्र में अत्यधिक वर्षा की घटनाओं पर अच्छी तरह से जानकारी प्राप्त करते हैं। महाराष्ट्र के चार मौसम उप-विभाजनों, अर्थात् कोंकण और गोवा, मध्य महाराष्ट्र, मराठवाड़ा और विदर्भ में से प्रत्येक के लिए आवरण वक्र उत्पन्न किए गए थे।**

महाराष्ट्र में, 1 **दिन की पीएमपी** 22.57 **से** 95.26 **सेमी तक होती है,** 2 **दिन की पीएमपी** 31.66 **से** 127.79 **सेमी तक होती है, और** 3 **दिन की पीएमपी** 36.1 **से** 134.22 **सेमी तक होती है।** 1-3 **दिनों में देखी गई वर्षा और पीएमपी का उच्चतम मान कोंकण और गोवा उप-मंडल स्टेशनों में पाया गया।** 1-**दिवसीय पीएमपी के लिए कोंकण और गोवा उप-डिवीजन स्टेशनों में सबसे अधिक भिन्नता देखी गई, जबकि मध्य महाराष्ट्र उप-डिवीजन में** 2-**दिवसीय और** 3-**दिवसीय पीएमपी के लिए सबसे अधिक भिन्नता प्रदर्शित हुई। कोंकण गोवा उप-विभाजन उच्च वर्षा और उच्च पीएमपी क्षेत्र का प्रतिनिधित्व करता है, इसलिए इस क्षेत्र में अधिक तैयारियों की आवश्यकता है।**

ABSTRACT. Probable Maximum Precipitation (PMP) is the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area. It can be thought of as a reasonable upper limit of the rainfall that could be anticipated in a given region.

PMP values have been estimated for 173 rainfall monitoring stations in Maharashtra, using 113 years long period daily rainfall data applying Modified Hershfield technique. Station data captures extreme behavior of rainfall in a better way as compared to gridded rainfall data sets as it represents normalized versions. The method is based on enveloped frequency factor analysis and on the assumption that long term rainfall records well capture information on extreme rainfall events in an area. The enveloping curves were generated for each of the four meteorological sub-divisions of Maharashtra, namely Konkan & Goa, Madhya Maharashtra, Marathwada, and Vidarbha.

In Maharashtra, 1-day PMP varies from 22.57 to 95.26 cm, 2-day PMP varies from 31.66 to 127.79 cm, and 3-day PMP ranges from 36.1 to 134.22 cm. The highest values of1-3 day observed rainfall and PMP were found to be located in the Konkan and Goa sub-division stations. Most variation was observed in the Konkan and Goa sub-division stations for 1-day PMP, whereas the Madhya Maharashtra sub-division exhibitedthe highest variation for 2-day and 3-day PMP. Konkan Goa sub-division represents high rainfall and high PMP region, so more preparedness needs to be realized in this region.

Key words – Precipitation, PMP, Hershfield, Frequency factor, Extreme.

1. Introduction

Precipitation constitutes the primary source of fresh water on earth. Butuneven and excess rainfall poses a danger,mainly when it occurs in areas with large population or regions which are topographically more vulnerable. India receives its significant share of precipitation in the summer and wintermonsoon seasons.Monsoon is a unique phenomenon in India due to its variable topography, intricate natural systems, and deep relationship with society and economy. The rainfall brings freshwater, maintains the water cycle, settles pollutants, serves monsoon-dependent agriculture, and gives hope to the nation's GDP. But uneven rain may pose a problem to the socio-economy. Extreme climate events are rising and are expected to increase in the coming years (IPCC, 2021).

As mentioned in AR6 by IPCC,climate change is affecting rainfall patterns. Precipitation may increase in high latitudes, while it is projected to decrease over large parts of the subtropics. Changes to monsoon precipitation are expected, which will vary by region. So regional studies play an essential role in understanding the local impacts of changing climate. IPCC AR6 also mentions about the intensification of the water cycle, indicating more intense rainfall with associated flooding and more intense drought in many regions (IPCC, 2021). A high amount of rainfall in a short time span may give rise to disastrous flood events, which are predicted to be increasing due to an increase in climate variability (Wetherald, 2002). The estimation of the highest rainfall that can occur in a region will be beneficial for assessing the vulnerability tothe population and infrastructure.

