Study On Urban Rainstorm Pattern of Short-Duration Double-Peak

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Study on urban Rainstorm Pattern of Short-duration Double-peak

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【Abstract】: At present, researches on urban short-duration rainstorm patterns mainly focus on single-peak rainstorm patterns, and rarely involve double-peak rainstorm patterns, or convert double-peak patterns into single-peak patterns directly, even ignore the impact of double-peak patterns, which directly affects the urban flood planning and early warning and rescue. To scientifically and rationally deduce the urban short duration double-peak rain pattern, this paper proposes a new function fitting rain pattern method by constructing double-peak virtual rain peak rainfall and virtual rain peak coefficient (RPC), based on the idea of convert double-peak to singel-peak, then revert to the double-peak, directly deducing the double-peak rain pattern.The results show that (1) The rain pattern derived by the function fitting rain pattern method(FFRPM) can effectively improve the accuracy of the double-peak rain pattern, and is also more practical; (2) The fitting degree of function fitting rainfall pattern and actual rain pattern is more than 90%, accounting for 80%， the fitting degree of main and secondary peak rainfall is more than 90%, with an average of about 95%; the accuracy of the main and secondary peak positions is also relatively high; (3) Compared with the P&C rain pattern method(RPM), whether the overall accuracy or local peak rainfall, the FFRPM has the higher accuracy, especially more accurate on rain peak rainfall.

Key words: Short-duration double-peak rainstorm; Virtual rain peak coefficient; Function fitting rain pattern; P&C rain pattern

Highlights

- This paper proposes a new function fitting rain pattern method by constructing double-peak virtual rain peak rainfall and virtual rain peak coefficient.
- And put forward the calculation formula of the double peak virtual rain peak coefficient based on the assumption.
- Then based on the assumptions, a series of calculation formulas for the peak rainfall of the double peak rain are proposed.
- There are few methods for estimating double-peak rain patterns in the world. The method for estimating double-peak rain patterns proposed in this paper greatly improves the overall accuracy of double-peak rain patterns.
- Compared with the traditional P&C rain pattern, the rainfall pattern proposed in this paper is more realistic and more accurate overall.

1. Introduction

Urban waterlogging caused by the large-scale short-duration rainstorm can pose a serious threat to the safety of people's lives and property.According to China's 2020 statistics, there are 178.96 billion RMB (Jun S, Linli C, Zhan T, 2020) loss in property caused by urban rainstorm and flood disasters. Usually, the short-duration rainstorm triggers urban waterlogging more easily. Short-duration rainstorm refers to a rainstorm within 120 minutes (Chunwei G et al.,2015), and its rain pattern shows the temporal distribution process of rainfall, namely the rainstorm intensity changes with time (Khaled H et al., 2015). Actually, the proportion of short-duration single-peak rainstorm is far higher than that of double-peak rainstorm, and it is with sudden rise and fall pattern, and more prone to cause flood disaster. Therefore, the characteristics of single-peak rainstorm, especially its rain pattern, are often the focus in the current study of urban storm flood, and currently many abundant research achievements are available and also are used to guide urban flood control and waterlogging planning and practice work (Dingkun Y et al., 2020). For example, by studying the relationship between rainfall intensity and duration, the Chicago rain pattern was analyzed and then proposed (Keifer et al., 1957), and the rainfall data of rainfall stations in central and eastern Illinois was analyzed and summarized, the time is divided into 4 types of rainfall (Huff et al., 1967), and the rainfall type is obtained through a sequential average method (Pilgrim et al., 1975).Proposed a single-peak triangle Shape rain pattern, used to calculate runoff in drainage area of small watershed（Yen B C, Chow V T,1980）.

However, affected by climate changes and urbanization development, some scholars found that the double-peak rainstorm occurred more frequently and even occupies about 20.5% of the short-duration rainstorms in China. So the urban waterlogging caused by double-peak rainstorm can not be ignored anymore, and it must be paid more attention. Nevertheless, it is rare in the study on double-peak rainstorm now, and the existing research is simply to convert double-peak rainstorm into single-peak (Yuan-Yuan L et al., 2020). This converting double-peak into single-peak method (CDPISPM) is simply and convenient, and it has certain precision, which can simplify the research and calculation process. In fact, the key features of double-peak rainstorm——The double peak rainfall and its location play a crucial role in urban rainstorm warning and emergency response. but it is fuzzed by the CDPISPM, so it can not truly reflect the characteristics of actual double-peak rainstorm, and this will reduce the accuracy of rainstorm forecasting and affect urban drainage and waterlogging prevention and emergency early warning. Therefore, this study proposes a new FFRPM to fit the actual double-peak rain pattern method (DPRPM).

The paper aims to that (1) analyzing the characteristics of short-duration double-peak rainstorm in China firstly; (2) by constructing double-peak combined virtual rain peak coefficient (DPCVRPC), the double-peak rainstorm is converted into single-peak rainstorm firstly, and then they are reverted again, thus the FFRPM is derived; (3) by fitting the actual urban double-peak rainstorm, the FFRPM is verified, and also compared with the P&C RPM.

2. Data and methods

2.1 Data sources

Zhengzhou city lies in the north-central part of Henan Province of China, and also in the middle and lower reaches of the Yellow River. It belongs to the north temperate continental monsoon climate with four distinct seasons (Chi WF, Shi WJ, Kuang WH, 2015). The annual average of rainfall is about 640mm in Zhengzhou City and more concentrated rainfall is in summer, which causing serious urban waterlogging.

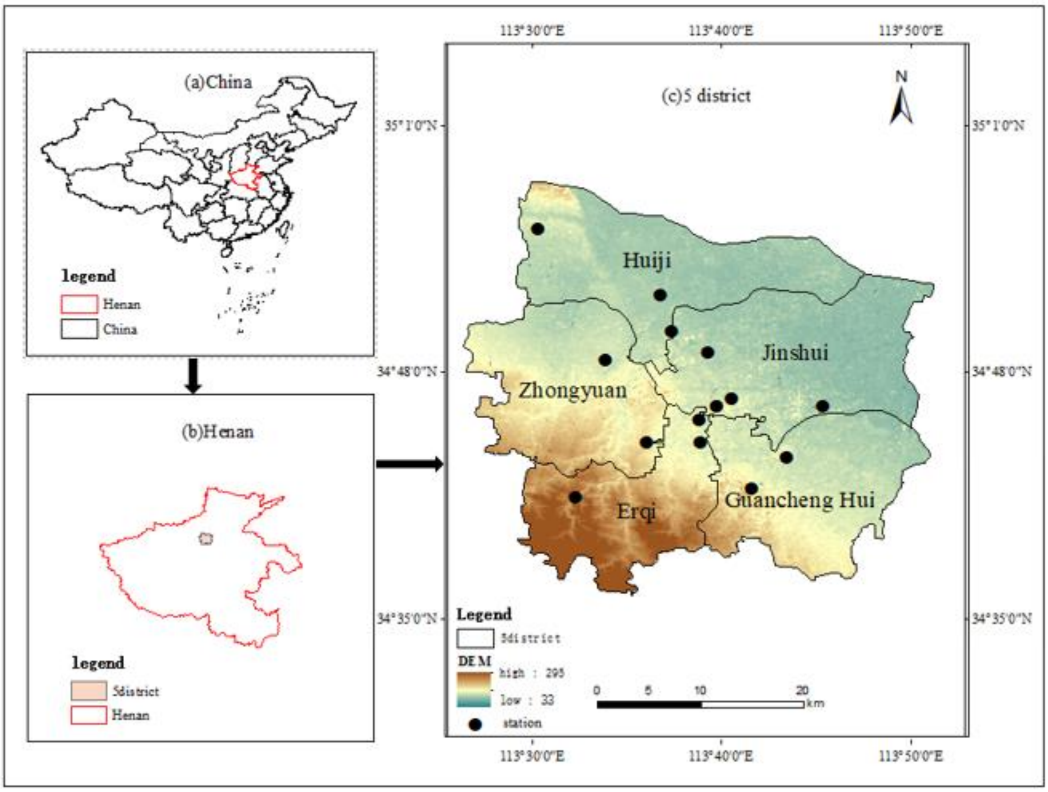


Fig. 1. Distribution map of five districts and rainfall stations in Zhengzhou City, Henan Province

The study area is the five districts within Zhengzhou City, and date uses the 10-minute rainstorm excerpts from the ground hydrological station from 2009 to 2018 , including Jinshui District, Huiji District, Erqi District, Zhongyuan District and Guancheng Hui Nationality District. There are 14 rainfall observation stations (as shown in Fig.1), respectively located in North China University of Water Resources and Electric Power, Zhengzhou Hydrology Bureau, Water Conservancy Design Institute, Shibalihe River, High-tech Zone, Shangjie District, Huiji District, Zhengzhou

Earthquake Bureau , Railway Bureau, Economic Development Zone, Provincial Party Committee, Yellow River Tourist Area, Laoyachen, and Water Conservancy Bureau.

2.2 Short-duration rainstorm classification

According to the actual investigation and statistical data analysis, the rainstorm causing the flood disaster in Zhengzhou city is mainly the short-duration rainstorm within 2 hours (Dingkun Y et al., 2020). Short-duration rainstorm refers to a rainstorm lasting no more than 120min, and usually 30, 60, 90 and 120min are used as the rainfall statistics periods. According to the 10-minute observed rainstorm data from 2009 to 2018, the rainstorm events are classified by no rainfall or rainfall less than 0.1mm within 2 hours, thus a series of continuous rainfall data are classified into several independent rainstorm events (WenLin Y, Lei F,2019). The classification of rainstorms events are shown in Table 1.

Table 1

The classification of rainstorms events

Rainfall duration (min)	30	60	90	120
The critical value (mm)	⩾10	⩾12	⩾15	⩾20

2.3 Selection of double-peak rainstorm samples

Double-peak rainstorms in Zhengzhou City are mainly concentrated within 1h and 1.5h, especially within 1.5h, there are 19 events of double-peak rainstorms accounting for 47.5% of the total rainstorms. Fig. 2 and Table 2 show the main peak-rain (MPR) and secondary peak-rain (SPR) of double-peak rainstorm within 1.5h as well as their locations.

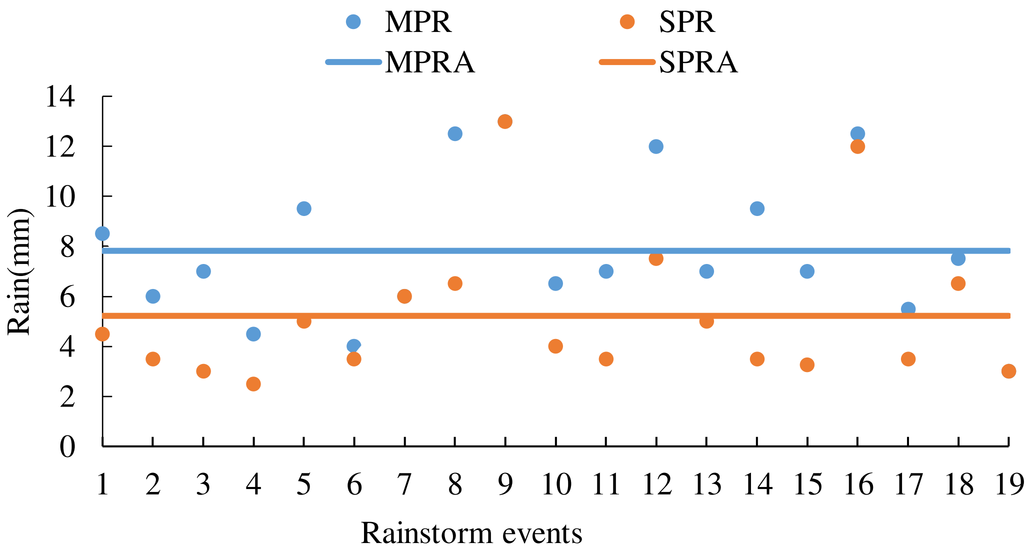


Fig. 2. MPR and SPR of double-peak rainstorm

Table 2

Peak rain and location of double-peak rainstorm within 1.5h

Features	MPR (mm)	SPR (mm)	Difference of MPR and SPR (mm)	Proportion of front main peak - rain (FMPR)	Proportion of behind main peak - rain (BMPR)
Average value	7.82	5.22	2.60	57.9%	42.1%

Based on the amount of statistical analysis of double-peak rainstorms (Diomede T et al.,2008), it is known that in the double-peak rainstorm event, the value of SPR can not be too small, otherwise the impact of SPR on the whole rain pattern will be lower that will result in unevidently double-peak rain. Similarly, the ratio of SPR to MPR as well as the difference between SPR and trough should reach a certain value so as to reflect the double-peak characteristics. The selection standard of double-peak rainstorm are used in Table 3.

