# Utilizing an Enhanced Statistical Approach for Accurate Assessment of short-term Probable Maximum Precipitation

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**Abstract.** Numerous comprehensive studies, both domestically and internationally, have extensively investigated the estimation of Probable Maximum Precipitation (PMP) over durations ranging from 1 to 3 days. However, there remains an unaddressed need for a systematic approach to estimate PMP over short-term. In this study, we present a novel methodology for estimating short-term PMP. This method, grounded in an enhanced statistical estimation approach, is coupled with the intensity-duration-frequency relationship. It offers a solution to the challenge of estimating PMP for short-term when essential storm data is scarce. We apply this approach to estimate short-term PMP for a nuclear power project located in Shandong. Through rigorous comparison and analysis, our method yields estimations that are notably more rational and precise. This improvement holds valuable potential for future general purpose real-world applications.

**Keywords:** probable maximum precipitation; short-term heavy rainfall; enhanced statistical approach; intensity-duration-frequency relationship; urban hydrology

## 1 Introduction

The Probable Maximum Precipitation (PMP) is a defined concept denoting the maximum theoretical depth of precipitation attainable within a specific geographic area during a particular time of the year [1,2]. It holds immense significance in the design of substantial hydraulic structures like dams, serving as a foundational parameter to ensure their resilience against potential failures during extreme flood events. Addi-


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tionally, PMP finds utility in evaluating the risk of direct flooding to critical infrastructure, as elucidated by Hufman et al. [3].

Various approaches have been proposed for Probable Maximum Precipitation (PMP) estimation, broadly categorized into two groups: statistical and deterministic methods. Hirschfield's method [4–6] falls under the statistical approach category and provides a singular PMP value. This approach is particularly applicable in areas where there is an adequate record of precipitation but a lack of other meteorological data such as humidity, wind speed, and dew point temperature.

In this method, the PMP value is derived using rainfall data from a meteorologically homogeneous zone, employing hydrological frequency analyses in conjunction with a regional generalized approach. Its widespread adoption can be attributed to the simplicity of performing these analyses. It has even earned recognition as one of the standard methods recommended by the World Meteorological Organization [2] for PMP estimation. The formulation of this method is articulated as follows:

$$K_m = \frac{P_m - \bar{P}_{n-1}}{S_{n-1}} \tag{1}$$

$$PMP = \bar{P}_n \left(1 + K_{mm} \times C_{vn}\right) \tag{2}$$

where $P_m$ represents the maximum value within the measured data series; $\bar{P}_{n-1}$ signifies the mean value calculated without the inclusion of the maximum value; $S_{n-1}$ denotes the mean squared deviation computed after removing the maximum value; $K_{mm}$ corresponds to the maximum value of $K_m$, in the study watershed;$\bar{P}_n$ represents the mean value computed across the entire data series;$C_{vn}$ stands for the coefficient of variation pertaining to the n-year data series, inclusive of the extraordinary value.

Casas [7] have conducted studies demonstrating that the Hershfield method yields more accurate PMP estimates when compared to deterministic approaches. Koutsoyiannis [8] argued that this method effectively represents the entire rainfall dataset through statistical parameters. Furthermore, Papalexiou & Koutsoyiannis [9] asserted that the statistical approach for estimating extreme precipitation values aligns more closely with natural behavior and serves as a superior basis for estimation compared to moisture maximization methods. Given that the Hershfield method relies on average precipitation and standard deviation of precipitation, it bears resemblance to the frequency factor method described by Chow [10]. Casas et al. [11] used the Hershfield method to estimate the PMP values for one-day duration and their return periods, and spatial resolution over the Catalonia region. In more recent research, Rezacova et al. [12] employed statistical techniques to derive point-PMP estimates for durations spanning 1 to 5 days. Subsequently, these estimates were converted to basin-average PMP values.

High-risk reservoir projects, flood control and drainage management projects, and similar endeavors frequently necessitate the extrapolation of short term PMP. In this context, short-calendar-time PMP typically referred to as the PMP for rainfall events lasting less than 24 hours [12]. Theoretically, the statistical method is not constrained by the duration [6]. However, in practice, it becomes challenging to apply statistical method directly for estimating short-term PMP when there is insufficient available short-term rainstorm data [5].

In this study, a novel integrated approach is introduced to estimate short-term PMP. This method combines the enhanced statistical technique with the intensity-duration-frequency（IDF）relationship. To validate the effectiveness of this approach, it is applied to the calculation of short-term PMP in the context of a nuclear power project in Shandong province, thereby confirming the validity of this combined method for estimating short-term PMP.

