GENERALIZED PHYSICAL APPROACH OF ESTIMATING AREAL PROBABLE MAXIMUM PRECIPITATION (PMP) FOR PLAIN REGION OF THE GODAVARI RIVER BASIN (INDIA)

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ABSTRACT

In this paper a generalized physical approach of estimating areal probable maximum precipitation (PMP) for the non-orographic region of the Godavari river basin has been developed. In this method, highest average areal rain depths of different size areas and duration from the major rainstorms were considered, using 105 years rainfall data (1891-1995). The transposition limits of major rainstorms have been identified. The Depth-Area-Duration (DAD) rain depths were then moisture maximized at its original location of occurrence and then transposed at different grid points. After applying various corrections, Probable Maximum Precipitation (PMP) values at different grid points were estimated. By using this method, generalized PMP estimates at different locations were obtained and with the help of these estimated PMP values generalized charts for 1000, 5000 and 10,000 km$^2$ areas have been prepared. These PMP maps for different size areas and duration will be very useful for estimating design storm rain depths of PMP magnitudes for any sub-catchment in the Godavari basin whose areas area falling in range of 1000 to 10,000 km$^2$.

Keywords: Probable Maximum Precipitation (PMP), Depth-Area-Duration (DAD) analysis, Transposition, Moisture Maximization, Dew point Temperature, Rainstorm and Perceptible Water

1 INTRODUCTION

Among the peninsular river basins of India, the Godavari is the largest river basin in the northern half of the Indian peninsula. Total catchment area 3,12,812 km$^2$, which is about 10% of the total Indian area (Area of India is 32,92,054 km$^2$). The major tributaries of this river are: the Manjra from the southeast, the Penganga and the Wardha from the west, the Wainganga from the north and the Indravati and the Sabri from the east. Throughout the entire course of about 1465 km from west to east, the catchment area of the Godavari spreads over five adjoining peninsular states of which 48.6% lies in Maharashtra, 20.7% in Madhya Pradesh, 1.4% in Karnataka, 5.5% in Orissa and 23.8% in Andhara Pradesh. The Godavari River map is given in figure 1. In the present study, an attempt has been made to prepare generalized probable maximum precipitation (PMP) charts for various standard areas and duration at non-orographic and non-coastal regions of the Godavari river basin for 1, 2 and 3-day duration. The India has long period rainfall records for large number of stations. In the present study daily rainfall, data of 105-year (1891-1995) has been used for the estimation of PMP over the basin.

Techniques used in India to estimate PMP of non-orographic or plain area regions are:
(i) Statistical approach utilizing data of long period for raingauge stations and
(ii) Rainstorm analysis and their transposition over the basin, coupled with moisture maximization.

Estimates of PMP by statistical method are made may be used where sufficient rainfall data are available and are particularly useful for making quick estimates for basins having size less than 1000 km² (WMO, 1986). A major shortcoming in this method is that it yields only point values of PMP and thus requires area reduction curves for adjusting the point values to various size areas.

Figure 1. Basin plan of Godavari River

PMP estimates derived by using physical or synoptic method involve limited transposition and moisture maximization of major-recorded rainstorms in and around the catchment. The degree of accuracy depends on how many storms are available for analysis and how extreme the storms have been. As such, PMP estimates derived by physical method proved to be adequate but lacks confidence if only a short period of storm records is available and an extreme storm with near maximum efficiency has not been occurred near the region under consideration. This aspect has led to the development of a generalized method in which maximum recorded rainfall depths of rainstorms over a for a large area and adjustment for moisture source are made in applying the maximum recorded rain depths to a particular catchment.

In the absence of adequate severe rainstorm, data United States Weather Bureau (1970) applied the generalized method to estimate probable maximum precipitation (PMP) over the Mekong river basin in Southeast Asia. Schwarz (1972) advocated the use of above method with U.S. data to estimate probable maximum precipitation over areas affected by tropical cyclones. WMO (1986) also have recommended to use this approach. This generalized method has been
applied with modifications to catchments in Australia by using Australian database as described by Kennedy (1982). This method has been applied to the Indian region where tropical cyclones and monsoon depressions are the cause of major floods (Rakhecha and Kennedy, 1985). In this paper, as such the generalized physical approach has been used for estimation of PMP over the Godavari basin. Procedures followed have been described in details in the subsequent sections of the paper.

