Probable Maximum Precipitation Estimation in a Humid Climate

Zahra Afzaligorouh[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
Abstract. Probable maximum precipitation (PMP) estimation is necessary to design floods for optimal design of hydraulic structures. The aim of this study was the estimation of 24-hour PMP (PMP_{24}) using the statistical and hydro-meteorological (physical) approaches in a humid climate of Qareh-Su Basin which is located in the northern part of Iran. Firstly, for the statistical estimate of PMP, the equations of empirical curves of Hershfield method were extracted. Then the Hershfield standard and revised methods were written in JAVA programming language, as a user-friendly and multi-platform application called the PMP Calculator. Secondly, a hydro-meteorological approach which is called convergence model was considered to calculate PMP_{24}. The depth-area-duration (DAD) curves were extracted to estimate average depth of precipitation for each storm. The results indicated that for the Hershfield standard and revised method, the 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 standard method was obtained 447.7 mm and for the revised method was 200.7 mm. Using the physical approach, PMP_{24} was 143.1 mm. Comparison of PMP_{24} values with the maximum 24-hour precipitation demonstrated that based on performance criteria including MAE, MSE, RMSE, MAPE, r, and R^2, the physical approach performed better than the statistical approach. Also, the accuracy of the Hershfield revised method was better than the standard method using modified K_m values.

1 Introduction

Intensive rainfall and heavy floods are one of the most catastrophic natural hazards which have caused social damages all over the world. In order to reduce the destructive effects of these phenomena, flood risk management is essential. One of the most important components in flood risk management is the probable maximum flood (PMF) estimation. Hydrologists use PMF to design a specific project in a given basin, such as major spillway, dam storage capacity, and flood protection structures. In order to compute PMF accurately, it is necessary to calculate the probable maximum precipitation (PMP). PMP has been defined as "The greatest depth of precipitation for a certain duration meteorologically possible for a given size storm area at a specific time of year (WMO, 2009). The World Meteorological Organization has widely proposed the use of statistical and hydro-meteorological (physics-based) approaches for estimating PMP (WMO, 2009). A statistical procedure is a probabilistic approach that requires statistical analysis based on the historical extreme precipitation in the meteorological stations where at least 30 years daily data are available. This procedure is mostly used for small basin up to 1,000 square kilometres (WMO, 2009). Among the several statistical approaches, the Hershfield method is well known and most used

(Hershfield, 1961, 1965; WMO, 1986, 2009). Generally, this method is applied for quick assessment of PMP. Hydro-meteorological estimation approaches which are characteristic of the deterministic approaches can be usually divided into various methods, such as a storm model approach (convergence and orographic models) (Collier and Hardaker, 1996; Beauchamp, et al., 2013), a generalized method (Rakhecha et al., 1995), moisture maximization method (WMO, 1986; Papalexiou and Koutsoyiannis, 2006; Casas et al., 2011; Micovic et al., 2015), and storm transportation method (Rakhecha and Singh, 2009). However, it is not always easy to use these methods. For example, determining the maximum humidity content in some places may not be effortless. For this reason, such physical-based approaches have not been completely established and need to be widely verified. Some studies indicated that both statistical and physical approaches provide reliable estimates of the PMP (Rezacova et al., 2005; Casas et al., 2011). In some cases, the PMP value obtained from the statistical approach is about two times higher than the estimated value of the physical approach (Desa et al., 2001; Fattahi et al., 2010; Chavan and Srinivas, 2015). The results of these researchers have indicated that although the statistical approaches provide larger estimates of PMP, it is proposed for areas where hourly rainfall, dew point temperature, wind speed, and vertical radiosonde measurements are unavailable (Rakhecha and Soman, 1994; WMO, 2009). There are many studies using hydro-meteorological and statistical approaches in different parts of Iran (Ghahraman, 2008; Naseri Moghadam et al., 2009; Fattahi et al., 2010; Shirdeli, 2012). Naseri Moghadam et al. (2009) estimated one-day PMP for 23 meteorological stations in the four central provinces of Iran using the Hershfield method. Their emphasis was to correct the frequency factor of the Hershfield method for these stations. The results indicated that the highest value of the frequency factors was 7.6. In another study for the central regions of Iran, Soltani et al., (2014) estimated the PMP using statistical and physical approaches. They observed that the PMP estimated by the statistical approach were greater than those estimated by the physical approach.