# 2 Methodology

## 2.1 Hirschfield's Constrained Method

The pivotal concept of the Hirschfield method lies in the accurate estimation of the frequency factor ($K_m$) and the technique used to envelope it. It's worth noting that there is no universally accepted enveloping technique for $K_m$. Various researchers worldwide have proposed and employed different values of $K_{mm}$ along with various enveloping techniques.

The value of $K_m$ is determined using rainfall data from various stations, and the station selection criteria are defined according to Lin [1], as depicted in Equations 3~5:

$$N_m \geq \Phi_m{}^2 + 2 \tag{3}$$

$$N_s = \left(\Phi_m{}^2 + 2\right) \times 5.76 \tag{4}$$

$$N_s \leq 3.5n \tag{5}$$

Where $N_m$ represents the minimum number of years of data necessary for a valid calculation; $N_s$ is the minimum number of years of data required to control the calculation error of $K_m$ within 10 %; and $n$ is the number of years of the measured data available at the site; $\Phi_m$ represents the departure coefficient.

$$\Phi_m = \frac{P_m - \bar{P}_n}{\bar{P}_n \times C_{vn}} \tag{6}$$

Sites that satisfy the three aforementioned criteria are regarded as appropriate selections. In this study, we utilize data from these screened sites and incorporate it into the traditional Hirschfield's method. Therefore, the accuracy of the statistic $K_{mm}$ is enhanced and subsequently increasing the reliability of PMP estimations.

## 2.2 Intensity-duration-frequency relationship

In the absence of short-duration heavy rainfall data, a more rational approach is to initially calculate the 24-hour maximum potential precipitation and subsequently employ the intensity-duration-frequency relationship to estimate the short-duration PMP.

The formulation of intensity-duration-frequency relationship is constructed as follows:

$$X_{t,p} = S_p t^{1-n} \tag{7}$$

Where $X_{t,p}$ represents the design rainfall with a duration of $t$ ($t \leq$ 24h) and a design frequency $p$; $t$ stands for the rainfall duration; $n$ denotes the rainstorm attenuation index (RAI); and $S_p$ is the 1-hour rainfall at the design frequency $p$. Please note that the RAI, denoted as "$n$", varies with duration. When the rainfall duration $t$ < 1 hour, $n=n_1$. When the rainfall duration 1h≤t ≤ 24h, $n=n_2$."Sp" is typically derived from the 24-hour design rainfall and can be expressed as follows:

$$S_p = X_{24h,p} 24^{n_2-1} \tag{8}$$

When the rainfall duration "$t$" is less than 1 hour, the design rainfall is calculated as follows:

$$X_{t,p} = X_{24h,p} 24^{n_2-1} t^{1-n_1} \tag{9}$$

When the rainfall duration "$t$" is greater than 1 hour but less than 24 hours, the design rainfall is calculated as follows:

$$X_{t,p} = X_{24h,p} 24^{n_2-1} t^{1-n_2} \tag{10}$$

The rainstorm attenuation index of the design storm is employed as an approximate substitute for the storm indexes "$n_1$" and "$n_2$" of the probable maximum storm. The intensity-duration-frequency relationship is then applied to derive the PMP for each short-calendar time based on the 24-hour probable maximum storm. The RAI "$n_1$" and "$n_2$" are derived from the following equations:

When t < 1h,

$$n = n_1 = 1 - \frac{\ln X_{1h,p} - \ln X_{t,p}}{\ln 24 - \ln t} \tag{11}$$

When 1h ≤ t ≤ 24h,

$$n = n_2 = 1 - \frac{\ln X_{24h,p} - \ln X_{t,p}}{\ln 24 - \ln t} \tag{12}$$

# 3 Study areas and data

The nuclear power studied in this research is situated within Haiyang city, located in the southern expanse of the Jiaodong Peninsula within Shandong province. This locale falls under the purview of a temperate monsoon climatic zone.

The extrapolation of the PMP using the enhanced statistical approach necessitates access to data regarding extremely heavy rain as well as typical heavy rainfall occurrences in this basin and adjacent ones. In this investigation, data encompassing 24-hour periods with recorded rainfall exceeding 300 mm, classifying as exceptionally heavy rainfall, serves as a foundational criterion. After conducting extensive research and assessment grounded in the climate coherence zone data and the information concerning neighboring stations, a selection of 15 rainfall stations spanning Shandong, Jiangsu, and Henan provinces were made, signifying these stations as representative in the context of this study.

# 4 Application of the proposed algorithm

## 4.1 Extrapolating the 24-hour PMP for the study area using the statistical estimation method

To enhance the validity of the Km statistic, a screening process was conducted on 15 representative stations using Equations (3) ~ (5). The outcomes of this screening are presented in Table 1.

