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The Return Period Analysis of Heavy Rainfall Disasters Based on Copula Joint Statistical Modeling

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ABSTRACT

In the last few years, with the frequent occurrence of extreme weather across the globe, it has become clear that a comprehensive understanding of the patterns and main characteristics of disaster occurrence is essential, and the willingness to study these variables has become more urgent than ever. This paper analyses the multivariate and spatial distribution characteristics of heavy precipitation disasters and proposes a method for estimating the degree of disaster-causing risk using a joint statistical model. This paper tests the model's validity with hourly precipitation data from 122 national meteorological stations in Shandong from 1990 to 2023. Based on heavy precipitation events in the past thirty years, different marginal distribution functions fit the duration of heavy precipitation and precipitation amount. The joint probability distribution model of two related variables is established based on the Copula joint distribution to analyze the change rule of heavy precipitation recurrence

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period in different periods and to analyze the characteristics of heavy precipitation causing disasters in Shandong Province on this basis. Compared with the disaster return period calculated by relying on univariate variables, the Copula function can more reasonably simulate the natural occurrence of the degree of disaster. The joint return period (JRP) estimated by the Copula function shows that the JPR of heavy rainfall with a duration of 1 hour is 89% higher than that of 6 hours, indicating a significant increase in the risk of disasters caused by short-term heavy rainfall in Shandong region. This method can more scientifically describe the risk of disasters caused by heavy precipitation in different scenarios, especially the characteristics of disasters caused by short-term heavy precipitation, which can provide an adequate scientific basis for disaster prevention and mitigation planning and disaster risk management.

KEYWORDS

Copula joint distribution; heavy rainfall; recurrence period

1. INTRODUCTION

In its 6th Assessment Report on Climate Change, the IPCC states that, as a result of global warming, the frequency and intensity of heavy precipitation events may increase in the 21st century as a result of human activities and changes in natural systems if future warming is not limited to 1.5 degrees Celsius, and that there is a consensus in the IPCC that the frequency and intensity of heavy precipitation events may increase in the 21st century as a result of human activities and changes in natural systems (Zhou et al., 2024).

Heavy precipitation, as an essential form of extreme weather and climate events, is a natural phenomenon that frequently occurs in different regions of the globe and is prone to induce derivative hazards, such as flash floods, geological hazards, and urban waterlogging, with far-reaching impacts on food security, economic activities, and water resources. For example, the flooding caused by heavy precipitation in Shandong on 9 August 2010 resulted in 1,243,700 people being affected, with crops affecting an area of 159.1,000 hectares, including 16.6,000 hectares of crops that were out of harvest, nearly 3,000 houses collapsed, nearly 2,300 houses damaged, and a direct economic loss of 520 million yuan. It is, therefore, essential for disaster prevention and mitigation to quickly assess the return period of extreme precipitation disasters and to increase monitoring and forecasting efforts.

The return period, which measures how often the hazard from heavy precipitation exceeds a certain threshold, is significant for understanding regional risks due to heavy precipitation and addressing possible future climate challenges. While previous studies have recognized the importance of return period indicators as a means of quantifying the risk of disasters such as heavy precipitation and droughts, the essence of the evaluation methodology is to reduce multi-influence factors to univariate ones, resulting in the loss of correlation information on the vital

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disaster-causing factors in the reliance on a univariate approach to portraying the return period (Cheng et al., 2022; Tan et al., 2023). In order to avoid the problem of overestimation or underestimation of the return period caused by relying on univariate calculations, some scholars have attempted to establish a multivariate model for portraying the risk of disaster-causing events (Vergni et al., 2015; Wang et al., 2023). However, traditional multivariate models need to ensure that the variables are independent of each other and, at the same time, obey a specific type of marginal distribution (Zhang et al., 2007). Independence between variables is difficult to satisfy in real disaster-causing scenarios, and it is difficult to satisfy the prerequisite of obeying a specific marginal distribution simultaneously. Therefore, the approach of premising multivariate models on extreme assumptions only applies to some disaster-causing scenarios. In this paper, we consider multivariate models premised on relatively flexible assumptions to analyze the probability of heavy precipitation.

In recent years, some scholars have proposed using the Copula function to portray multivariate dependencies more flexibly in various disaster-causing scenarios and to overcome the constraints of the assumptions that satisfy both the independence and the marginal distribution types (Sklar, 1959). Copula functions have been widely used in drought event risk identification. Li et al. (2015) studied the joint return period of drought events in Beijing and assessed the impact of drought risk on winter wheat growth. Zhang et al. (2022) used a multivariate risk assessment method based on Copula functions to analyze the return period of high-temperature compound drought events in the Yangtze River Basin. Wen et al. (2023) established a drought risk model through copula functions to reveal the response relationships among drought variables in Henan Province.

