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Probable Maximum Precipitation Estimation in a Humid Climate

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5   **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 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.

10   Convergence model was considered to calculate PMP by physical method. The depth- area- duration (DAD) curves were extracted to estimate PMP_{24} using physical method and then PMP_{24} was estimated for each storm. The results showed that for the standard and revised approaches, 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 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

15   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

20   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). PMP and PMF (Probable Maximum Flood) estimates are of remarkable importance to hydrologists for calculating the PMF for designing spillways on large dams, for maximum reliability and safety. The main objective of designing spillways using the PMF is to avoid the overtopping of dams as a result of river flooding (Desa and

25   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 dew point 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

5   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). Many researchers have investigated climate change impact on PMP over the world (Rousseau et al., 2014; Stratz and Hossain, 2014; Afrooz et al., 2015; Rouhani and Leconte, 2016; Rastogi et al., 2017; Sen

10   et al., 2017). There are many efforts on calculating PMP using physical and statistical methods, recently. For instance, Chavan and Srinivas (2015) estimated PMP_{1-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. Other researchers have calculated PMP by using the statistical and physical methods (Rakhecha et al., 1995;

15   Rakhecha and Clark, 1999; Rakhecha and Clark, 2000; Deshpande et al., 2008; Fernando and Wickramasuriya, 2011; Tingsanchali and Tanmanee, 2012; Hussain et al., 2014; Singh et al., 2014). Lan et al., (2017) estimated 24-h PMP value by using the revised Km-value method in Hong Kong based on the local rainfall data is about 1753 mm. 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.

20   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. 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

25   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 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 physical method based on the maximization of actual storms from 5 minutes to 30 hours. Their

30   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 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 gage positions and used maximized area reduction factors (ARFs) that defined from radar based rainfalls, converted point PMPs to areal

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PMPs. There are many studies over the wide area such as U.S. weather bureau (1961); Hansen (1986); and Miller (1963). Extreme rainfall and PMP are the main factors for designing hydraulic structures and disaster risk reduction. 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

Golestan province is located in the northern part of Iran. The Qareh-Su basin, with nearly 1760 km^2 area is one of the most important basins in north of Iran with humid climate. The Qareh-Su basin is located in the northern slopes of the Alborz, at the eastern shores of the Caspian Sea and Gorgan Bay. The annual average precipitation in this basin is 596 mm. Fig. 1 shows location of stations and study area. Climatological data that are applied in calculating of PMP values in physical method are dew point temperature, wind speed and direction, pressure and precipitation. The records of six rain gage 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 ranges 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)	Type
Ziarat	54° 30'	36° 42'	950	Rain gage station
Kord Kooy	54° 07'	36° 45'	140	Rain gage station
Edareh Gorgan	54° 25'	36° 51'	75	Rain gage station
Shast Kelateh	54° 20'	36° 44'	150	Rain gage station
Ghaz Mahalleh	54° 12'	36° 47'	6	Rain gage station
Siah Ab	54° 30'	36° 45'	-26	Rain gage station
Gorgan	54° 25'	36° 54'	13.3	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:

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

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 (K_m). In this approach, K_m is calculated by K_m chart given in the manual for estimation of probable maximum precipitation (WMO, 2009, Fig. 4.1, Page 65) based on duration and average of annual maximum rainfall that these curves were extracted based on records of 24-hour rainfall for some 2700 stations in the climatological observation of America. The standard approach of Hershfied method is modified by Desa et al., (2001) in Malaysia. In modified approach, K_m is calculated by the following Eq. (2):

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

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 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 physical characteristic of storm, i.e. dew point 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. Severe and widespread storm is a weather condition that leads to produce 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 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.

2.4 Moisture maximization

The moisture maximization method is one of the acceptable procedures to calculate PMP for specific areas and consists of moisture maximization adjustment to observed areal 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 dew point temperature. After selection of severe and widespread storms and calculation of average rainfall depth for 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. Dew point 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 dew point 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 dew point in a simultaneous period with storm (WMO, 2009).

2.5 Wind maximization

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).

3 RESULTS AND DISCUSSION

3.1 Statistical approaches

The focus of the study is the calculation of PMP_{24} by using statistical and physical method in 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 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. (5).