1.1. *Probable Maximum Precipitation (PMP)*

The greatest of extreme rainfall for a given duration that is physically possible over a station or a basin is defined as the Probable maximum precipitation (PMP) (Subramanya, 2014). It can be thought of as a reasonable upper limit of the rainfall that could be anticipated in a given region. World Meteorological Organization (WMO) defines PMP as the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends (WMO-No. 1045, 2009).

Before 1956, the terms "maximum possible precipitation (MPP)" and "maximum possible flood (MPF)" were used to denote PMP. Afterward, the terminology was changed to probable maximum precipitation (PMP) and probable maximum flood (PMF) to recognize the highest possible rainfall and highest possible flood along with associated uncertainties in the estimates (FEMA, 2012). Conversion of PMP to PMF comes with more uncertainties due to non-consideration of unknowns and unmeasured atmospheric and topographical parameters, which also contribute to overall runoff(ASCE, 1988; Tomlinson & Kappel, 2009).

1.2. *Importance of calculating PMP*

PMP values are important for design flood or Probable Maximum Flood (PMF) estimates while designing dams and other hydrological structures. PMF is defined as the flooding due to the most severe storm theoretically possible in the region by the manual of Dam Safety in India (D. Damle, 2021; CAG Report, 2013).

Engineers and hydrologists derivePMF using PMP in a catchment to assess the risk of dam overtopping. Design flood or PMF constitutes a major factor while constructing structures across the rivers (dam, weir, barrage, culvert, etc.) as it needs to be designed to withstand maximum flood occurring in that region to prevent potential hazards to downstream areas.Design flood or Probable Maximum Floods (PMF) is important for water resource structure designs especially spillways. If a spillway is unable to release PMF, dam wall breaching can happen which may cause loss of lives and property (WMO, 1969). PMF constitutes a standard variable for the safety design of dams in many parts of the world (Vivekanandan, 2015).

PMP can be used in the assessment of risk and vulnerability in a region. Integrating PMP with demography, topography and climate data has the potential to contribute in assessing the risk and vulnerability of the population. In the current scenario of changing climate, increasing disasters, and more vulnerability of the population, the requirement for the estimation of PMP and vulnerability is of high priority.

1.3. *Approaches for the calculation of PMP*

WMO, in its manual on the Estimation of PMP (WMO-No. 1045, 2009) suggests two approaches for the estimation of PMP - physical, also known as meteorological and statistical. The physical approach is the one that takes into consideration the physiography of terrain, catchment characteristics, and the capacity with which the atmosphere holds moisture during the movement of the particular weather system. The process involves working out the Depth-Duration method, Depth-Area-Duration method and storm transposition technique. PMP is calculated after inducing the Moisture Maximization Factor into observed extreme rainfall events.

The second approach is the statistical approach which has based on the general frequency formula. This method is very useful when there is a large amount of rainfall data, and moisture maximization factors are not accessible. The method involves statistical analysis of large rainfall records using the Hershfield technique, which is based on obtaining PMP using extreme rainfall events while considering their mean, standard deviation and then enveloping the inverse relationship between frequency factor and mean of annual maximum rainfall events.

2. Literature review

There are several methods available for the estimation of PMP. There is flexibility in using these methods based on the data availability (WMO-No. 1045, 2009). Various suggested approaches for estimating PMP are the local method which focuses on the maximum storm; the transposition method, which considers nearby extraordinary storm; the combination method with a theme of spatial & temporal maximization; the inferential method with the basics of generation of a simplified physical storm equation; the generalized method by grouping the observed rainfall convergence and orographic rainfall; and the Statistical method which was proposed by Hershfield and is based on hydrological frequency analysis.