The main purpose of this study was the estimation of 24-hour PMP (PMP$_{24}$) using the statistical and physical approaches in the Qareh-su basin in north-eastern Iran which is prone to frequent floods. An attempt is also made to written user-friendly and multi-platform program in JAVA for the PMP calculation using Hershfield method. The values obtained from both physical and statistical approaches will also be compared with the observed maximum 24-hour precipitation in the study stations.

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 centres, 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 the study area.

Climatological data that were applied in calculating of PMP values in the physical approach were 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. The required data such as air temperature and rainfall were taken from available climatological, rain-gauge 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 rain-gauge stations and one synoptic station located in the Qareh-Su basin were taken into account in this study (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	Rain-gauge station
Kord Kooy	54˚ 07'	36˚ 45'	140	606	Rain-gauge station
Edareh Gorgan	54˚ 25'	36˚ 51'	75	591	Rain-gauge station
Shast Kelateh	54˚ 20'	36˚ 44'	150	735	Rain-gauge station
Ghaz Mahalleh	54˚ 12'	36˚ 47'	6	604	Rain-gauge station
Siah Ab	54˚ 30'	36˚ 45'	-26	607	Rain-gauge station
Gorgan	54˚ 25'	36˚ 54'	13.3	569	Synoptic station

2.2 Statistical approach

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

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

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 Hershfield standard method is modified by Desa et al., (2001). In the modified method, K_m is calculated by the following Eq. (2):

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

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

5   replacing K_m with $K_{envelope}$ value (Alias and Takara, 2013).

2.3 Physical approach

There are two common physical approaches 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,

10   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

15   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

20   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

25   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

30   (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) 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 approaches 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), Eq. (10)), and coefficient of determination (R^2, Eq. (11)).

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

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

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

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

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

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

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 approach

The focus of the study is the calculation of PMP_{24} using the statistical and physical approach in the north of Iran. In order to calculate PMP using the statistical approach, 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 using a computer. The 24-hour duration K_m was gained by Eq. (12).

$$K_m = -5 \times 10^{-8} x^3 + 8 \times 10^{-5} x^2 - 0.052x + 19.794 \tag{12}$$

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 using both Hershfield standard and revised methods. 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 approach in study area, which was calculated by PMP Calculator application. Fig. 3 shows PMP_{24} isohyetal map using the Hershfield standard and revised methods in the study area. Using the PMP Calculator application, PMP can be calculated by Hershfield standard and revised methods 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 indicated that for the Hershfield standard method, 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 Hershfield standard method, 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 Hershfield revised method, 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 Hershfield standard method.

TABLE 2: PMP$_{24}$ values using Hershfield standard and revised methods in the study area.

stations	Maximum 24-hour precipitation (mm)	Mean 24-hour precipitation (mm)	Standard deviation Maximum 24-hour precipitation (mm)	(CV) (%)	Standard method			Modified method		
					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

Therefore, the corresponding values of K_m for Hershfield revised method 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 method is about half of the corresponding values of the standard method. In order to compare two these methods 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 method was obtained 2.8 and 4.3 whereas these values for the revised method was obtained 1.4 and 1.9. The ratio of PMP$_{24}$ to $(P_{24})_{max}$ in the revised method is closer to 1; therefore, the results of the revised method are more rational. Finally, based on the revised method, 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 method but all of them lead to a high estimation of PMP. In the revised method, 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 method was more stable results than the standard method in the study area. After calculation of storm maximization factor using the wind and moisture maximization factors, the physical PMP$_{24}$ was estimated.