2. THE GENERALIZED METHOD OF ESTIMATING PROBABLE MAXIMUM PRECIPITATION

The first requirement of any method of estimating PMP is to build up an adequate database using rainfall depths recorded in severe rainstorms. The location and dates of these rainstorms are usually available in published form. Also it is required to update this information by using latest rainfall data in and around the problem basin.

Notable rainstorms are generally outlier, because they are few in numbers even in physically large regions. There is possibility of occurrence of such heavy rainstorms over any part of a meteorological homogeneous region. By considering local topographical features, it is necessary to delineate separate regions within which the major local storms could be transposed. The effect of topography is more prominent in the areal distribution of rainfall in average rainstorms as compared to the more severe rainstorms. In these cases, the topography has no effect on underlying isohyetal patterns. In the succeeding section of this paper, stepwise procedures for developing the generalized PMP have been described.

2.1 ESSENTIAL STEPS FOR DEVELOPING THE GENERALIZED PMP

Procedural steps for the preparation of generalized PMP maps for a plain-area using moisture maximization and storm transposition techniques used in this study are given below:

1. At the place of occurrence of a severe rainstorm, its DAD analysis is carried out first and rainstorm depths for different duration (i.e. 1-day, 2-day & 3-day etc.) and areas 100, 500, 1000 etc. km$^2$ are obtained.
2. Determine areas of transposibility limit of major observed rainstorm in and around the region.
3. Construct an adequate grid systems or out line transposition limits for all rainstorms on suitable base map or maps.
4. The rain depths obtained by DAD analysis are then maximized for maximum moisture charge at their original location of the rainstorms.
5. All the severe most rainstorms are then transposed to different grid points with following adjustments, (i) Change in location i.e. transposition factor for new location, (ii) Topography adjustments, and (iii) Barrier correction.
6. The envelope rain depths values which are obtained after various adjustments for different standard areas i.e. 100, 500, 1000 etc km$^2$ and for different duration (i.e. 1-day, 2-day & 3-day etc) are plotted on different grid points. These basic data are used for construction of PMP isohyetal maps.

The detail explanation for each step mentioned above are given in following sections.
3 EXPLANATION OF ESSENTIAL STEPS FOR DEVELOPING THE GENERALIZED PMP

The detail discussions of procedural steps given in section 2.1 are as follows:

3.1 ANALYSIS OF SEVERE RAINSTORMS

First step in the generalized method is the determination of major rainstorms that have occurred over large area under study. Examination of daily rainfall data from 1891 to 1995 for raingauge stations in and around the Godavari basin showed that in the past 22 severe rainstorms were experienced by the basin. Figure 2 shows the location of heavy rain centers of these rainstorms, sub-catchments. The sub-catchment numbers (Figure 2) are given according to Khosla (1949) classification. The quantitative analysis of all rainstorms was made by Depth-Area-Duration (DAD) method using standard technique given in the WMO manual of Depth-Area-Duration analysis (1969). The DAD analysis has been carried out for 1, 2 and 3-day duration. However to keep the paper concise DAD data for 1-day duration only are given in Table 1. All the rainstorms were found to occur in the monsoon months of June to September. From figure 2, it is seen that the centers of all the rainstorms have their preferred location.

Table 1: - DAD raindepths (Cm) for 1-day duration of severe rainstorms over odavari Basin.