**Table 1.** Results of the screening of representative stations.

| NO | Station | $n$ | $P_m$(mm) | $\bar{P}_n$(mm) | $C_{vn}$ | $\Phi_m$ | $N_m$ | $N_s$ | 3.5$n$ | Yes or No |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Linzhuang | 65 | 1060.3 | 124 | 0.7 | 11.19 | 127 | 733 | 228 | No |
| 2 | Xiangshuikou | 63 | 825 | 122 | 0.6 | 9.79 | 98 | 564 | 221 | No |
| 3 | Chaoqiao | 61 | 822 | 118 | 0.6 | 9.75 | 97 | 559 | 214 | No |
| 4 | Shihetou | 60 | 740 | 100 | 0.6 | 10.67 | 116 | 667 | 210 | No |
| 5 | Dafengzha | 65 | 672.6 | 121 | 0.6 | 7.68 | 61 | 351 | 228 | No |
| 6 | Sanlizhuang | 63 | 599.6 | 120 | 0.7 | 5.71 | 35 | 199 | 221 | Yes |
| 7 | Haitangcun | 50 | 599.1 | 110 | 0.6 | 7.41 | 57 | 328 | 175 | No |
| 8 | Tanyi | 51 | 537 | 120 | 0.7 | 4.96 | 27 | 153 | 179 | Yes |
| 9 | Houwangjian | 55 | 536 | 123 | 0.6 | 5.78 | 35 | 204 | 193 | Yes |
| 10 | Beijiushui | 60 | 516.5 | 188 | 0.7 | 3.18 | 12 | 70 | 210 | Yes |
| 11 | Shifuzi | 55 | 499 | 110 | 0.7 | 5.05 | 28 | 159 | 193 | Yes |
| 12 | Xiakou | 50 | 466.2 | 85 | 0.6 | 7.47 | 58 | 333 | 175 | No |
| 13 | Chengshantou | 61 | 458.8 | 113 | 0.7 | 4.37 | 21 | 122 | 214 | Yes |
| 14 | Madianguangzha | 63 | 378.7 | 110 | 0.55 | 4.44 | 22 | 125 | 221 | Yes |
| 15 | Weihai | 60 | 353 | 120 | 0.6 | 3.24 | 12 | 72 | 210 | Yes |

As indicated in Table 1, out of the 15 representative stations, only 8 representative stations successfully pass the screening. Therefore, only these 8 representative stations are taken into account when computing the PMP value. Ultimately, by employing Equation 1 to compute the Km for each of these stations and selecting the maximum value Kmm=6.91, and then substituting this value into Equation 2, the result is PMP=188× (1+6.91×0.7) =1097.36mm. The detailed calculation results are presented in Table 2.

**Table 2.** Results of PMP estimation based on constraints.

| NO | Station | $P_m$(mm) | $\bar{P}_{n-1}$(mm) | $C_{vn}$ | $K_m$ | $K_{mm}$ | PMP(mm) |
|---|---|---|---|---|---|---|---|
| 1 | Sanlizhuang | 599.6 | 112.3 | 0.7 | 6.79 | 6.91 | 700.44 |
| 2 | Tanyi | 537 | 111.7 | 0.7 | 5.46 | 6.91 | 694.60 |
| 3 | Houwangjian | 536 | 115.4 | 0.6 | 6.53 | 6.91 | 632.96 |
| 4 | Beijiushui | 516.5 | 182.4 | 0.7 | 3.25 | 6.91 | **1097.36** |
| 5 | Shifuzi | 499 | 102.8 | 0.7 | 5.71 | 6.91 | 642.07 |
| 6 | Chengshantou | 458.8 | 107.2 | 0.7 | 6.91 | 6.91 | 659.581 |
| 7 | Madianguangzha | 378.7 | 105.7 | 0.55 | 5.15 | 6.91 | 528.055 |
| 8 | Weihai | 353 | 116 | 0.6 | 3.85 | 6.91 | 617.52 |

By examining the contour map illustrating the potential maximum 24-hour point rainfall in Jiaodong Peninsula (Fig. 1), it becomes evident that the potential maximum 24-hour point rainfall in the vicinity of the plant site is approximately 1050 mm which is close to the estimation result. Consequently, these estimations are deemed rational and reliable.