Different researchers have used different approaches. D. Koutsoyiannis mentioned Hershfield's method as a widespread and reliable tool for hydrologic design, which has a purely probabilistic basis and does not provide any evidence of the existence of PMP as the upper physical limit of precipitation amount (Koutsoyiannis, 1999). Fernando and Wickramasuriya compared hydro-meteorological and statistical approaches in calculating PMP in Sri Lanka. After considering the ease of analysis and comparable results, the study emphasized the use of the statistical method as efficient and appropriate for estimating PMP in design office practice and for developing PMP maps for Sri Lanka (Fernando & Wickramasuriya, 2007). Walega and Michalec used Hershfield's statistical method for Calculated PMP (Walega & Michalec, 2014). Indian Institute of Tropical Meteorology (IITM) used both statistical and physical approachesfor the calculation of PMP in the Krishna basinand generated an atlas (IITM, 2005).

Several researchers have used Hershfield's statistical method for the estimation of PMP (Dhar & Kamte, 1969; Rakhecha *et al*., 1992). Daba calculated PMP in an Ethiopian sub-basin(N.N. Daba, 2022); Vivekanandan used the same approach to estimate PMP for Devarapalle and Visakhapatnam (Vivekanandan, Estimation of Probable Maximum Precipitation Using Statistical Methods, 2015); Chavana used both Moisture maximization method and the Hershfield method for the calculation of PMP in Mahanadi River basin. The results indicated higher estimates for PMP in the case of the Hershfield approach as compared to the moisture maximization method (Chavana, 2015). Sammen *et al.* calculated 1-day and 3-day PMP for Temengor catchment stations in Perak state, Malaysia. The author mentions that though the Statistical approach is the second most common technique in Malaysia, but it is very powerful when meteorological data, other than an abundance of rainfall data, are unavailable, such as wind speed and dew point temperatures (Sammen, 2018). In order to reduce the uncertainty in PMP estimations, a basin specific-enveloping curve is suggested (Singh *et al*., 2018). Casas *et al*. used statistical approach in Catalonia for PMP estimation and mentioned it as simple, reliable and based on actual precipitation records (M.C. Casas, 2008). The frequency analysis method has been widely used in most parts of Europe due to its storm homogeneity (Hydrometeorological Advisory Service, 2003).

2.1. *Modified Hershfield Method*

The statistical method used for estimating extreme rainfall (PMP) at a station or over an area is based upon the assumption that information regarding extreme rainfall is contained in the long rainfall records of that station. The Hershfield statistical method was used to estimate 1, 2, and 3-day PMP values for stations with daily rainfall data for an extended time. The method is based on a general frequency formula for analyzing hydrological data (IITM, 2005; Pant *et al*., 2007; Dhar & Kamte, 1969). The method is considered a compelling, popular, and efficient statistical instrument for estimating probable maximum precipitation (Maity, 2020). Yu Zhang also mentions about the reliability of the Hershfield statistical method, its capability for the analysis of large data sets, less restricted assumptions, improvement in methodology, and recognition by WMO (Zhang, 2021).

The Hershfield statistical formula for estimating point PMP for a station is as follows:

$$X_{PMP} = \overline{X}_n + S_n . K_m \tag{1}$$

where,

X_{PMP} = PMP estimate for a station,

$\overline{X}_n$ = mean of the annual maximum series,

S_n = standard deviation of the annual maximum series, and

K_m = frequency factor, which depends upon the availability of data period and the return period

According to Hershfield (1961), the value of the frequency factor 'K_m' is obtained by using the following equation:

$$X_m = \left(X_{max} - \overline{X}_{n-1}\right) / S_{n-1} \quad (2)$$

where,

X_{max} = largest value of the annual maximum series

S_{n-1} = Standard deviation of the annual maximum series omitting the largest value from the series

Hershfield worked out with K_m values and found that K_m varies inversely with the mean of the annual maximum rainfall series $\left(i.e., \overline{X}_n\right)$ and used the envelope K_m curve technique for obtaining K_m values for different values of $\left(\overline{X}_n\right)$. He prepared the envelope Km curve for obtaining K_m values for different values of $\left(\overline{X}_n\right)$. In this modified approach K_m value does not depend on the single highest value of K_m in a region, but each station has its own K_m value depending upon its magnitude of $\left(\overline{X}_n\right)$.