<table>
<thead>
<tr>
<th>Sr No.</th>
<th>Rainspell Storm Centre</th>
<th>Area in hundreds of Squ. kms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Point</td>
</tr>
<tr>
<td>1</td>
<td>20.7.1894 Telhara</td>
<td>34.8</td>
</tr>
<tr>
<td>2</td>
<td>26.6.1908 Sakoli</td>
<td>38.0</td>
</tr>
<tr>
<td>3</td>
<td>27.9.1908 Sangareddy</td>
<td>30.7</td>
</tr>
<tr>
<td>4</td>
<td>4.8.1912 Armori</td>
<td>27.7</td>
</tr>
<tr>
<td>5</td>
<td>2.8.1913 Pachmarhi</td>
<td>48.3</td>
</tr>
<tr>
<td>6</td>
<td>27.6.1914 Parbhani</td>
<td>40.1</td>
</tr>
<tr>
<td>7</td>
<td>17.6.1927 Arvi</td>
<td>29.1</td>
</tr>
<tr>
<td>8</td>
<td>2.7.1933 Wani</td>
<td>36.0</td>
</tr>
<tr>
<td>9</td>
<td>16.6.1936 Ummer</td>
<td>20.0</td>
</tr>
<tr>
<td>10</td>
<td>16.7.1938 Saleteka</td>
<td>35.1</td>
</tr>
<tr>
<td>11</td>
<td>12.7.1942 Tamia</td>
<td>39.4</td>
</tr>
<tr>
<td>12</td>
<td>31.8.1947 Bodkasa</td>
<td>37.6</td>
</tr>
<tr>
<td>13</td>
<td>14.8.1951 Kanker</td>
<td>29.0</td>
</tr>
<tr>
<td>14</td>
<td>3.8.1953 Brahmapuri</td>
<td>30.5</td>
</tr>
<tr>
<td>15</td>
<td>14.8.1953 Ahiri</td>
<td>32.0</td>
</tr>
<tr>
<td>16</td>
<td>15.7.1965 Nizamsagar</td>
<td>50.6</td>
</tr>
<tr>
<td>17</td>
<td>23.7.1965 Bhopalpatnam</td>
<td>14.4</td>
</tr>
<tr>
<td>18</td>
<td>13.8.1986 Rajura</td>
<td>31.0</td>
</tr>
<tr>
<td>19</td>
<td>24.7.1989 Bhir</td>
<td>34.6</td>
</tr>
<tr>
<td>20</td>
<td>22.8.1990 Mul</td>
<td>31.0</td>
</tr>
<tr>
<td>21</td>
<td>2.9.1992 Kej</td>
<td>28.5</td>
</tr>
<tr>
<td>22</td>
<td>12.7.1994 Chandur Rly</td>
<td>46.8</td>
</tr>
</tbody>
</table>

Envelope Raindepths → 50.6 47.5 45.0 43.5 41.6 37.0 32.0 26.0 22.5 20.0 18.2 16.5 15.0 13.7 12.7 11.3
3.2 RAINSTORM TRANSPOSITION ZONES

After plotting rain centers of all selected rainstorms on large-scale maps of the basin, it was found that there were three zones in the basin where heavy concentration of these raingauge stations occurred (Figure 3). In delineating rainstorm zones of severe rainstorms, due care has been taken to the topography of the study region. Also, in India at present there is a general practice to make rainstorm transposition within $2^\circ$ to $3^\circ$ Lat/Long belts only. Therefore rain centers of each of these rainstorm have not been moved beyond $2^\circ$ to $3^\circ$ Lat./Long. It can be seen from figure 3 that rainstorms have occurred over preferred zones. Nandargi (1995) had also shown that there are preferred rainstorm zones over the Indian region. The rainstorm zones are shown in figure 3 and designated as A, B and C. The bulk of severe rainstorm activity has taken place within these preferred zones and few severe rainstorms have occurred outside these zones. It is, therefore, felt that in a zone, rainstorms can be freely transposed from one part to another. Table 2 gives details about area, number of raingauge stations etc. over each of these rainstorm zones.

Table 2: - Details about transposition zones of severe rainstorm over the Godavari basin.

<table>
<thead>
<tr>
<th>Non Transposition Zones</th>
<th>Transposition Zones</th>
<th>Zone</th>
<th>Area (km²)</th>
<th>Area (km²)</th>
<th>No. of heavy rain centres enclosed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orographic Western Ghat</td>
<td></td>
<td>A</td>
<td>1,01,194</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Coastal Area</td>
<td></td>
<td>B</td>
<td>80,327</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>89,923</td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>
Figure 3. Distribution of severe rainstorm centres in different rainstorm zones in the Godavari Basin

Zone A and Zone B are the main areas, which enclose the maximum number of raingauge stations. In Zone A, there are 15 raingauge stations, while in Zone B there are 7 raingauge stations. Zone C contains only 4 raingauge stations. It can be seen from the figure 3 that Zone A contains the Wainganga and the Wardha catchments (Catchment No. 315 and 314). Zone B contains area of the Upper Godavari excluding orographic area and the Manjra catchment. It also includes some part of the Middle Godavari (catchment No. 313). Zone C contains the Middle Godavari east of 79°E (Catchment No. 313). It also contains catchment No. 316 i.e. the Indravati catchment and catchment No. 317, the River Sabri.

