Probable Maximum Precipitation Estimation in a Humid Climate

Zahra Afzali Gorouh[1], Bahram Bakhtiari[1], Kourosh Qaderi[1]

[1]Department of Water Engineering, Collage of Agriculture, Shahid Bahonar University of Kerman, Kerman, Iran

Correspondence to: B. Bakhtiari (drbakhtiari@uk.ac.ir)

Abstract. Due to the importance of probable maximum precipitation (PMP) for designing and planning hydraulic structures, the aim of this study is the estimation of 24-hour PMP (PMP_{24}) by using the statistical and physical methods in a humid climate of Qareh-Su Basin which is located in the northern part of Iran. For the statistical estimate of PMP, the equations of empirical curves of Hershfield method were extracted. Then the standard and revised approaches of Hershfield method were written in JAVA programming language, as a user-friendly and multi-platform application called the PMP Calculator. Convergence model was considered to calculate PMP by using the physical method. The depth- area- duration (DAD) curves were extracted to estimate PMP_{24} by using the physical method and then PMP_{24} was estimated for each storm. The results showed that for the standard and revised approaches, frequency factor (K_m) was found to be varied the range of 17-18.0 and 2.2-5.3, respectively. The maximum values of PMP_{24} for the first approach was obtained 447.7 mm and for the second approach was 200.7 mm. Using the physical method, PMP_{24} was 143.1 mm. The results of this study will be helpful for planning, designing, and management of hydraulic structures and water resources projects in the study area.

1 Introduction

Probable maximum precipitation (PMP) was once known as maximum possible precipitation (MPP), and this abbreviation term is found in most reports on estimates of extreme precipitation made prior to about 1950. The main reason for the name change to PMP was that MPP carried a stronger implication of physical upper limit of precipitation than does PMP, which is preferred because of uncertainty surrounding any estimate of maximum precipitation (Wang, 1984). PMP is the greatest depth of precipitation for a certain duration under meteorological condition possible for a given size storm area at a specific time of year (WMO, 2009). Extreme rainfall, PMP and PMF (Probable Maximum Flood) are the main factors for designing hydraulic structures and disaster risk reduction. The main objective of designing spillways using the PMF is to avoid the overtopping of dams as a result of river flooding (Desa and Rakhecha, 2007). There are different models used for assessment of PMP, one of which to be selected based on the condition of the catchment area, limitations and accuracy of the data series, length of the record period, and other factors (Joos et al., 2005). So, the approaches of PMP calculation can be divided into three major categories: (a) Statistical methods are particularly useful for making quick estimates for small basins and include statistical analysis of extreme rainfalls from the precipitation measurement, which can be utilized wherever sufficient precipitation data are available, and are especially useful where other such meteorological data such as dewpoint and wind records are not available. These methods strongly depend on the length of data series and quality of recorded precipitation data. (b) The maximization and transposition of observed storm rainfall. The main disadvantages of this approach consist of defining the transposition limits and difficulty applying the effect of orography. (c) Storm model approach is a typical storm that indicates the specifications of extraordinary storms of the design watershed, which pose serious threats to flood control in the project (Rezacova et al., 2005). The statistical methods (a) are based on measured precipitation values, whereas the (b) and (c) are based on the meteorological analysis of the conditions responsible for the development of extreme precipitation (Rezacova et al., 2005; WMO, 2009). There are many efforts on calculating PMP using the physical and statistical methods, recently. For instance, Chavan and Srinivas (2015) estimated $PMP_{1\text{-day}}$ in Mahanadi river basin using a storm model and Hershfield approach. Their results showed that the Hershfield approach tends to give higher estimates for PMP as compared to the storm model approach. Sharma et al., (2015) calculated one-day PMP for design of different soil and water conservation structures in Agra, India. Lan et al., (2017) estimated PMP_{24} value about 1753 mm, by using the revised K_m-value method in Hong Kong based on the local rainfall data. Fikre et al., (2016) calculated one-day PMP by using the statistical method and developed the one-day PMP isohyetal maps for a region in Ethiopia. The corresponding frequency factor values varied from 2.24 to 5.09 and PMP varied from 51.43mm to 234.81mm. Ishida et al., (2015) used a physically based method called Relative Humidity to estimate the maximum precipitation over three watersheds in Northern California. Micovic et al., (2015) investigated the uncertainty analysis of PMP in La- joie basin, British Colombia. Bhim et al., (2014) calculated PMP_{24} in Jhalarapatan region of Rajasthan by using the Hershfield statistical method and Gumbel's theory of extreme values. They found PMP_{24} and the appropriate frequency factor 509.1 mm and 6.12, respectively. Hussain et al., (2014) estimated PMP for Linau river basin in Sarawak by using the statistical method. Due to having a long discontinuity in the data set, they used from one station dataset and estimated PMP_{24} about 691 mm. Soltani et al., (2014) applied the statistical and physical methods to estimate the PMP in Isfahan province, Iran. They found that the PMP point values estimated by the statistical method were greater than those estimated by the physical method. Yigzaw et al., (2013) investigated the impact of artificial reservoir size and land use/land cover patterns on PMP and PMF on the American River. Fattahi et al., (2010) compared a physical method with a statistical method to calculate PMP in the southwest arid areas of Iran and showed that the PMP values obtained by a statistical method are more than the physical method, for all the stations. There are many studies using a statistical method in various areas in Iran (Ghahraman, 2008; Naseri Moghaddam et al., 2009; Shirdeli, 2012). Casas et al., (2010) estimated PMP in Barcelona using Hershfield method and the physical method based on the maximization of actual storms from 5 minutes to 30 hours. Their results indicated that the PMP values obtained using the two methods were very similar. In both methods, the expected increasing behavior of the PMP with duration was found. Papalexiou and Koutsoyiannis (2006) investigated the maximum precipitation depths using the physical method in Netherlands. They concluded that probabilistic procedure for the calculation of extreme precipitation value is more stable. Rezacova et al., (2005) calculated PMP for 1-5 day duration at rain gauge positions and used maximized area reduction factors (ARFs) that defined from radar based rainfalls, converted point PMPs to areal PMPs. There are many studies over the wide area such as U.S. weather bureau (1961); Hansen (1986); and Miller (1963). Since investigation of one day PMP in each basin is necessary for the planning and designing of hydraulic structures, the aim of this study is the estimation of 24-hour PMP by using the statistical and physical methods in the study area as the area is prone to frequent floods. In order to calculate PMP by the statistical method, a user-friendly and multi-platform application is developed in JAVA, which is called PMP Calculator. This application calculates PMP for 5 minutes, 1, 6 and 24-hour durations. Also, this application can calculate frequency factor based on actual maximum occurred rainfall.

