Study on Urban Rainstorms Design Based on Multivariate Secondary Return Period

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Abstract

In order to reveal the correlations between rainstorm characteristics variables, and make the return period of rainstorm more reasonable and objective, in this study, the joint distribution models of rainstorm elements are established by using copula theory based on the rainfall data in a Chinese megacity, Zhengzhou. Then their combined design values of the primary return period (PRP) and secondary return period (SRP) derived by the maximum probability method (MP) and same frequency method (SF) are obtained, finally using the Pilgrim & Cordery method (PC) the rainstorm pattern is designed. The results indicate that the calculation of rainstorm return period (RRP) with SRP is more reasonable compared with PRP. For the same RRP, the rainstorm volume (RV) of “Or” return period (ORP) type is largest, while the “And” return period (ARP) is smallest, and the RVs of Kendall return period (KRP) and survival Kendall return period (SKRP) are between them. For the KRP, the RVs calculated by MP and SF are pretty close, and their relative errors is between -5.84% and 4.69%. Compared to ORP, the rainstorm patterns of KRP can reduce the magnitude and investment of the stormwater infrastructure. Moreover, the rainfall of the designed rainstorm pattern of SKRP mainly concentrated before the rain peak in contrast with KRP.

1 Introduction

In recent years, rainstorms are becoming more frequently affected by climate changes and human activities, which have led to serious urban waterlogging disasters and become the focus of public's concern worldwide (Bertilsson et al., 2019; Liao et al., 2019; Loke et al., 2021). Zhengzhou city, a super-large central city of China, also suffers from urban flooding. A typical example of extreme rainstorm in Zhengzhou city is happened on 7/20/2021, resulting in 292 deaths and 1.736 million affected people. Thus, the risk assessment of rainstorm event is significant for the urban flood control and disaster reduction.

Rainstorm return period (RRP) is widely used to evaluate the occurrence risk of rainstorm event. RRP refers to the average time interval of a specific rainstorm event. However, the traditional calculation of RRP only considers the RV, but for other rainstorm characteristic elements as peak rainfall intensity (PR), pre-peak cumulative rainfall, peak appearance time, and rainstorm duration are not involved, thus the correlations of these characteristic elements are ignored. Actually, the multivariable return periods are now gradually applied to the hydrology field, such as drought (Chen et al., 2013; Tu et al., 2016; Van de Vyver and Van den Bergh, 2018; Zhou et al., 2019), sea wave (Chen et al., 2017, 2018a) and flood events (Chen et al., 2018b; Li et al., 2014; Requena et al., 2016), but it is still rare for rainstorm. RV and PR are two mainly considerate elements for a rainstorm event, but rainfall after peak (RAP) can reflect the possible urban waterlogging. So, it is important to involve RV, PR and RAP into rainstorm risk evaluation.

ORP and ARP are two common multivariable return periods types and often called as PRP, but they cannot identify the disaster events' hazard area accurately (Salvadori and De Michele, 2004; Salvadori et al., 2011; Huang and Chen, 2015). To overcome this shortcoming, (Salvadori et al., 2011, 2013) proposed KRP and SKRP in 2011 and 2013 respectively. Compared with ORP and ARP, the theoretical identification

of dangerous domain is improved by KRP and SKRP, so their calculations are more accurate. KRP and SKRP are also called as SRP. For the previous study of SRP, more concerns are contributed to KRP, while SKRP is less, even be ignored, which results in an incomplete study on SRP. Therefore, in this study, KRP and SKRP are clearly involved in SRP firstly, and then they are introduced to design the urban rainstorm, this is also the innovation of this study.

This paper aims to analyze the characteristic elements of rainstorm events firstly, and then the main correlated rainstorm elements including RV, PR and RAP are presented. Using the Copula method, the joint distribution of rainstorm elements is constructed, with which the PRP and SRP of the rainstorm elements combinations are displayed to show their difference. Finally, application with the MP method and the SF method, the rainstorm elements are combined to design the rainstorm pattern. Overall framework of this paper is shown in Fig. 1.