Table 3

The selection standard of double-peak rainstorm pattern

SPR (mm)	ratio of SPR to MPR	difference between SPR and trough (mm)
≥2.5	≥1/4	≥1.5

Therefore, the double-peak rainstorm samples within 1.5h can be obtaind by the following two steps: (1) classfing the short-duration rainstorm according to Table 1 to obtain the rainstorm data within 1.5h firstly, and finding out all double-peak rainstroms, then arranging them in order of total rainfall from large to small; (2) with the selection standard in Table 3, the double-peak rainstorm samples are selected to derive the double-peak rainstorm pattern.

2.4 Calculation of DPCVRPC

2.4.1 Double-peak virtual rain peak coefficient (DPVRPC)

For a single-peak rainstorm, its RPC (Dan C, Zhenghong C , Yi F,2015) is calculated as follows:

$$r_i = \frac{t_i}{T} \tag{1}$$

Where i is the i-th rainstorm, i=1, 2, ... n, r_i is the single-peak RPC, t_i is the peak occuring time, and T is the total duration of the whole rainstorm.

For double-peak rainstorm, its double rain peaks is divided into the MRP and the SRP, so if the formula (1) is used, there will be two rain peak coefficients. However, these two rain peaks can be converted into one peak with the formula (1) by the CDPISPM. The idea of the CDPISPM is to assume a virtual rain peak of single-peak rainstorm which is located between the MRP and the SRP of double-peak rainstorm, and also just at the position of the combined CRPC, thus the position of this virtual rain peak is called as the virtual rain peak cofficient of double-peak rainstorm.

Based on the above assumption, the double-peak virtrual rain peak cofficient (DPVRPC) is calculeted as:

$$r_i = \frac{t_i\left(\frac{h_i}{h_i+h_j}\right)+t_j\left(\frac{h_j}{h_i+h_j}\right)}{T} \tag{2}$$

Where r_i is the DPVRPC, t_i and t_j are the occuring time of the MRP and SRP in double-peak rainstorm, h_i and h_j are the MPR and SPR respectively, and T is the total duration of rainstorm.

2.4.2 DPCVRPC

The DPCVRPC of double-peak rainstrom within 1.5h is (Guoping C, Jin S, Rongsheng F,1998) expressed as follows:

$$r_j = \frac{1}{n}\sum_{i=1}^{n} r_i \tag{3}$$

Where r_j represents the DPCVRPC, n represents the total number of double-peak rainstorm within 1.5h, and r_i represents the DPVRPC of each double-peak rainstorm.

$$x_k = r_j n \tag{4}$$

In the formula, n represents the number of time periods, and x_k is the position corresponding to the comprehensive virtual rain peak coefficient(CVRPC).

2.5 Calculation of double-peak virtual peak rain (DPVPR)

For a double-peak rainstorm with the FMPR and behind BSPR, suppose the MPR is h_i, the SPR is h_j, and the DPVPR is H_i satifing the following requirements (1)-(4):

(1) After the conversion of double-peak to single-peak, the virtual rainfall peak value meets the following requirements:

$$H_i = h_i y_i + h_j y_j \quad (5)$$

Where y_i and y_j respectively represent the coefficients of MRP and SRP.

(2) The virtual rain peak rainfall should also satisfy the following requirements:

$$h_j < H_i < h_i + h_j \quad (6)$$

Where y_i and y_j satisfies $0 < a \leqslant y_i \leqslant 1$, $0 < b \leqslant y_j \leqslant 1$, $a, b \in (0,1)$.

If y_i=y_j=1, the MRP and SRP are both at the position of the DPVRPC, thus the doubule-peak rainstorm pattern become the single-peak one.

(3) The DPVRPC is related to the position of MRP and SRP. If the position of the MRP x_i is closer to the DPVRPC, the coefficient y_i in formula (5) is more larger, and the relationship between Xi and Yi is linear. Similarly, if the position x_j of the SRP is closer to the DPVRPC, the coefficient y_j in formula (5) will be larger, and the relations between x_j and y_j is linear as well.

(4) Set any initial value in the range of a and b, and then carry out linear fitting for the DPVPR and the total rainfall. If the best fitting is found and the DPVPR also satisfies the formula (6), the corresponding values of a and b at this time are the required values.

For a double-peak rainstorm with the front sencondary peak rain (FSPR) and BMPR, y_i and y_j represent the coefficients of SRP and MRP in formula (5) respectively, and x_i and x_j represent the positions of SRP and MRP respectively.

Based on the above assumptions, it can be derived:

if $x_i \in [1,\ x_k]$, y_i in formula (5) is calculated as:

$$y_i = \frac{a-1}{1-x_k} x_i + \frac{1-a x_k}{1-x_k} \tag{7}$$

if $x_j \in [x_k,\ n]$, y_j in formula (5) is calculated as:

$$y_j = \frac{1-b}{x_k-n} x_j + \frac{b x_k-n}{x_k-n} \tag{8}$$

Where, n represents the number of time periods (for example, if the rain data extracted every 10 minutes in the rainstrom lasting 1.5h, n is 9).

The relations between y_i, y_j and x_i, x_j in the formula (7) and (8) are shown in Fig.3:

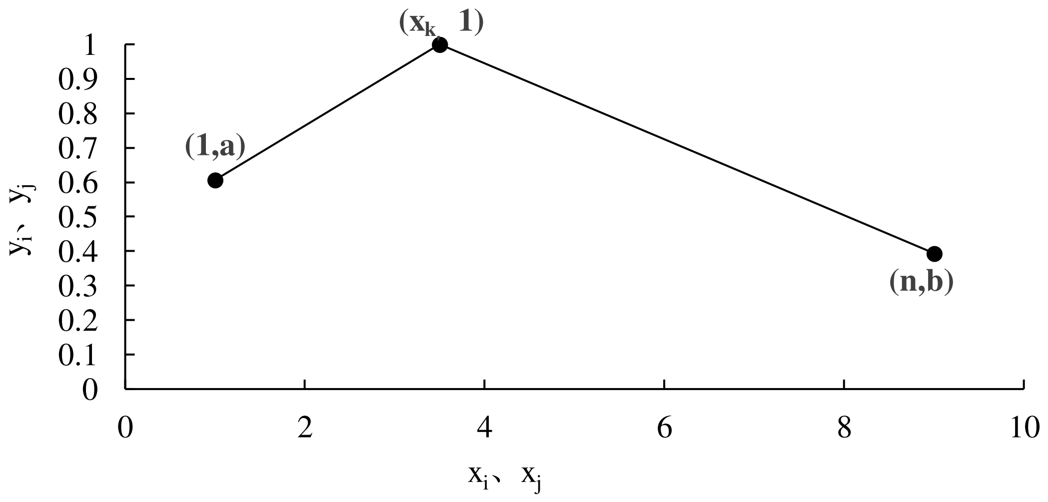


Fig. 3. The relations between y_i, y_j and x_i, x_j

It can be seen from Fig.3 that if the MRP is in front, $y_i \in$ [a,1] and $y_j \in$[b,1]; conversely, if the MRP is in behind, $y_i \in$ [b,1] and $y_j \in$ [a,1] , so the DPVPR can be derived as follows:

For the MRP: $$H_i = \left(\frac{a-1}{1-x_k}x_i + \frac{1-ax_k}{1-x_k}\right)h_i + \left(\frac{1-b}{x_k-n}x_j + \frac{bx_k-n}{x_k-n}\right)h_j \quad (9)$$

For the BMP: $$H_i = \left(\frac{a-1}{1-x_k}x_i + \frac{1-ax_k}{1-x_k}\right)h_j + \left(\frac{1-b}{x_k-n}x_j + \frac{bx_k-n}{x_k-n}\right)h_i \quad (10)$$

In formulas (9) and (10), H_i is the DPVPR, the rests are the same meaning as before.

2.6 Calculation of double-peak rainstorm pattern（CDPRPP）——FFRPM

①The peak coefficient and location of the main peak and secondary peak of double-peak rainstorm were statistically analyzed, Calculate the mode and average of the main and secondary peak positions, and select the position with the best fit as the position of the main and secondary peaks in the rain pattern of the double-peak rainstorm design;

②The virtual peak coefficients of double-peak rainstorm pattern in all measured events are calculated by formula (2), and the comprehensive virtual peak coefficient of double-peak rainstorm pattern is obtained by formula (3).

③Take any initial value of coefficient a and b in (0,1) through step (4) in 2.5, and substitute it into formula (9) and formula (10). The least square method is used to perform linear fitting for the peak rainfall and total rainfall of the double-peak virtual rain in all events,fields, when the fitting is optimal, the values of a and b are the desired values.

④Substituting the values of a and b into Equations (9) and (10), the calculation formula of virtual peak rainfall of double-peak rainstorm can be obtained, from which the virtual peak rainfall of double-peak rainstorm can be calculated.

⑤Perform linear fitting on the sum of virtual rain peak rainfall and main peak rainfall, secondary peak rainfall, main and secondary peak rainfall(MASPRA) of all the actual measured double-peak rainstorms to achieve the best, and substitute the fitting formula to obtain the fitted MASPRA.

⑥ After subtracting the main and sub-peak rainfall from the total rainfall, the rainfall in the rest of the period is calculated by the P&C RPM.

It can be seen that the design rain pattern of double-peak rainstorm can be obtained by the steps ① determining the location of the main and sub-peak rainstorm, ②-⑤ determining the MASPRA, and ⑥ determining the time-history distribution of the remaining rainfall.

3. Calculation results of design rain pattern of double-peak rainstorm

3.1 FFRPM

3.1.1 Selection of rainfall envents

(1) Arrange the rainfall of 19 double-peak rainstorms in 1.5h from large to small, numbered 1-19 respectively.

(2) Calculate the corresponding frequency of each rainfall through hydrological empirical frequency formula (Chun Z, Dongming G,2010) (11), find the frequency corresponding to each rainfall. Then use the formula of frequency and period (Shenglian G,Shouze Y,1992) (12) to select the rainfall in the return period of 1a, 3a, 5a, and 10a.

$$P = \frac{m}{1+n} \tag{11}$$

$$T = \frac{1}{P} \tag{12}$$

In formulas (11) and (12), P is the frequency, m is the rainfall number of the events, n is the total rainfall events, and T is the return period.

(3) Obtain the rainfall of 15mm, 28.7mm, 38mm, 46mm corresponding to the return period of 1a, 3a, 5a, and 10a. Choose four rainstorms with similar or the same total rainfall to replace 1a, 3a, 5a, 10a, and select the total rainstorm results to be 15.5mm, 28mm, 38mm, 46mm.

3.1.2 Determination of Main and Secondary Peak Locations

The positions of the main peak and the secondary peak during the 1.5h double-peak rainstorm are shown in Fig.4.

