Comparative study of multi-station method and Hershfield's approaches for PMP determination (case study: Northeast of Iran)

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Abstract

The maximum daily rainfall values for 36 homogeneous stations in the northeast of Iran were adopted to estimate the appropriate Probable annual Maximum Precipitation 1-day precipitation (PMP_{24}) values. PMP_{24} was found as 128.2–284.2, 62.7–160.2 and 124 mm for Hershfield 1, Hershfield 2 and multi-station approach, respectively. The ratio of PMP_{24} to the highest observed 1-day rainfall was consistent for the second approach of Hershfield. It was in harmony with the multi-station method, but varied widely for Hershfield 1. This may be the result of different record length effect on Hershfield 1 approach. Finally, the map of PMP_{24} isochrones was prepared for the second approach of Hershfield for over northeast of Iran.

Keywords Probable maximum precipitation · Hershfield · Multi-station · Northeast of Iran

Introduction

Estimates of probable maximum precipitation (PMP) have been used for many years to derive a “maximum” loading for designs of high hazard infrastructure such as dams and nuclear power plant structures (Prasad et al. 2011; Nathan et al. 2016). The PMP is most commonly used to derive an extreme flood using an appropriate model of the rainfall–runoff process (Federal Energy Regulatory Commission 2001), or it can be used to assess the risk of direct flooding on critical infrastructure due to localised rainfall (Huffman et al. 2014).

World meteorological organization (WMO) defined PMP as the greatest depth of precipitation for a given duration which is meteorologically possible over a given station or a specified area (WMO 1986). There are two main methods, including hydro meteorological and statistical approaches to calculate PMP. The second method is more useful when

meteorological data such as dew point, temperature, and wind speed are not available, but it requires a large amount of rainfall data.

Hershfield was a pioneer who developed a statistical method for estimating PMP values for small areas around the world. In this method, series of maximum annual daily rainfalls at an observation point are required, yet the partial duration series (Ghahraman and Khalili 2004) may be an alternative. He assumed the frequency factor (K_m) is equal to 15, but Koutsoyannis (1999) showed 15 for K_m is starter of a return period equal to 6000 years, which is not in harmony to PMP definition (Koutsoyannis 1999). In 1986, WMO modified the Hershfield method and introduced the record length, and the maximum value observed for the correction of the K_m .

In 1997, Eliasson presented multi-station method by applying the annual maximum 1-day precipitation (P_{24}) in the United States of America and Iceland (Eliasson 1997). This approach is based on Gumbel type 1 and its derived distributions (EV1). Since PMP can occur at every point within a homogenous region, this method is based on a combination of data from all stations in such a region. In multi-station method, PMP is less affected by data length and the highest values. Independency of P_{24} in different stations is the base of the multi-station method. In dry regions, more than 30 km is the suggested average distance between stations (Buishand 1984).

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Desa et al. (2001) and Desa and Rakhecha (2007) introduced a new approach to the Hershfield method. They considered the maximum value of observed rainfall, which caused a severe decrease in K_m . In Iran, Ghahreman used this method over Atrak watershed (Ghahreman 2008).

The moisture maximization approach has a simple technique for controlling the risk of overestimating PMP where the maximization ratio is limited by an upper bound. The upper bound limit depends on storm records and watershed characteristics (Rouhani and Leconte 2016). Rouhani and Leconte (2016) proposed an approach to estimate the maximization ratio which does not impose an upper limit. Their approach, was based on constructing annual maximum precipitable water time series with precipitable water values for which atmospheric variables are similar to the original event to be maximized. Results showed that maximization ratio values were lower than the proposed upper bound value in the province of Quebec, Canada. In comparison to the approach using an upper bound, the proposed approach reduced the PMPs in the study area by 11% (Rouhani and Leconte 2016).

To understand how PMP may respond to projected future climate forcings, Rastogi et al. (2017) used a physics-based numerical weather simulation model over the Alabama-Coosa-Tallapoosa River Basin in the southeastern United States. Results showed that atmospheric warming could be one important factor controlling the increase in PMP (Rastogi et al. 2017).