2 Methodology

2.1 Study area and data sources

Zhengzhou city is located in the south of the North China Plain and the lower reaches of the Yellow River, and it lies between 112°42' E-114°14' E and 34°16' N-34°58' N. There is little precipitation in spring and winter, but more in hot summer season. The average annual precipitation is about 625 mm. The downtown area in Zhengzhou City is classified into five regions: Huiji District, Zhongyuan District, Jinshui District, Erqi District and Guancheng Ethnic Minority District. Now, the concentrated administrative, commercial and residential buildings exist in these regions, once urban flooding is occurred, the huge economy losses will be produced and the public safety will be threatened.

In this study, the observed rainstorm data of 13 rain gauge stations from 2011 to 2018 are collected from the Zhengzhou Meteorological Bureau. The locations of rain gauge stations are shown in Fig. 2.

2.2 Methods

2.2.1 Copula theory

Copula theory is firstly proposed by Sklar (Sklar, 1959), which can connect the multivariate marginal distributions with a joint distribution. Four commonly used Copula functions are selected including Gumbel Copula, Clayton Copula, Frank Copula and Gaussian Copula to construct the three-dimensional joint distribution of rainstorm elements. The formulas of Gumbel Copula, Clayton Copula, Frank Copula and Gaussian Copula are shown respectively as follows:

$$C(u, v, w) = \exp\left\{-\left[(-\ln u)^\theta + (-\ln v)^\theta + (-\ln w)^\theta\right]^{1/\theta}\right\}$$

$$C(u, v, w) = \left(u^{-\theta} + v^{-\theta} + w^{-\theta} \right)^{-1/\theta}$$

2

$$C(u, v, w) = -\frac{1}{\theta} \ln \left[1 + \frac{(e^{-\theta u} - 1)(e^{-\theta v} - 1)(e^{-\theta w} - 1)}{(e^{-\theta} - 1)^2} \right]$$

3

$$C(u, v, w; \Sigma) = \int_{-\infty}^{\Phi^{-1}(u)} \int_{-\infty}^{\Phi^{-1}(v)} \int_{-\infty}^{\Phi^{-1}(w)} \frac{1}{(2\pi)^{3/2} |\Sigma|^{1/2}} \exp \left(-\frac{1}{2} W^T \Sigma^{-1} W \right) dW$$

4

where u, v and w are marginal distribution of variables respectively, θ is a coefficient representing the dependence of variates, Φ is the standard normal distribution function, Σ is the correlation coefficient matrix of Gaussian Copula. is the integral variable matrix.

2.2.2 Secondary return period

Suppose a two-dimensional joint distribution (X, Y) , its return period is usually defined as the following two types (Shiau, 2006): (1) if X or Y exceeds the setting thresholds, the calculated return period is called ORP; 2) if X and Y both exceed the setting thresholds, the calculated return period is called ARP. The ORP and ARP are achieved by formula 5 and 6 respectively, and their schematic diagram is shown in Fig. 3.

$$ORP = \frac{1}{P(X \geq x \vee Y \geq y \vee Z \geq z)} = \frac{1}{1 - C(u, v, w)}$$

5

$$ARP = \frac{1}{P(\left(\{X \geq \text{x}\} \wedge Y \geq \text{y}\} \wedge Z \geq \text{z} \right))} = \frac{1}{1 - u - v - w + C(u, v) + C(u, w) + C(v, w) - C(u, v, w)}$$

6

where u, v and w are the marginal distribution of X, Y, Z , respectively; is the joint distribution value.

As shown in Fig. 2, the curves of "" and "" denote the return period contours. For any point $(,)$ on the contour line, the corresponding $(,)$ can be obtained by $x = \{F^{-1}\} \left(u \right)$ and $y = \{F^{-1}\} \left(v \right)$. In addition, selecting different points from the same return period contour will result in different risk regions, that is, there are multiple combination events corresponding to the same return period. Moreover, the definitions of ORP and ARP are presented irrationally. For the variables X and Y , the event of "X exceeding the threshold" or "Y exceeding the threshold" is considered as dangerous, larger return period usually means the smaller danger zone, and the dangerous events with larger return period should

be involved in the events with smaller return period, but some events that cannot satisfied these rules that existed in ORP and ARP. Fig. 3a is a sketch figure of ORP, is a point on the line and is a point on the line. If , the danger region corresponding to point A should be included in the danger region corresponding to point B, so the existing C* area is obviously unreasonable, the same situation is happened for ARP in Fig. 3b. This identifies that some defects are presented in PRP in describing the event return period (Salvadori et al., 2004; Huang and Chen, 2015).