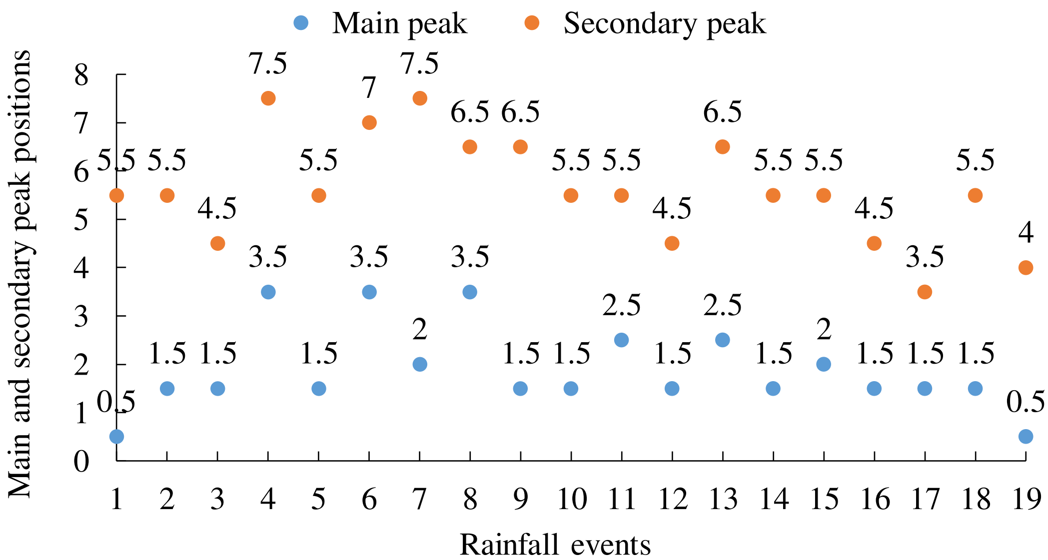


Fig. 4. location of main and secondary peaks

In Fig.4, in the first 11 double-peak rainstorms, the relative position of the main and secondary peaks is that the main peak is in the front and the secondary peak is in the back, while in the second 12-19 double-peak rainstorms, the relative position of the main and secondary peaks is that the main peak is in the back and the secondary peak is in the front.

Table 4

Location statistics of main and secondary peaks of 1.5h double-peak rainstorm

Classification	Average value of main peak position	Average value of secondary peak position	Main peak position mode	secondary peak position mode
The main peak is ahead	2.6	6.6	2	6
The main peak is behind	5.4	2.1	6	2

It can be seen from Table 4 that when the main peak is in the front, the average positions of the main peak and the secondary peak are 2.6 and 6.6 respectively, and the positions where the main peak and the secondary peak appear most are 2 and 6; when the main peak is in the back, the average positions of the main peak and the secondary peak are 2.1 and 5.4 respectively, and the positions where the main peak and the secondary peak appear most are 6 and 2. Taking into account the CVRPC and the fitting degree of rain pattern, the positions of the main and secondary peak of the double-peak are 2 and 6 when the main peak is in the front and the secondary peak is in the back, and 5 and 2 when the main peak is in the back and the secondary peak is in the front.

3.1.3 Double-peak CVRPC

According to equations (2) and (3), the virtual rain peak coefficients and comprehensive virtual rain peak coefficients of all 1.5h measured double-peak rainstorms are obtained. In order to facilitate comparison, the rain peak coefficients of all 1.5h measured single-peak rainstorms are also calculated. The rain peak coefficients of 1.5h measured single-peak and double-peak rainstorms are shown in Fig.5 and Table 5 below.

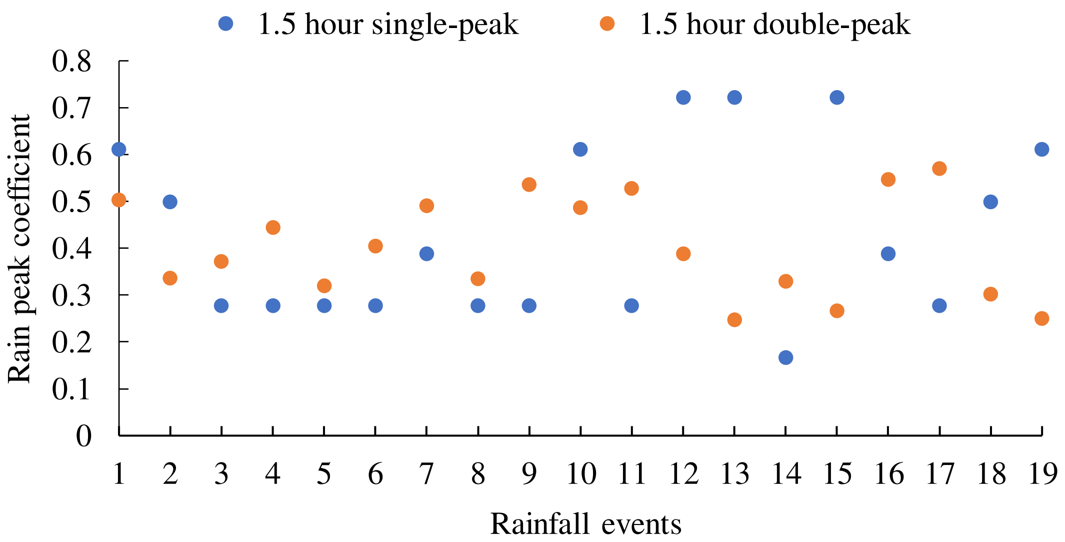


Fig. 5. Comparison chart of 1.5h single-peak and double-peak rainstorm peak coefficient

Table 5

Ratio of 1.5h single-peak and double-peak coefficient

Classification	Coefficient ≤ 0.5	Coefficient＞0.5	CRPC
Single-peak	73.6%	26.4%	0.40
Double-peak	68.4%	31.6%	0.39

As shown in Table 5, the RPC of 1.5h single-peak rainstorm is very similar to that of double-peak rainstorm.The proportion of RPC ≤ 0.5 is relatively high, and the peak rainfall is mainly in front, and the difference between the two comprehensive rain peak coefficient(CRPC) is not significant.

3.1.4 Calculation of double-peak virtual peak rainfall

(1) Take any value in (0,1) for a and b, and then put them into formula (9) and (10) to calculate the virtual peak rainfall, and then make linear fitting between the virtual peak rainfall and the total rainfall to make the best fitting. At this time, a = 0.5 and b= 0.5, as shown in Fig. 6.

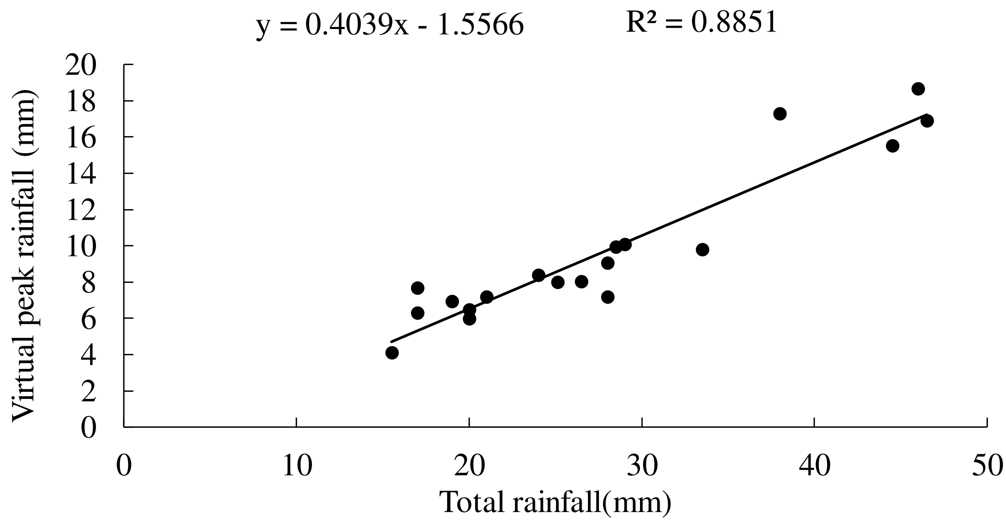


Fig.6. relationship between total rainfall and virtual peak rainfall

(2) Substitute a=0.5 and b=0.5 into Equations (9) and (10), and r_j=0.39 into Equation (4) to get the rainfall and the position of virtual rain peak.

The main and secondary peak coefficient formula:

$$x_i \in [1,\ 3.5], \qquad y_i = 0.2x_i + 0.3 \tag{13}$$

$$x_j \in [3.5,\ 9], \qquad y_j = -0.0909x_j + 1.3182 \tag{14}$$

Therefore:

When the main peak is in front, the peak rainfall of the virtual rain peak is:

$$H_i = (0.2x_i + 0.3)h_i + (-0.0909x_j + 1.3182)h_j \tag{15}$$

When the main peak is behind, the peak rainfall of the virtual rain peak is:

$$H_i = (0.2x_i + 0.3)h_j + (-0.0909x_j + 1.3182)h_i \tag{16}$$

According to formulas (18) and (19), the virtual peak rainfall of the double-peak rainstorm can be calculated in 1.5h for 19 envents, and the peak rainfall of the single-peak rainstorm in 1.5h for 21 envents can be compared. The results are shown in Fig. 7 and Table 6.

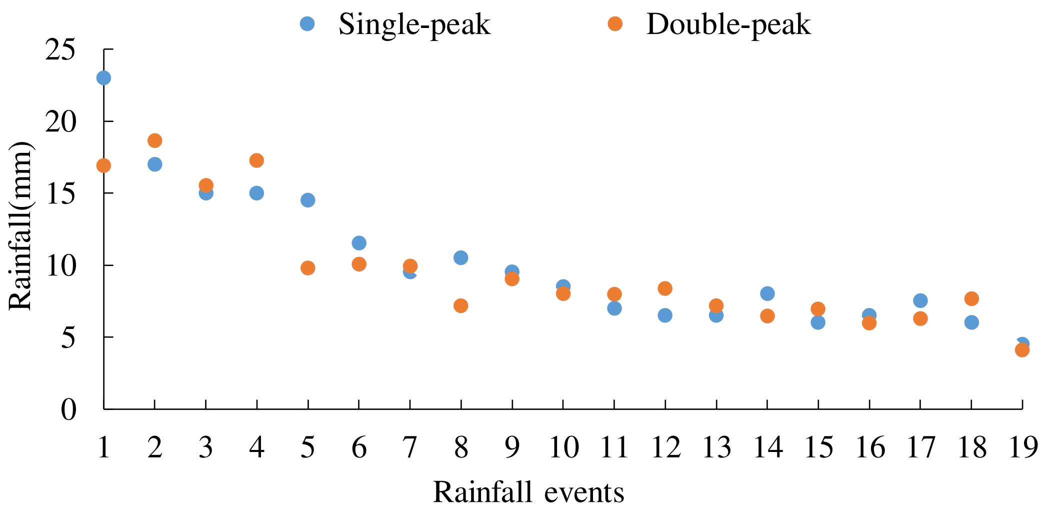


Fig .7. Comparison of 1.5h measured Single-peak and Double-peak rainfall

Table 6

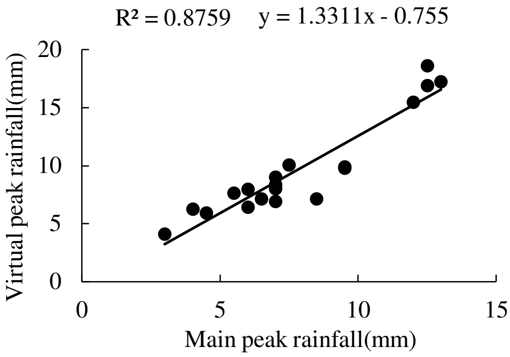
Comparison of statistical characteristic values of 1.5h single-peak rainfall and double-peak virtual rainfall

Eigenvalues	Average(mm)	Median(mm)	Standard deviation
Single-peak	10.64	9.5	4.99
Double-peak	10.54	9.1	4.43

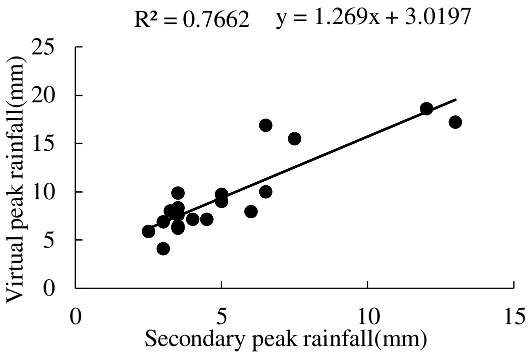
It can be seen from Fig. 7 and Table 6 that the peak rainfall of the single-peak and double-peak rainstorms during the 1.5h field measurement are in good agreement, whether it is the average value, median, or sample standard deviation, the peak rainfall of double-peak and single-peak The result of peak rainfall is very close.