Meanwhile, the Copula function has also been applied in disaster risk analysis of flooding events; De Michele et al. (2023) first proposed the use of the Copula function to portray the frequency of heavy precipitation and fitted the relationship between the duration of natural precipitation and the intensity of precipitation through the generalized Pareto distribution. X Tong et al. (2015) analyzed the variation of flood data over time using selected Copula models. Haile M M et al. (2023) demonstrated the effectiveness of Copula in flood management through binary modeling of flood peak and flood volume characteristics. The above studies have shown that the Copula function is an effective tool for analyzing extreme events such as droughts or floods. However, the studies on the disaster risk of heavy precipitation events have mainly focused on analyzing the frequency characteristics of heavy precipitation through the daily precipitation amount and the number of days of precipitation. It is difficult to highlight the disaster-causing hazards associated with short-calendar duration heavy precipitation events (Utsumi N et al., 2022).

In order to solve these problems, this study establishes a joint probability density distribution model of precipitation time and precipitation amount based on hourly-scale precipitation data. It analyses the long-term change characteristics of heavy precipitation, based on which we analyze the disaster-causing risk of short-calendar-time heavy precipitation in Shandong, which can assess the impacts of short-term heavy precipitation more accurately, quantitatively, and scientifically. The

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purpose of the study is to construct the joint probability density distribution of precipitation duration and precipitation amount through the Copula function and to use this function to calculate the return period, based on which to carry out the research related to the frequency of heavy precipitation and the spatial distribution characteristics of the coupling of heavy precipitation duration and precipitation amount in Shandong, and to analyze the changes and connections of the multi-scenarios of heavy precipitation in the Shandong region from the viewpoint of the return period, and to obtain the frequency of heavy precipitation and the spatial and temporal distribution characteristics and the disaster risk of the heavy precipitation in Shandong. The spatial and temporal distribution characteristics of heavy precipitation frequency in Shandong and the disaster risk can be based on the above results to derive the countermeasures of heavy precipitation in different recurrence periods. The study has a positive effect on improving disaster prevention and mitigation during flood seasons and the ability to make scientific decisions, especially in the Asian region, where population densities are in the billions, to effectively monitor and predict the level of hazards posed by heavy precipitation. The study has a positive effect on improving disaster prevention and mitigation during flood seasons and the ability to make scientific decisions, especially in the Asian region, where population densities are in the billions, to effectively monitor and predict the level of hazards posed by heavy precipitation.

The structure of this article is as follows. Section 2 introduces a dataset used to simulate the recurrence period of heavy precipitation and various disaster scenarios

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caused by heavy precipitation. Section 3 introduces the definition of the edge distribution function used in the Copula model, explains how to use appropriate testing methods to select the optimal type of edge distribution function, and explains how to calculate the return period of joint precipitation duration and precipitation. Section 4 statistically analyzed the marginal probability distribution of various disaster causing factors in heavy precipitation events and the joint distribution characteristics of the binary Copula model, and evaluated the improvement results of the joint recurrence period compared to the univariate recurrence period. It simulated the spatial distribution changes of multiple scenario heavy precipitation recurrence periods and analyzed the frequent occurrence scenarios and key determining factors of heavy precipitation disasters. For example, we found that the recurrence interval of a scenario with a duration of 1 hour of heavy precipitation was much higher than the threshold of 6 hours for heavy precipitation duration. Compared with the average frequency of occurrence of heavy precipitation events within 1 hour, the frequency increased by 89%, resulting in an increased risk of disaster. Section 5 summarizes the research results and provides a more in-depth discussion on potential applications.

2. MATERIALS

2.1. The Definition of a severe heavy rainfall

Extreme precipitation is a measure of rainfall that generally refers to highly

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intense and destructive rainfall. Extreme precipitation events, as one of the manifestations of extreme weather events, are highly susceptible to secondary disasters, such as flash floods and mudslides in small watersheds, and have caused enormous losses in many countries and regions of the world. According to the definition of extreme weather indicators recommended by WMO, rainfall events with daily rainfall exceeding 95% and 99% quartiles are defined as heavy and extremely heavy rainfall events, respectively. Internationally, indicators such as annual extreme precipitation, frequency of occurrence, extreme precipitation intensity, and annual maximum daily precipitation are usually chosen to study the characteristic patterns of extreme precipitation events.

According to the China Meteorological Administration (CMA), heavy precipitation events are defined as rainfall of 16 mm or more in one hour or 50 mm or more in 24 hours, and heavy rainfall is further classified into general rainstorms, heavy rainstorms, and hefty rainstorms according to the intensity of the precipitation. An average rainstorm is defined as less than 70 millimeters in 12 hours or less than 100 millimeters in 24 hours, while a heavy rainstorm is defined as more than 70 millimeters but less than 140 millimeters in 12 hours, and a hefty rainstorm is defined as more than 140 millimeters in 12 hours or more than 200 millimeters in 24 hours. Therefore, the case studies of rainfall events in this paper include heavy rainfall and weighty rainfall events to analyze the characteristics of changes in disaster-causing factors in different scenarios from the perspective of heavy precipitation disaster prevention and mitigation.