According to the Kendall distribution function defined by Nelson (Nelson, 2006), three categories of safe, critical and dangerous are classified by Salvadori (Salvadori, 2011) by judging the joint distribution probability. In 2013, Salvadori (Salvadori, 2013) further divides the two-dimensional space into three parts using curves formed by pair (x, y) satisfying $\bar{F}(x, y) = t$. The KRP and SKRP make up for the PRP's defects by improving the identification of dangerous zone. $\bar{F}(x)$, KRP and SKRP can be expressed respectively as following:

$$\bar{F}(x) = 1 - F(x)$$

7

$$KRP = \frac{1}{P\left\{C\left(\{u, v, w\}\right) \geq t\right\}} = \frac{1}{1 - K_C(t)}$$

8

$$SKRP = \frac{1}{P(X < x, Y < y, Z < z)} = \frac{1}{\hat{C}(\bar{F}(x), \bar{F}(y), \bar{F}(z))} = \frac{1}{1 - \bar{K}_C(t)} \quad (9)$$

where $K_C(t)$ is the Kendall function value with cumulative probability t (Graler et al., 2013), $\bar{K}_C(t)$ is the survival Kendall function value (Salvadori, 2013). Since $K_C(t)$ and $\bar{K}_C(t)$ cannot be figured out by analytic formula, thus the Monte Carlo simulation method is used to generate event combinations based on the joint distribution of variables, then the KRP and SKRP will be calculated with empirical frequency method.

3 Results And Discussions

3.1 Joint distributions of rainstorm elements

3.1.1 Correlation analysis

For the urban stormwater events, the rainstorm with 1h duration accounts for 45 percent, and in which 80 percent present the single-peak rain pattern. Therefore, the rainstorm event with one-peak in 1h is focused in this paper.

Fig .4 shows the correlations of rainstorm element. It can be seen that the correlation coefficients between RV and PR, RV and RAP, and PR and RAP are 0.8623, 0.7446 and 0.5175, respectively, which indicating that there is a positive correlation among them.

3.1.2 Marginal distribution

Pearson Type III Distribution (P-III), Gaussian Distribution, Gamma Distribution, Generalized Extreme Value Distribution (GEV) and Weibull Distribution are employed to select the fitting univariate marginal distribution. Firstly, Kolmogorov–Smirnov (KS) test is used to which ones can pass the significance test at 0.05 level, and then the fitting degree between theoretical and empirical frequency of univariate is calculated. Eventually, P-III distribution is chosen as the optimal type of TR and PR, and Gamma distribution is the best one for RAP (as shown in Fig .5). The fitting degree between theoretical and empirical distribution of RV, PR and RAP are 0.9769, 0.9836 and 0.9718, respectively.

3.1.3 Joint distribution of rainstorm elements

Application with the maximum likelihood estimation method (Xu et al., 2008), the parameters of Gumbel Copula, Frank Copula, Clayton Copula and Gaussian Copula are calculated. The square Euclidean distance method (d^2) (Li et al., 2021) and OLS method (Kong et al., 2020) of different Copulas are shown in Table. 1. It can be seen that for the bivariate joint distributions of RV-PR and RV-RAP, the Gumbel Copula is the best, while for the PR-RAP, the Gaussian Copula is the optimal. For the tri-variate joint distribution of RV-PR-RAP, the Gaussian Copula is chosen.