3.1.5 Calculation of MASPRA

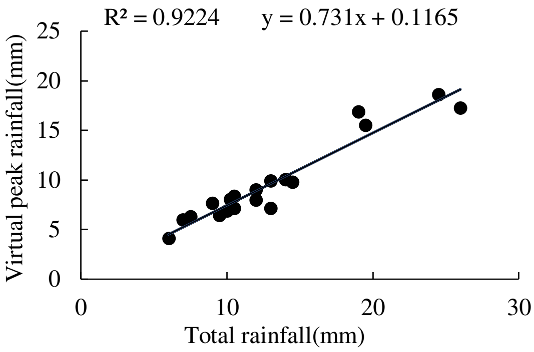
The best linear fit is performed on the sum of the virtual peak rainfall and the secondary peak rainfall, the main peak rainfall, the MASPRA of all the measured double-peak rainstorms, and the results are shown in Fig. 8 a, b, and c. The rain peak-correlation coefficient is the worst at 0.7662, so the MASPRA can be obtained according to the relationship between total rainfall-virtual rain peak, main peak-virtual rain peak, major and secondary peaks and-virtual rain peak.



(a) Main peak-virtual rain peak



(b) Secondary peak-virtual rain peak



(c) Relationship between primary and secondary peaks and virtual rain peak

Fig.8. The relationship between Main peak or secondary peak or total peak with virtual rain peak

3.1.6 Rainfall distribution in other periods

After subtracting the MASPRA from the total rainfall, the rainfall during the rest of the period is calculated by the P&C RPM, and finally the distribution ratios of the main peak before and after the main peak of the double-peak rainstorm can be obtained respectively, such as Table 7 and Table 8:

Table 7

Rainfall ratio based on fitting method (main peak in front)

Period (10min)	1	2	3	4	5	6	7	8	9
Proportion	0.1315		0.2682	0.1753	0.1227		0.1303	0.1263	0.0457

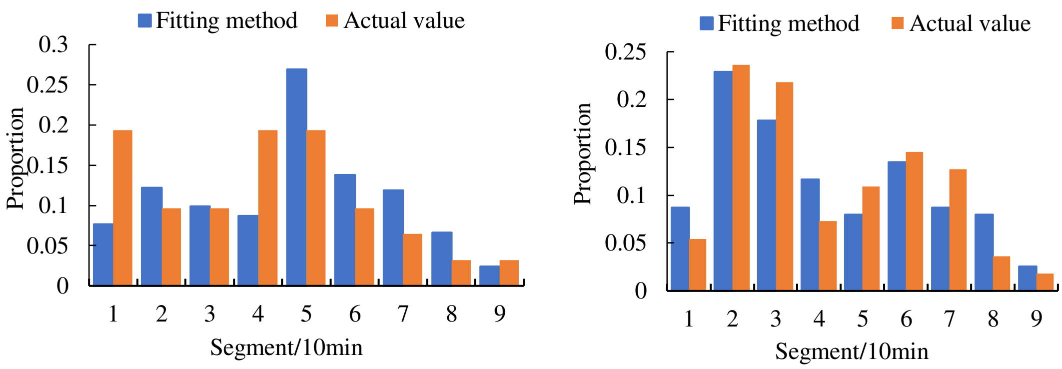
Table 8

Rainfall ratio based on fitting method (main peak in behind)

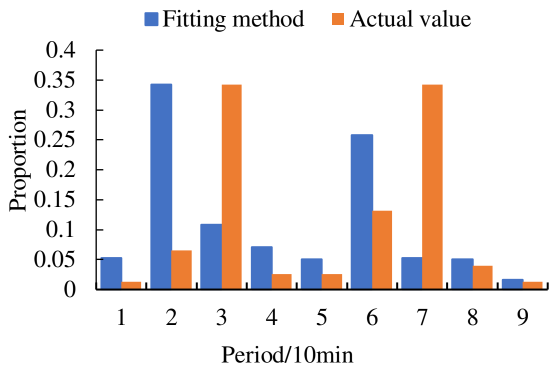
Period (10min)	1	2	3	4	5	6	7	8	9
Proportion	0.1259		0.1623	0.1428		0.2261	0.1948	0.1082	0.0398

3.1.7 Fitting rain pattern results

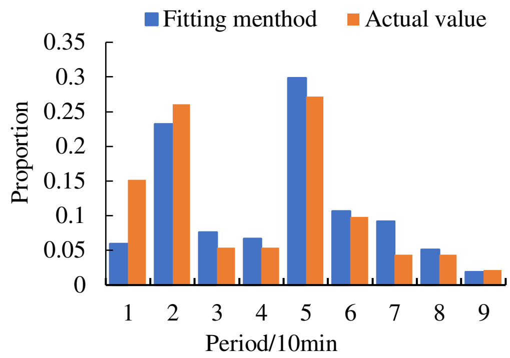
Selecting four double-peak rainstorms with the return period of 1a, 3a, 5a, and 10a as examples，the compared results of fitting rain pattern and actual rain pattern are shown in Fig.9.



(a) 1a (b) 3a



(c) 5a



(d) 10a

Fig. 9 . Comparison of the fitted rain pattern and the actual rain pattern with the different return period

3.2 P&C rain pattern method

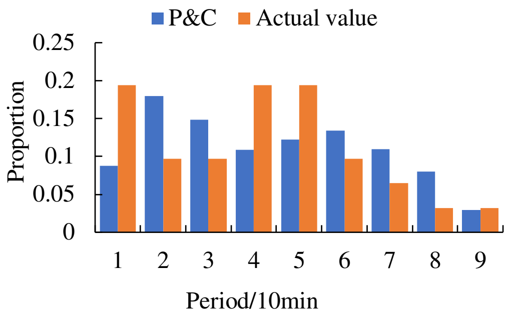
According to the obtained 1.5h double-peak rainstorm data, and apply with the P&C method, the rainfall proportion results of each period within 1.5h double-peak rainstorm can be obtained,as shown in Table 9.

Table 9

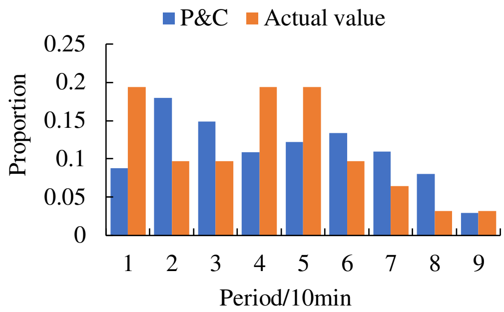
The average rainfall proportion based on P&C method

Period (10min)	1	2	3	4	5	6	7	8	9
Proportion	0.0877	0.1797	0.1487	0.1089	0.1220	0.1341	0.1094	0.0802	0.0293

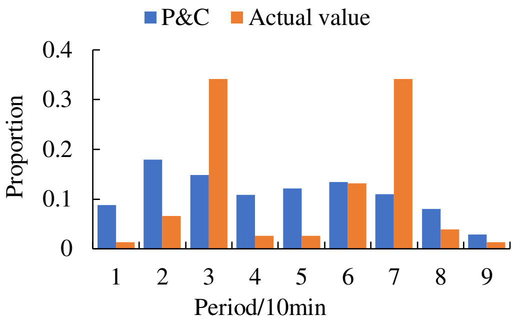
Thus, the rain pattern time distribution of the four double-peak rainstorms with the different return periods of 1a, 3a, 5a, and 10a can be achieved. Fig. 10 is the comparsion of the P&C rain pattern and actual rain pattern with the different return periods below.



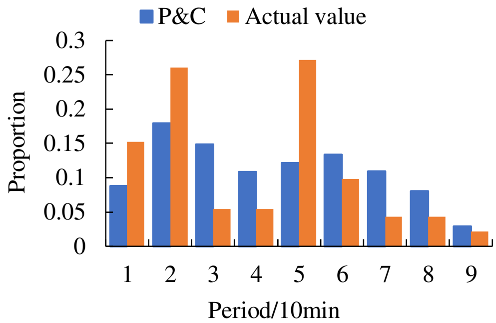
(a) 1a



(b) 3a



(c) 5a



(d) 10a

Fig. 10 Comparison results of the P&C rain pattern and actual rain pattern with the different return periods

3.3 Comparison of results between FFRPM and P&C RPM

3.3.1 Analysis of results of P&C RPM

(1) Overall rain pattern fitting analysis

Using the fuzzy recognition method (Abhishekh Srivastava et al.,2019), the fitting degree of the rainstorm patterns and the corresponding measured rainstorm pattern can be calculated as fourmula (17).

$$e = 1 - \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \tag{17}$$

where e is the overall rain pattern fitting degree, x_i is the distribution ratio for the i-th period of the measured rainstorm, y_i is the distribution ratio for the i-th period of the corresponding P&C rain pattern, i =1, 2, ..., n.

The oveall rain pattern fitting degree of the P&C RPM is shown in Table 10.

Table 10

The oveall rain pattern fitting degree of the P&C RPM

Return period	1a	3a	5a	10a
Fitting degree	0.934	0.961	0.940	0.923

Larger value of fitting degreee means the P&C RPM is more avaiable, so from Table 10, it can be seen that the P&C RPM is relatively good for the overall rain pattern fit for the double-peak rainstorm with the return period of 1a, 3a, 5a, and 10a.

(2) Main and secondary peak analysis

The main and secondary peak fitting formula (18) is used to calculate and analyze the main and secondary peak errors of the four rainstorm types, the results are shown in Table 11, and the formula is as follows:

$$e = 1 - \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2} \tag{18}$$

In formula (18), x_1 and x_2 respectively represent the proportion of the main peak rainfall and the secondary peak rainfall calculated by the P&C rain pattern to the total rainfall, and y_1 and y_2 respectively represent the proportion of the main peak rainfall and the secondary peak rainfall of the measured rainfall in the total rainfall. The larger the value of e, the higher the degree of fitting, so as to verify the accuracy and rationality of the fitting of P&C rain patterns on the local main and secondary peaks.

Table 11

Calculation results of the main and secondary peak fit degree

Return period	1a	3a	5a	10a
Fit degree	0.926	0.942	0.736	0.804

It can be seen that for the double-peak rainstorm with the return period of 1a and 3a, the P&C RPM fits better in the main and secondary peaks, but for the double-peak rainstorm with the return period of 5a and 10a, the P&C RPM is in the main. There is a big gap between the secondary peak fit degree and the true value, and the calculated main peak is only about half of the actual value; and the P&C RPM cannot distinguish between the main peak before and the main peak after.

(3) Analysis of overall rainfall

Using formula (19) to calculate and analyze the overall rainfall difference of the four rainstorm patterns, the results are as follows in Table 12, and the formula is as follows:

$$m = \frac{\sum_{i=1}^{n}|h_i-H_i|}{2} \tag{19}$$

In formula (19), m is the total rainfall difference, n is the number of periods, h_i is the rainfall obtained in each period of the P&C method, and H_i is the actual measuredrainfall in each period.

Table 12

Calculation result of total rainfall difference

Rainstorm events	1a	3a	5a	10a
Total rainfall	4.108	3.987	16.192	13.588

difference/mm				
Percentage of total rainfall	26.5%	14.2%	42．6%	29.5%

3.3.2 Analysis of the results of FFRPM

Through the comparison and analysis with the measured rainstorm data, the calculation results of the fitting degree of the overall rain pattern, the fitting degree of the main and secondary peaks, and the difference of total rainfall can be obtained as shown in Table 13, Table 14 and Table 15:

Table 13

Calculation result of rain pattern fit degree

Return period	1a	3a	5a	10a
Fit degree	0.936	0.968	0.838	0.962

Table 14

Calculation results of fit degree of main and secondary peaks

Return period	1a	3a	5a	10a
Fit degree	0.939	0.987	0.916	0.962

Table 15

Calculation results of total rainfall difference

Return period	1a	3a	5a	10a
Total rainfall difference /mm	4.385	3.500	19.900	11.529
Proportion in total rainfall	28.3%	12.5%	52.4%	25.0%

3.3.3 Comparison of results between FFRPM and P&C RPM

From Table 10, Table 11 and Table 12, it can be seen that for the double-peak rainstorms with the return period of 1a and 3a, the P&C RPM has a better fit between the main and secondary peaks, but for the double-peak rainstorm with return period of 5a and 10a, the P&C RPM has a large gap between the main and secondary peaks and the true value, and the calculated main peak is only about half of the actual value; And the P&C RPM cannot distinguish between the main peak in the front and the main peak in the back.