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2.2. Data Used

The data used in this paper are hourly precipitation data from 122 national stations in Shandong (Fig. 1) for May-September 1990-2023, with the original data coming from the consolidated data of the Meteorological Data Centre of Shandong Province after removing dubious and erroneous data through quality control. For hourly precipitation compilation data with more than 30 years of observation (the reference year for climate averages), precipitation processes with 1-hour intervals are combined into a single precipitation event. The cumulative precipitation of the event is screened to see if the cumulative precipitation of the event is greater than or equal to 15 mm. The precipitation intensity is greater than 5 mm·h-1 to obtain a heavy precipitation event (She et al., 2011; Wang et al., 2023). This paper calculates the return period based on a sample of heavy precipitation events.

From the records of the Shandong Meteorological Bureau of extreme precipitation events from 1990 to 2023, it can be seen that 122 stations in Shandong have experienced heavy precipitation within 1 hour, with an average of about 157 occurrences, the longest average duration of 7 h, and the shortest average duration of 4 h. The average precipitation of the heavy precipitation process at each station is 47 mm. The maximum average precipitation occurs at 59 mm, the most extended duration of the most precipitation process is 79 h, and the maximum precipitation is 595 mm. The average precipitation amount of the heavy precipitation process at each

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station is 47 mm, the maximum average precipitation amount is 59 mm, the most extended duration of the most precipitation process is 79 h, and the maximum precipitation amount is 595 mm. The Kendall rank correlation coefficients of precipitation amount and precipitation duration are between 0.4 and 0.8, and there is a significant correlation between heavy precipitation duration and precipitation amount, which is suitable for establishing the joint probability density distribution.

3.COPULA-BASED RETURN PERIOD

3.1. Copula's theoretical foundations

The Copula function originates from Sklar's theorem in 1959 [(7)], also known as the "connection" function, i.e., if there are two random variables that have their own fitted marginal distribution function, then you can find a unique joint distribution function to "connect" the marginal distributions of the two variables, making the Copula function "connect" the marginal distributions of the two variables. Copula function that "connects" the marginal distributions of the two variables such that

$$\mathcal{J}(x,y) = C(u(x),v(y))\mathcal{J}(x,y) = C(u(x),v(y)) \tag{1}$$

Equation (1) is a binary joint distribution function containing continuous marginal distributions and features. From the above equation, the structure of the Copula function can be independent of a particular marginal distribution function and, therefore, can better characterize the dependent structure of two random variables.

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This paper selects Gumbel, Frank, and Clayton, who are in the Copula function cluster, as candidates. The above three Copula distribution functions and their parameter value ranges are given in Table 1. The maximum likelihood estimation method is used to obtain the parameters of the Copula marginal distribution function. The fit of the candidate Copula function was tested according to the AIC (Akaike information criterion) method, and the smaller the test value, the better the fit of the function (Jiang et al., 2008; Song et al., 2023).

3.2. Identification of the Appropriate Marginal distribution function

The selection of an appropriate marginal distribution function is a prerequisite for constructing a Copula joint distribution model for heavy precipitation events, and a specific marginal distribution function is often chosen in previous characterization studies of heavy precipitation (Wang et al., 2006; Ummul et al., 2014; Salvadori et al., 2015). Considering the variability of the probability distribution of heavy precipitation events in different regions and the reliability of the model estimation results, six candidate marginal distribution functions (Table 2), which are the most widely used in natural sciences and engineering, are selected the candidate marginal distribution functions are Gamma (Gam), Weibull (Wbl), Exponential (Exp), Lognormal (Ln), Generalised Extreme Value (Gev), Generalised Pareto (Gp), and the parameters of the marginal distribution were estimated using maximum likelihood estimation. Comparison of the goodness of fit of candidate marginal distribution

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functions using the K-S (Kolmogorpv-Smirnov) test (Frank et al., 1951; Li et al., 2024). The optimal marginal distribution fitting functions for the duration of heavy precipitation and the amount of precipitation at each station in each region of Shandong are determined sequentially.

3.3. Calculation of the Return Period

When a single variable is critical to the assessment of the risk of heavy precipitation, it is reasonable to assess the level of hazard based on the return period estimated by a single variable, and when a single variable is deterministic or the correlation is weak between two variables, a return period that relies on the cumulative amount of precipitation from a single precipitation process being greater than or equal to a certain threshold is defined as univariate return period. Assume that the marginal distribution function of heavy precipitation is u(x); the univariate return period is calculated as:

$$T_w = \frac{T}{N(1-u(x))} T_w = \frac{T}{N(1-u(x))} \tag{2}$$

Where T is the number of years in the time series at the study site, and N is the number of heavy precipitation events that occurred.