Table.1 d^2 and OLS of different Copulas

		Gaussian Copula	Gumbel Copula	Clayton Copula	Frank Copula
RV-PR	d^2	0.0625	0.0491*	0.1055	0.0522
	OLS	0.0300	0.0254*	0.0373	0.0262
RV-RAP	d^2	0.1518	0.1319*	0.2466	0.1841
	OLS	0.0447	0.0417*	0.0570	0.0492
PR-RAP	d^2	0.1390*	0.7343	0.7315	0.7386
	OLS	0.0428*	0.0983	0.0981	0.0986
RV-PR-RAP	d^2	0.1403*	1.0297	0.3982	1.4428
	OLS	0.0430*	0.1164	0.0724	0.1387
* Representing the optimal					

3.2 RRP calculation

The planning RRP in the central area of Zhengzhou city is generally within 1~5 years, and the key areas will be 10~20 years. Therefore, the return periods of 2 years, 5 years, 10 years and 20 years are selected to calculate the recurrence period of rainstorm elements combinations (REC) here. According to the Section 2.2.2, the SRP of REC cannot be calculated analytically, so Fig. 6 only displays the calculated PRP of ORP and ARP of REC. However, PRP and SRP of REC can be shown in Table 2.

Table 2
RRP and SRP of REC

Return period/a	Frequency	ORP/a	ARP/a	KRP/a	SKRP/a
2	50%	1.39	3.58	2.43	1.70
5	80%	2.77	15.98	9.29	4.55
10	90%	4.99	50.1	26.54	10.91
20	95%	9.25	156.49	72.10	26.88

According to the risk domain represented by each return period type as well as the non-diminishing property of Copula method, for the given return period, ORP is less than KRP and ARP is greater than SKRP. As shown in Table 2, for the given RRP, ORP is the smallest and even smaller than the given RRP. Besides, the relationship $ORP < SKRP < KRP < ARP$ is existed. As mentioned above, ORP's and ARP's identification of risk ranges are both unreasonable, thus PRP will result in lower or higher standards for flood control and drainage engineering, and further bring out waterlogging disasters or finical wasting. For safety reasons, it is more reasonable to adopt KRP than ORP for the situation that any rainstorm element exceeds the set standard, and SKRP should be considered for the event that all rainstorm elements are bigger than the set standard as well.

3.3 Design value of REC

In the three-dimension space, the combined rainstorm elements with the same RRP can form a curve surface. According to (Salvadori et al., 2013; Tu et al., 2018), and there must be a REC $(\{u_m\}, \{v_m\}, \{w_m\})$ with the maximum joint probability density $f\left(\{x,y,z\}\right)$. This means the greatest occurrence probability is exhibited on REC $(\{u_m\}, \{v_m\}, \{w_m\})$. Consequently, this REC can be treated to design the rainstorm pattern. The calculation of $(\{u_m\}, \{v_m\}, \{w_m\})$ and $f\left(\{x,y,z\}\right)$ are shown as follows:

$$\left(\{u_m\}, \{v_m\}, \{w_m\}\right) = \arg \max f\left(\{x,y,z\}\right)$$

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$$f\left(\{x,y,z\}\right) = c\left(\{u_x\}, \{v_y\}, \{w_z\}\right) \cdot f\left(x\right) \cdot f\left(y\right) \cdot f\left(z\right)$$

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where $\{u_m\}$, $\{v_m\}$ and $\{w_m\}$ are the univariate marginal distribution of rainstorm elements of the maximum occurrence probability.

In order to compare the difference of various RRP types and the impact of MP and SF methods, the univariate design values of rainstorm elements and their combined design values using MP and SF methods are shown in Table. 3. RV is selected as the major characteristic element and been analyzed here. The results demonstrate that:

(1) For the RRP of 2a~20a, the RVs figured by the MP method of SRP are smaller than its univariate value, and the RVs of different RRP is sorted as $RV_{ARP} < RV_{SKRP} < RV_{KRP} < RV_{UNI} < RV_{ORP}$. Furthermore, the

relative errors between TR_{ORP} and TR_{UNI} , TR_{ARP} and TR_{UNI} , TR_{KRP} and TR_{UNI} , TR_{SKRP} and TR_{UNI} are 21.46%~63.18%, -36.36%~-28.10%, -19.31%~-11.89% and -25.81%~-20.26%, respectively.

(2) The RVs by the SF method of ORP and SKRP are larger than its univariate value, while the RVs of the ARP and KRP is just opposite, and the relative errors between TR_{ORP} and TR_{UNI} , TR_{ARP} and TR_{UNI} , TR_{KRP} and TR_{UNI} , TR_{SKRP} and TR_{UNI} are 20.35%~29.96%, -25.00%~-18.50%, -22.92%~-6.61% and 13.90%~24.23%, respectively.