PMP in Barcelona (Spain) was estimated for durations ranging from 5 min to 30 h by Casas et al. (2011). Two different techniques were used: the Hershfield method, and a physical method based on the maximization of actual storms. The PMP values obtained using the two techniques were very similar. In both cases, the increasing behavior of the PMP with duration was found, with the increase especially

notable for the durations 2–9 h, and not significant from 12 h on up (Casas et al. 2011).

Climate change effects on PMP were analyzed by Kunkel et al. (2013). Climate model simulations indicated a significant future increase in water vapor concentrations. The changes in maximum values for the continental United States were approximately 20–30% by 2071–2100. The authors concluded that PMP values would increase in the future due to higher levels of atmospheric moisture content and as a result of higher levels of moisture transport into storms.

The purpose of this research is to carry out a study on the estimation of PMP for a 24-h duration using multi-station method and two approaches of Hershfield technique for stations in the northeast of Iran and to select the most appropriate method.

Study area and data used

The need for the development of water resources has become a considerable importance in the northeast of Iran with a view to ensure sufficient potable and industrial water supplies, providing irrigation for food production and flood control. The study area, with more than 60,000 km² areas, is located in the northeast of Iran. The rivers within this area are run either outside the Iranian borders or drain into the interior deserts. This watershed is bordered in the north by Turkmenistan, in the northwest by Semnan and Golestan provinces, and in the west, east and south by Khorasan Razavi province (Fig. 1). The characteristics of the stations are given in Table 1. The data record ranges from 13 to 48 years. The highest station is Marashk (1870 m) and the lowest one is Hatam Ghale (490 m). The average annual relative humidity and the annual average rainfall (for 30 years)

Fig. 1 Location map of the study area

Table 1 List of stations within the study area

Number	Station name	Geographic characteristics			Station parameters				
		Latitude	Longitude	Height	N	P_4	$\bar{P}_{24}$	S	C_V
1	Aghmazar	37-41-32	56-55-10	580	30	50	25.1	9.36	0.37
*2	Radkan	36-48-23	59-0-30	1210	28	52	24.7	7.65	0.30
3	Dahaneh-ye-Akhlamad	36-36-00	58-57-0	1460	26	58	25.8	10.27	0.39
4	Ali Mohammad	37-45-00	57-37-28	1260	30	62	28.2	10.71	0.37
5	Ardak	36-43-47	59-23-32	1310	26	49	23.3	7.49	0.31
6	Asadli	37-17-37	57-21-33	1800	16	56	36.1	12.27	0.33
7	Baba Aman	37-28-40	57-26-19	1020	28	39	25.1	7.52	0.34
8	Barbar Qaleh	37-28-23	57-18-00	1070	33	50	24.2	9.61	0.39
9	Bar-Aryeh	36-27-34	58-42-18	1560	48	55	32.6	10.71	0.32
10	Barezoo	37-35-55	57-57-48	1400	31	50	22.8	10.0	0.43
11	Besh Ghardash	37-24-50	57-17-58	1160	17	35	22.7	6.90	0.30
12	Qareh Qanloo(Bahar)	38-16-42	56-45-20	840	20	60	24.5	11.33	0.45
13	Esfarayen	37-04-44	57-30-40	1210	29	47	28.3	9.44	0.33
14	Bojnord	37-28-00	57-19-00	1091	27	41	24.4	8.18	0.33
15	Chenaran	36-38-56	59-07-36	1170	15	49	21.1	10.12	0.46
*16	Dolat-Abad	36-26-17	59-10-00	1510	27	42	24.3	7.21	0.29
17	Darkesh	37-26-12	56-45-00	1060	30	47	32.9	7.51	0.22
18	Farooj	37-14-00	58-13-00	1200	30	40	20.6	7.46	0.35
19	Garmkhan	37-31-45	57-28-38	920	30	45	27.7	8.14	0.29
20	Ghadir Abad	36-48-19	58-58-22	1175	13	10	19.8	5.77	0.28
21	Gholaman	38-03-23	57-08-39	1240	13	57	29.7	11.37	0.37
22	Qezelqan	37-39-52	57-25-12	1040	25	61	26.1	12.67	0.47
23	Golmakan	36-28-48	59-09-00	1450	32	41	25.3	7.68	0.30
24	Hatam Ghale	37-18-40	59-22-00	490	34	45	22.8	9.55	0.43
25	Hesseh Gah	37-39-23	57-01-55	620	19	35	25.4	5.91	0.23
*26	Incheh-Olya	37-37-29	56-24-14	770	25	26	17.2	5.26	0.30
27	Jahan Abad	37-18-11	58-12-34	1185	23	50	25.3	9.04	0.35
28	Kabkan	37-15-00	58-54-37	1435	21	30	23.8	5.25	0.22
29	Khartoot	37-55-24	56-39-40	695	30	19	28.9	7.37	0.25
30	Marashk	36-49-12	59-32-48	1870	20	58	26.4	10.86	0.40
31	Chaman Bid	37-28-40	57-26-19	1020	30	60	25.1	7.52	0.34
32	Sar Asiab	36-24-00	59-20-00	1270	21	47	24.3	8.01	0.32
33	Se Yek Ab	37-24-39	57-56-49	1110	31	46	24.9	8.61	0.34
34	Shamkhal	37-35-21	58-27-12	1495	26	53	28.0	10.21	0.36
35	Shir Abad	37-30-56	56-55-30	860	31	63	35.6	17.18	0.47
36	Taghun	36-25-27	58-40-50	1495	28	50	27.5	7.56	0.27
37	Yangajeh	36-49-52	58-15-40	1680	24	58	34.2	11.24	0.32
38	Dar Band	37-36-01	56-59-13	700	30	41	23.9	7.67	0.32
39	Qatlish	37-46-00	57-18-04	980	31	45	20.6	8.38	0.41