3.2 Physical approach

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. Table 4 illustrated the moisture and wind speed maximizations at 1000 mb for selected storms in Gorgan station. DAD curve for the storm of September 2008 showed that the amount of rainfall decreased with increasing area (Fig. 5). The results of the physical approach demonstrated that the storm of October 1993 was the severest storm and whiles the storm of November 2006 was revealed as the most moderate one (Table 5). 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.

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: The PMP values estimated by the Physical approach 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

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, the physical approach could perform better than the statistical approach. Furthermore, between two Hershfield statistical methods, the accuracy of the revised method was better than the standard method 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	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 approach is suitable and more reliable than the statistical approach, 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 approach 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 approach requires close cooperation between hydrologists and meteorologists. Although the application of the physical approach is preferred, use of the Hershfield revised method is recommended for quick and accurate PMP estimates when dewpoint temperature data were unavailable.

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 approaches for calculation of PMP. In this study, statistical (the Hershfield standard and revised methods) and physical (convergence model) approaches 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 Hershfield standard and revised methods. Also, for calculation of PMP using the physical approach, 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 and 200.7 mm for the Hershfield standard and revised methods, respectively. While PMP_{24} value using the physical approach was 143.1 mm. The results of the revised method come closest to the physical PMP. The result of the physical approach was 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.

Beauchamp, J., Leconte, R., Trudel, M., Brissette, F.: Estimation of the summer-fall PMP and PMF of a northern watershed under a changed climate. Water Resour. Res., 49, 3852–3862, 2013.

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, 2011.

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.

Collier, C. G., Hardaker, P. J.: Estimating probable maximum precipitation using a storm model approach. J. Hydrol., 183(3-4), 227-336, 1996.

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.

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

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.

Hershfield, D. M.: Estimating the probable maximum precipitation, ASCE J. Hydraul. Div., 87, 99-106, 1961.

Hershfield, D. M.; Method for estimating probable maximum precipitation, J. Am. Water Works Assoc., 57, 965–972, 1965.

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.

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

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.

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

Rakhecha, P. R., Soman, M. K.: Trends in the annual extreme rainfall events of 1 to 3 days duration over India. Theor. Appl. Climatol., 48, 227–237, 1994.

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.

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.

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.

World Meteorological Organization (WMO).: Manual for Estimation of Probable Maximum Precipitation, Operational Hydrology Report 1, 2nd edition, Publication 332, World Meteorological Organization, Geneva, 1986.