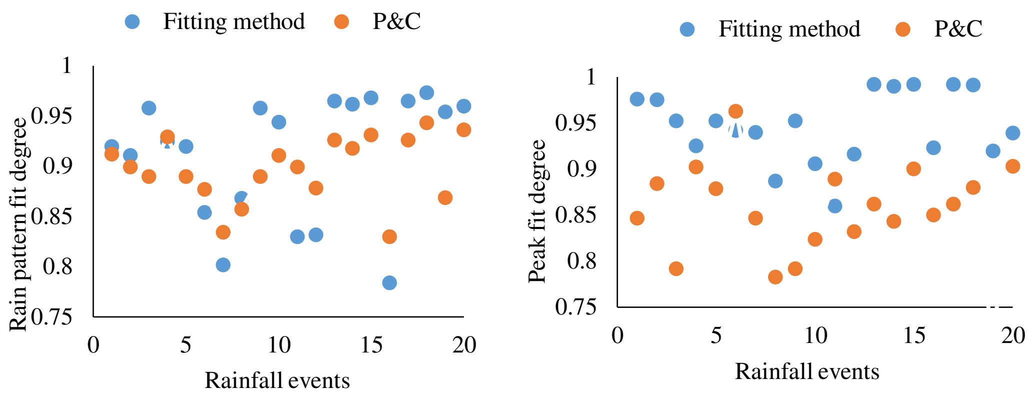
It can be seen from Table 12 that the P&C RPM only has a small total rainfall difference in 3a, the total rainfall difference between 1a and 10a is relatively large, and the 5a total rainfall deviation is the largest, with a deviation ratio of 42.6%.

From Table 13, Table 14 and Table 15, it can be seen that the fitting rain pattern method is superior to P&C method in three events of the overall rain pattern. Except for the rainstorm with a recurrence period of 5a, the fitness of the main and secondary peaks are higher than that of P&C method. Because FFRPM divides double-peak rainstorm into two types, i.e. the front of main peak and the back of main peak, the calculation results are more realistic than P&C method which does not distinguish the position of main and secondary peak. On the total rainfall difference, the difference between the total rainfall of 3a and 10a is smaller, the difference between the total rainfall of 1a is larger, and the difference between the total rainfall of 5a is the largest, and the comparison results are similar to P&C method. It can be seen that the FFRPM improves the fitness of main and secondary peaks greatly, and is more accurate in the similarity of the overall rain pattern, which is more in line with the actual situation.

3.4 Deducing results of all double-peak rainstorms with short-duration in Zhengzhou City

The short-duration double-peak rainstorms were mainly concentrated within 1h and 1.5h, there were a total of 20 double-peak rainstorms within 1h, accounting for 23%, and 19 double-peak rainstorms within 1.5h, accounting for 47.5%. In order to more clearly verify the practicability of the FFRPM proposed in this paper, P&C method and FFRPM are respectively used to calculate and compare all 1h and 1.5h double-peak rainstorms in Zhengzhou City the calculation steps are the same as above.

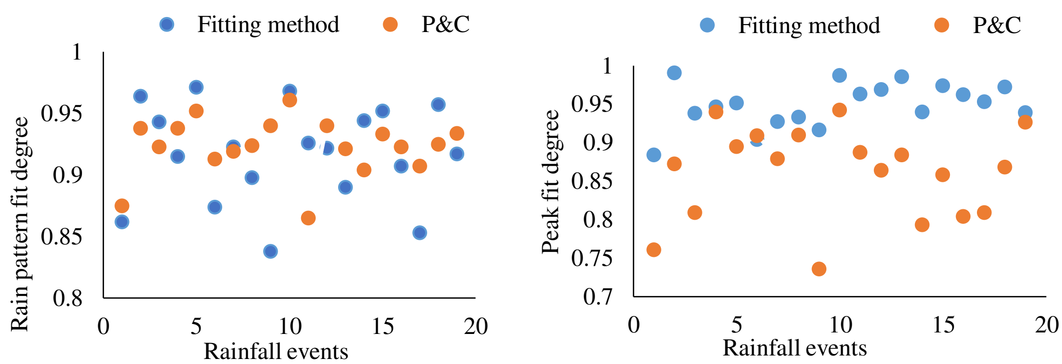
(1) The fitting degree of rain pattern and the main and secondary peak fitting degree of double-peak rainstorm 1h 20 rainstorms were analyzed, and the results are as follows: Fig.11 a and b:



(a) (b)

Fig.11. Schematic diagram of fit results

(2) Analyze the fit degree of the double-peak rainstorm pattern and the fit degree of the main and secondary peaks during 1.5h19 in Zhengzhou City, and the results are shown in Fig.12 a and b:



(a) (b)

Fig.12. Schematic diagram of fit results

Table 16

1h and 1.5h double-peak rainstorm pattern fit and the average value of the main and secondary peak fit

Fit degree	1h rain pattern fit	1h peak fit	1.5h rain pattern fit	1.5h peak fit
Fitting method	0.913	0.946	0.920	0.949
P&C method	0.897	0.852	0.923	0.860

Table 17

Average value of 1h and 1.5h total rainfall difference

Methods	1h total rainfall difference	1.5h total rainfall difference
P&C method (mm)	5.67	7.61
P&C method proportion	25.4%	27.5%
Fitting method (mm)	4.41	7.62
Fitting method proportion	19.7%	27.5%

It can be seen from Fig. 11 (a, b), the overall rain pattern fitting degree of 20 double-peak rainfall within 1h shows that the fitting degree of 14 of 20 double-peak rainfall events is greater than that of P&C, and only 6 events are less than that of P&C; In the fitting degree of local main and secondary peak rain patterns, the fitting method was larger than P&C method in 18 of 20 events, and only 2 events were smaller than that of P&C method; It can be seen from Fig. 12 (a, b), for 1.5h 19 double-peak rainfall overall rain pattern fit, 11 of 19 overall rain pattern fits are greater than the P&C method and 8 are less than the P&C method; For the fitting degree of local primary and secondary peak rain patterns, the fitting method was larger than P&C method in 18 of 19 events, and only 1 event was smaller than P&C method; On the whole, whether it is 1h or 1.5h double peaks, the fitting method is better than the P&C method in the degree of fit between the primary and secondary peaks; It can be seen from Table 16 that the fitting degree of overall rainfall pattern, main and secondary peak rainfall pattern in 1H is greater than that of P% C method, the fitting degree of main and secondary peak rain patterns is improved more, , and the main and secondary peak rain pattern fitting degree of 1.5h is slightly lower than that of the P&C method, but the main and secondary peak rain pattern fitting degree are also greatly improved. The fitting method is superior to the P & C method in 1 and 1.5 hours for the overall rain pattern fitting degree.

3.5 Discussion

The fitting rain pattern method proposed in this paper is based on the characteristics of short-duration double-peak rainstorm patterns and the characteristics of P&C rain pattern. The advantage of this method is that the rainfall of the main peak and the secondary peak in the double-peak can be calculated very accurately, at the same time, the rest of the rainfall also maintains a higher accuracy, so that the overall rain pattern can maintain a higher similarity.

In order to better explain the applicability of FFRPM, this paper takes P&C rain pattern method as an example to compare and analyze the differences between them., and the rain pattern of rainfall is always unchanged, which is quite inconsistent with the actual short-duration rainstorm in the city(Shufang O et al.,2018). Compared with P&C rain pattern, the precision of fitting rain pattern, main and secondary peak rainfall and location are improved, especially the precision of MASPRA is improved more. Urban flood disasters are often caused by the large and concentrated quantity of main and secondary peaks. This method can effectively estimate the peak quantity, which is of great significance to urban flood control and waterlogging prevention.

For rainfall with a return period of 3a, it can be seen that in the FFRPM, the MASPRA differs greatly from the measured rainfall. The main reason is that the locations of the main and secondary peaks are not accurate enough. The measured locations are 3 and 7, while the deduced locations are 2 and 6, there is a big difference between them. At present, no matter the research of double-peak rain pattern or single-peak rain pattern, it is impossible to accurately determine the location of the rain peak of each rainstorm.

For the rainfall with a return period of 1a, it can be seen that in the measured rainfall, there are three identical rainfall locations 1, 4 and 5(all peak rainfall is 6mm), and there should be a higher peak between 4 and 5. However, due to the low precision of data, the main peak location can only be set as 4.5, and 6mm for the peak rainfall. This leads to certain errors in the location of the rain peak and the rainfall of rain peak, and the final result is not accurate enough. This study is based on the 10-minute rainstorm extract data of Zhengzhou City. If there are 5-minute or 1-minute rainstorm extract data, it is believed that the simulation result will be more accurate.

4. Conclusions

(1) Based on the idea of CDPISPM and then reverting to double-peak, the proposed FFRPM can be used to calculate the DPRPM with short-duration in Zhengzhou City.

(2) The short-duration double-peak rainstorms mainly concentrated within 1h and 1.5h. The comprehensive peak coefficient of double-peak rainstorms is 0.3918 by using

the FFRPM, indicating that the rainfall of double-peak rainstorms mainly concentrated in the first half, which is consistent with the performance of single-peak.

(3) Compared with the traditional P&C method, the fitting degree of the overall rain pattern of the fitting method is 0.75 ~ 1, and the fitting degree of the main and secondary peak rainfall is 0.9 ~ 1, and the location accuracy of the MASPRA is also higher.

(4) In the rain pattern fitting method, the fitting degree of a few overall rain patterns,and main and secondary rain peaks are low, mainly because of the inaccurate locations of main and secondary peaks, or the insufficient data accuracy. Therefore, the overall rain pattern can be properly corrected by combining P&C RPM, which is more in line with the reality. For the location of rainstorm peak, the data accuracy should be improved and the duration of rainstorm extraction should be shortened, so as to further improve the location accuracy of rainstorm peak.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

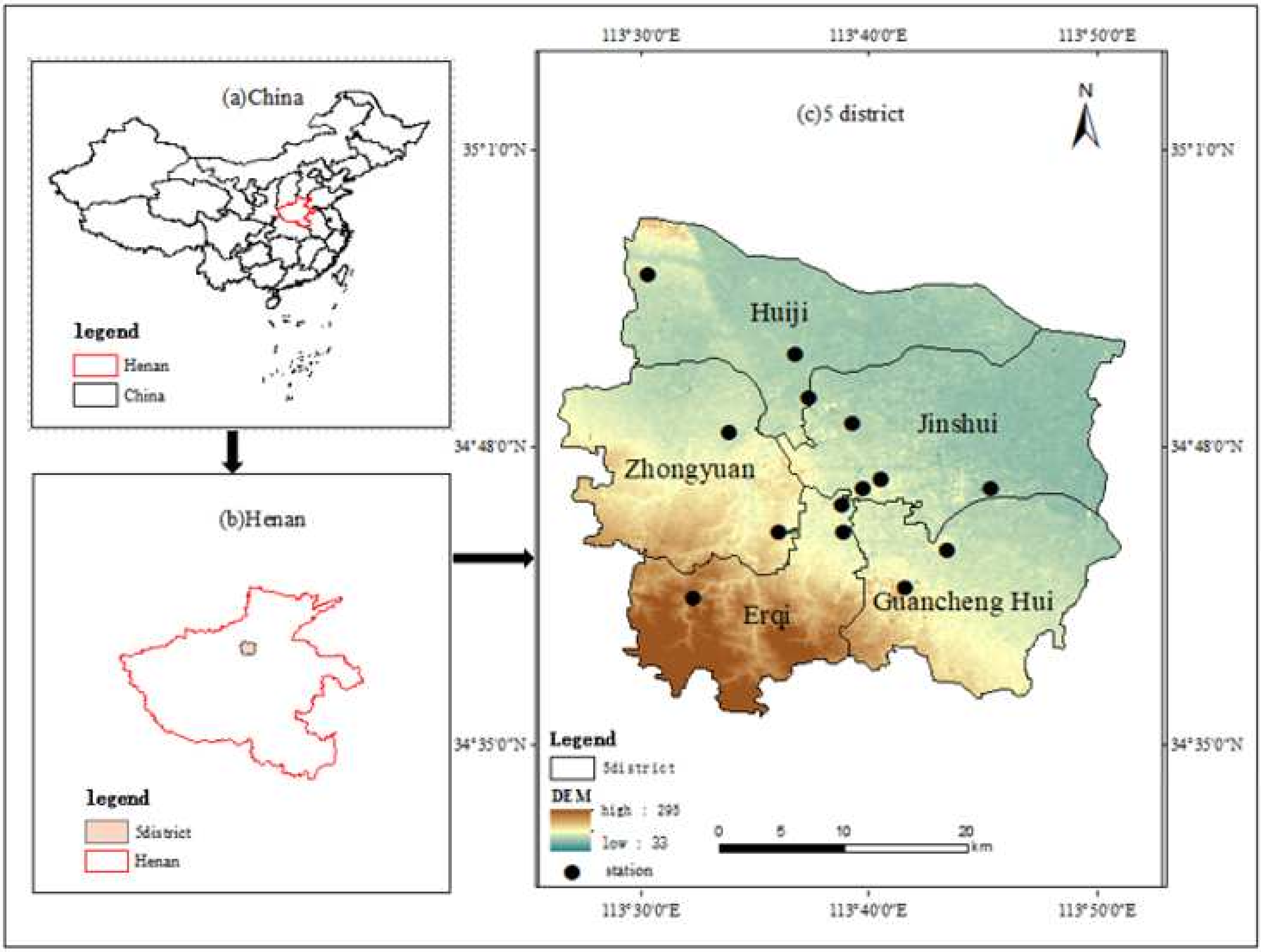

Figure 1

Distribution map of five districts and rainfall stations in Zhengzhou City, Henan Province Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