In hilly and mountainous areas transposition of rainstorms is not applicable because orography plays a vital role in the distribution of rainfall over these areas. As such, regions where orography plays an important part, like the Western Ghat region i.e. West of 75°E, are not considered in the present study.

Dhar et al. (1990) while analysing rainstorms of coastal area of India have stated that there are no major dams located in the coastal area and as such coastal rainstorms pose no risk to their safety. It is also suggested by India Meteorological Department (IMD, 1972) that rainstorms which are occurring inland are not advisable to transpose over the coastal area and visa versa. As such coastal part of the basin is also not considered for this study.
3.3 CONSTRUCTION OF GRID SYSTEM

The generalised method considered the liberal transposition of rainstorms and therefore the most important element in rainstorm transposition is the area where particular storm can be transposed. Setting of transposition limits involves a detailed study of the storms to determine the meteorological reasons for heavy rainfall.

The rainstorms that occurred over the basin have been found to cause due to tropical disturbances such as monsoon depressions and cyclonic storms from the Bay of Bengal.

In this study grid point transposition is preferred. Transposition to grid points has the advantage of allowing ready comparisons between rain depths from different rainstorms.

On a large-scale base map of the Godavari basin, a suitable grid system of 1° latitude, by 1° longitude has been constructed. According to WMO (1986), the fineness or coarseness of the grid system depends on the topography. The points found by the inter-section of grid lines indicate the locations to which maximised storms were transposed and maximum values were plotted.

Transposition of rainstorms DAD values means relocation of rainstorm rainfall (i.e. DAD values) within a homogeneous region. Transposition increases the available data for evaluating the rainfall potential of a basin.

3.4 MOISTURE MAXIMISATION OF RAINSTORM

Before rainstorms are actually transposed to grid points in different zones of the basin each severe most rainstorm is maximised for maximum moisture charge at its original place of occurrence. According IMD (1972), for adjustment of moisture maximisation at the original occurrence of rainstorm, the DAD rain depths are multiplied by moisture maximisation factor (MAF). The MAF is the ratio of maximum moisture available for the month in which a storm has occurred (by considering long period maximum persisting dew point data) to the maximum moisture during the storm period.

The dew point temperature data for 13 meteorological stations for the 30-year period (1961 to 1990) recorded at 0830 and 1730 hrs. IST (Indian Standard Time) was considered for the preparation of a generalised map of maximum persisting dew point temperature for the Godavari basin (Figure 4).

Moisture maximization factors (MAFs) were worked out for all the rainstorms in the different transposition zones and the same are given in Table 3. Before transposing rainstorms to different grid points the DAD values (Table 1) were multiplied by respective MAF factors to obtain moisture-maximised rain depths. Figure 5 shows envelope moisture maximised DAD rain depths for different zones.
## Table 3(a): - Maximization Factor for Zone A