(3) The RVs by the SF method of ARP and SKRP are larger than MP's, and the RVs by the SF method of ORP are less than MP's reversely. As for KRP, the RVs are varying from the RRP, as 2a and 5a, the TRs using SF method are bigger than MP's, while the results are reversed for 10a and 20a. Furthermore, the relative errors of TR of ORP, ARP, KRP and SKRP with SF method and MP method are 47.72%~65.64%~9.24%~21.02%~-22.99%~-0.14% and -4.48%~6.20%, respectively.

Table 3
The designed rainstorm elements of different RRP's by the MP and SF method

Type		2a		5a		10a		20a	
		MP	SF	MP	SF	MP	SF	MP	SF
Return period calculated by marginal distribution	TR	22.7	22.7	35.2	35.2	45.2	45.2	55.4	55.4
	PR	9.6	9.6	14.9	14.9	18.7	18.7	22.3	22.3
	RAP	8.7	8.7	15.7	15.7	20.5	20.5	25.1	25.1
ORP	TR	29.6	29.5	48.5	44.1	54.9	54.4	90.4	69.6
	PR	12.2	12.4	17.5	18.6	21.2	21.9	33.2	27.7
	RAP	13.1	13.0	21.3	21.0	29.4	29.4	25.9	29.2
ARP	TR	15.3	18.5	22.4	26.4	32.5	35.5	38.4	44.1
	PR	4.6	7.4	7.7	11.5	11.7	15	21.8	19.8
	RAP	8.6	5.6	14.2	11.0	18.4	15.7	6.4	20.4
KRP	TR	20.0	21.2	28.6	29.3	36.5	35.1	44.7	42.7
	PR	8.7	8.7	12.0	12.6	14.7	15.2	16.1	18.9
	RAP	8	7.5	13.8	12.6	16.1	16.2	21.5	18.4
SKRP	TR	18.1	28.2	26.2	43.4	35.3	52.2	41.1	63.1
	PR	7.0	12.1	10.6	17.9	12.4	21.4	14.0	24.8
	RAP	4.8	12.0	10.0	19.6	12.4	24.0	14.6	28.1

The above studied results show that, the rainstorm designed values of a single rainstorm element with its marginal distribution is deviated from the actual, and the designed values of REC with PRP may be lower

or higher, so it is a better choice to design the rainstorm pattern using SRP with the MP method.

3.4 Rainstorm patterns

Pilgrim & Cordery (PC) method is widely used to designing the rainstorm pattern (Pilgrim and Cordery, 1975; Yan et al., 2021). Based on the designed rainstorm elements of SRP with the MP method, a new rainstorm pattern is proposed. With 10 minutes as the division period, the rainstorm in 1h can be divided into six periods. The designed steps of this new rainstorm pattern are as follows:

Step 1: Referring to the determination of the rain peak position by the PC method, the rainfall in each division period of the rainstorm event is sorted firstly, and the larger RV means its corresponding division period has the smaller serial number.

Step 2: Taking the smallest serial number as the rain peak location period, the peak rainfall of SRP with the MP method listed in Table 3 will be placed at this period.

Step 3: Computing out the proportion of RV in each period, and then calculating their mean proportion.

Step 4: Normalizing the proportion of rainfall in the pre-peak period and post-peak period separately, and then the rainfall distribution is carried out. According to Section 3.3, the rainfall before peak (RBP) is distribution in the pre-peak periods, and RAP is designed in the post-peak periods, thus the rainstorm patterns of different RRP are obtained.

The rainstorm patterns based on the SKPR with MP method are as shown in Fig. 7. It can be seen from Fig. 7c that the RV is mainly concentrated in the pre-peak periods, and the rain intensity increases rapidly and the RV is accumulated quickly. By contrast, the RV deduced from the KRP with MP method is more focused after the rain peak (as shown in Fig. 7b). Moreover, the rainstorm patterns based on the single rainstorm element with its marginal distribution (Fig. 7a) are similar to KRPs'.

Although the rainstorm patterns of SRP are presented in Fig. 6, the differences between PRP and SRP are needed to be further exploited. In Fig. 8, (i) represents the rainstorm patterns of OPR and KRP, and (ii) shows the rainstorm patterns of ARP and SKRP.

