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Estimation of probable maximum precipitation for one day duration: A case study of Gujjar Khan in Potwar region, Pakistan

Muhammad Waseem Boota, Ghulam Nabi, Haseeb Ahsan and Tanveer Abbas
Centre of Excellence in Water Resources Engineering, UET Lahore, Pakistan

Abstract

Daily rainfall data of Gujjar khan for a period of 30 years (1961-1990) were collected from Pakistan meteorological department (PMD), Lahore. Annual maximum one day precipitation was sorted from the precipitation data to compute the probable maximum precipitation (PMP) for 1-day duration. The Hershfield technique and Gumble distribution of extreme values were used for the estimation of 1-day probable maximum precipitation based on frequency factor. The frequency factor was used to compute for 1-day PMP values in the study area. The PMP for Gujjar khan was estimated to be 357.39 mm and the ratio of the 1-day PMP to highest 1-day precipitation was 1.19. The maximum 1-day precipitation for different return periods 2, 5 10, 20, 25, 50, 100, 200, 500 and 1000 years were also estimated. The estimated maximum rainfall and PMP values could be useful in designing of soil and water conservation practices, design of small dams in the study area.

Keywords: Probable maximum precipitation; Hershfield method; Gumble method; Frequency factor.

1. Introduction

The water scarcity trends are evident in the Potwar plateau and there are chances that it might result in severe water crisis in the near future. Agriculture in the Potwar is dependent upon rainfall. In Potwar region two third of the total rainfall occurs during the three months of monsoon while the nine remaining months are dry and get only one-third of annual precipitation (Majeed et al., 2010). The topography of the hilly area with steep slopes erodes the fertile land; delayed monsoon and erratic winter rainfall make the crops yield very uncertain. Drought is frequently experienced and now witnessed in the recent years. Ground water lowered due to the installation of tube wells to meet the water requirements resulting in intrusion of saline water into fresh layer as well as extremely restricted well yield (Majeed et al., 2010).

The major source of water in this area is rainfall about 30 % of rainfall is lost which is sufficient to irrigate two million acres if properly managed. Precipitation in Potwar region varies from 500 to 1000 mm per annum. 60 % of the rainfall occurs in the monsoon season and 40% in the remaining season (Siddiqui et al., 2011). During the dry spell (1997-2003) there was little rainfall and the farmers started migrating to other areas for their survival. Water table also lowered as a result of dry spell at rate of 0.6 to 2.5 m per annum and intrusion of saline water into fresh water take place (Majeed et al., 2010). Water scarcity problem and efficient management of ground water as well as artificial re-charging of groundwater aquifer in Potwar region can be enhanced by construction of water conservation construction structures such as mini dams, check dams, intermediate dams and small dams.

The need for the development of storage reservoirs and dams has become of considerable importance in the Pakistan with a view to ensuring sufficient potable and industrial water supplies, providing irrigation for food production and flood control. The study of PMP for Potwar region is important in the designing of dams and water conservation structures to store the water. In the design of reservoir and flood control dams in upstream of populated areas, most important issues are to measure the possible flood at a location to ensure the safety of local residence (Maidment, 1992). There are many examples where improper design caused catastrophic incidents such as Fukushima earthquake. Probable maximum precipitation study provides rational information that assist in optimal design of dam, reservoir storage capacity and flood-carrying structures (spillway and flood carrying tunnel). Hydrologist use the Probable maximum precipitation magnitude to calculate the probable maximum flood (PMF) and PMF is used for design of hydraulic and water conservation structures.

According to WMO (2009) Probable Maximum Precipitation (PMP) is defined as the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends. Statistical approach is used to calculate the PMP in those areas where at least 30 to 40 years daily precipitation data is available. Statistical approach is used for the quick estimation of PMP. This technique also used for much larger areas and mostly used for small areas of watershed up to 1000 km. No meteorologist is needed in statistically approach and this technique requires less time to apply (WMO, 2009).