<table>
<thead>
<tr>
<th>Sr.No.</th>
<th>Rainstorm Date</th>
<th>Location</th>
<th>Max. Per. D.P. at the location of storm (1000hpa) (°C)</th>
<th>Max. Precipitable water (mm) corresponding to Max. D.P. at location of storm (1000hpa)</th>
<th>Max. Per. D.P. at location of storm during storm month (1000hpa) (°C)</th>
<th>Max. Precipitable water (mm) during month in which storm occurred (1000hpa)</th>
<th>Maximization Factor MAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25-27 June 1908</td>
<td>Sakoli</td>
<td>22.5</td>
<td>64.9</td>
<td>26.5</td>
<td>91.9</td>
<td>1.42</td>
</tr>
<tr>
<td>2</td>
<td>3-5 Aug. 1912</td>
<td>Brahmapuri</td>
<td>22.9</td>
<td>67.3</td>
<td>27.0</td>
<td>95.9</td>
<td>1.42</td>
</tr>
<tr>
<td>3</td>
<td>1-3 Aug. 1913</td>
<td>Pachmarhi</td>
<td>24.0</td>
<td>74.0</td>
<td>26.5</td>
<td>91.9</td>
<td>1.24</td>
</tr>
<tr>
<td>4</td>
<td>17-19 June 1927</td>
<td>Arvi</td>
<td>23.6</td>
<td>71.6</td>
<td>26.0</td>
<td>88.0</td>
<td>1.23</td>
</tr>
<tr>
<td>5</td>
<td>1-3 July 1930</td>
<td>Wani</td>
<td>22.8</td>
<td>66.7</td>
<td>26.5</td>
<td>91.9</td>
<td>1.38</td>
</tr>
<tr>
<td>6</td>
<td>11-13 July 1942</td>
<td>Tamia</td>
<td>24.0</td>
<td>74.3</td>
<td>27.0</td>
<td>95.9</td>
<td>1.29</td>
</tr>
<tr>
<td>7</td>
<td>3-5 Aug. 1953</td>
<td>Brahmapuri</td>
<td>24.1</td>
<td>74.7</td>
<td>27.0</td>
<td>95.9</td>
<td>1.28</td>
</tr>
<tr>
<td>8</td>
<td>13-15 Aug. 1953</td>
<td>Ahri</td>
<td>24.1</td>
<td>74.7</td>
<td>26.5</td>
<td>91.9</td>
<td>1.23</td>
</tr>
<tr>
<td>9</td>
<td>12-14 Aug. 1986</td>
<td>Rajura</td>
<td>23.8</td>
<td>71.9</td>
<td>26.5</td>
<td>91.9</td>
<td>1.28</td>
</tr>
<tr>
<td>10</td>
<td>11-12 July 1994</td>
<td>Chandur Rly/Pauni</td>
<td>24.3</td>
<td>76.2</td>
<td>26.5</td>
<td>91.9</td>
<td>1.21</td>
</tr>
</tbody>
</table>

Max. Per. D. P. = Maximum Persisting Dew Point temperature (°C)

![Figure 4. Maximum precipitating 24 hr. 1000hPa dew point temperature (°C)](image-url)
Figure 5. Envelope moisture maximized depth-area-duration curves different rainstorm zones.
3.5 CALCULATION OF ADJUSTMENT FACTORS

Different adjustment factors used in this study are given in the succeeding sections:

3.5.1 TRANSPOSITION FACTOR AT NEW LOCATION

Having adjusted the storm at its original location of occurrence, the storms were then transposed to the different grid points. At its transposed location, it is again adjusted for change in moisture at new location. The transposition adjustment factor for change in location is the ratio of maximum moisture content at the transposed location of the storm to the maximum moisture content at the original location of the storm. This factor may be greater or less than unity depending upon whether the transposition is carried out towards or away from moisture source.

3.5.2 TOPOGRAPHY ADJUSTMENT

Adjustment for the effect of topography has been used as given by the United States Weather Bureau (1970) and recommended by the WMO (1986). Average percentage changes in rainfall that can be applied to whole area is selected from the following categories:

(i) No variation in rainfall for elevation less than 300 m.
(ii) Increasing the rainfall by 10% per 300 m of ascent
(iii) Decreasing the rainfall by 5% per 300 m of descent to the bottom of valley.

3.5.3 BARRIER ADJUSTMENT

An adjustment factor is required when there is a barrier or mountain range in the path of moist air being fed into the storm area as the mountain range blocks off a certain fraction of the moist inflow into the storm area. The usual method (WMO 1969) of estimation of the effect of a barrier is to reduce PMP (P) values by the ratio of the perceptible water in a column of air above the height of the barrier to perceptible water extending to ground level in the windward side of the barrier, i.e.

\[
P_1 = P \times \frac{W_2}{W_1}
\]

where,
- \( P_1 \) = Adjusted rainfall behind a barrier
- \( P \) = Rainfall value not behind a barrier
- \( W_1 \) = Perceptible water in a saturated pseudoadiabatic atmosphere from ground to some great height corresponding to maximum surface dew point at location of storm.
- \( W_2 \) = Perceptible water in a saturated pseudoadiabatic atmosphere from the top of barrier to same great height.