When the risk of heavy precipitation is influenced by the combination of two variables, for example, the degree of damage caused by heavy precipitation is closely related to the duration and amount of precipitation, usually the shorter the duration of heavy precipitation and the more precipitation, the greater the degree of risk of

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damage. The joint return period algorithm constructed using the Copula function can calculate the frequency characteristics of heavy precipitation under the joint influence of two variables. In the case of heavy precipitation events, the joint return period can be used to characterize the situation where heavy precipitation events are more catastrophic in a short period; considering that there is more heavy precipitation during the flood season in Shandong, the joint return period is defined:

$$T_C = \frac{T}{N \cdot P(X \geq x | Y \leq y)} = \frac{T}{N \cdot (1 - C(u(x), v(y))/v(y))} \quad (3)$$

where $P(X \geq x|Y \leq y)$ is the conditional probability of an intense precipitation event with process precipitation greater than x and precipitation duration less than y (Shen et al., 2013).

4. RESULTS

4.1. Characteristics of the marginal probability distribution of heavy precipitation events

In order to select appropriate types of fitted marginal probability distributions for precipitation duration and precipitation amount, the six candidate marginal probability distributions were tested for goodness-of-fit by the K-S test, and the marginal distribution function with the most miniature K-S test statistic and a p-value greater than 0.05 was selected as the optimal type of fitting function. In the case of heavy precipitation of more than 50 mm with a duration of less than six h at Laoshan Station in Qingdao City, Shandong Province, for example, based on the above test method, the optimal fitting function type of the marginal probability density function of the precipitation duration is the generalized extreme value distribution (Gev). The optimal fitting function type of the precipitation amount is also the generalized extreme value distribution (Gev). The suitability of the above two marginal distributions is verified by comparing the six candidate marginal distributions of the precipitation duration and precipitation amount at Laoshan Station. The fit degree of the above two marginal distributions is verified by comparing the matching degree of the six candidate marginal distributions of precipitation duration and precipitation amount (Fig.2). Therefore, the optimal function type for the matching of precipitation duration and precipitation amount at Laoshan Station is selected as the generalized extreme value distribution. By counting the optimal fitting function types for 122 stations in Shandong (Fig.3), it can be seen that the optimal fitting function types for precipitation duration and precipitation amount are dominated by the generalized extreme value (Gev) and lognormal (Ln) distributions and the optimal function type for 1% of the precipitation with precipitation duration as an indicator is the Weber distribution (Wbl). Overall, the duration of heavy precipitation events and the marginal distribution of precipitation are suitable for selecting the generalized extreme value (Gev) and lognormal (Ln) distribution types.

4.2. Characterisation of the joint binary Copula distribution

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In order to select the optimal binary Copula joint distribution type for heavy precipitation events, this paper adopts the AIC method to test the fit matching degree of the three candidate Copula functions; the smaller the AIC value indicates that the selected family of functions has a higher degree of matching for the site where the fit is located, and accordingly selects the optimal matching type of the Copula function for heavy precipitation events. The percentage of the optimal joint distribution function types for the scenarios with different lengths of heavy precipitation and precipitation amounts of 50 mm or more is statistically derived (Fig. 4). It can be seen that the scenarios with precipitation durations of more than 10 h are suitable for the Clayton Copula joint distribution function type. In contrast, the scenarios with precipitation durations of less than 10 h have the applicable joint distribution function types dominated by the Gumbel Copula and the Clayton Copula. Gumbel Copula and Clayton Copula are the main types of joint distribution functions, and the above two types of joint distribution functions fit well for most stations in Shandong. In addition, it can be seen from Fig. 5 that the optimal fitting function type is Frank Copula for the scenario of precipitation duration of 9 h with precipitation more significant than 50 mm, which indicates that the distribution type of heavy precipitation in the above areas has some unique characteristics compared with the areas where the Gumbel Copula joint distribution function was applied before, and the characteristics of the heavy precipitation need to be further investigated. Thus, the Copula joint distribution of heavy precipitation is constructed and completed, laying the foundation for analyzing the region's heavy precipitation recurrence period and catastrophicity.