World Meteorological Organization (WMO).: Manual on Estimation of Probable Maximum Precipitation, 3rd edition, publication 1045, Geneva, 2009.
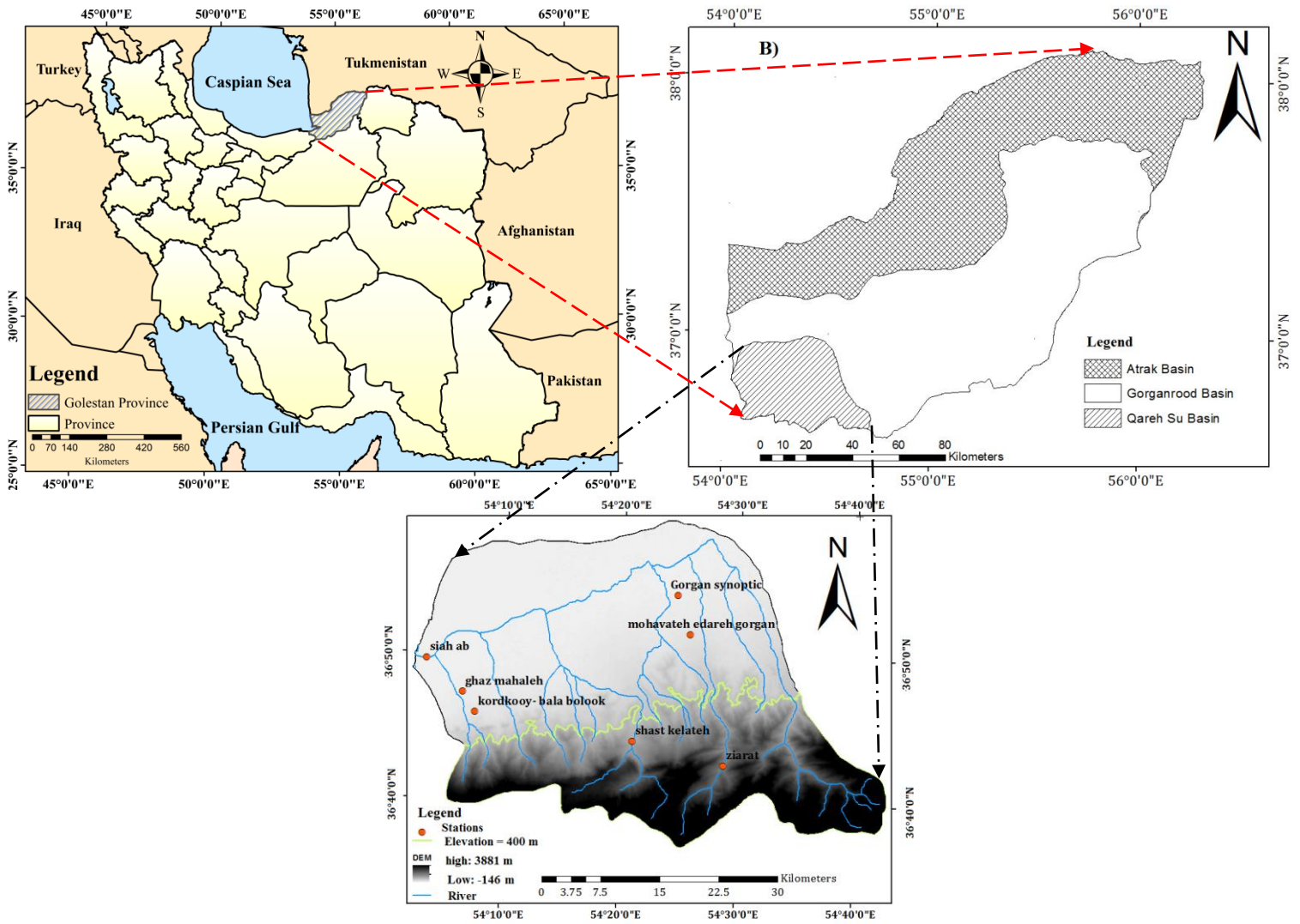
Figure 1: Spatial distribution of stations over the study area.
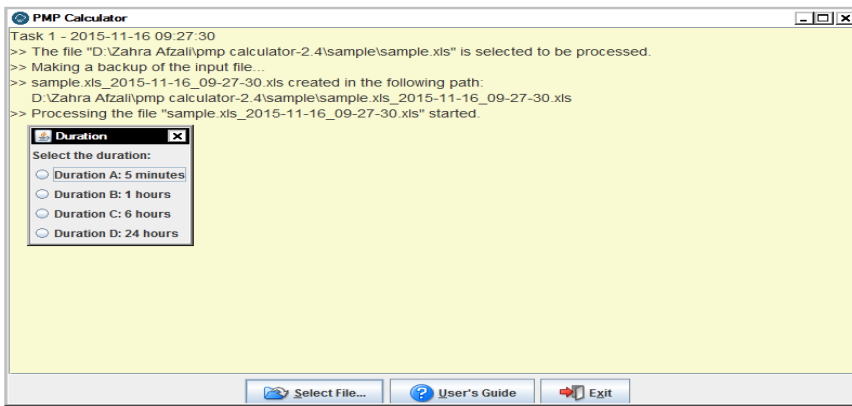
Figure 2: Window for determining PMP duration in PMP Calculator application.
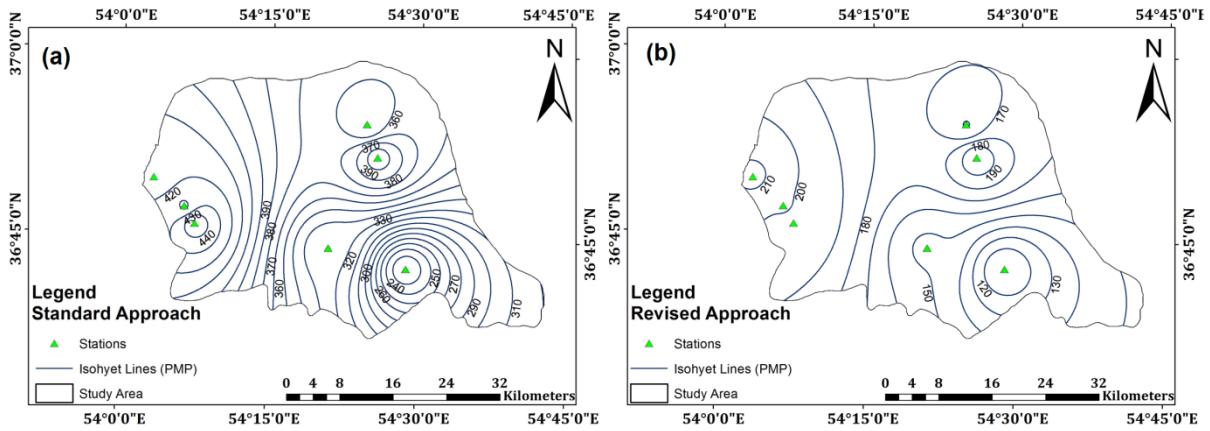