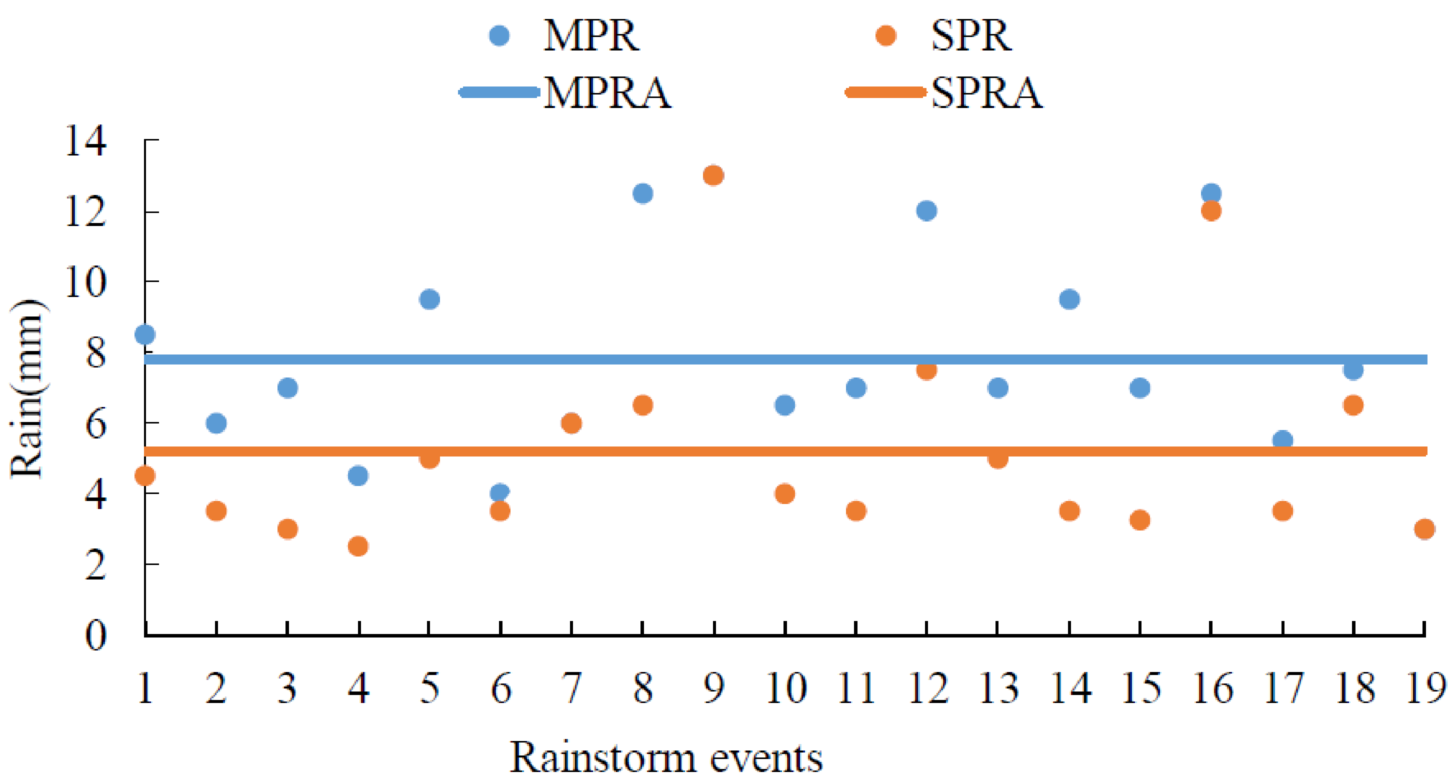

Figure 2

MPR and SPR of double-peak rainstorm

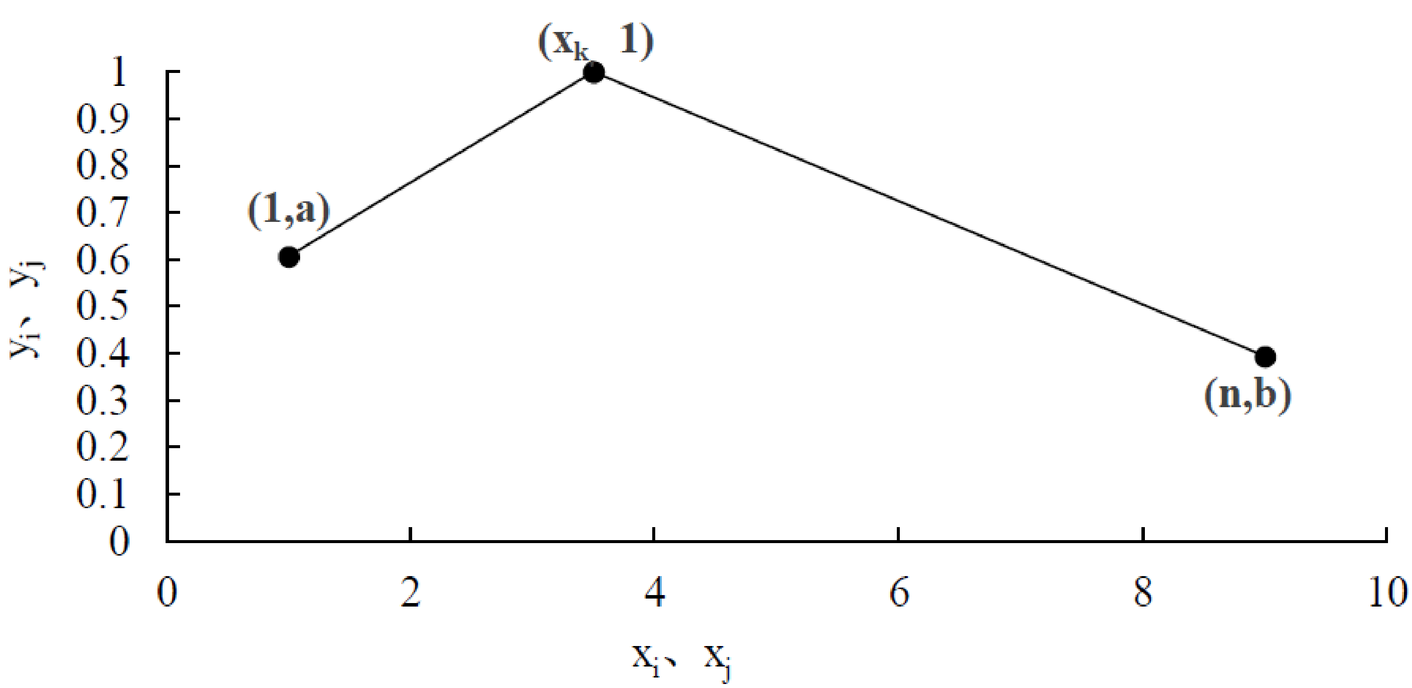

Figure 3

The relations between yi, yj and xi, xj

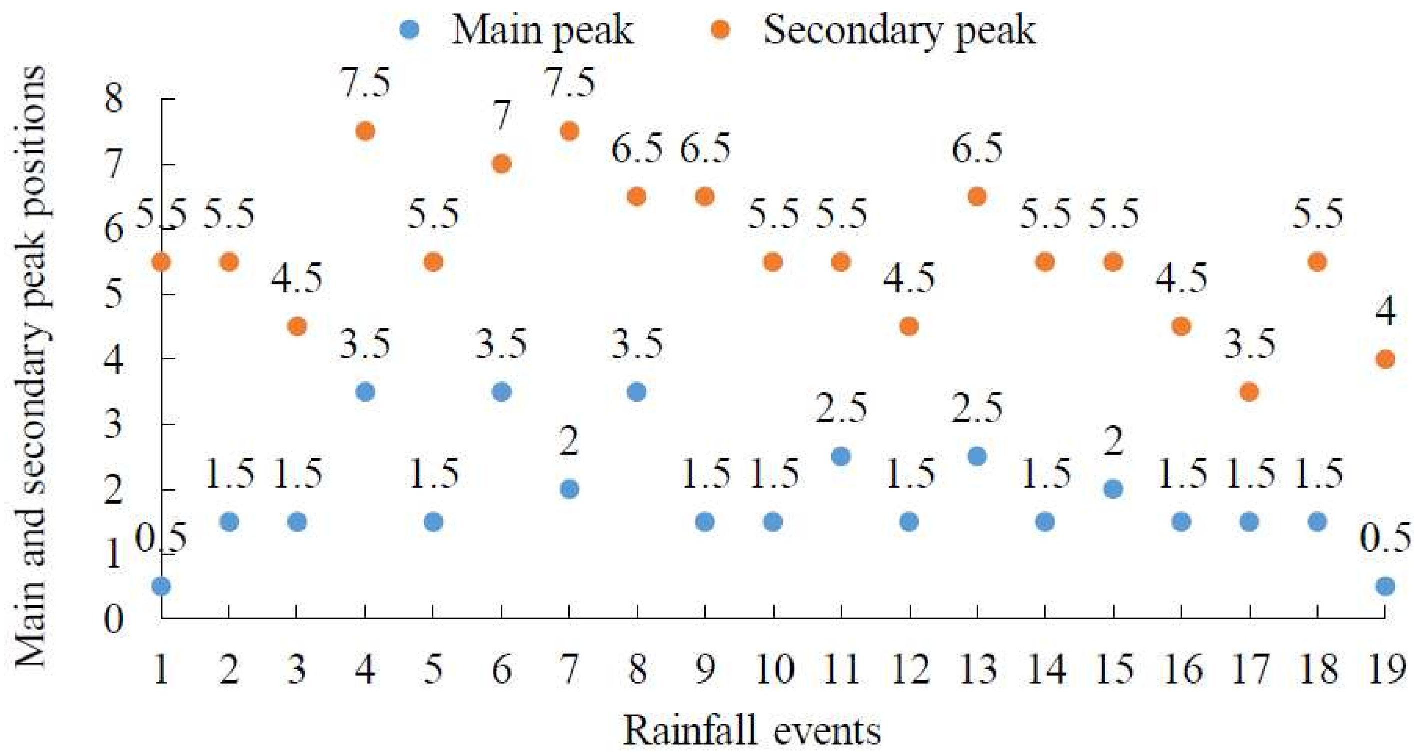

Figure 4

Location of main and secondary peaks

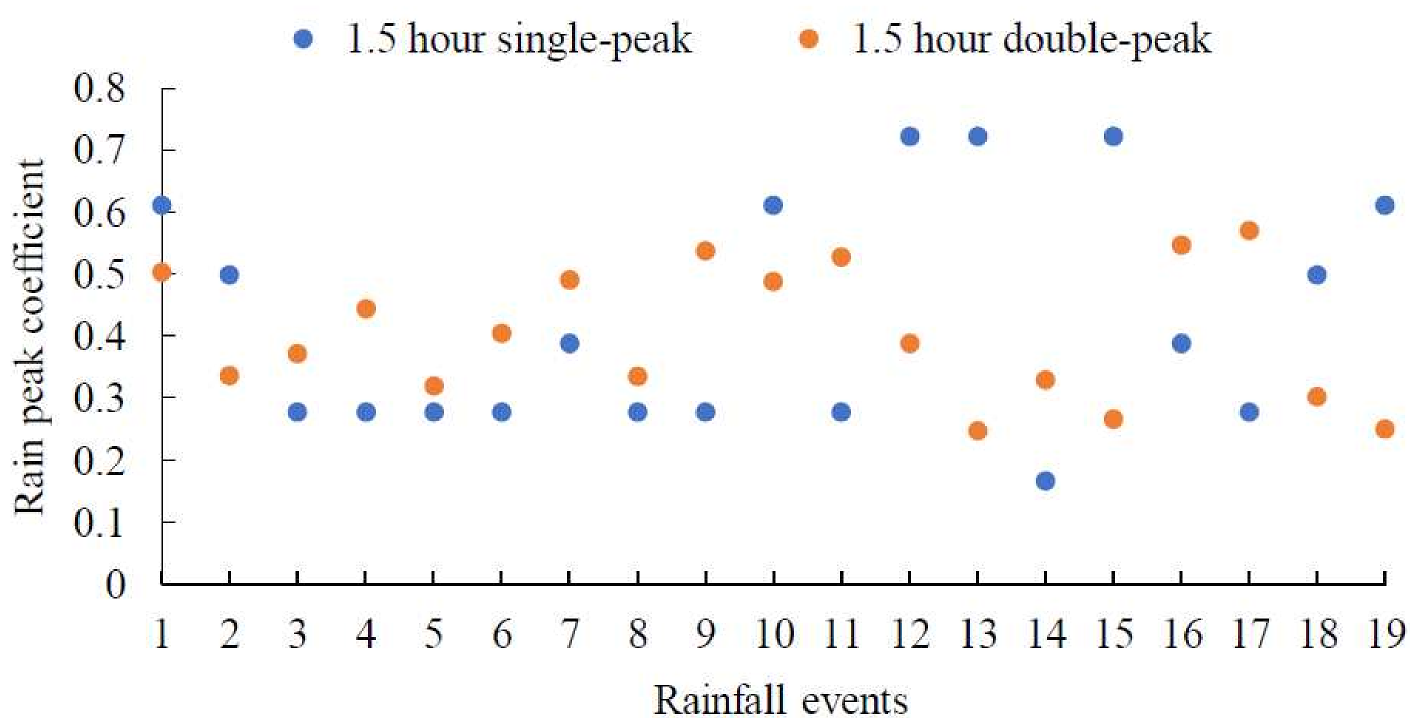

Figure 5

Comparison chart of 1.5h single-peak and double-peak rainstorm peak coefficient