N data length (years), P_{24} observed 1 day highest rainfall value (mm), $\bar{P}_{24}$ mean observed 1 day highest rainfall value (mm), S standard deviation, C_V Coefficient of variation ($C_V = S/\bar{P}_{24}$)

*Heterogeneous stations by Mann–Kendall rank test

are about 55.6% and 270 mm, respectively, indicating dry weather.

Methodology

Homogeneity of the data series

The use of longer series in the estimation of PMP, is only valid if they show no long-term changes in their behavior

(Desa et al. 2001). To investigate such inhomogeneities, in the annual maximum rainfall series for 39 stations, non-parametric Mann–Kendall rank test was applied. The statistic is computed from $\tau = \left\{ 4 \sum n_i / [N(N-1)] \right\} - 1$ (n_i is the number of values larger than i th value in the series subsequent to its position in the series of N values). Its expected value in a random series is zero, and its standard deviation (S_τ) is given by $S_\tau = \sqrt{\{(4N+10)/[9N(N-1)]\}}$. The ratio of $\tau-S_\tau$ is considered as an indication of a possible trend in the data. For no trend in the data series, this value lies within the limits of ± 1.96 at the 5% level of significance (Hirsch and Slack 1984).

Theoretical background of the Hershfield method

The Hershfield technique for estimating PMP is an adapted version of Chow (1951) for the frequency analysis of rainfall. Chow (1951) suggested the following formula for most frequency distributions applicable for hydrological analysis:

$$X_t = \bar{X}_n + K_t S_n \quad (1)$$

where X_t is the annual maximum rainfall for the return period of t years, $\bar{X}_n$ and S_n is the mean and standard deviation of the annual maxima of size n , respectively and K_t is the frequency factor depending only on t and the frequency distribution fitting extreme values of hydrologic data (Chow 1951).