2 Materials and Methods

2.1 Study area and data

Qareh-Su basin is located in Golestan province in the northern parts of Iran with a humid climate. The Qareh-Su basin, with nearly 1760 km^2 area is one of the most important basins in the north of Iran. This area is important from the viewpoint of the existence of different cities and villages, population densities, industrial and agricultural centers, flood, and watershed management schemes. 8% of the surface water (equal to 100 million cubic meters) in Golestan province is derived from the Qareh-Su basin. There are two main dams including Kowsar and Shast kalateh to supply water demand of agricultural and residential land located in this area. Also, it is one of the most flood-prone areas that has suffered severe floods throughout its long history, so that in recent years, many people have died in destructive floods. Over the period 1951–2013, the annual average precipitation in this basin is 596 mm. Fig. 1 shows the location of stations and study area. Climatological data that are applied in calculating of PMP values in the physical method are 3-hour dewpoint temperature, 3-hour wind speed and direction at 10 m elevation, 3-hour and monthly air pressure, 3-hour and 24-hour precipitation, and . The required data such as air temperature and rainfall were taken from available climatological, Hydro-meteorological station and synoptic stations in the study area, but dewpoint temperature data was taken from an available synoptic station in the study area which is called Gorgan station. The records of six Hydro-meteorological stations and one synoptic station located in the Qareh-Su basin were taken into account in this study. The station names and geographical characteristics are given in Table 1. The analysis was carried out for the duration of 33 years ranging from 1981 to 2013. The data was obtained from Islamic Republic of Iran’s Meteorological Organization (IRIMO) and Iran Water Resources Management Company.

TABLE 1: Characteristics of different stations in study area.

Station	Longitude (E)	Latitude (N)	Altitude (m)	The average annual precipitation (mm)	Type
Ziarat	54° 30'	36° 42'	950	460	Hydro-meteorological station
Kord Kooy	54° 07'	36° 45'	140	606	Hydro-meteorological station
Edareh Gorgan	54° 25'	36° 51'	75	591	Hydro-meteorological station
Shast Kelateh	54° 20'	36° 44'	150	735	Hydro-meteorological station
Ghaz Mahalleh	54° 12'	36° 47'	6	604	Hydro-meteorological station
Siah Ab	54° 30'	36° 45'	-26	607	Hydro-meteorological station
Gorgan	54° 25'	36° 54'	13.3	569	Synoptic station

2.2 Statistical Hershfield's method

The procedure as developed by Hershfield is based on the general frequency equation (WMO, 2009; Chow, 1951). The equation of this method as follows:

$$X_{PMP} = \overline{X}_n + K_m . S_n \quad (1)$$

Where X_{PMP} is the PMP estimate for a certain station at the particular duration, $\overline{X}_n$ and S_n are the average and standard deviation of the annual extreme series for a given duration, respectively. K_m is frequency factor as a function of duration and average of annual maximum rainfall (the maximum depth of 24-hour precipitation in each year). In other words, K_m is then the number of standard deviations to be added to obtain PMP. In this approach, K_m is calculated by K_m charts which were extracted based on records of rainfall from around 2700 stations in the climatological observation of the United States of America (WMO, 2009). The standard approach of Hershfield method is modified by Desa et al., (2001) in Malaysia. In modified approach, K_m is calculated by the following Eq. (2):

$$K_m = \frac{X_{max} - \overline{X}_{n-m}}{S_{n-m}} \quad (2)$$

where X_{max} is maximum observed rainfall data, $\overline{X}_{n-m}$ and S_{n-m} are the average and standard deviation of the annual extreme series without the largest value, respectively. First, the parameters in Eq. (1) are estimated. Next, the K_m values for all the stations are mapped against the $\overline{X}_n$ values respectively and a smooth envelope curve is drawn. The $K_{envelope}$ value is picked up from the curve for each station's $\overline{X}_n$. The value of PMP for each station is then estimated using Eq. (1) by replacing K_m with $K_{envelope}$ value (Alias and Takara, 2013).