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4.3 Analysis of the results of the reproduction period improvement

In order to analyze the trend between the precipitation duration and the estimated joint return period for scenarios with cumulative precipitation more significant than 50 mm in Shandong, it is evident from the plot of the duration of heavy precipitation with the joint return period in Shandong (Fig.5) that the joint return period gradually decreases with the prolongation of the duration of heavy precipitation. When the duration of heavy precipitation is less than 8 h, the joint return period decreases more obviously. When the duration is more significant than 8 h, the joint return period gradually approaches 0 and stabilizes. The trend of the variation of the difference rate between the joint and univariate return periods of heavy precipitation (Fig.5) shows similar characteristics, with the difference rate being more apparent when the duration is less than 8 h and decreasing rapidly when the duration is more significant than 8 h. The results show that the frequency of heavy precipitation can be calculated by combining the duration and precipitation amount in a short-calendar-time scenario, which is essential for the scientific analysis of the hazardous risk. The above results show that in the short-calendar-time heavy precipitation scenario with a duration of less than 8 h, it is essential to calculate the frequency of heavy precipitation by combining the duration and precipitation amount to scientifically analyze the disaster risk of heavy precipitation.

By analyzing the relationship between the joint and univariate reproduction

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periods of different precipitation durations at Laoshan Station (Fig. 6), it can be found that under the scenarios of 12 h and 6 h, when the duration of heavy precipitation is the same, the joint reproduction period is prolonged accordingly along with the increase of precipitation. When the precipitation is the same, the joint reproduction period is prolonged accordingly, along with a decrease in the duration of heavy precipitation. The joint reproduction period is also lengthened when the duration of heavy precipitation decreases with the same precipitation amount. The Copula function for estimating the joint return period takes into account both the duration of heavy precipitation and the amount of precipitation, i.e., the average precipitation intensity of heavy precipitation, which implies that for the same amount of precipitation, the shorter the duration of heavy precipitation, the higher the average precipitation intensity, the lower the probability of occurrence, and the longer the joint return period, which means that under the same conditions of disaster, the hazard level of this type of heavy precipitation event will also increase. This indicates that the risk of such heavy precipitation events will increase under the same host conditions. Therefore, estimating the joint return period using the Copula function can distinguish the degree of disaster-causing hazard in different heavy precipitation scenarios.

From the results of the joint reproduction period for the 24-hour duration of heavy precipitation in Fig.6, it is evident that it is almost the same as the results of the univariate reproduction period. Compared with the estimation method of the univariate return period, the joint return period is the frequency of occurrence of a specific type of heavy precipitation scenario estimated under the condition that the

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duration of heavy precipitation is less than a certain threshold. The univariate return period is the frequency of occurrence of heavy precipitation events estimated based on the amount of precipitation, so the difference between the two estimation methods is more minor when the duration of the heavy precipitation is longer. The difference between the two estimation methods is close to 0 when the threshold value of the duration of the heavy precipitation is large enough. Values of the reproduction period estimates have a difference close to zero. The most extended precipitation duration of the heavy precipitation events in the last three decades at Laoshan station is only 21 h, which is smaller than the heavy precipitation duration of 24 h estimated by the joint recurrence period; therefore, when the threshold value of the duration of heavy precipitation at Laoshan station is the scenario with 24 h, the results of its univariate recurrence period and the joint recurrence period are almost the same.

It is noteworthy that, in the disaster risk assessment of heavy precipitation processes, the use of daily cumulative precipitation as an indicator for calculating the return period or evaluating the degree of disaster risk is equivalent to the estimation of the univariate return period in scenarios with a duration of less than 24 h, which is a significant limitation for objectively evaluating the degree of disaster risk of heavy precipitation in Shandong. Considering that the short duration of most heavy precipitation events in Shandong means that there will be a significant difference between the estimated univariate and joint return periods of heavy precipitation events, the previous indicator values calculated from daily precipitation will seriously underestimate the hazardousness and disaster-causing degree of short-duration heavy

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precipitation processes.[2,3] The joint return period of heavy precipitation estimated using the Copula joint distribution describes the dependence between the duration of heavy precipitation and the amount of precipitation. The estimation method takes the intensity of heavy precipitation into account, which can more objectively characterize the frequency information of the heavy precipitation scenarios of different calendars, and thus is conducive to a more reasonable description of the risk of the heavy precipitation-causing factors in different scenarios.

4.4 Characteristics of the spatial distribution of multi-scenario heavy precipitation return periods

For the scenario of heavy precipitation events with precipitation exceeding 50 mm, comparing the spatial distribution of the joint and univariate return periods under the scenario of duration less than the 8-h threshold in Shandong (Fig. 7), the heavy precipitation of the above scenario may cause disasters such as mudslides, urban flooding, and landslides, etc. Analyzing the joint return period of the above scenario has positive significance for the prevention and mitigation of heavy precipitation and the construction of the urban drainage system, and it will provide a basis for decision-making. The analysis of the joint recurrence period of the above scenarios is of positive significance for preventing and mitigating heavy precipitation and constructing urban drainage systems. From Fig. 8, it can be seen that the spatial distribution of the joint recurrence period of heavy precipitation shows different spatial distribution characteristics with the change of duration thresholds. However,