Hershfield (1961, 1965) considered that for the PMP estimation, there is a value of the frequency factor which will not be exceeded, say K_m , and he used Chow's equation in a modified form as:

$$X_{\text{pmp}} = \bar{X}_n + K_m S_n \quad (2)$$

where X_{PMP} is the PMP rainfall for a given station for specific duration, $\bar{X}_n$ and S_n , respectively, are the mean and standard deviation of the annual maxima, and K_m is the frequency which is considered to be 15. This value may not be suitable for different stations under different climatic conditions.

Statistical estimation of PMP₂₄

World meteorological organization modified Hershfield method and introduced it as a manual for estimation of PMP, in this approach (a) K_m is estimated according to $\bar{X}_n$, (b) the highest observed data is excluded, and $\bar{X}_{n-1}$ and S_{n-1} are calculated, (c) the correction factors for $\bar{X}_n$ and S_n is estimated using $\bar{X}_n$, S_n , $\bar{X}_{n-1}$, and S_{n-1} , (d) by considering the data length another correction factor for $\bar{X}_n$ and S_n is estimated, (e) $\bar{X}_n$ and S_n are adjusted, (f) X_{PMP} is calculated (W.M.O. 1986). In this paper, the recent method is named as Hershfield 1 approach.

Desa et al. (2001) used this formula for calculating K_m :

$$K_m = (X_1 - \bar{X}_{n-1}) / S_{n-1} \quad (3)$$

where X_1 is the highest observed annual maximum rainfall in the series, and $\bar{X}_{n-1}$ and S_{n-1} are the mean and standard deviation of the annual maximum, respectively, when the highest value is excluded in calculating the parameters (Desa et al. 2001). By applying Eqs. (3) and (2), K_m and the corresponding 1-day PMP value was determined, respectively. The so-called method is named as Hershfield 2 approach.

Theoretical background of the multi-station method

Annual maximum 1-day precipitation (P_{24}) is usually considered to be an independent identically distributed (i.i.d.) stochastic variable. An i.i.d. may have any distribution function, and the maximum will be distributed according to the extreme value distribution function to whose domain of attraction it belongs (Leadbetter et al. 1983). The most commonly applied extreme value distribution function is type 1 (EV1), or the Gumbel, distribution. EV1 is in its own domain of attraction, therefore, both the i.i.d. and its maximum will be asymptotically distributed according to EV1, when this distribution function is used. The distribution function for annual maxima of individual meteorological stations will often follow the EV1 very closely in the medium-range of values, but it deviates from it for the highest and lowest return periods. These deviations and EV1's lack of an upper limit complicate the use of this distribution function in estimating PMP values (Eliasson 1997). This problem may be solved using a transformed distribution function (TDF) and cut-off distribution function (ODF), both derived from the basic distribution function (BDF) EV1. They are defined as follows (Eliasson 1997):

$$\text{BDF} : F(z) = \exp[-\exp(-z)] \quad (4)$$

$$\text{TDF} : F(z) = \exp \left[-\exp \left(-z + \frac{k}{y_{\text{lim}} - z} \right) \right] \quad (5)$$

$$\text{ODF} : \begin{cases} F(z) = \exp[-\exp(-z)] & z < y_{\text{lim}} \\ F(z) = 1 & z \geq y_{\text{lim}} \end{cases} \quad (6)$$

$$z = \frac{x}{a} + m, \quad y_{\text{lim}} = \frac{x_{\text{PMP}}}{a} + m$$

where y_{lim} is limiting reduced variate, a is scale parameter, m is location parameter, k is a negative constant and x_{PMP} is Index for probable maximum. The ODF is the limit of the TDF when $k \rightarrow 0$. It belongs to the domain of attraction of EV1 (Eliasson 1997).

In this paper, it will be assumed that annual maximum precipitation is an i.i.d. variable X .

We further assume:

(I): the distribution function is a TDF, (II): $y_{\lim} > 9$ and (III): $k > -1$.