2.3 Physical Method

There are two synoptic models namely the mountainous and convergence models to calculate PMP (Joos et al., 2005). The convergence model is based on the physical characteristic of storm, i.e. dewpoint temperature, wind speed, wind direction and etc. The main steps to calculate PMP, using the convergence model are the selection of severe storms, producing the depth- area- duration (DAD) curves, moisture maximization, and wind maximization. A severe and widespread storm is a weather condition that leads to producing precipitation in all stations in the basin and even around the basin. The most severe and widespread storms are selected based on maximum discharge and maximum 24 hours rainfall data. Producing isohyets maps are one of the main steps in the preparation of DAD curves. Using an analysis of the storms, DAD curves can be obtained. DAD curves are also applied to generalized relations for other areas or other basins with similar climate and topographic characteristics. The first step to develop DAD curve is collecting the precipitation data for all areas in the storm.

The storm maximization factor is calculated by the moisture maximization factor multiplied by wind maximization factor. The moisture maximization method is one of the acceptable procedures to maximize the rainfall values associated with severe storms (Rakhecha and singh, 2009). This method assumes that the atmospheric moisture would hypothetically rise up to a high value that is regarded as the upper limit of moisture and the mentioned limit is estimated from historical records of dewpoint temperature. After selection of severe and widespread storms and calculation of average rainfall depth for the study area, it is necessary to calculate maximum humidity source in order to maximize selected storms. By converting mean monthly pressure data at each station to 1000 mb pressure level, the effect of topography could be ignored. Dewpoint temperature and maximum 12-hour persisting condition at the stations during all storm events were computed and reduced to equivalent mean sea level (MSL, i.e. 1000 mb pressure level). The moisture maximization factor (FM) is calculated by Eq. (3).

$$FM=\frac{W_m}{W_s} \tag{3}$$

where W_m is the maximum precipitable water in the 1000 to 200 mb levels, which can be obtained on the basis of the maximum 12-hour duration dewpoint with 50-year return period and W_s is the maximum precipitable water at 1000 to 200 mb levels which can be obtained on the basis of maximum 12-hour duration dewpoint in a simultaneous period with storm (WMO, 2009). Wind maximization is most commonly used in orographic regions when it appears that observed storm rainfall over a mountain range might vary in proportion to the speed of the moisture-bearing wind blowing against the range. The wind maximization ratio is simply the ratio of the maximum average wind speed for some specific duration and critical direction obtained from a long record of observations, e.g. 50 or 100-years, to the observed maximum average wind speed for the same duration and direction in the storm being maximized. The wind speed maximization factor (MW) is defined by Eq. (4).

$$MW = \frac{MW_1}{MW_2} \tag{4}$$

where MW_1 and MW_2 are the maximum wind speed with 100-year return period and the maximum persisting 12-hour wind speed during the storm, respectively (WMO, 2009). Finally, PMP is determined by the precipitation depth R (found using DAD curves) multiplied by moisture maximization and wind maximization factors based on Eq. (5).

$$PMP = FM \times MW \times R \tag{5}$$

2.4 Performance criteria

The performance of the statistical and physical methods for estimating PMP_{24} was judged by comparing the observed maximum 24-hour precipitation values with the corresponding average estimated PMP_{24} values. This comparison was conducted based on six error statistics, in terms of mean absolute error (MAE, Eq. (6)), mean square error (MSE, Eq. (7)), root mean square error (RMSE, Eq. (8)), mean absolute percentage error (MAPE, Eq. (9)), correlation coefficient (R(XY), Eq. (10)), and coefficient of determination (R^2, Eq. (11)).

$$MAE=\frac{\sum_{t=1}^{n}\left|O_t-C_t\right|}{n} \tag{6}$$

$$MSE=\frac{\sum_{t=1}^{n}(O_t-C_t)^2}{n} \quad (7)$$

$$RMSE=\sqrt{\frac{\sum_{t=1}^{n}(O_t-C_t)^2}{n}} \quad (8)$$

$$MAPE=\frac{\sum_{t=1}^{n}|O_t-C_t|}{n}\times 100 \quad (9)$$

$$r=\frac{n(\sum(O_t\times C_t))-(\sum O_t)(\sum C_t)}{\sqrt{(n\sum(O_t)^2-(\sum(O_t))^2).(n\sum(C_t)^2-(\sum(C_t))^2)}} \quad (10)$$

$$R^2=\left(\frac{\sum_{t=1}^{n}\left(O_t-\bar{O}\right)\left(C_t-\bar{C}\right)}{N\times\sigma_{O_t}\times\sigma_{C_t}}\right)^2 \quad (11)$$

Where O_t is maximum 24-hour precipitation, C_t is calculated PMP_{24}, and n is data number. RMSE reveals the actual division among the estimated and observed values. When RMSE value is closer to or equal to zero, performance is more accurate. Also, the smaller values of MAE, MSE, and MAPE show the more accurate performance. The correlation coefficient varies from +1 to -1. Complete correlation between two variables is expressed by either + 1 or -1 and complete absence of correlation is represented by 0. R^2 varies between 0-1 that closer amount to 1 represents the better performance.