Figure 3: The spatial distribution of PMP$_{24}$ using (a) the standard and (b) the revised approaches in study area.
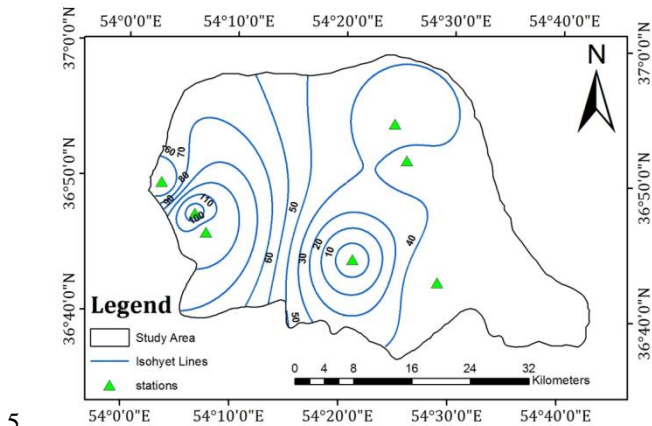
Figure 4: Spatial distribution of rainfall for the storm of September 2008 in study area.
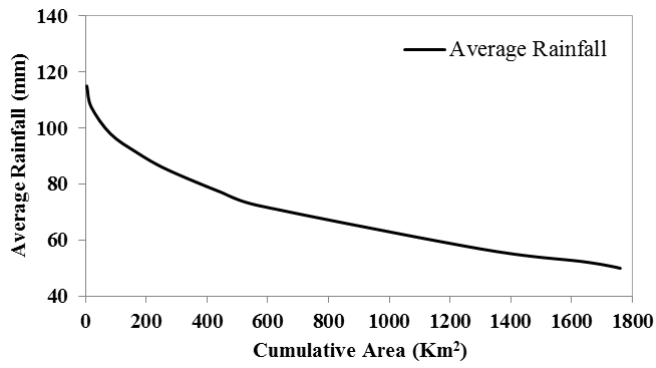
Figure 5: Depth-Area-Duration curve for the storm of September 2008 in study area.