3. Study area and data

The research was carried out to estimate the probable maximum precipitation (PMP) of all rainfall monitoring stations of Indian Meteorological Department (IMD) in Maharashtra. Point PMP was estimated and spatially analyzed in the form of information maps. Observed historical point values of rainfall were used for the estimation.

Maharashtra is a state in western peninsular India, occupying the western & central part of India between 15.45 to 22.0 North latitude (degrees) and 72.45 to 80.45 East longitude (degrees) (Fig. 1). The western coastal side is bounded by the Arabian Sea, the Indian states of Karnataka and Goa to the south, Madhya Pradesh lies in the north, Gujarat in the northwest, Chhattisgarh in the east, and Telangana in the southeast. The State has a geographical area of 3,07,713 sq km with a 720 km long coastline along the Arabian Sea.

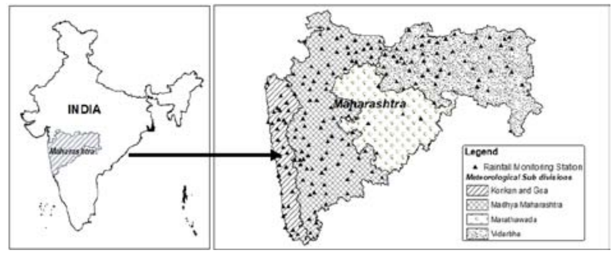


Fig. 1. Location of the Study Area and meteorological sub-divisions

Maharashtra falls under two physical divisions - The Deccan Plateau and the Coastal Plains & Islands. The two divisions are demarcated by the Sahyadri hill ranges, also known as the Western Ghats, which run from north to south in the State and form an important climatic divide. The meteorological sub-divisions represent climatically homogeneous regions (Kulkarni *et al*., 2020; Kelkar & Sreejith, 2020) and are delineated by IMD throughout India. Considering the meteorological homogeneity, there are four meteorological sub-divisions in the State (Guhathakurta & Rajeevan, 2008). These are Konkan and Goa, Vidarbha, Madhya Maharashtra, and Marathwada. The meteorological sub-division Konkan & Goa is to the extreme west, elongated north-south along the west coast of India. Due to this topographical feature, the region receives very high rainfall during the monsoon season. The Vidarbha region is to the extreme east of the State. The mean monsoon or annual rainfall of this region is less than that of the Konkan & Goa sub-division but more than the other two sub-divisions. The other two subdivisions, Madhya Maharashtra and Marathwada have almost similar rainfall patterns, although Madhya Maharashtra has a slightly higher mean monsoon or annual rainfall. The rainfall patterns have high intraseasonal variability (Guhathakurta, 2013). Also, there is high spatial variability of rainfall over the districts of Maharashtra.

There are 173 rainfall monitoring stations by IMD in the State, having more than centurial daily data. The same data was used for calculating 1-day,2-day and 3-day PMP along with generation of maps.

4. Methodology

The modified Hershfield technique was used for the estimation of PMP. The calculations were performed on 113-year daily rainfall observation records of 173 rainfall monitoring stationsby IMD. Point observation data captures extreme data in a better way as compared to gridded datasets, which represent mainly normalized versions. So, point 1 day, 2-day and 3-day PMP was taken into consideration for the calculations.