3 RESULTS AND DISCUSSION

3.1 Statistical approaches

The focus of the study is the calculation of PMP_{24} by using the statistical and physical method in the north of Iran. In order to calculate PMP using the statistical method, the equations of adjustment factors of Hershfield method were extracted, based on the coefficient of determination (R^2). Adjustment factors that are applied in statistical estimation of PMP values are K_m, adjustment of average and standard deviation for the maximum observed event and for sample size, adjustment for fixed observational time intervals and area reduction curves. These equations permit estimation to be carried out rapidly by using a computer. The 24-hour duration K_m was gained by Eq. (12).

$$K_m = -5\times10^{-8}x^3 + 8\times10^{-5}x^2 - 0.052x + 19.794 \quad (12)$$

Where x is 24-hours mean annual maximum rainfall (mm). Thus, a user-friendly and multi-platform JAVA application, which is called PMP Calculator, was developed that is shown in Fig. 2. This application was supported by all operating system such as Windows, Linux, and Macintosh OS X. It seems that this is the first attempt to design an application which is calculated PMP in four durations by using both approaches of Hershfield's method. Also, in order to compare PMP in all stations, this application calculates the ratio of PMP to the maximum depth of rainfall as a criterion independent of climatic conditions. Table 2 shows the result of PMP_{24} using statistical method in study area, which was calculated by PMP Calculator application. Fig. 3 shows PMP_{24} isohyetal map by using the standard and revised approaches in the study area.

TABLE 2: PMP_{24} values using two different approaches of Hershfield method in the study area.

stations	Maximum 24-hour precipitation (mm)	Mean 24-hour precipitation (mm)	Standard deviation Maximum 24-hour precipitation (mm)	(CV) (%)	Standard approach			Modified approach		
					K_m	PMP_{24} (mm)	$\frac{PMP_{24}}{(P_{24})_{max}}$	K_m	PMP_{24} (mm)	$\frac{PMP_{24}}{(P_{24})_{max}}$
Siah Ab	150.2	53.6	25.6	47.7	17.2	417.6	2.8	5.2	212.6	1.4
Kord Kooy	104.7	59.9	21.8	36.3	17.0	447.7	4.3	2.2	197.1	1.9
Ziarat	63.5	36.2	11.9	32.7	18.0	232.4	3.7	2.9	111.4	1.8
Ghaz Mahalleh	132.0	54.4	23.4	43.0	17.2	419.1	3.2	4.2	200.7	1.5
Shast Kelateh	92.0	51.3	15.2	29.7	17.3	321.7	3.4	3.1	148.3	1.6
Edareh Gorgan	139.0	47.3	24.2	51.1	17.5	395.4	2.8	5.3	197.1	1.4
Gorgan	95.0	50.9	17.2	33.8	17.3	350.0	3.7	2.9	159.7	1.7

Using the PMP Calculator application, PMP can be calculated by two approaches of Hershfield method for durations such as 5 minutes, 1, 6 and 24-hour durations. In this study, maximum 24 hours duration rainfall values for selected stations located in the north of Iran with a record length of 33 years was adopted to estimate the appropriate K_m values. The results showed that for the standard approach, K_m was found to be varied the range of 17 and 18. The minimum and maximum values for point PMP_{24} were 232.4 and 447.7 mm. Based on table 2, in the standard approach, there are substantial variations in the PMP results with the variation range of 215.3 mm and average and the standard deviation of 369.1 and 74.2 mm. It shows the effect of record length on the results of the standard approach and substantial variation in the results causes uncertainty. In the revised approach, in order to calculate the k_m values, just the maximum values were considered. It caused a considerable decrease in the K_m values comparing with the standard approach. Therefore, the corresponding values of K_m for this approach ranged from 2.2 to 5.3 and the minimum and maximum values for point PMP_{24} were 111.4 to 200.7 mm. The variation range, average, and the standard deviation of the revised approach is about half of the corresponding values of the standard approach. In order to compare two approaches and compare stations, the ratio of areal PMP_{24} to the maximum of 24 hours precipitation $(P_{24})_{max}$, as a criterion independent of climatic conditions was used. The maximum and minimum value of the ratio of PMP_{24} to $(P_{24})_{max}$ for the standard approach was obtained 2.8 and 4.3 whereas these values for the revised approach was obtained 1.4 and 1.9. The ratio of PMP_{24} to $(P_{24})_{max}$ in the revised approach is closer to 1; therefore, the results of the revised approach are more rational. Finally, based on the revised approach, the maximum K_m of Hershfield equation in the study area was found to be 5.3. The approximated K_m is in accordance with corresponding research in the Atrak watershed (Ghahraman, 2008) and (Desa et al., 2001; Desa and Rakhecha, 2007) Malaysia. Much research has been done on K_m in the standard approach but all of them lead to a high estimation of PMP. In the revised approach, just the maximum values were considered and caused a severe and perceptible decrease in K_m values which were more rational (Desa et al., 2001). Due to considering actual rainfall in the calculation of K_m, the revised approach was more stable results than the standard approach in the study area. After calculation of storm maximization factor by using the wind and moisture maximization factors, physical PMP_{24} was estimated.