A variety of procedures are available to compute the PMP such as Local storm maximization method, Storm transposition method, Inferential method, Generalized method and Statistical method. The above mentioned procedures are used with respect to watershed location and data availability (WMO, 1986; Rakhecha et al., 1992; Collier and Hardaker, 1996). Singh et al. (2014) computed the 1-day PMP in Jhalarapattan which is the region of Rajasthaan. 51 years rainfall data were collected from Jhalarapattan meteorological department. The Hershfield techniques and Gumble distribution were used for the estimation of 1-day PMP. The frequency factor K was found to be 6.12 which are used to estimate PMP value. The probable maximum precipitation for the Jhalarpattan was calculated 509.11 mm and the ratio of 1-day PMP value to the highest 1-day precipitation was found 1.24. Casas et al. (2011) estimated the PMP in Barcelona for duration of 5 minutes to 30 hour. Hershfield method and Physical method were used based on maximization of actual storms. It was concluded that PMP results obtained using two techniques are close to each other.

Ghahraman et al. (2008) estimated the 1-day PMP over Attrak watershed by using the Hershfield formula with frequency factor of 15. Rakhecha and Soman (1994) estimated the 2-day PMP in southern Indian region using the Hershfeld's formula. Two day precipitation data for 80-years were obtained. They developed a mathematical relationship between the "K" and mean annual precipitation Xn i.e. $m = 18.15 \exp(-0.0448Xn)$. Desa et al. (2001) carried out the PMP in Malaysia by using Herrshfield technique. 1-day maximum precipitation data of about 30-60 years for 33 stations in Malaysia were used to estimate the PMP. The value of "K" was calculated 8.7 which are based on the real precipitation data.

Statistically technique is a convenient approach which is based on frequency analysis. Statistically approach is preferred in those areas where meteorology parameters such as hourly precipitation, dew point temperature and winds speed data are unavailable (Rakhecha and Soman, 1994). A major shortcoming of statistically approach exists' in that sense it gives points value of probable maximum precipitation. Area-reduction curve required for modifying the points value for numerous sizes. Another problem for estimating the PMP is to determine the frequency factor, so many researcher use different frequency factor values (Dhar and Damte, 1969). In present study, PMP for 1-day duration is estimated by using Hershfield technique and Gumble theory of extreme value for Gujjar khan station which is located in the Potwar region.

2. Study area descriptions

Gujjar khan is tehsil of Rawalpindi District and it is the largest tehsil of Punjab. The land use classification of study area is shown in Figure 1. It is approximately 56 kilometers southeast of Islamabad and 221 km to the north west of Lahore and covering an area of 1,466 Km^2.The elevation of the study area is 453 m above mean sea level and it is located between latitudes 33°25' N and longitudes 73°3' E. Gujjar Khan is bounded on the east by Azad Kashmir and Kahuta, on the west by Chakwal and Khushab on the north by Rawalpindi, Islamabad and Attock, on the south by Jhelum, Lahore and Gujrat. Gujjar khan area lies in medium rainfall zone (450-750mm) and number of mini dams in this area is 61 (Majeed et al., 2010). The soil texture of the study region is different; loess, mixed material, alluvial and colluvial in nature and it is derived from sandstone and shale (Siddiqui et al., 2011).

3. Data analysis

Daily rainfall data for thirty year (1961-1990) was collected from Pakistan Meteorological Department (PMD) for rain gauge station at Gujjar khan. Annual maximum daily rainfall was sorted out as presented in Table 2. The Hershfield method was used to estimate the Probable maximum precipitation and Gumble method was used to compute the one day maximum rainfall for different return period i.e. 50, 100, 500, 1000 years for Gujjar khan.

4. Methodology

Statistically technique is most frequently used in under developing countries and rest of the world. This approach is important in a sense that in under developing and sometime in developed countries meteorology parameters data such as hourly precipitation, dew point temperature and wind speed data is unavailable. In meteorological approach above mention parameters are very important for the estimation of PMP. Hershfield method was used to estimate the PMP and and Gumble method was used to calculate the 1-day maximum precipitation at various return periods.

4.1. Hershfield technique

The Hershfield technique was used to estimate the PMP which is based on general frequency equation modified by Chow et al. (1988) as;

$$PMP = \bar{X}_n + K_m \times S_n \qquad (1)$$

Where: $\bar{X}_n$, S_n is the mean and standard deviation of maximum series of N years, and K_m is frequency factor. The empirically derived coefficient Km is calculated by using formula given as:

$$K_m = \left[\frac{(X_m - \bar{X}_{n-1})}{S_{n-1}}\right] \qquad (2)$$

Where: K_m is the frequency factor, X_m is the largest value of the annual series, $\bar{X}_{n-1}$ is Mean of the annual series omitting the largest value and S_{n-1} standard deviation of annual series omitting the largest value.