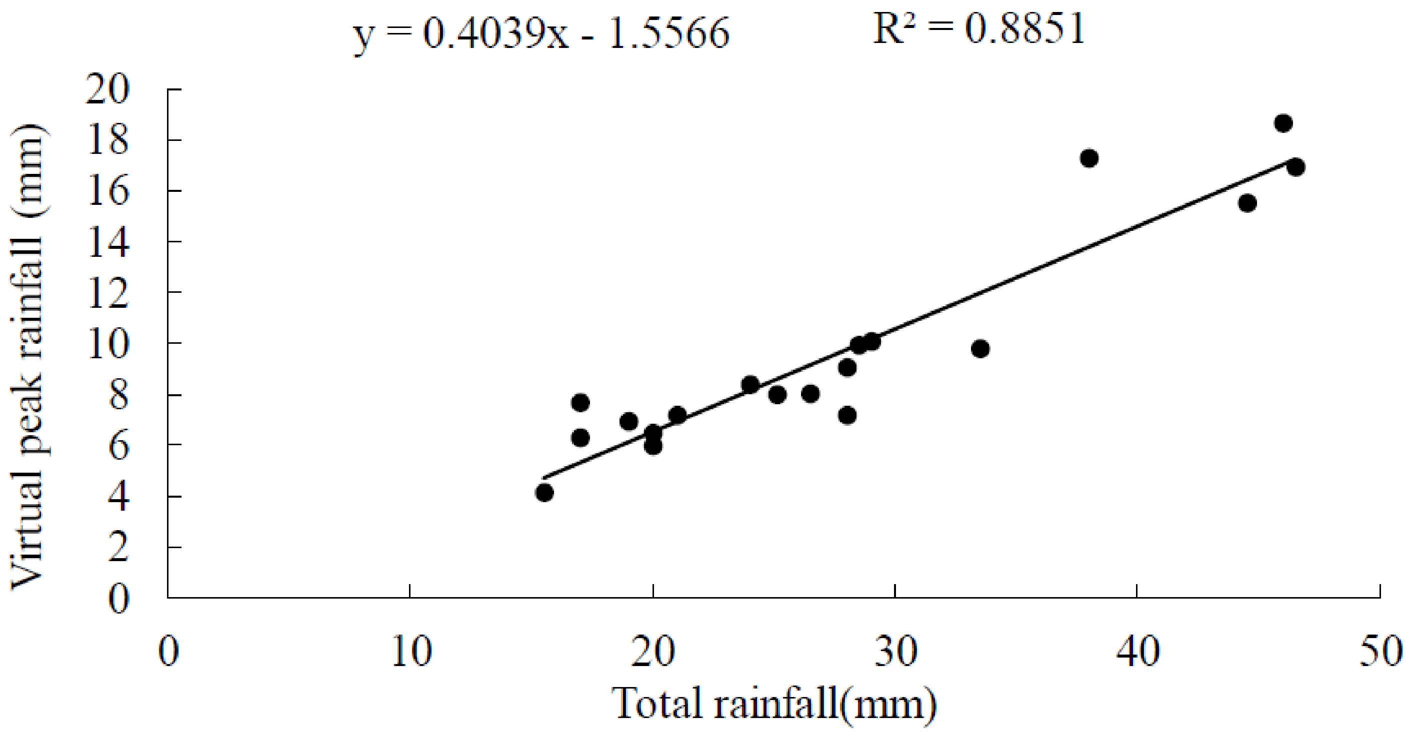

Figure 6

Relationship between total rainfall and virtual peak rainfall

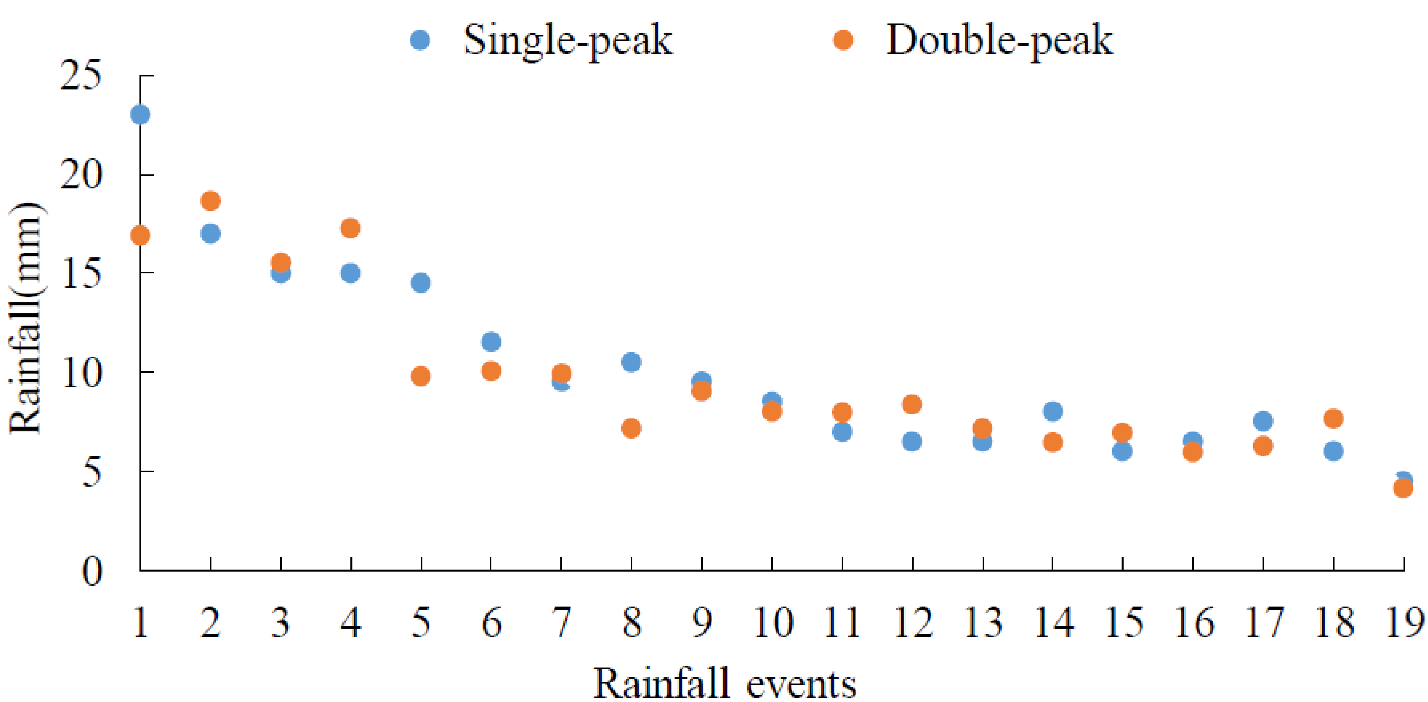

Figure 7

Comparison of 1.5h measured Single-peak and Double-peak rainfall

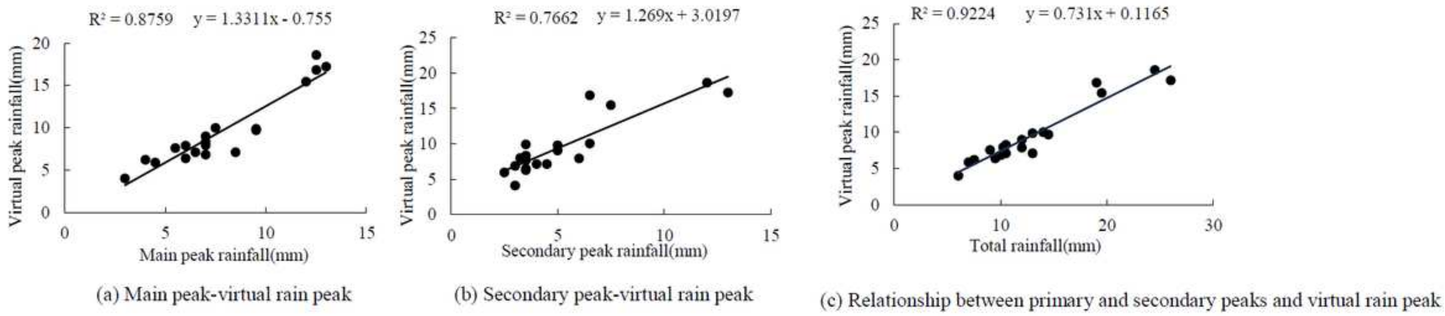

Figure 8

The relationship between Main peak or secondary peak or total peak with virtual rain peak