3.2 Physical method

In this study based on maximum discharge and the daily rainfall data with 24-hours duration obtained from Iran water resources management company and IRIMO as a reliable source, 8 storms were selected as the most severe and widespread storms during 1981 to 2013. The date of occurrence these storms have been given in Table 3. After selection of severe and widespread storms, the isohyet maps for each storm were plotted in ArcGIS 9.3. To produce the DAD curves, the area bounded by each isohyet line was calculated in ArcGIS 9.3. Based on Fig. 4 that shows the spatial distribution of precipitation during the storm of September 2008 as one of the most severe storms, the greatest amount of precipitation occurred over the western parts of basin that is nearest to sea, whereas the smallest amounts of precipitation occurred over the eastern parts of basin. Based on this figure, in the western parts of the basin, isohyet lines are found close to each other and the magnitude of the rainfall gradient increases; thus the variation of rainfall in this part of the basin was elevated. Also, Fig. 5 shows DAD curve for the storm of September 2008. Table 4 shows the moisture and wind speed maximizations at 1000 mb for selected storms in Gorgan station. DAD curve showed that the amount of rainfall decreased with increasing area.

TABLE 3: Date of 24 hours duration severe and widespread storms in the study area.

No.	Date of occurrence	No.	Date of occurrence
1	11/12/1995	5	01/11/2013
2	10/29/1993	6	09/29/2008
3	11/09/2006	7	09/27/1995
4	07/17/2012	8	10/13/1991

TABLE 4: The moisture and wind maximization at 1000 mb for selected storms in Gorgan station.

Date of occurrence	Maximum persisting 12hr dewpoint in 1000 mb level (˚C)		moisture maximization factor	Maximum persisting 12hr wind (Knot)		Wind maximization Factor	PMP Factor
	In the storm time	50 year return period		In the storm time	100 year return period		
11/12/1995	15	17.5	1.17	8	13.6	1.70	1.98
10/29/1993	14.1	20.6	1.46	7	10.7	1.53	2.24
11/09/2006	15	19	1.27	8	10.2	1.28	1.62

07/17/2012	20.9	25	1.20	8	8.8	1.10	1.32
01/11/2013	8.1	11.9	1.47	12	16.3	1.36	2.00
09/29/2008	20.9	23.8	1.14	7	10.1	1.45	1.65
09/27/1995	19	23.8	1.25	6	9.7	1.62	2.02
10/13/1991	13.8	21.2	1.54	7	10.7	1.53	2.35

Table 5 shows the PMP values estimated by the physical method for selected storms over the study area.

TABLE 5: The PMP values estimated by the Physical method for selected storms in the study area.

Date of occurrence	Average rainfall (mm)	PMP Factor	PMP (mm)
11/12/1995	72.1	1.98	143.0
10/29/1993	64.0	2.24	143.1
11/09/2006	24.8	1.62	40.1
07/17/2012	91.8	1.32	120.8
01/11/2013	60.9	2.00	121.7
09/29/2008	75.7	1.65	124.6
09/27/1995	57.6	2.02	116.5
10/13/1991	59.5	2.35	139.9

In order to estimate the moisture maximization factor, W_m with 50-year return period was calculated. Also, to calculate the wind speed maximization factor, based on Eq. (4), MW1 with 100-year return period was determined. Then wind and moisture maximization factors were estimated and the amount of PMP was calculated using the multiplication PMP factor on average rainfall in a cumulative area. Based on table 5, maximum PMP value is related to the storm that occurred at 10/29/1993 and minimum PMP value is related to the storm that occurred at11/09/2006. Based on performance criteria including MAE, MSE, RMSE, MAPE, R, and R^2, the physical model could perform better than the statistical method. Furthermore, between two statistical approaches, the accuracy of the revised approach was better than the standard approach by using modified K_m values (Table 6).

Table 6: Statistical comparison between $(P_{24})_{max}$ and average estimated PMP_{24} values

method	MAE	MSE	RMSE	MAPE	R(XY)	R^2
Standard	258.2	69090.5	262.9	241.7	0.8	0.63
Revised	64.36	4311	65.7	61.2	0.9	0.86
Physical	7.1	50.4	7.1	4.7	-	-

The physical method is suitable and more reliable than the statistical method, for consideration the physical characteristics of air mass and application of meteorological data such as dew point that is an indicator of the incoming air into the storm lead to more accurate estimates. The calculation of PMP using the physical methods is difficult because this method needs more meteorological data and must be investigated the meteorological maps in a different level of atmosphere that needs for a long time. Also, calculating PMP using the physical method requires close cooperation between hydrologists and meteorologists. Although the application of the physical method is preferred, use of the revised approach of Hershfield method is recommended for rapid PMP estimates.