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

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 on Fig. 2. This application was supported by all operating system such as Windows, Linux, and Macintosh OS X. Also, in order to compare PMP in all stations, this application calculates the ratio of PMP to maximum depth of rainfall as criteria independent of climatic conditions. Table 2 shows the

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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 standard and revised approach in study area.

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

3.2 Physical method

5   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

10   precipitation during the storm of September 2008 as one of the most severe storm, 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. 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.

TABLE 3: Date of 24 hours duration severe and widespread storms in 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 dew point 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 physical method for selected storms over the study area.

TABLE 5: The PMP values estimated by Physical method for selected storms in 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

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 north of Iran with 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. In revised approach, just the maximum values were considered and caused a severe
and perceptible decrease in K_m values which were more rational. 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 ratio of areal
PMP_{24} to maximum of 24 hours precipitation $(P_{24})_{max}$, as a criteria independent of climatic conditions was used to compare
PMP_{24} in the study area. The maximum and minimum value of the ratio of PMP_{24} to $(P_{24})_{max}$ for standard approach was
obtained 2.8 and 4.3 whereas these values for revised approach was obtained 1.4 and 1.9. Finally, based on 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 standard approach but all of them lead to 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). The findings of this study imply that the revised approach was more stable results than the standard approach in north of Iran (Qareh-Su basin), for this method uses the actual rainfall to calculate K_m. 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

5   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. 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, leads to more accurate

10   estimates. The calculation of PMP using physical methods is difficult because this method needs more meteorological data and must be investigated the meteorological maps in different level of atmosphere that need to long time. Also, calculating PMP using physical method requires close cooperation between hydrologists and meteorologists. Although application of the physical method is preferred, use of revised approach of Hershfield method is recommended for rapid PMP estimates.

4 Conclusions

15   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 (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 standard and revised approach of the Hershfield method. Also, for calculation of PMP using physical

20   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 standard and 200.7 mm for revised approaches of Hershfield method. While PMP_{24} value using physical method was 143.1 mm. The results of 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

25   physical characteristics of the air mass in the physical method.

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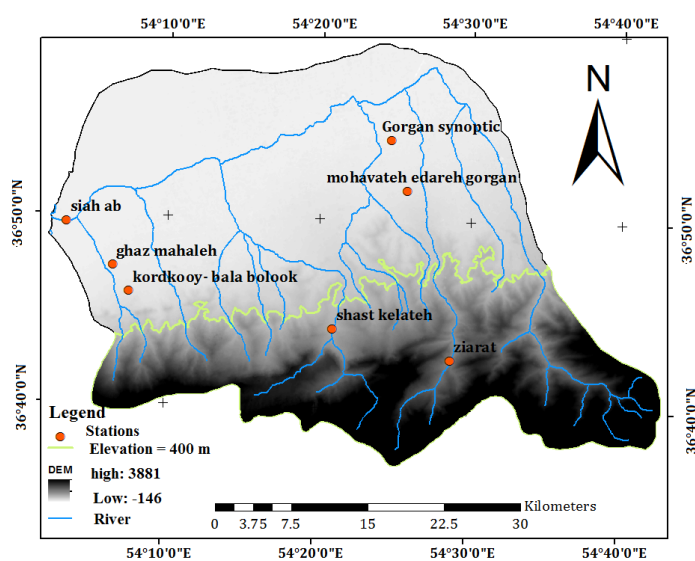
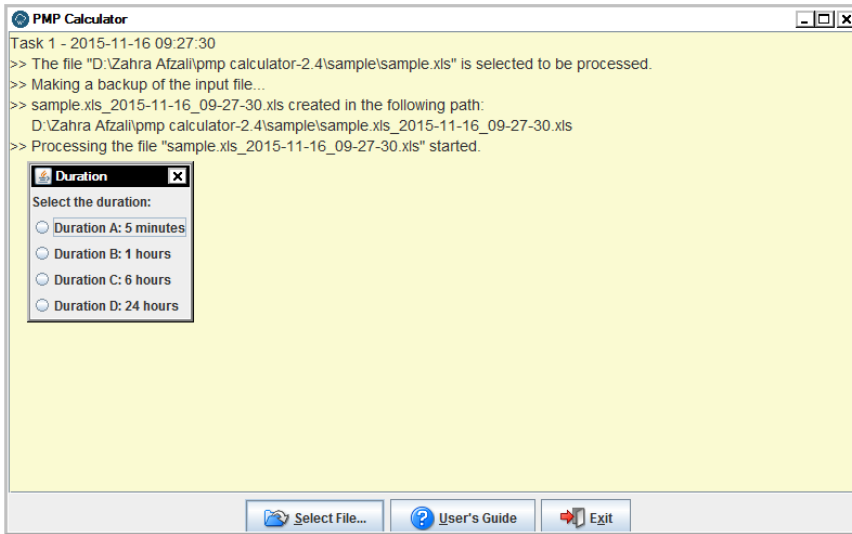Figure 1: Spatial distribution of stations over the study area.