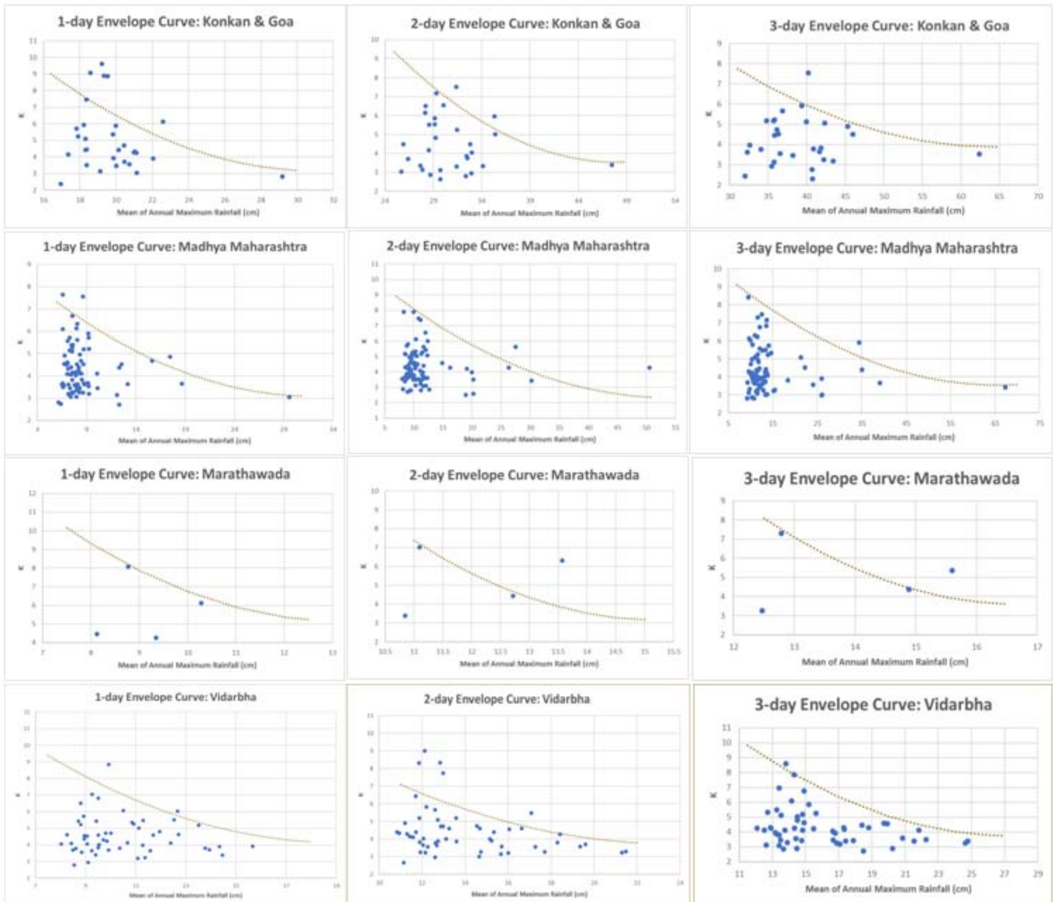


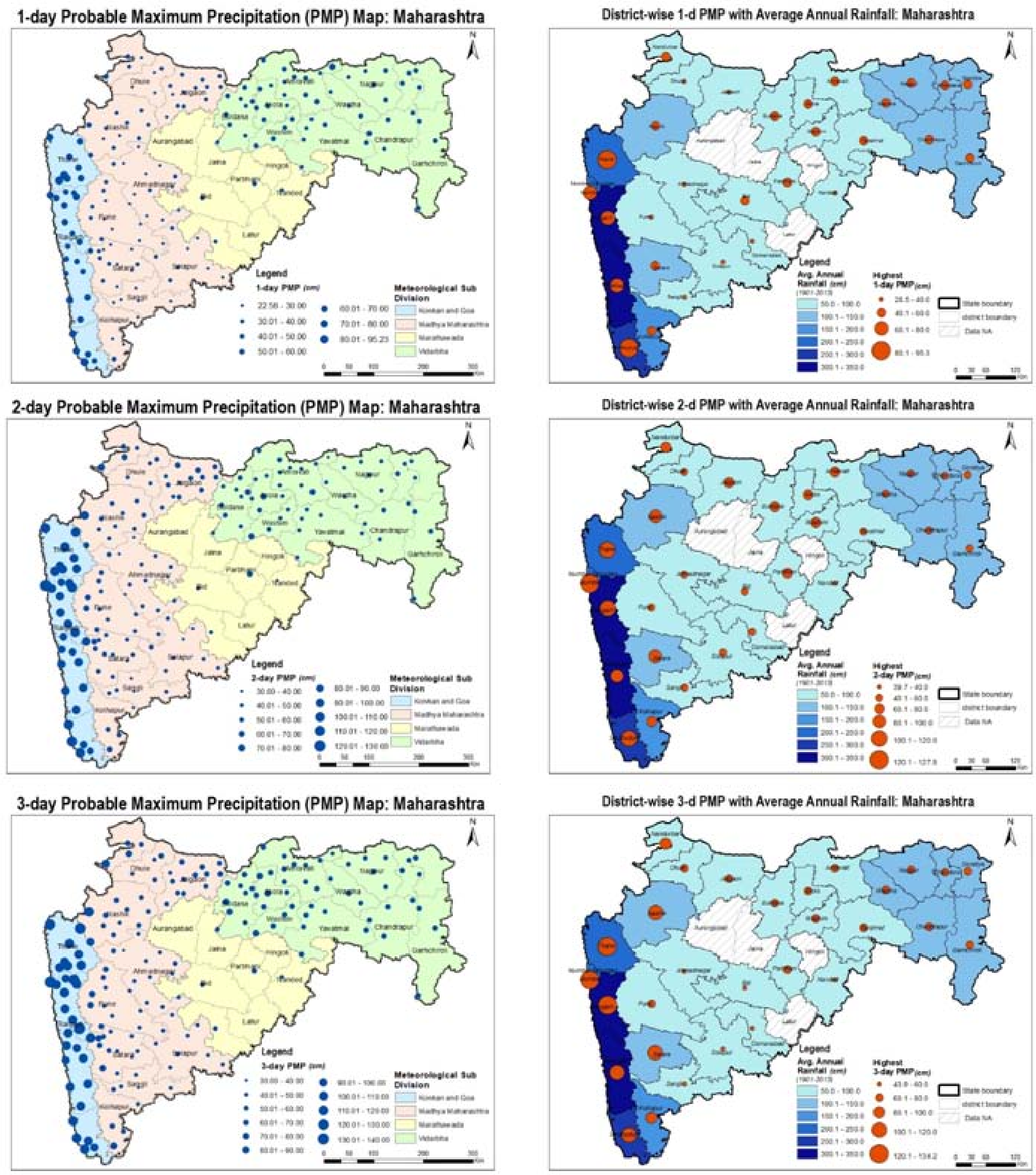
Fig. 2. Envelope Curves for frequency factor Analysis

The data was converted into a readable format, and the quality of daily data was checked using long-term mean, standard deviation, and checking of outliers for their historical existence. The daily data was then processed into 1-day, 2-day, and 3-day rainfall. Special care was taken for leap years while calculating 2-day and 3-day data. Station-wise highest annual 1-day, 2-day, and 3-day rainfall were extracted. The extreme rainfall with other statistical variables were used to generate the frequency factors. Spatial intersection with meteorological sub-divisions was used to locate the stations falling in meteorologically homogeneous regions. There were 30 stations in Konkan Goa, 85 in Madhya Maharashtra, 4 in Marathawada and 54 in Vidarbha. The fitting curve was established between the variables, and a new enveloped K was calculated using the polynomial fitted mathematical equation (Fig. 2). There were rainfall incidences that occur outside the envelope curve representing the outliers. The outliers in each sub-division were assumed to have achieved the highest rainfall and their calculated K was considered instead of the enveloped value of K. These values were then used with other statistical parameters for the calculation of 1-day, 2-day, 3-day PMP of each station.

The modified Hershfield technique has been used to estimate point PMP on the daily rainfall data(CWC, 2015). The frequency factor (K_m) envelope was determined for each meteorological subdivision of Maharashtra state for 1, 2, and 3-day durations separately. Using these K_m factors, PMP estimates of individual stations over different sub-catchments were computed by using Eqn. l. The obtained PMP was used to generate generalized PMP maps for 1,2, and 3-day duration.

5. Results

The PMP presented here is calculated using the modified Hershfield technique using enveloped frequency factor (K) obtained from envelope curves and mean maximum annual rainfall data extracted from 113-year daily rainfall data (1901-2013). The PMP was obtained for



Figs. 3(a&b). (a) Spatial Representation of 1-day, 2-day and 3-day PMP (b) District-wise highest 1-day, 2-day and 3-day PMP with average annual Rainfall

1-day, 2-day and 3-day rainfall observed at point locations of IMD rainfall monitoring stations. The calculated PMP is presented as 1-day, 2-day, and 3-day point PMP maps (Fig. 3).