If assumption (I) is true, the annual maximum data for each station are distributed according to (4). In an EV1 plot, the data will follow the BDF up to a certain point that depends on the value of k and $y_{\lim}$, and there it will deviate from the EV1 line in the direction of higher y values. To see this trend in one station, we need more observation years than are available in one meteorological station. This difficulty may be overcome by regional pooling of data. Data from different meteorological stations have different means and standard deviations. The following standardisation is used to deal with these differences:

$$\mu = (x_i - \bar{X}_i) / S_i \quad (7)$$

$\bar{X}_i$ estimated mean of annual maxima at station i , S_i estimated standard deviation at station i , μ standardised annual maxima.

Using this standardisation, the estimated BDF is the same for all stations as long as it is a two parameter EV1 distribution function because all stations are now with an estimated zero mean and a standard deviation of one. The BDF does not have to be EV1 as stated in assumption I, but if it is, the pooled standardised data will plot on a line in an EV1 plot, and the line will be straight apart from the previously mentioned deviations that depend on the value of k and $y_{\lim}$ (Eliasson 1997).

If assumption (II) holds, first and second moments will be almost identical for the ODF and the BDF, therefore, estimates of scale and location parameters can be made without knowing the limiting reduced variate. If this assumption holds, we can use the model without a regional estimate of the limiting reduced variate. We do not have to use its value except in PMP estimates, and in this case, an envelope curve may be used to define the probable maximum value, as is done in the Hershfield and NERC methods. Using ODF instead of BDF has the advantage that ODF has the upper limit that BDF does not have (Eliasson 1997).

If assumption (III) holds, the difference between ODF and TDF will be so small that the estimates of scale and location parameters in the TDF can be made without knowing the actual value of k (Eliasson 1997). To summarise, if assumptions I–III holds, we can standardise the annual maxima for each station with its estimated mean and standard deviation.

The cumulative density function for EV1 is:

$$F(x) = \exp[-\exp(-y)], \quad \text{where } y = (x - m)/a \quad (8)$$

The parameters a and m are scale and location parameters. We used the method of moments (MOM) to estimate the parameters by $a = 0.7797S$ and $m = \bar{x} - 0.45S$ where S is

the standard deviation of data and $\bar{x}$ is the mean of the data (Eliasson 1997).

$y_{\lim}$ and PMP₂₄ calculation

From NERC report (1975) it is possible to derive the following relation for $y_{\lim}$:

$$y_{\lim} = 10.7 - 0.0071P_5 \quad 25 < P_5 < 200 \text{ mm/day} \quad (9)$$

where P_5 is defined as the maximum annual precipitation with return period of 5 years. The ODF may now be written as follows:

$$\begin{aligned} x &= p_5[1 + C_i(y_i - 1.5)] & y_i < y_{\lim} \\ x &= x_{PMP} & y_i \geq y_{\lim} \end{aligned} \quad (10)$$

The simplest way to derive (Eq. 10) is to take the double logarithm of the ODF (Eq. 6), write down the P_5 value and subtract it from the formula for x . The coefficient C_i may be denoted as the slope coefficient because it is a dimensionless slope of the line (Eq. 10) in a x/P_5 - y plot. Each station brings about one value of C_i . Now Eq. 10 contains the two parameters P_5 and C_i . The mean and the standard deviation may be used instead, and P_5 and C_i calculated in terms of these parameters. Doing so C_i becomes (Eliasson 1997):

$$C_i = 0.78S_i / (\bar{X}_i + 0.72S_i) \quad (11)$$

$\bar{X}_i$ average at station i , S_i standard deviation at station i .

While $y_{\lim}$ is a regional parameter, both P_5 and C_i are local parameters playing the same role of the average and the coefficient of variation in Hershfield 1 approach.