4 Conclusions

PMP is the greatest or the extreme rainfall for a given duration that is physically possible over an area. There are physical and statistical methods for calculation of PMP. In this study, statistical (the standard and revised approaches) and physical methods are used to calculate the 24-hour PMP over the study area. In order to calculate PMP using the Hershfield method, an application, which is called PMP Calculator, is designed. This application calculates PMP with 5 minutes, 1, 6 and 24-hour durations for the standard and revised approach of the Hershfield method. Also, for calculation of PMP using the physical method, convergence model is considered. After selection of the most severe and widespread storms and drawing DAD curves, moisture and wind factors are estimated. Finally, PMP for each storm is calculated. The results indicated that the maximum point PMP_{24} values were 447.7 mm using the standard and 200.7 mm for the revised approaches of Hershfield method. While PMP_{24} value using the physical method was 143.1 mm. The results of the revised approach come closest to the physical PMP. The result of the physical method is reasonable and in compliance with real rainfall over the study area, for considering physical characteristics of the air mass, in the physical method.

5 Acknowledgements

The authors wish to express their sincere thanks to Mr. Farzad Mahdikhani for invaluable support during the designing of PMP Calculator application.

References

Alias, N. E., and Takara, K,: Estimating the probable maximum precipitation of Kuala Lumpur, Malaysia and Yodo river basin, Japan using statistical method. J. Disaster Res., 8(1), 197-198, 2013.

Bhim, S., Satya, P., and Jitendra1, S.: Estimation of probable maximum precipitation for one day duration in jhalarapatan region of Rajasthan. Indian J. Soil Conserv., 42(2), 130-134, 2014.

Casas, M. C., Rodriguez, R., Prohom, M., Gazquez, A., and Redano, A.: Estimation of probable maximum precipitation in Barcelona (Spain). Int. J. Climatol., 31(9), 1322-1327, 2010.

Chavan, S. R., Srinivas, V. V.: Probable maximum precipitation estimation for catchments in Mahanadi river basin. International conference on water resources, coastal and ocean engineering, Aquatic Procedia 4, 892–899, 2015.

Chow, V. T.: A general formula for hydrologic frequency analysis. Eos Transactions Geophysical Union, 32(2), 231–237, 1951.

Desa, M. N., and Rakhecha, P. R.: Probable maximum precipitation for 24-h duration over an Equatorial Region, Part 2-Johor, Malaysia. J. Atmos. Res., 84, 84- 90, 2007.

Desa, M. N., Noriah, A. B., and Rakhecha, P. R.: Probable maximum precipitation for 24-h duration over Southeast Asian monsoon region- Selangor, Malaysia. J. Atmos. Res., 58, 41-54, 2001.

Deshpande, N. R., Kulkarni, B. D., Verma, A. K., and Mandal, B. N.: Extreme rainfall analysis and estimation of probable maximum precipitation (PMP) by statistical methods over the Indus river basin in India. J. Spat. Hydrol., 8(1), 22-36, 2008.

Fattahi, E., Noorian, A. M., and Noohi, K.: Comparison of physical and statistical methods for estimating probable maximum precipitation in southwestern basins of Iran. DESERT, 15, 127-132, 2010.

Fernando, W. C. D. K., Wickramasuriya, S. S.: The hydro-meteorological estimation of probable maximum precipitation under varying scenarios in Sri Lanka. Int. J. Climatol., 31, 668–676, 2011.

Fikre, A., Quraishi, S., and Bezabih, B.: Development of One Day Probable Maximum Precipitation (PMP) and Isohyetal Map for Bale Zone, Oromiya Region, Ethiopia. Civ. Environ. Res., 8(12), 22-26, 2016.

Ghahraman, B.: The estimation of one day duration probable maximum precipitation over Atrak watershed in Iran. Iranian J. Sci. Technol., 32(B2), 175-179, 2008.

Hansen, M. E. Probable maximum precipitation for design floods in the United States. J. Hydrol., 96, 267-278, 1987.

Hussain, M., Nadya, S., and Chia, F. J.: Estimating probable maximum precipitation for Linau river basin in Sarawak. UNIMAS E-J. Civil Eng., 5(3), 1-5, 2014.

Ishida, K., Kavvas, M., Jang, S., Chen, Z., Ohara, N., and Anderson, M.: Physically based estimation of maximum precipitation over three watersheds in northern California, Atmospheric boundary condition shifting. J. Hydrol. Eng., 04014052-2- 04014052-15, 2015.

Joos, B., Darakhani, J., Mouvet, L., Mehinrad, A.: An integrated probabilistic approach for determining the effects of extreme hydrological events on a flood evacuation system. 73rd annual meeting of ICOLD, Tehran, Iran, 2005.

Lan, P., Lin, B., Zhang, Y., and Chen, H.: Probable Maximum Precipitation Estimation Using the Revised K_m-Value Method in Hong Kong. J. Hydrol. Eng., 05017008-1 - 05017008-8, 2017.