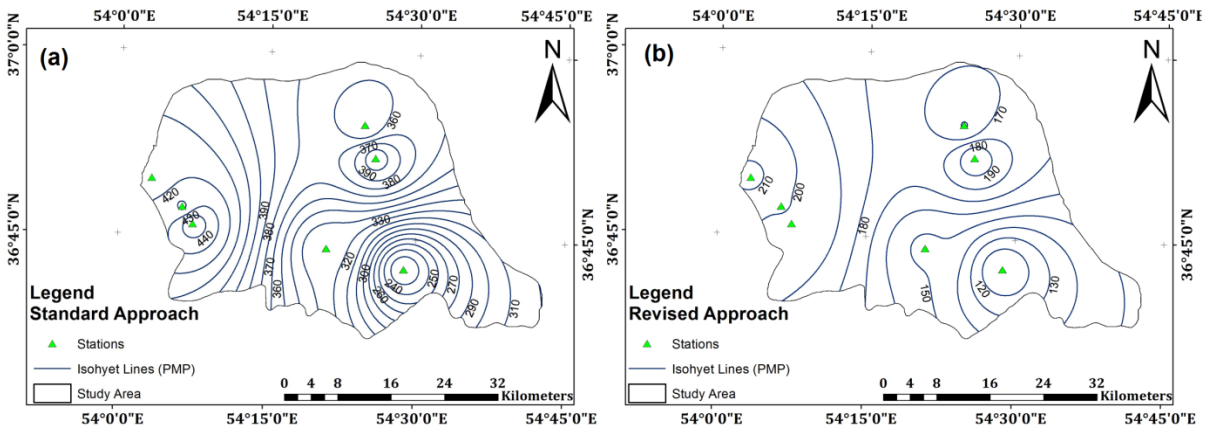**Figure 2: Window for determining PMP duration in PMP Calculator application.**

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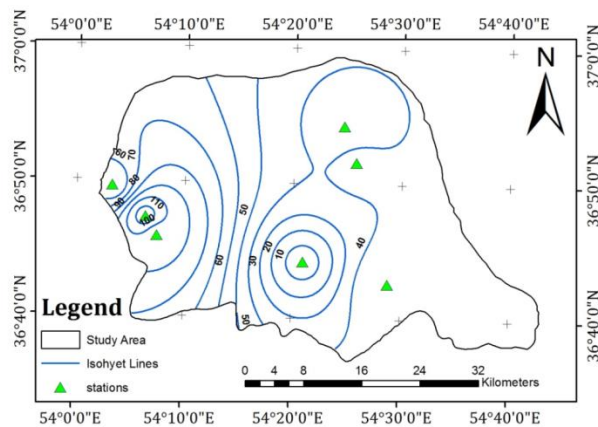

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Figure 4: Spatial distribution of rainfall for the storm of September 2008 in study area.
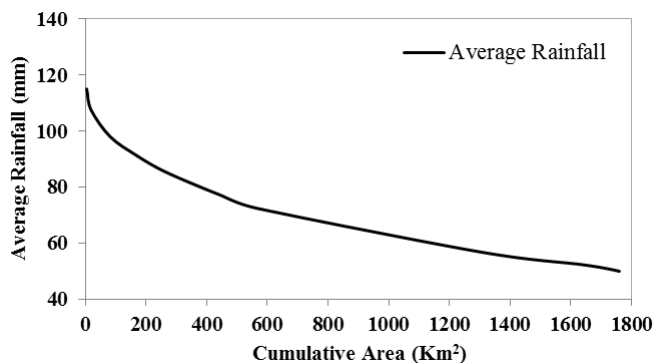
Figure 5: Depth-Area-Duration curve for the storm of September 2008 in study area.