3.6 PREPARATION OF GENERALISED PMP MAP

In order to determine PMP at each grid the envelope moisture maximised rain depths for 1000, 5000, and 10,000 km\(^2\) were multiplied by transposition factor at respective grid points. This
operation was carried out for different standard areas of 1000, 5000 and 10,000 km² for different zones.

The PMP value at each grid point has been determined after applying various adjustment factors as stated above for 1000, 5000 and 10,000 km² for 1-day, 2-day and 3-day duration. The PMP estimates were then plotted at each grid point and smooth isolines were drawn so as to show the regional variation of areal PMP.

The PMP isohyetal maps thus obtained are then smoothened to remove any discontinuities in PMP estimates between adjacent areas and basins in the region. This process may sometimes result in undercutting or over-enveloping the data of a few grid points for maintaining PMP consistency in the region and giving a smooth PMP isohyetal pattern for the region.

In drawing smooth PMP isohyetal maps, meteorological and geographical factors such as moisture source, storm tracks, orographic barrier etc. have constantly to be kept in view. In the case of some orographic features, such as hills or mountain barriers in the region, PMP isohyetes are drawn taking into their effect on the distribution of storm rainfall. Figure 6(a), Figure 6(b) and figure 6(c) are showing generalised PMP patterns of 1-day duration.

Figure 6(a). Generalised chart of 1-Day probable maximum precipitation (cm) for 1000 km² over Godavari Basin.
Figure 6(a). Generalised chart of 1-Day probable maximum precipitation (cm) for 5000 km² over Godavari Basin.
Figure 6(a). Generalised chart of 1-Day probable maximum precipitation (cm) for 10,000 km² over Godavari Basin.

The PMP estimates for 1-day, 2-day and 3-day duration that can possibly occur over the areas 1000, 5000 and 10,000 km² in the Godavari basin have been given in Table 4. The highest values of PMP occurred in the Wainganga sub-basin i.e. Catchment No. 315 and coastal basin i.e. Catchment NO. 316 and 317 i.e. River Indravati and River Sabri catchments. The magnitudes of PMP are progressively decreasing inland. The lowest values of PMP occurred in the Manjira catchment i.e. Catchment No. 312.

Table 4: - Variation of areal PMP (cm) for 1-Day, 2-Day and 3-Day duration for 1000, 5000 and 10,000 km²

<table>
<thead>
<tr>
<th>Catchment No.</th>
<th>1-Day</th>
<th>2-Day</th>
<th>3-Day</th>
<th>Area in km²</th>
<th>1-Day</th>
<th>2-Day</th>
<th>3-Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>311</td>
<td>48-50</td>
<td>35-40</td>
<td>30-35</td>
<td>68-70</td>
<td>60-65</td>
<td>55-60</td>
<td>75-80</td>
</tr>
<tr>
<td>312</td>
<td>45-50</td>
<td>35-35</td>
<td>25-30</td>
<td>65-68</td>
<td>60-65</td>
<td>55-55</td>
<td>70-75</td>
</tr>
<tr>
<td>313</td>
<td>45-50</td>
<td>35-40</td>
<td>30-35</td>
<td>80-90</td>
<td>65-80</td>
<td>60-70</td>
<td>80-100</td>
</tr>
<tr>
<td>314</td>
<td>50-55</td>
<td>40-45</td>
<td>35-40</td>
<td>75-80</td>
<td>65-68</td>
<td>60-65</td>
<td>85-90</td>
</tr>
</tbody>
</table>
4. APPLICATION OF THE GENERALISED METHOD TO ESTIMATE PMP FOR THE WAINGANGA RIVER CATCHMENT