In each station, we can estimate the PMP value using Eq. 10 and inserting the local C_i value and $y_{\lim}$. At station i we will have:

$$x_i = p_5[1 + C_i(y_{\lim} - 1.5)] \quad (12)$$

According to assumption (I) there is no higher x value possible at point i . Therefore, this value is the PMP value at this particular location i . However, a higher PMP value in the region as a whole may exist. We seek the maximum x in the region remembering that $y_{\lim}$ is the same in all points (or stations).

$$\begin{aligned} \text{PMP} &= \text{Max}\{x_i\} = \text{Max}\{P_5[1 + C_i(y_{\lim} - 1.5)]\} \\ &= \text{Max}(P_5)[1 + \text{Max}\{C_i\}(y_{\lim} - 1.5)] \end{aligned} \quad (13)$$

Using a guideline length of 5–30 km between independent stations (Buishand 1984), in the P_5 range of 25–200 mm, the distribution of the $\text{Max}\{C_i\}$ may be calculated by Eliasson (1997):

$$\text{Max}\{C_i\} = \bar{C}_i + \text{Ln}(N_s S C_i / C) \quad (14)$$

Table 2 Frequency distribution of K_m values for Hershfield 1 approach

K_m	< 17.9	17.9–18.2	18.2–18.5	> 18.5
Frequency	1	7	22	9

Fig. 2 The plot of K_m versus $\bar{P}_{24}$ for Hershfield 1 and Hershfield 2 approaches

$\bar{C}_i$ expected value of the highest C_i in the region, $\bar{C}_i$ estimated average C_i value for the region, SC_i estimated standard deviation of C_i values in the region, N_s number of stations, $C = 1/a$, a theoretical value of the EVI scale parameter for pooled data ($C = 1.283$).

Results

Data were thoroughly checked, and any doubtful observations were eliminated. The homogeneity of all 39 stations was checked by non-parametric Mann–Kendall rank test. The ratio of τ/S_τ for three stations of Radkan (station no. 2,

Table 1), Dolat-Abad (station no. 16), Incheh-Olya (station no. 26) were 2.3, 4.4 and 3.9, respectively; hence, these heterogeneous stations were discarded.

Hershfield 1 approach

To estimate PMP; 1-day annual maximum rainfall values of 36 stations were analyzed and for each station the values of $\bar{X}_{n-1}$, $\bar{X}_n$, S_n , S_{n-1} and the coefficient of variability ($C_V = S_n/\bar{X}_n$) were calculated. The range of K_m and PMP values was 17.6–18.8 and 128.2–284.2 mm (Tables 2, 4; Fig. 2), respectively. K_m , PMP_{24} and P_{24} are affected by location and cannot be used as a comparative factor, but the ratio of PMP_{24}/P_{24} is shown to facilitate comparisons for different stations (Desa et al. 2001; Desa and Rakhecha 2007; Ghahraman 2008). The so-called ratio varied between 2.54 and 6.77 (Table 4; Fig. 3); the partially wide range of PMP_{24}/P_{24} is in part influenced by short record length of the stations.

Hershfield 2 approach

In this method, Eqs. (3) and (2) were applied to K_m and PMP calculation. The results are summarized in Table 4. As shown, the values of K_m varied between 1.82 and 6.18 (Tables 3, 4; Fig. 2), with the latter being the upper limit of the estimated K_m . As PMP deals with unusual rainfall values, the corresponding frequency factor must also be chosen from the extremely high values. For the study area, K_m would be 6.18 (the maximum value of K_m for Hershfield 2 approach—Table 4). Using K_m of 6.18, the mean ($\bar{X}_n$) and standard deviation (S_n) for each station, PMP values for a 1-day duration for all stations were computed using Eq. (2). An average factor of 1.13 (Tomlinson 1980) was used to convert 1-day PMP estimates into 24-h PMP. Values of estimated PMP_{24} were between 62.7 and 160.2 mm, and the ratio of PMP_{24}/P_{24} varied between 1.50 and 2.72 (Table 4; Fig. 3) which was in harmony with Desa et al.