5.1. *Distribution of PMP*

The 1-day PMP of Maharashtra ranges from 22.57 to 95.26 cm. The lowest 1-day PMP was found at Sangamner station at Ahmednagar district in Madhya Maharashtra region,whereas the highest 1-day PMP was found at Bhiwandi station in Thane district in Konkan & Goa region. The mean 1-day PMP of Maharashtra was found to be 40.89 cm. The 2-day PMP of Maharashtra ranges from 31.66 to 127.79 cm.The lowest 2-day PMP was found at Vaduj station at Satara district in Madhya Maharashtra region, whereas the highest 2-day PMP was found at Bombay Colab station at Mumbai city in Konkan & Goa region. The mean 2-day PMP of Maharashtra was calculated to be 56.22 cm. The 3-day PMP of Maharashtra ranges from 36.1 to 134.22 cm. The lowest 3-day PMP was found at Tasgaon, Sangliin Madhya Maharashtra region, whereas the highest 3-day PMP was found at Mahad, Raigad in Konkan & Goa region. The mean 3-day

Fig. 4. 1-day, 2-day and 3-day PMP with maximum 1-day, 2-day & 3-day rainfall in 113 years

TABLE 1

Meteorological Sub division wise range of PMP

S. No.	Met Sub-division	Range of PMP (cm)		
		1-day	2-day	3-day
1.	Konkan and Goa	52.64 to 95.26 ($\bar{x}$=66.69; σ=11.30)	78.52 to 127.79 ($\bar{x}$=96.39; σ=10.28)	93.04 to 134.22 ($\bar{x}$=110.45; σ=9.89)
2.	Madhya Maharashtra	22.57 to 50.71 ($\bar{x}$=31.09; σ=5.59)	31.66 to 96.23 ($\bar{x}$=47.12; σ=10.84)	36.1 to 119.7 ($\bar{x}$=56.37; σ=15.30)
3.	Marathawada	38.26 to 47.37 ($\bar{x}$=42.14; σ=3.50)	39.67 to 63.56 ($\bar{x}$=47.95; σ=9.21)	43.93 to 61.57 ($\bar{x}$=52.35; σ=6.39)
4.	Vidarbha	35.41 to 58.26 ($\bar{x}$=41.88; σ=4.10)	37.46 to 68.89 ($\bar{x}$=48.85; σ=6.84)	48.68 to 75.28 ($\bar{x}$=60.94; σ=5.40)

PMP for Maharashtra was found to be 67.08 cm.The meteorological sub-division-wise distribution of 1,2,3-day PMP is presented in Table 1.

Station wise occurrence of highest rainfall that has already occurred in comparison with the calculated values of PMP is presented in Fig. 4. The chart clearly indicates that the calculated PMP just envelopes the highest rainfall (1, 2 and 3-day) that has happened in the last 113 years. The estimated 1-day, 2-day, and 3-day PMP were found to be forming an envelope over the high estrealized actual rainfall. The bound indicates the probable highest achievable rainfall that can occur at a particular station.

5.2. *Spatial Interpretation*

For 1-day PMP,high values (81-100 cm) were observed at the coastal Maharashtra stations located in the Konkan Goa sub-division in the west of the Sahyadri hill ranges, also known as the Western Ghats. Low values (20-40 cm) are distributed evenly in the remaining State and were seen prominently in Madhya Maharashtra (Fig. 3). The distribution is expected as in Maharashtra, Konkan Goa sub-division receives high amount of rainfall due to its proximity to the sea coast and reach of monsoon winds.

For 2-day PMP,high values (81-130 cm) were observed at coastal Maharashtra stations located in the Konkan Goa sub-division in the west of the Sahyadri hill ranges. The lower range (30-40 cm) was mainly seen in Madhya Maharashtra, with sparse stations in Marathwada and Vidarbha. The middle range PMP (41-60 cm)was evenly distributed in the eastern Plateau of Maharashtra, covering the entire Maharashtra except forthe coastal Konkan area (Fig. 3).