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the spatial distribution of the univariate recurrence period with different duration thresholds is nearly the same. For the scenarios with precipitation exceeding 50 mm and duration thresholds lower than 1 h, the high values of the spatial distribution of the joint recurrence period are roughly concentrated in the central, eastern, and southern regions, and the frequency of heavy precipitation in the western region is relatively low; with the gradual increase of the precipitation duration, the area of high values of the joint recurrence period is gradually narrowed down to the eastern region, and the area of low values of the joint recurrence period is continuously expanding in the western part of Shandong. The spatial distribution of scenarios with precipitation exceeding 50 mm and a duration threshold of 8 h is similar to that of 3 h, indicating that most heavy precipitation in samples with precipitation durations of up to 8 h lasted less than 3 h. The spatial distribution of scenarios with precipitation exceeding 50 mm does not differ significantly from those with a duration threshold of 8 h. However, the spatial distribution of the joint return period (JRP) is significantly different for the scenario with a threshold of 1 h compared with the scenario with a threshold of 6 h. The spatial distribution of the JRP is highly uneven. The high values of the JRP are concentrated in the south, and the east of the country, which suggests that the heavy precipitation events in the above areas occur more frequently within 1 h, and the risk of disaster is correspondingly higher. The spatial distribution of the joint return period also indicates the impacts of the short-term heavy precipitation events (Zheng et al., 2014). The above differences in the spatial distribution of the return period scenarios with different precipitation duration thresholds indicate that

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analyzing the risk of heavy precipitation in combination with the duration and amount of precipitation can more objectively characterize the spatial distribution of the intensity and frequency of the risk factors of heavy precipitation in different scenarios, and provide a reference basis for decision-making on how to cope with the disaster risk of heavy precipitation events with different durations in Shandong.

Scientific estimation of the precipitation amount during the return period of heavy precipitation for different scenarios is an essential reference for urban construction and planning of drainage systems. In this section, the Copula joint distribution is used to estimate the precipitation thresholds for the return periods of 10 a and 30 a, and the spatial distribution characteristics of precipitation for the above two scenarios are given, which are used as important references to analyze the hazardousness of heavy precipitation processes. In both scenarios, with a return period of 10 a (Fig. 8a) and 30 a (Fig. 8b), the precipitation thresholds gradually increase along with the extension of the precipitation duration. The increase in precipitation is more pronounced in the scenario with a return period of 30 a compared to the scenario with a return period of 10 a (Fig. 8a). For the scenario with a return period of 30 a, the precipitation threshold gradually widens in the southeastern mountain region with the increase in the duration of heavy precipitation (Fig. 8b), and is expected to exceed 300 mm. The analysis of the above results shows pronounced regional differences in the risk of disasters caused by different scenarios of heavy precipitation events, in which the risk of a once-in-thirty-years heavy precipitation event is higher in areas such as the southeast and east of the mountain. It is recommended that the construction of urban stormwater

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systems and planning flood prevention and mitigation in the above areas should be prioritized.

5.CONCLUSION AND DISCUSSIONS

This paper introduces the method of establishing the Copula binary joint distribution of heavy precipitation duration and precipitation amount based on hourly heavy precipitation data, calculating the joint return period (JRP), which can reflect the risk of disasters caused by heavy precipitation events and statistically evaluating the degree of disasters caused by heavy precipitation of the same scenario in the mountains based on the JRP. The results show that the Copula joint distribution can be used to effectively characterize the dependence structure of heavy precipitation duration and precipitation amount and describe the frequency information under different ephemeral heavy precipitation scenarios, especially the impacts brought by short-duration heavy precipitation. Compared with the previous approach of relying on univariate estimation of the return period (Utsumi N et al., 2022; Wang et al., 2023), the two-dimensional intensity and frequency information of heavy precipitation-causing factors can be more reasonably portrayed to provide a scientific basis for the prevention and mitigation planning of heavy precipitation events and their disaster risk management.

The observed duration of heavy precipitation and precipitation amount are highly correlated, with Kendall rank correlation coefficients between precipitation amount and precipitation duration ranging from 0.4 to 0.8 (having passed the 0.01 significance level test), and the precipitation amount increases with the duration, showing a clear positive correlation with a correlation coefficient of 0.62. From the spatial distribution of Kendall correlation coefficients between precipitation duration and precipitation (Fig. 9a), it can be seen that the correlation is more pronounced in the coastal and southern regions. As seen from Fig. 9, the heavy precipitation in Shandong in the past 30 years is concentrated in the central and southern parts of the country, and the frequency of occurrence is about 157 times on average. Overall, there is a significant dependence between the precipitation amount and the duration of heavy precipitation in Shandong. This is suitable for calculating the return period by constructing a joint distribution through the Copula function.