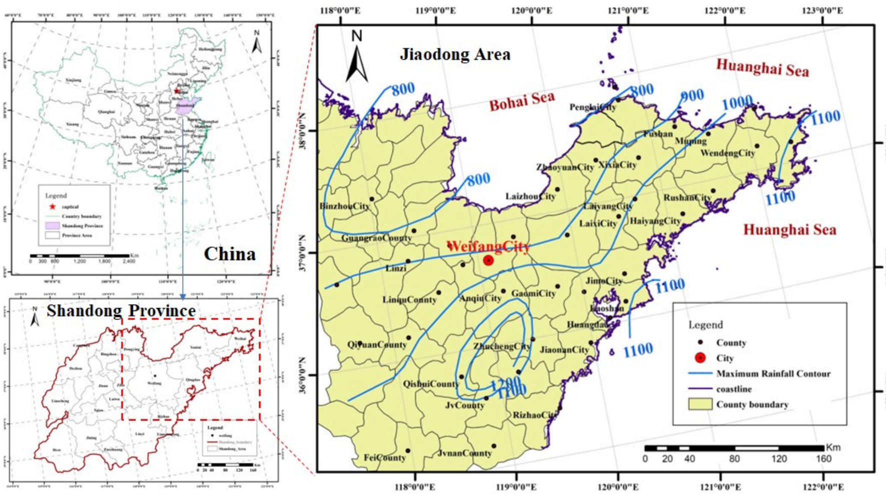


**Fig. 1.** Contour Map of Potential Maximum 24-Hour Precipitation in the Jiaodong Peninsula.

## 4.2 Calculation of Short-Term PMP for the Study Area Using the Intensity-Duration-Frequency Relationship

As the initial step of our study, we selected the annual maximum rainfall data for a range of short durations specific to our study area. These durations were chosen to

encompass a variety of timeframes relevant to our research. Subsequently, we embarked on a frequency analysis of this data, a process essential for ascertaining the appropriate design rainfall values corresponding to each of these short durations.
The results of this rigorous analysis have been meticulously tabulated and are presented in Table 3.

**Table 3.** Design rainfall with different frequencies for short durations in the study area (in mm).

| Duration | 10min | 30min | 1h | 6h | 12h | 24h |
|---|---|---|---|---|---|---|
| P=0.01% | 59.07 | 128.59 | 230.35 | 604.4 | 757.77 | 893.94 |
| P=0.1% | 48.44 | 102.15 | 164.73 | 449.41 | 564.69 | 660.45 |
| P=1% | 37.42 | 75.25 | 101.57 | 297.07 | 374.7 | 458.80 |

The rainfall data for the design frequency P=0.01%, which is the closest to the PMP, was selected and brought into Eqs. (11) and (12) to calculate the RAI, $n_1$=0.24 and $n_2$=0.57. To calculate the Probable Maximum Precipitation (PMP) for various shortened time intervals within our research area, we utilized the values $X_{24h,p}$=1097.36mm, $n_1$=0.24, and $n_2$=0.57 as inputs into Equations (9) and (10). These equations are critical components of our methodology for PMP estimation.
The outcomes of these calculations, which provide precise PMP estimates for the specified time intervals, have been meticulously documented and are presented in Table 4.

**Table 4.** Results of probable maximum precipitation (PMP) for different durations in the study area.

| Duration | 10min | 30min | 1h | 6h | 12h | 24h |
|---|---|---|---|---|---|---|
| PMP/mm | 71.86 | 165.62 | 280.48 | 606.05 | 816.49 | 1097.36 |
| 0.01%/mm | 59.07 | 128.59 | 230.35 | 604.4 | 757.77 | 893.94 |
| ratio | 1.22 | 1.29 | 1.22 | 1.00 | 1.08 | 1.23 |

Table 4 presents a comprehensive depiction of the ratio between Probable Maximum Precipitation (PMP) and design rainfall across a spectrum of time durations, all under the umbrella of a design probability of P=0.01%. The consistent pattern showcased in this table reveals that, regardless of the duration considered, the PMP-to-design rainfall ratio consistently remains within the range of 1.00 to 1.29. This remarkable consistency underscores the stability and reasonableness of the outcomes derived from our analysis, thereby affirming the robustness of our findings. Such steadfast results provide a firm foundation for decision-making and further research within the field of water resources management and planning.

## 5 Conclusions

In our study area, the procedure for calculating short-term Probable Maximum Precipitation (PMP) is achieved through the harmonious combination of statistical methodologies and the utilization of intensity-duration-frequency (IDF) relationships. The resulting estimates obtained through this integrated approach consistently demonstrate both stability and reasonableness within our specified study area. This underscores the general applicability and effectiveness of this method for PMP determination.

Furthermore, it is worth emphasizing that this method presents an effective resolution to the persistent challenge of estimating short-duration PMP in regions where data availability is scarce. In areas blessed with ample rainfall data, an enhanced statistical approach can be harmoniously integrated with the classical Hirschfield's methods. This harmonization allows for in-depth comparative evaluations and enables us to establish a preference for short-duration PMP estimates based on a more comprehensive understanding of the precipitation patterns in the region.

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