For 3-day PMP, high range (81-140 cm) were associated with coastal Maharashtra stations located in the Konkan Goa region, on the western side of the Sahyadri hill ranges. The remaining Plateau, which is at the east of the Sahyadri hills, is covered mainly by the middle range of 3-day PMP from 41 to 80 cm. Both classes, 41 to 60 cm and 61 to 80 cm, were well distributed and almost entirely covering the non-coastal regions of Maharashtra (Fig. 3).

5.3. *District wise Interpretation*

District wise variation in PMP indicates that 1-day PMP varies from 28.52 cm at Sangli district to 95.26 cm at Thane district. The variation in 2-day PMP is from 39.67 cm at Nanded district to 127.79 cm at Mumbai city. 3-day PMP varies from 43.93 cm at Nanded district to 134.22 cm at Raigad district in Maharashtra. Spatial distribution across Maharashtra indicates high ranges of occurrence of PMP at Konkan coastal districts and low PMP will be expectation at the districts of Marathwada region, which is known for unprecedented water scarcity these days (Kulkarni etal., 2016).

District wise spatial variation in PMP with average annual rainfall is presented in Fig. 3. Highest PMP among all the stations within a district represents PMP of a district and average of cumulative annual rainfall from 1901 to 2013 of all stations within a district represents average annual rainfall. Spatial distribution of average annual rainfall among districts depicts that most of the districts in Maharashtra lies in 50 to 150 cm range. The districts lying in Konkan region has average annual rainfall variation from 200 to 250 cm for Thane, Mumbai and 250 to 350 cm for coastal districts of Ratnagiri and Raigarh. Comparing PMP spatially, it is observed that highest values of 1 day, 2-day and 3-day PMP are associated with coastal districts in Konkan region of Maharashtra. 1-day PMP ranges from 28.5 to 60 cm in Madhya Maharashtra, Marathwada and Vidarbha districts whereas for Konkan region these values range from 60 to 95.3 cm.For 2-day PMP, most of the districts in the Maharashtra except coastal region have lower ranges (39.7 to 80 cm) covering most of the state whereas coastal districts along with Nashik and Satara has higher ranges (80.1 to 127.8 cm). for 3-day PMP, the spatial distribution is similar to 2-day PMP, where lower ranges (43.9 to 100 cm) cover most of the districts in the state and coastal districts along with Nashik and Satara exhibit higher ranges (100.1 to 134.2 cm).

6. Conclusion

PMP in Maharashtra ranges from 22.57 to 95.26 cm for 1-day, 31.66 to 127.79 cm for 2-day, and 36.1 to 134.22 cm for 3-day. The highest values of PMP, as well as highest rainfall occurred, were found to be located in the Konkan Goa sub-division, which represents coastal Maharashtra lying on the western side of the Sahyadri hill ranges or the western Ghats. Mean, Standard deviation, and range indicate that most variation was observed in the Konkan and Goa sub-division stations for 1-day PMP, whereas Madhya Maharashtra sub-division exhibits the highest variation for 2-day and 3-day PMP. So, the Konkan Goa sub-divisionhaving the highest PMP, highest observed 1-day, 2-day, and 3-day extreme rainfall in 113 years, and the highest variation for 1-day PMP, more preparedness needs to be realized in this region. Among other regions, Vidarbha has high PMP with moderate variations, whereas Marathwada has intermediate PMP and variations, but we need more observation data to conclude for Marathwada. Lower ranges of PMP seem to be associated with the Madhya Maharashtra region, but it shows the highest variability for 2-day and 3-day PMP.

District-wise analysis indicates that higher PMP values (1-day, 2-day and 3-day) were associated with districts located in coastal regions of Maharashtra which also has higher ranges of average annual rainfallduring the time period considered in the study.

It is known that more flood events are expected to occur at places with high precipitation and high PMP. The regions with high PMP and high variability requires more preparedness. Further vulnerability to high rainfall is determined by the kind of land use, soil, vegetation cover and population. There is a need to overlay PMP with land use, soil, topography, and demography for the precise assessment of the vulnerability and planning for better mitigation and preparedness measures.

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