The (i) in Fig. 8 denotes that the rainstorm pattern of KRP is nearly involved in the ORP's. This indicates that the waterlogging disaster caused by the later rainstorm pattern is more severe than the former. Once the waterlogging control and drainage engineering is carried out according to the ORP type, it is easier to lead to the higher designing standard, thus resulting in unnecessary project scale.

The (ii) in Fig. 8 illustrates that the RV of rainstorm pattern based on the SKRP is mainly concentrated before the rain peak, while the ARPs' are just the reverse at 2a, 5a and 10a of RRP. The situation is quite different from the RRP of 20a, which causes the rain peak is more prominent of ARP type.

In addition, Fig. 8 also provides a proof that the better regularity is existed in the rainstorm patterns of PRP and SRP of 2a and 5a, but for the higher RRP of 10a and 20a, the regularity is not obviously. For

example, for the RRP of 10a and 20a, though the rainstorm pattern of KRP are involved in the ORPs', the excess RV of 10a return period mainly distributed after the rain peak, while the 20a return period is in reverse. This regularity may reflect the regional rainstorm characteristics and explains that the RV of various rainstorm magnitudes will have their various rainstorm patterns.

Therefore, compared with the ORP, the KRP can decrease the scale of waterlogging control and drainage projects by guaranteeing the reasonable return period, thus the project cost will be reduced. The RV of SKRP type is slightly larger than that of ARP, and the RV of SKRP type is mainly concentrated before the peak, while the RV of ARP is in reverse.

4 Conclusions

In this study, the concept of SRP is redefined firstly, and then using Copula theory and MP method, the combination values of rainstorm elements are calculated and the rainstorm patterns are designed successfully.

It is concluded that the extra-threshold risk of rainstorm element can be described well by the designed value of REC based on the SRP with MP method, and the designed RV of different return period types can be sorted as $RV_{ARP} < RV_{SKRP} < RV_{KRP} < RV_{Marginal} < RV_{ORP}$.

Compared with ORP, the rainstorm patterns of KRP with MP method can achieve a proper magnitude of waterlogging control and drainage engineering to reduce the unnecessary investment. While compared with ARP, the RV of the rainstorm patterns based on the SKRP type is mainly concentrated before the rain peak, it consequently will cause different urban waterlogging process and inundation regions.

Declarations

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Author Contributions

All authors contributed to the study conception and design. Conceptualization: Jinping Zhang; Methodology, Data analysis and Writing-original draft preparation: Hang Zhang; Writing-review and editing: Hongyuan Fang. All authors read and approved the final manuscript.

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References

1. Bertilsson L, Wiklund K, de Moura Tebaldi I, Rezende OM, Veról AP, Miguez MG (2019) Urban flood resilience – A multi-criteria index to integrate flood resilience into urban planning. *J Hydrol* 573:970–982
2. Chen YD, Zhang Q, Xiao MZ, Singh VP (2013) Evaluation of risk of hydrological droughts by the trivariate Plackett copula in the East River basin (China). *Nat Hazards* 68(2):529–547
3. Chen ZX, Liu ZM, Zhao Q (2018b) Comparative analysis on four recurrence levels of joint distribution of flood peak discharge and volume. *Acta Sci Nat Univ Sunyatseni* 57(1):130–135
4. Chen ZX, Lu JF, Yu JT (2017) Analysis on return levels of trivariate stormy waves based on asymmetric Archimedean copula function. *Mar Sci Bull* 36(6):631–637
5. Chen ZX, Shi WY, Lu JF (2018a) Comparative analysis on four recurrence levels of joint distribution of wave height and period. *J Trop Oceanogr* 37(4):18–23
6. Graler B, van den Berg MJ, Vandenberghe S, Petroselli A, Grimaldi S, De Baets B, Verhoest NEC (2013) Multivariate return periods in hydrology: a critical and practical review focusing on synthetic design hydrograph estimation. *Hydrol Earth Syst Sci* 17:1281–1296
7. Huang Q, Chen ZS (2015) Multivariate flood risk assessment based on the secondary return period. *J Lake Sci* 27(2):352–360
8. Kong XJ, Song LF, Xu B, Zou DG (2020) Correlation and distribution model for nonlinear strength parameters of rockfill based on Copula function. *Chin J Geotech Eng* 42(5):797–807
9. Li TY, Guo SL, Hong XJ (2014) Design flood estimation based on bivariate joint distribution of flood peak and volume. *J Hydraul Eng* 45(3):269–276
10. Li YW, Xu FX, Guo YF (2021) Construction and application for a class of one-parameter perturbation of Copula functions. *J Northwest Normal U* 57(03):32–38
11. Liao X, Xu W, Zhang J, Li Y, Tian Y (2019) Global exposure to rainstorms and the contribution rates of climate change and population change. *Sci Total Environ* 663:644–653