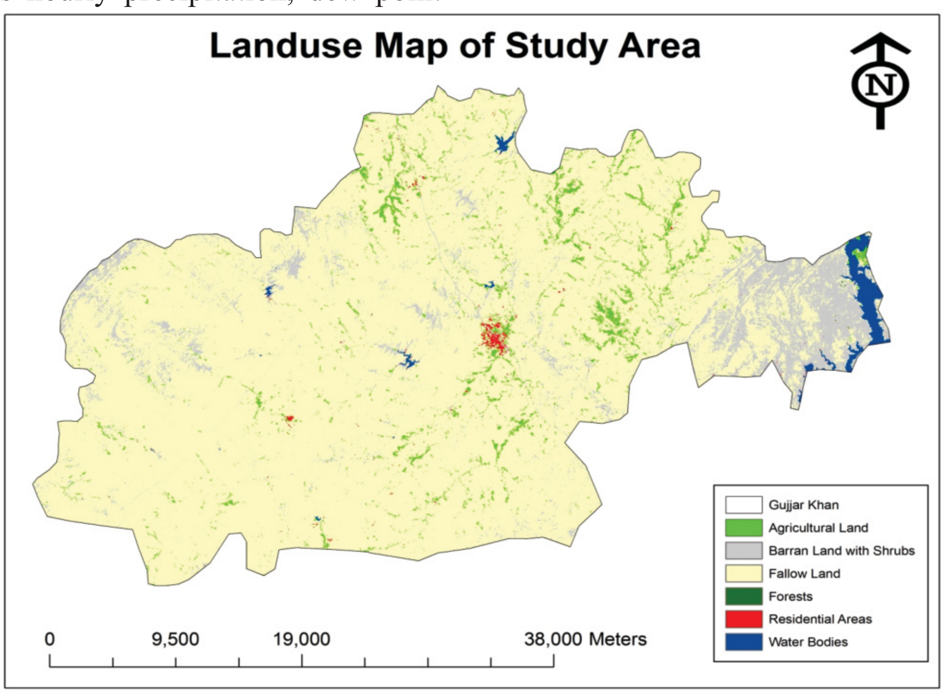

Fig.1. Land use map of Gujjar Khan.

4.2. Gumbel's method

Gumble Distribution is worldwide used probability density functions for hydrological and meteorologically study for the prediction of maximum rainfalls and floods peak. Gumble method of frequency analysis was used to determine the frequency factor at different return periods given below.

$$X_T = X^{-} + K\,\sigma_{n-1} \qquad (4)$$

Where σ_{n-1} = standard deviation of the sample of size and K = frequency factor.

$$K = -\sqrt{6}/\pi\,(\gamma_e + \{\ln[T_X/(T_X - 1)]\}) \qquad (5)$$

Where "γ_e" is the Euler number (0.577216) and "T_X" is the desired return period of the quantity.

$$Y_t = -\left[\ln * \ln\left(\frac{T}{T-1}\right)\right] \qquad (6)$$

In which "Y_t" is known as reduced variate, a function of T (Return period).

5. Results and discussions

Daily 1-day maximum precipitation for thirty years (1961-1990) is presented in Figure 2. Results revealed that the maximum (300 mm) and minimum (48.7 mm) annual 1-day maximum precipitation was observed in the year 1980 and 1963, respectively. Hershfield (1961) method was used to estimate the probable maximum precipitation (PMP) and Gumbel's method (1958) was used to compute one day maximum rainfall for different return period 2years, 5 years, 10 years, and 25 years ... for the study area. The frequency factor (K) and corresponding PMP were determined using Equations (1) and (2), respectively and the statistical parameters like mean, standard deviation, coefficient of variability were computed. Mean and standard deviation were also calculated. The frequency factor (K) was estimated to be 9.49 for 1-day duration and this frequency factor was used to estimate the 1-day PMP.