Fig. 3 The ratio of PMP_{24}/P_{24} for different studies

Table 3 Frequency distribution of K_m values for Hershfield 2 approach

K_m	2.4 >	2.4–3	3–3.6	3.6–4.2	4.2–4.8	4.8–5.4	5.4–6	6 <
Frequency	10	6	8	7	2	1	1	1

Table 4 PMP_{24} by different approaches

Method	Hershfield 1 approach			Hershfield 2 approach			Multi-Station approach			
Station number	K_m	PMP_{24} (mm)	PMP_{24}/P_{24}	K_m	PMP_{24} (mm)	PMP_{24}/P_{24}	m	a	P_5 (mm)	C_i
1	18.5	200.1	4.00	3.05	94.9	1.90	20.89	7.30	31.8	0.2293
3	18.5	207.3	3.57	4.15	100.9	1.74	21.18	8.01	33.2	0.2413
4	18.4	212.0	3.42	4.00	106.6	1.72	23.38	8.35	35.9	0.2326
5	17.6	143.6	2.93	4.89	78.7	1.61	19.93	5.84	28.7	0.2036
6	17.9	284.2	5.07	1.85	126.5	2.26	30.58	9.57	44.9	0.2130
7	18.5	172.6	4.41	2.00	80.9	2.07	21.72	5.86	30.5	0.1922
8	18.5	208.1	4.16	3.11	94.5	1.89	19.88	7.49	31.1	0.2409
9	18.1	233.2	4.24	2.22	111.6	2.03	27.78	8.35	40.3	0.2072
10	18.7	211.2	4.22	3.20	95.6	1.91	18.30	7.80	30.0	0.2600
11	18.7	167.6	4.77	2.05	73.8	2.11	19.60	5.38	27.7	0.1945
12	18.5	198.0	3.30	4.74	106.8	1.78	19.40	8.83	32.6	0.2706
13	18.5	200.2	4.26	2.18	97.9	2.08	24.05	7.36	35.1	0.2098
14	18.5	182.0	4.44	2.26	84.7	2.06	20.72	6.38	30.3	0.2106
15	18.7	191.0	3.90	4.38	91.0	1.86	16.55	7.89	28.4	0.2781
17	18.1	184.0	3.91	2.04	89.6	1.91	29.52	5.86	38.3	0.1529
18	18.7	170.0	4.25	3.02	75.3	1.88	17.24	5.82	26.0	0.2240
19	18.4	188.0	4.18	2.70	88.1	1.96	24.04	6.35	33.6	0.1892
20	18.8	150.0	5.00	2.16	62.7	2.09	17.20	4.50	23.9	0.1879
21	18.3	227.0	3.98	3.61	109.3	1.92	24.58	8.87	37.9	0.2341
22	18.4	197.0	3.65	3.50	110.3	2.04	20.40	9.88	35.2	0.2806
23	18.5	175.0	4.27	2.23	82.3	2.01	21.84	5.99	30.8	0.1943
24	18.7	209.2	4.64	2.59	92.5	2.06	18.50	7.45	29.7	0.2510
25	18.5	146.0	4.17	1.82	69.9	2.00	22.74	4.61	29.7	0.1554
27	18.5	189.5	3.79	3.47	91.8	1.84	21.23	7.05	31.8	0.2217
28	18.6	140.0	4.00	2.51	63.5	1.81	21.44	4.09	27.6	0.1485
29	18.3	180.0	3.53	3.71	84.1	1.65	25.58	5.75	34.2	0.1681
30	18.4	264.0	6.77	4.10	105.9	2.72	21.51	8.47	34.2	0.2475
31	18.0	152.4	2.54	6.18	89.7	1.50	21.70	5.85	31.5	0.1918
32	18.5	159.0	3.38	3.80	83.4	1.77	20.69	6.17	29.9	0.2076
33	18.5	190.0	4.13	2.80	88.1	1.92	21.02	6.63	31.0	0.2159
34	18.3	222.0	4.19	3.45	92.1	1.74	23.41	7.96	35.4	0.2253
35	18.0	277.0	4.40	6.00	160.2	2.54	27.87	13.40	43.5	0.2794
36	18.4	162.0	3.24	3.74	83.6	1.67	24.10	5.89	32.9	0.1790
37	18.0	272.0	4.69	2.43	117.1	2.02	29.04	8.76	42.2	0.2078
38	18.2	178.4	4.35	2.45	72.2	1.76	20.45	5.98	29.4	0.2033
39	18.7	186.0	4.13	3.52	72.3	1.61	16.83	6.53	26.6	0.2454

(2001), Desa and Rakhecha (2007) and Ghahreman (2008) studies (Fig. 3).