12. Loke AY, Guo C, Molassiotis A (2021) Development of Disaster Nursing Education and Training Programs in the Past 20 Years (2000-2019): A Systematic Review. *Nurse Educ Today*, 104:809
13. NELSEN RB (2006) An introduction to copulas (springer series in statistics) [M]. Springer, New York, p 216
14. Pilgrim DH, Cordery I (1975) Rainfall temporal patterns for design floods. *J Hydraul Div* 101(1):81–95
15. Requena AI, Chebana F, Mediero L (2016) A complete procedure for multivariate index-flood model application. *J Hydrol* 535:559–580
16. Salvadori G, De Michele C (2004) Frequency analysis via copulas: Theoretical aspects and applications to hydrological events. *Water Resour. Res.* 40 (12)
17. Salvadori G, De Michele C, Durante F (2011) On the return period and design in a multivariate framework. *Hydrol. Earth Syst. Sci.* 15 (147)
18. Salvadori G, Durante F, De Michele C (2013) Multivariate return period calculation via survival functions. *Water Resour Res* 49(4):2308–2311
19. Shiau JT (2006) Fitting drought duration and severity with two-dimensional copulas. *Water Resour Manage* 20(5):795–815
20. Sklar A (1959) Fonctions de répartition à n dimensions et leurs marges. *Publications de l'Institut de Statistique de L'Université de Paris* 8, 229-231
21. Tu XJ, Chen XH, Zhao Y, Du YL, Ma MW, Li K (2016) Responses of hydrological drought properties and water shortage under changing environments in Dongjiang River basin. *Adv Water Sci* 27(6):810–821
22. Tu XJ, Du XX, Du YL, Chen XH, Li K (2018) Multivariate joint design of hydrological drought and impact of water reservoirs. *J Lake Sci* 30(02):509–518
23. Van de Vyver H, Van den Bergh J (2018) The Gaussian copula model for the joint deficit index for droughts. *J Hydrol* 561:987–999
24. Xu YP, Li J, Cao FF, Ran QH (2008) Application of Copula in hydrological extreme analysis. *J Zhejiang U* 42:1119–1122
25. Yan FJ, Li QF, Wang Y, Zhou ZM, Du Y, Peng F (2021) Medium and long duration design rainstorm calculation in Zhenjiang City. *Water Resour Prot* 37(2):108–111
26. Zhou P, Zhou YL, Jin JL, Jiang SM, Wu CG (2019) Understanding of Hydrological Bivariate Return Periods and its Application to Drought Analysis. *Adv Water Sci* 30(3):382–391
27. Bae S, Chang HJ (2019) Urbanization and floods in the Seoul Metropolitan area of South Korea: what old maps tell us. *Int J Disaster Risk Reduct* 37:11

Figures

Figure 1

Overall framework of this study

Figure 2

Location of rain gauge stations in Zhengzhou city

Figure 3

Schematic diagram of ORP and ARP

Figure 4

Correlation of rainstorm elements

(a)

(b)

(c)

Figure 5

Optimal fitting of rainstorm elements

Figure 6

RRP of ORP and ARP

(a)

(b)

(c)

Figure 7

a) Rainstorm patterns of single rainstorm element with its marginal distribution, b) Rainstorm patterns of KRP with MP method and c) Rainstorm patterns of SKRP with MP method

Figure 8

Comparison of rainstorm patterns of PRP and SRP with MP method: a) RRP of 2a, b) RRP of 5a c) RRP of 10a, and d) RRP of 20a