The Wainganga catchment (Catchment No 315) is located between 78° 05' E to 80° 55' E and 19° 35' N to 22° 42 N (see Figure 1). A multipurpose dam is under construction across the river Wainganga at Dhapewada (Lat. 21° 21' 16” N and Long. 79° 48' 50” E). The total area of the Wainganga basin up to Dhapewada dam site is about 18,215 km² (7032 miles²). The catchment receives about 149 cm of rainfall annually. Most of this rainfall is associated with the storm system that developed over the Bay of Bengal and affected the basin during their Northwest movement. The generalized techniques developed in this paper can be applied to the sub-area of the Wainganga catchment for PMP estimation for all duration. The Wainganga is a sub-basin (Catchment No. 315) of the Godavari basin. It lies in the transposition Zone A of the Godavari basin. In applying the technique, the adjustment factors need to be applied to the moisture maximised DAD values. The essential steps need to be used while obtaining PMP for a particular area /sub-basins are as follows: -

1. Select the sub-basin /area, where the generalized PMP technique has to be applied.
2. See in which transposition zone that particular area lies.
3. Using the envelope moisture maximised DAD rain depths graphs (Figure 5), read moisture maximised DAD valued corresponding to the area of problem basin.
4. Apply transposition correction i.e. the ratio of maximum moisture content at the transposed location of the storm to the maximum moisture content at the original location of the storm.
5. Multiply moisture maximised DAD rain depths by transposition factor obtained from step 4.
6. If necessary apply topographic as well as barrier correction as recommended by WMO (1986).
7. PMP for the basin / area can be obtained as
   \[
   \text{PMP} = (\text{Moisture Maximised DAD rain depths for corresponding the basin size}) \times (\text{Transposition factor}) \times (\text{Topographic factor})
   \]

The moisture maximised DAD values obtained from enveloping curve (Figure 6) for 1, 2 and 3- day duration for about 18,215 km² area have been found 32.6 cm, 52.0 cm and 64.8 cm respectively.

The extreme dew point temperature for the catchment has been taken from the maximum persisting dew point temperature map (see Figure 4). The extreme dew point temperature for the catchment has been found to be 26.5° C. The average persisting dew point for 1000 hpa during the storm period is found to be 26.5° C. Therefore adjustment factor for moisture is considered as
1.0. The most critical direction of low level inflow, which would give the heaviest rains from consideration of synoptic influence and height of intervening barrier over the catchment, was considered to be north-westerly. For this direction no effective barrier height for the catchment is determined. As such, the adjustment factor for topography as well as for barrier is considered as 1.0. The PMP for Wainganga catchment up to Dhapewada dam site for 1, 2 and 3-days duration have been found to be of the order of 33 cm, 52 cm and 65 cm respectively. Dhar et al (1991) has reported PMP estimates 33 cm, 57 cm and 82 cm for 1, 2 and 3-day duration respectively by physical method of limited transposition and maximisation. The PMP estimates obtained by the generalised method are well comparable with values obtained by the physical method for 1-day and 2-day duration, and for 3-day duration, limited transposition method gives higher estimates.

5. DISCUSSION OF RESULTS

It has been the standard practice to equip large earth and rockfill dams with spillway capacities, which can pass the Probable Maximum Flood (PMF). In order to determine the most appropriate estimates of PMF one has to determine PMP. It is known that there are still gaps in our knowledge of the variables and their interaction, which led to heavy extreme rainfall rates that have been observed. Objective decisions must be made on determining PMP base on hydrometeorological analysis of extreme storm rainfall.

This study describes the generalised method of estimation of Probable Maximum Precipitation (PMP) in the non-orographic area of the Godavari basin. The spillway design floods for most of the dams in the basin were computed by using empirical formulae. The use of empirical formulae have now been abandoned for estimating spillway design flood for most of the important dams wherein loss of human life and large economic loss are expected if dams were to fail. Maps of PMP for different size areas will be very useful for estimating design storm of PMP magnitude for catchments having area in the range of 1000 and 10,000 km². The estimates of 1, 2 and 3 days PMP for the Wainganga river catchment up to Dhapewada dam site (18,215 km²) by the generalised method have been found to be roughly 33 cm, 52 cm and 65 cm respectively. The PMP estimates obtained by the generalised method are well comparable with values obtained by the physical method for 1-day and 2-day duration, however for 3-day duration; limited transposition method gives higher estimates. The main advantage of the generalised method is that it gives more satisfactory and consistent results than estimates made on project wise basis.

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