Due to the short duration and high intensity of heavy precipitation in the study area in the past 30 years, most heavy precipitation lasts for less than 3 h. In the past, the reproduction period estimated by daily precipitation will underestimate the disaster risk of short-term heavy precipitation (Cheng et al., 2022; Vergni et al., 2015; Ummul et al., 2014). The joint reproduction period estimated by using hourly rainfall data is more accurate. The disaster risk of heavy precipitation in different scenarios can be recognized based on the Copula joint distribution, useful in disaster risk assessment and urban defense engineering construction. These different scenarios are very useful in disaster risk assessment and urban defense engineering construction and are of great significance in disaster prevention and mitigation planning and disaster risk management.

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In the Shandong region of China, the joint return period of heavy precipitation estimated by the Copula joint distribution has noticeable spatial differences with the extension of the precipitation time. The scenario of one in 10 years has a higher concentration of precipitation in the southeastern and eastern parts of the mountain, especially in 30 years of heavy precipitation, which has a very high risk of disaster in the southeastern and eastern parts of the mountain. It is recommended to focus on considering the urban stormwater system and the flood disaster prevention project in this region to Prevent economic and other losses.

The existing studies show apparent differences in the characteristics of changes in the frequency of heavy precipitation in different regions. In this paper, the hourly-scale precipitation samples of the last 30 years are selected, which mainly characterize the disaster-causing situation of heavy precipitation on the hourly scale and are suitable for reflecting the extreme precipitation situation. If precipitation events at other time scales are selected, the hazard identification of heavy precipitation events will change. Meanwhile, in the identification and analysis of heavy precipitation events based on the Copula function, there is no uniform regulation for threshold selection, which makes it easy to reduce the accuracy of identifying extreme events so that the threshold setting method can be further optimized.

In this paper, only two feature variables of heavy precipitation duration and heavy precipitation amount are combined, and the structure of the multivariate joint function will be more complicated with the increase of the feature variables of heavy

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precipitation events. The characteristics of heavy precipitation have a solid sensitivity to time and space, and the spatial and temporal characteristics of different regions make the Copula function time-varying for applying heavy precipitation. Therefore, future research will focus on solid precipitation indicator selection, threshold optimization, Copula multidimensional eigenvariable analysis, and time-varying exploration.

In recent years, some scholars have found that the frequency and intensity of natural disasters in recent years have been characterized by a significant increase in frequency and intensity, accompanied by the occurrence of multiple types of disasters, and the law of occurrence of natural disasters and sound factors have become more complex. A more scientific analysis of the probability of extreme weather and climate events will help decision-makers take measures more quickly and effectively to prevent, reduce, or avoid the impacts and losses caused by disasters. As uncertainties increase, the analysis of natural disasters needs to be more rationalized. One of the advantages of using the Copula function is that it can be extended to n-latitude frames. However, the current research and application of the Copula function is mainly limited to two-dimensional; with the advancement of computer technology and the complexity of the research problems, the application of three-dimensional and above Copula function and the accompanying problems of parameter estimation and the choice of the function type need to be further researched. Therefore, the Copula function has great potential in the risk assessment of natural disasters caused by multiple factors.

Conflict of 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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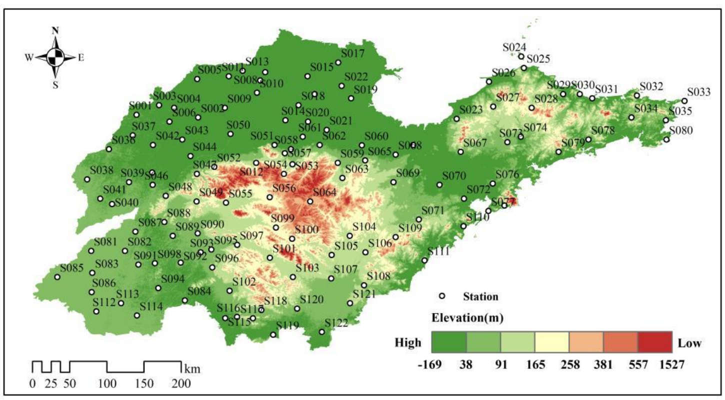

Figure 1. Spatial distribution of sites and topographic height distribution in Shandong.

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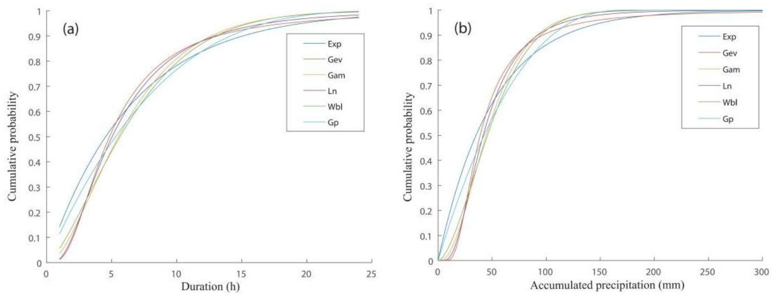