The observed one day maximum precipitation during the period of analysis is presented in Table 1. This table shows that the average annual 1-day maximum precipitation of Gujjar Khan is 83.58 mm with standard deviation and coefficient of variation 38.47 mm and 0.55, respectively. It was estimated that PMP for one day duration over the region computed 357.39 mm and the ratio of the one day PMP to highest 1-day rainfall (PMP/HOR) was calculated 1.19. The expected maximum one day rainfall and Reduced variate (Yt) for different return periods of study area was calculated by using the Gumble distribution as shown in Table 2. The nomograph of maximum 1-day rainfall for different return period up to 1000 years is plotted which was used for calculating maximum 1-day precipitation for return period up to 1000 years as shown in Figure 3.The trend analysis was carried out and it is observed that logarithm trend line gives the better coefficient of correlation (R2 =0.9989).The expected maximum 1-day rainfall for 50 and 100 years return period was 205 and 230 mm, respectively. A maximum of 78 mm rainfall is expected to occur at every 2 years. Singh et al. (2012) recommended that 2 to 100 return period is enough for construction of dams, soil and water conservation measures, irrigation and drainage works.

The PMF is calculated from the PMP which is used in drainage basin and major dams in the world are based on PMF. The spillway design floods for most of dams in world were computed by using the statistical approach and if dams were to fail then a large loss of economic and human life is expected. PMP also used to calculate the extent of flood plain areas at risk at maximum flood conditions. If reliable techniques of PMP are used then there should not be any risk of overtopping of dams. In design of hydrological and civil structures, the structures have to be designed to carry maximum runoff expected in a specified recurrence interval. Durbude (2008) has recommended different return periods for design of various hydraulic structures. The PMP for various hydrological structures were calculated and presented in Table 3.The PMP with different return period for vegetated waterways and terrace outlets, field diversion and small permanent masonry gully control structures were found as 146,161 and 146-161 mm, respectively. Similarly, PMP values for stock water dams, Earth fill dams-storage and storage and diversion dams having spillways were 180,180-230 and 205-230 mm, respectively.

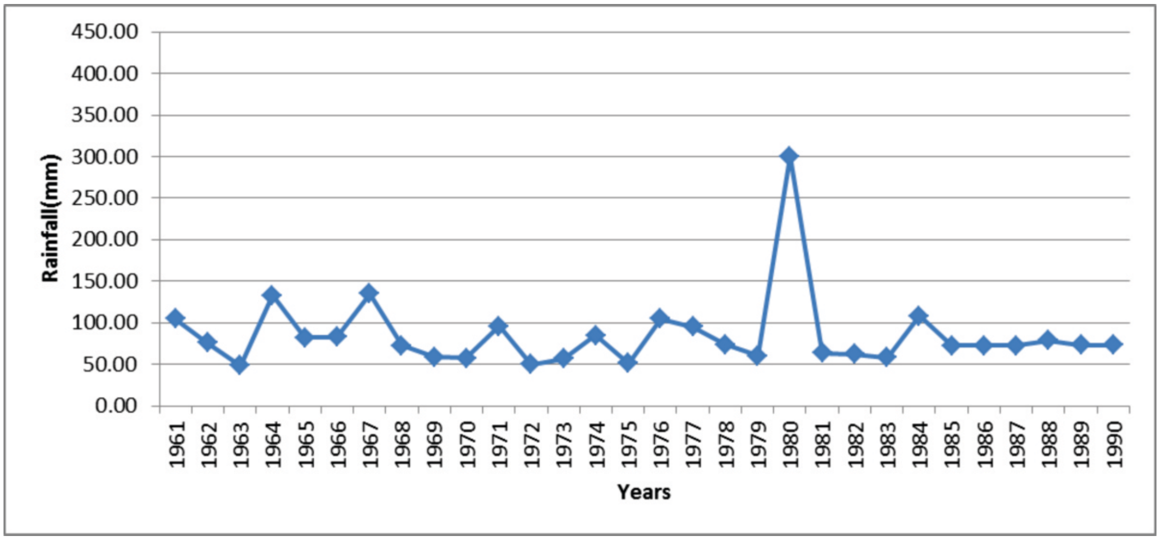

Fig. 2 . One day maximum daily rainfall for period of 1961 to 1990.