Micovic, Z., Schaefer, M. G., and Taylor, G. H.: Uncertainty analysis for probable maximum precipitation estimates. J. Hydrol., 521, 360–373, 2015.

Miller, J. F.: Probable maximum precipitation and rainfall-frequency data for ALASKA. U.S. Department of Commerce, 1963.

Naseri Moghaddam, M., Ghazanfari, S., Ghahraman, B., and Davari, K.: Probable maximum precipitation for 24-hour duration over four central provinces in Iran World Environmental and Water Resources Congress, 1-6, 2009.

Papalexiou, S. M., and Koutsoyiannis, D.: A probabilistic approach to the concept of probable maximum precipitation. Adv. Geosci., 7, 51-54, 2006.

Rezacova, D., Pesice, P., and Sokol, Z.: An estimation of probable maximum precipitation for river basins in Czech Republic. J. Atmos. Res., 77, 407- 421, 2005.

Rakhecha, P. R., and Singh, V. P.: Applied Hydrometeorology Springer, 384p, 2009.

Rakhecha, P. R., and Clark, C.: Point and areal PMP estimates for durations of two and three days in India. Meteorol. Appl., 7, 19-26, 2000.

Rakhecha, P. R., and Clark, C.: Revised estimates of one-day probable maximum precipitation (PMP) for India. Meteorol. Appl., 6, 343–350, 1999.

Rakhecha, P. R., Mandal, B. N., Kulkarni, A. K., and Deshpande, N. R.: Estimation of Probable Maximum Precipitation for Catchments in Eastern India by a Generalized Method. Theor. Appl. Climatol. 51, 67-74, 1995.

Sharma, K. K., and Dubey, S. K.: Probability analysis of rainfall for planning water harvesting and irrigation in semi-arid region of Uttar Pradesh. Indian J. Soil Conserv., 41(1), 14-19, 2013.

Shirdeli, A.: Probable maximum precipitation 24 hours estimation, A case study of Zanjan province of Iran. Manag. Sci. Lett., 2, 2237–2242, 2012.

Soltani, M., Khoshakhlagh, F., Zawar-Reza, P., Miller, S. T. K., Molanejad, M., and Ranjbar Saadat Abadi, A.: Probable maximum precipitation estimation using statistical and physical methods over Esfahan province of Iran. Res. J. For. Environ. Protection, 1(1), 38-55, 2014.

Tingsanchali, T., and Tanmanee, S.: Assessment of Hydrological Safety of Mae Sruai Dam, Thailand. Procedia Eng., 32, 1198-1204, 2012.

U S weather bureau.: Generalized Estimates of Probable Maximum Precipitation and Rainfall-Frequency Data for Puerto Rico and Virgin Islands Cooperative Studies Section Hydrologic Services Division U.S. Weather Bureau for Engineering Division Soil Conservation Service U.S. Department of Agriculture, 1961.

Wang, B. H. M.: Estimation of probable maximum precipitation, Case studies. J. Hydraulic Eng., 110, 1457–1472, 1984.

World Meteorological Organization.: Manual on Estimation of Probable Maximum Precipitation, 3rd edition, WMO- No 1045, Geneva, 2009.

Yigzaw, W., Hossain, F., and Kalyanapu, A.: Impact of Artificial Reservoir Size and Land Use/Land Cover Patterns on Probable Maximum Precipitation and Flood, Case of Folsom Dam on the American River. J. Hydrol. Eng., 18, 1180-1190, 2013.

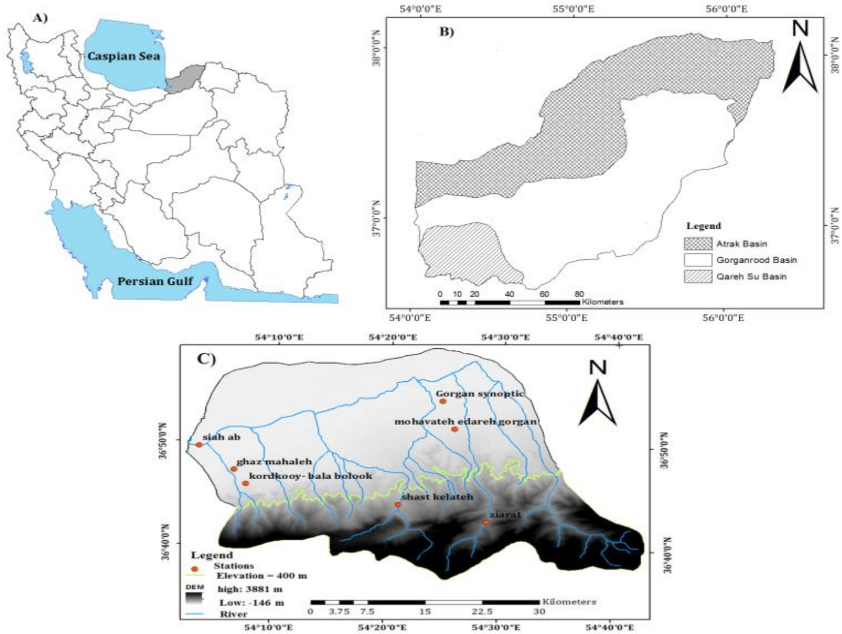

Figure 1: Spatial distribution of stations over the study area.