Multi-station method

P_5 and C_i factors were calculated after computing method of moment parameters (a and m), results are shown in Table 4, C_i values range between 0.1485 and 0.2806. The C_i station values in Fig. 4 seem to cluster around the average value

Fig. 4 The plot of C_i versus P_5

Fig. 5 EV1 plot of 500 values in the study area

and lack a specific pattern. This verifies the homogeneity of the stations. Standardised data were pooled. There are 1103 points altogether, and the 500 highest points are shown (Fig. 5). As shown the data follow the EV1 up to a certain point ($y=3$) and there it will deviate from the EV1 line in the direction of higher y values. Finally, y_{lim} , $\text{Max}\{C_i\}$ and PMP_{24} were calculated 10.4, 0.20 and 124 mm, respectively.

Ghahreman (2008) analyzed yearly maximum 1-day rainfall data of 20–36 years for 30 stations in the Atrak watershed region in the northeast of Iran to estimate PMP_{24} based on Hershfield 2 approach. The highest value of K_m was found to be 9.63, PMP_{24} over the Atrak watershed ranged from 97 to 295 mm and the ratio of PMP_{24}/P_{24} was between 1.95 and 3.01 (Ghahreman 2008). The result of Ghahreman analysis is in harmony with Hershfield 2 approach in the current study. However, such variations between the two results may be due to the differences observed in the climatic conditions and shorter record length in Ghahreman's study. In

2001, Desa et al. analyzed yearly maximum 1-day rainfall data of 30–60 years for 33 stations over Selangor in western Malaysia to estimate PMP_{24} by Hershfield 2 approaches. K_m and PMP_{24} were found between 2 and 8.7 and 375–500 mm, respectively, which were higher than the current study, such variations between two researches may originate from the difference in climatic conditions, and longer record length in Desa's study. Nevertheless, the ratio of PMP_{24}/P_{24} was equal between the two studies. Desa and Rackham (2007) used Hershfield 2 approach in southern Malaysia, K_m and PMP_{24} were obtained between 1.1 and 8 and 373–1209 mm, respectively (Desa and Rakhecha 2007). The higher PMP was calculated than Desa et al. (2001) study may be due to the differences in the climate, but the K_m was approximately equal.

Serious attempts were made to find a relation between PMP_{24} (by Hershfield 1 and Hershfield 2 approaches) and characteristics of the meteorological stations like height, data length, geographic characteristics, etc., but unfortunately no trend was found. In Hershfield 1 and Hershfield 2 approaches, we can claim that if we select just the PMP_{24} of one station, it is possible to have greater values for other points while in multi-station method, a common value is being yield for PMP_{24} which is because of using a combination of data from all stations.

The map of PMP_{24} was prepared for both approaches of Hershfield (Fig. 6). For both approaches, the high PMP_{24} values generally can be seen in the south and the southwest, and the low values can be seen in the east and the northwest of the study area (Fig. 6).

Conclusion

The main purpose of this study was to introduce a simple standardized method of PMP_{24} computation using multi-station method and two approaches of Hershfield technique for stations in the northeast of Iran. Due to record lengths, there is a high fluctuation in calculated data of Hershfield 1 approach. The so-called problem was adjusted by Hershfield 2 approach, in which the PMP range was approximately half of the Hershfield 1. The ratio of PMP_{24}/P_{24} was consistent and was in harmony with the multi-station value. Multi-station and Hershfield 2 methods could be recommended for other regions. However, future records may be needed to verify the ensuing results of PMP_{24} and the corresponding resulted probable maximum flood (PMF) values.

Fig. 6 The map of PMP₂₄ in the northeast of Iran according to **a** Hersfield 1 approach and **b** Hersfield 2 approach

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