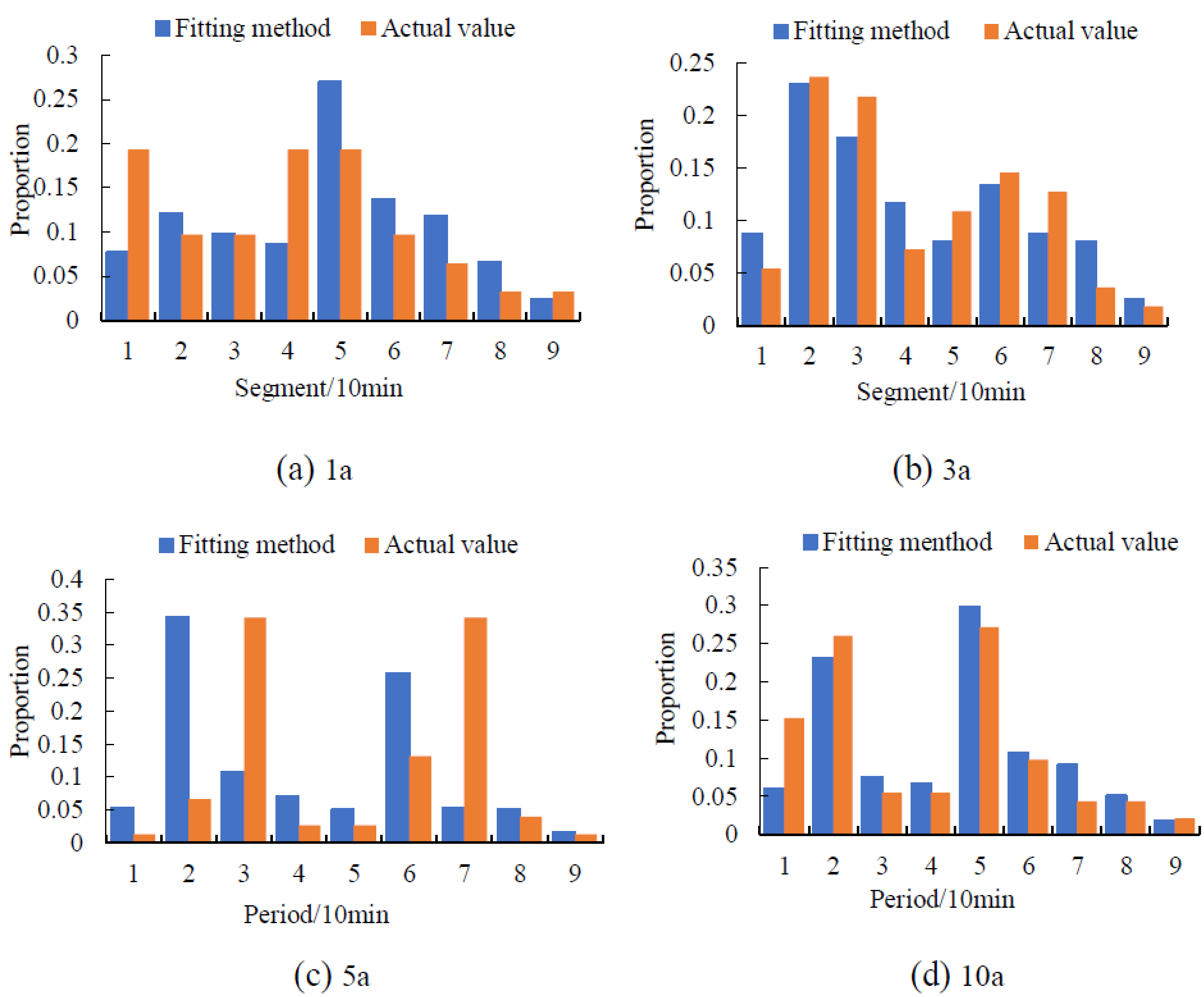

Figure 9

Comparison of the fitted rain pattern and the actual rain pattern with the different return period

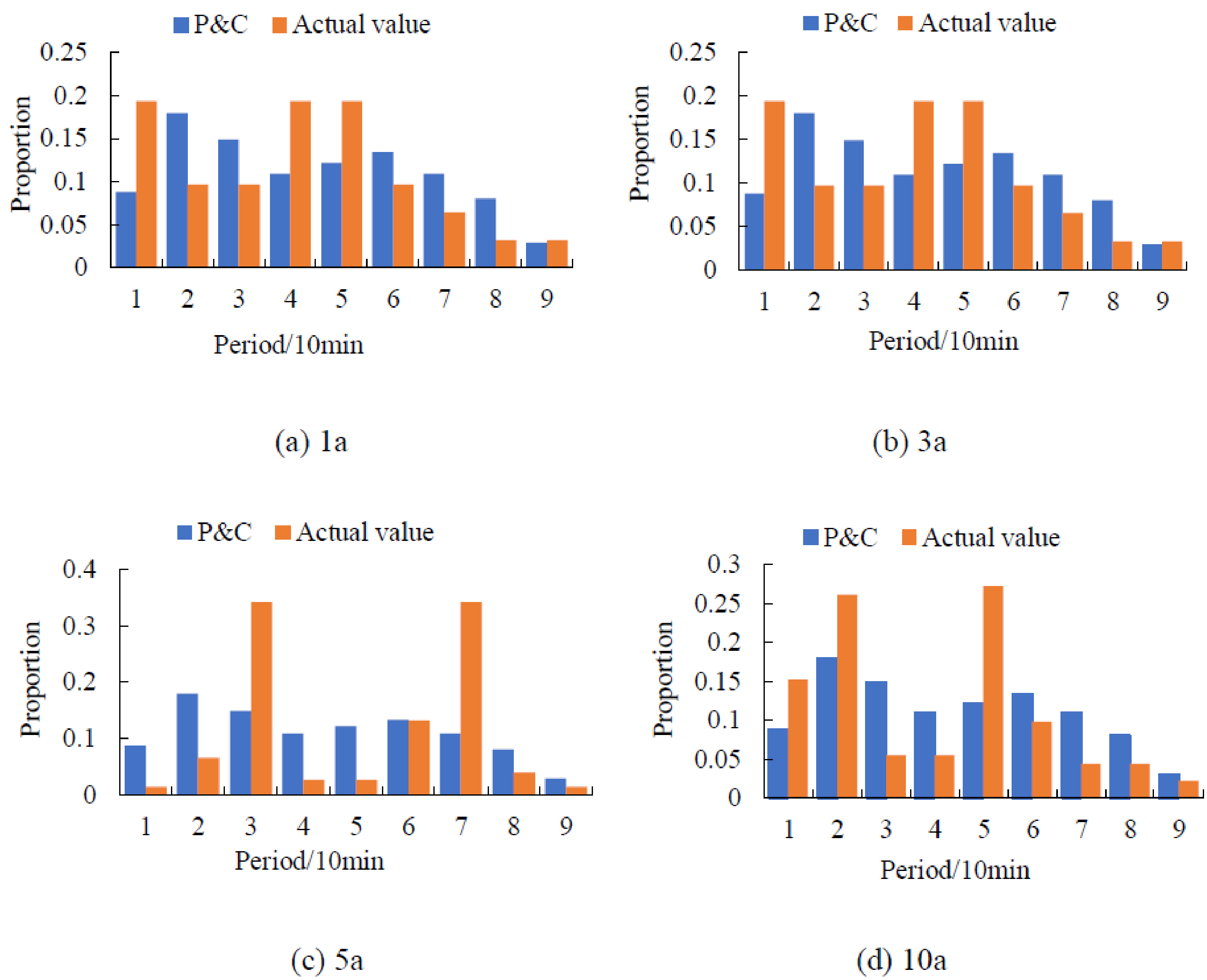

Figure 10

Comparison results of the P&C rain pattern and actual rain pattern with the different return periods

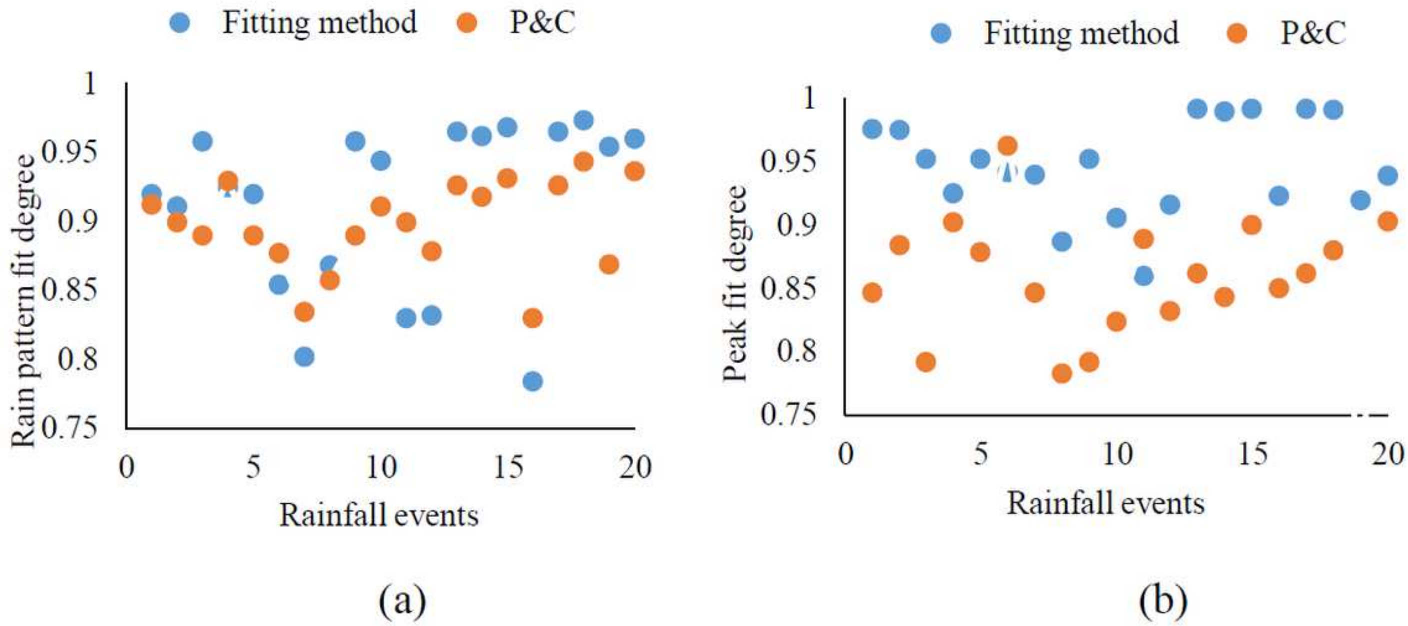

Figure 11

Schematic diagram of fit results

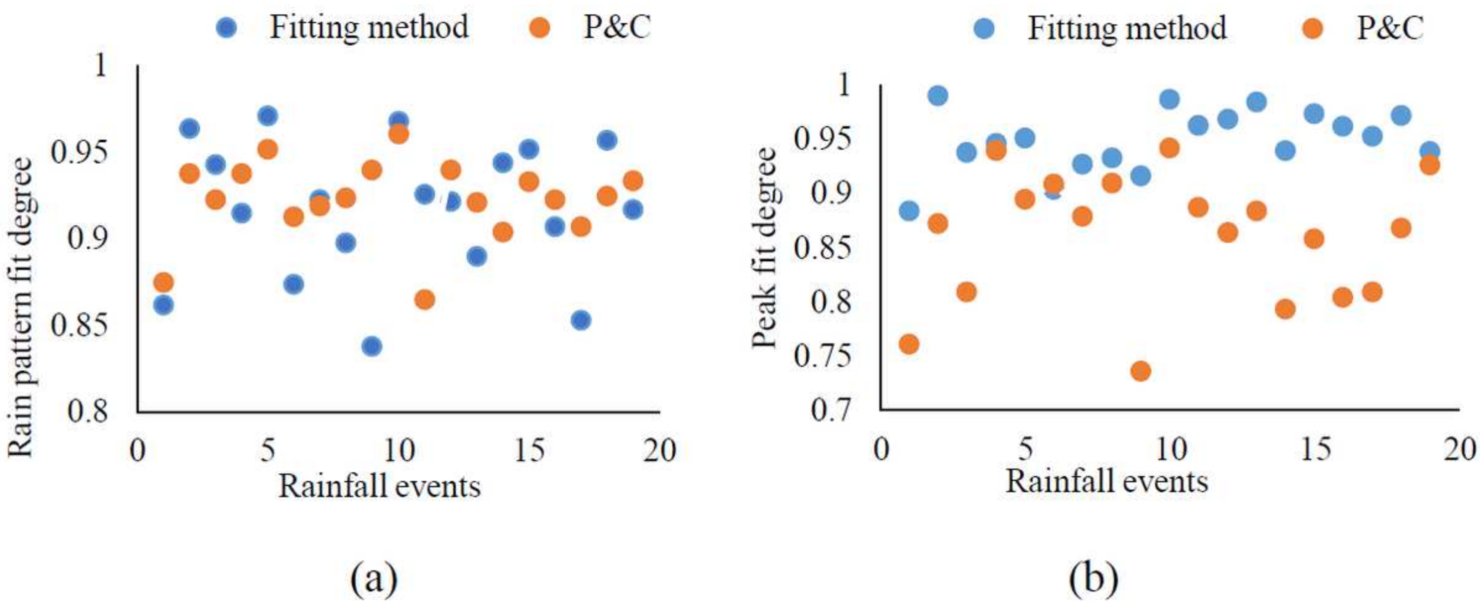

Figure 12

Schematic diagram of fit results

Supplementary Files

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