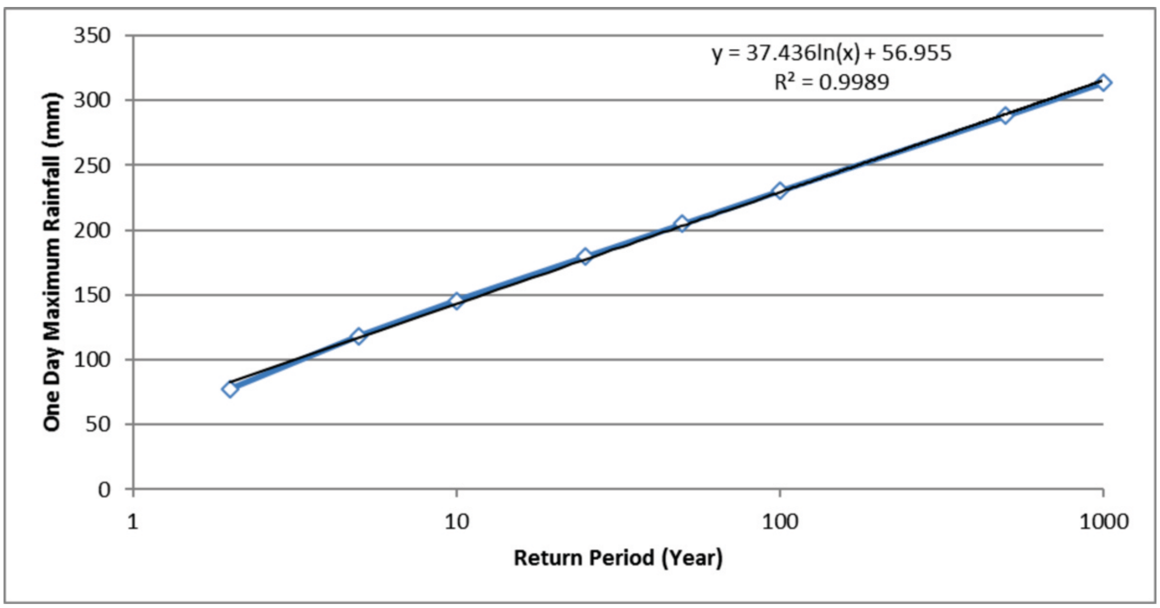

Fig.3. Estimated maximum one day rainfall for different return period.

6. Conclusions

The probable maximum precipitation helps design a civil structure properly in the study area. PMP value should be estimated by more than one method for critical hydrologic regulations, and preferably by both statistical and physical methods. Therefore, statistical method was used and recommended to estimate the PMP due to limitation of data availability. The Probable maximum precipitation estimated in the study area can be used in dams for spillway design. The maximum one day rainfall for different return periods can be used for design of overflow arrangement of conservation structure. PMP estimated in this study is helpful to plan soil and water conservation structures in the Gujjar Khan. The results derived are applicable in developing crop plan and to calculate design flow rate for maximizing crop production.

Table 1. Probable maximum one day rainfall in study area.

Sr. No	**Parameters**	**values**
1	Average One Day Maximum Rainfall (mm)	83.58
2	Standard Deviation (mm)	38.47
3	Coefficient of variation (Cv)	0.5423
4	Highest Observed rainfall (mm) - HOR	300
5	Probable Maximum Precipitation (mm) – PMP	357.39
6	Frequency factor (Km)	9.49
7	Ratio PMP/HOR	1.19

Table 2. Estimated maximum one day rainfall and reduce variate at different return period.

Sr. No.	**Return Period (Years)**	**Reduced Variate (Y_t)**	**Estimated Maximum One Day Rainfall (mm)**
1	2	0.37	78
2	5	1.50	119
3	10	2.25	146
4	20	2.97	172
5	25	3.20	180
6	30	3.38	186
7	40	3.68	197
8	50	3.90	205
9	60	4.09	212
10	70	4.24	217
11	80	4.38	222
12	90	4.49	226
13	100	4.60	230
14	250	5.52	263
15	500	6.21	288
16	1000	6.91	313

Table 3. The return period and PMP for design of various structures.

Sr. No	**Type of Soil and Water Conservation Structures**	**Return Period (Year)**	**PMP(mm)**
1	Terrace Outlets and Vegetated Waterways	10	146
2	Field Diversion	15	161
3	Stock Water Dams	25	180
4	Small Permanent Masonry Gully Control Structures	10-15	146-161
5	Earth fill Dams-Storage having Natural Spillway	25-100	180-230
6	Storage and Diversion Dams having Spillways	50-100	205-230

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