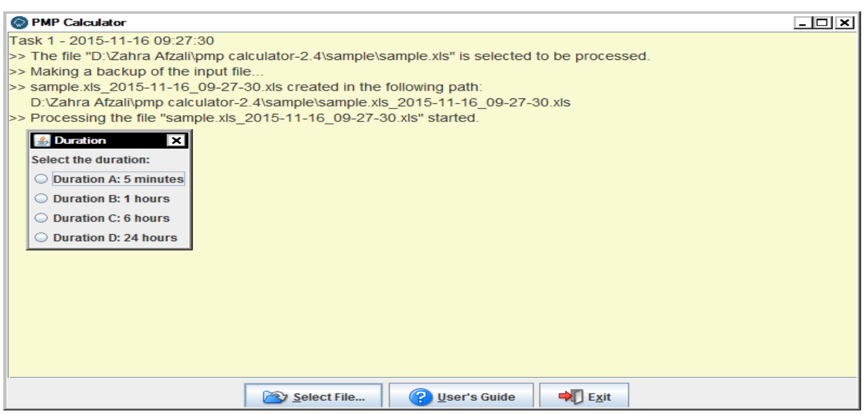

Figure 2: Window for determining PMP duration in PMP Calculator application.

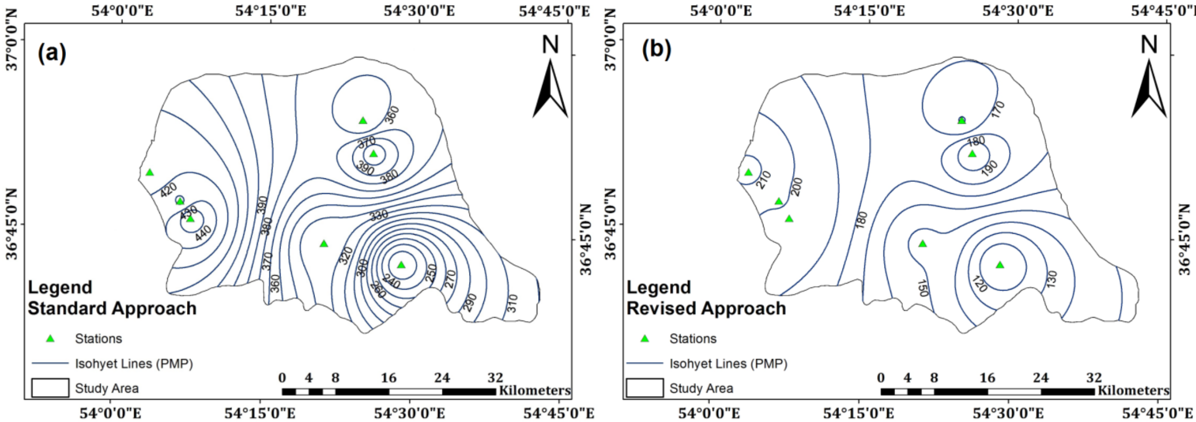

Figure 3: The spatial distribution of PMP24 using (a) the standard and (b) the revised approaches in study area.

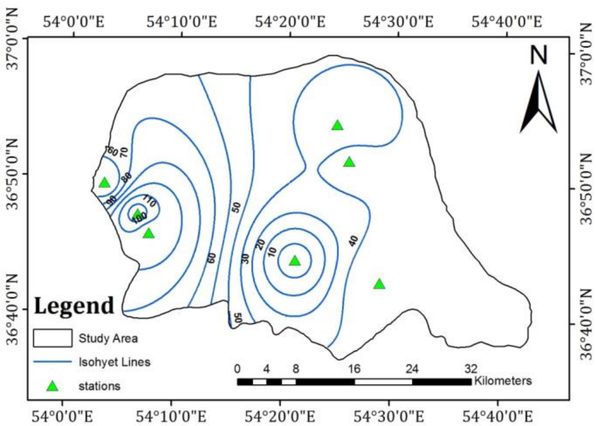

Figure 4: Spatial distribution of rainfall for the storm of September 2008 in study area.

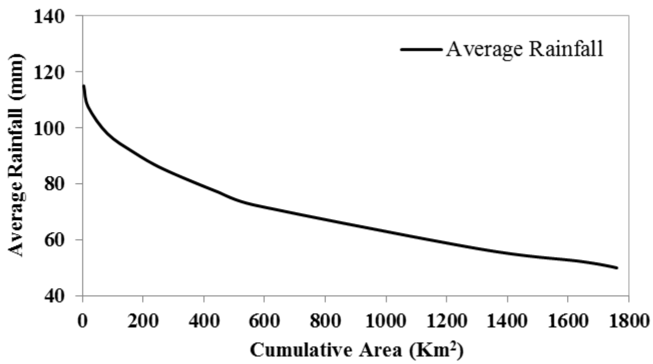

Figure 5: Depth-Area-Duration curve for the storm of September 2008 in study area.