Figure 2. Candidate Marginal Distribution Fitting for Duration (a) and Duration (b) of Heavy Precipitation at Laoshan Station, Qingdao, Shandong, China

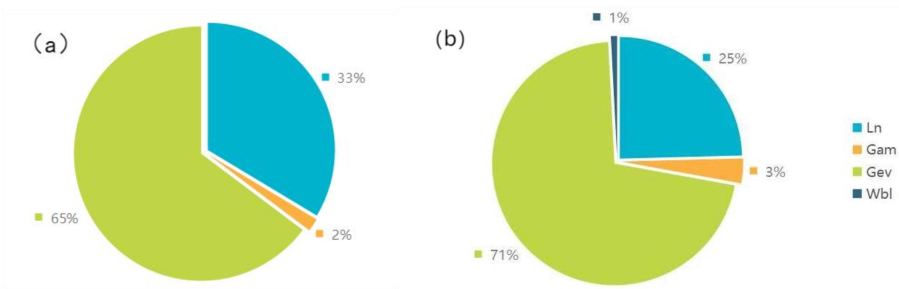

Figure 3. Percentage of optimal marginal distribution of heavy precipitation precipitation (a) and duration (b) at **122** observation stations in Shandong Province

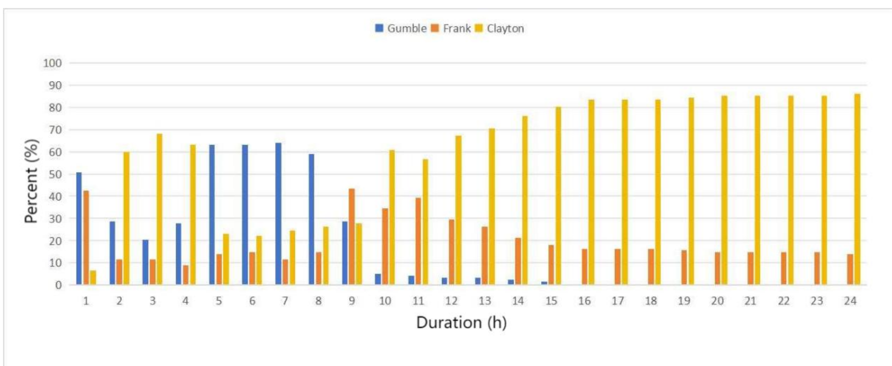

Figure 4. Percentage of types of best-fit Copula joint distribution functions for different time-lengths of intense precipitation

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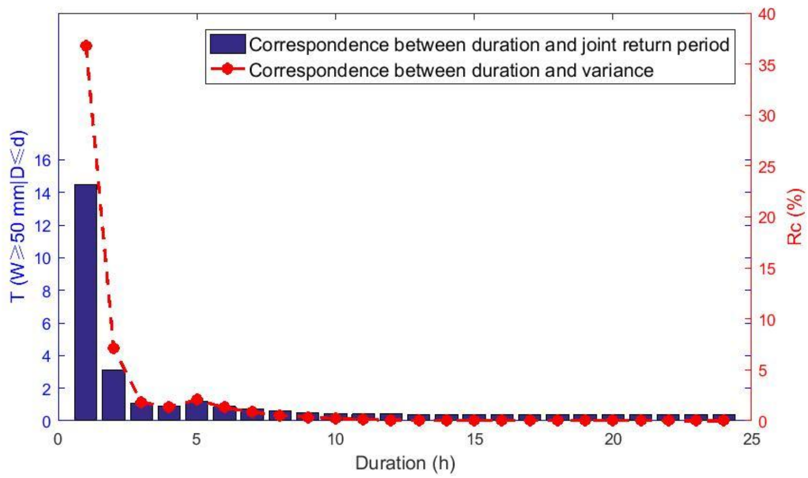

Figure 5. Duration of heavy precipitation in Shandong in relation to the conditional return period (a) and the rate of difference Rc(b)

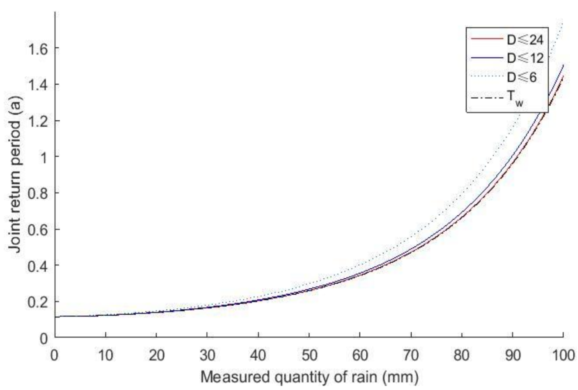

Figure 6. Comparison of joint and univariate return periods for different heavy precipitation durations at Laoshan station

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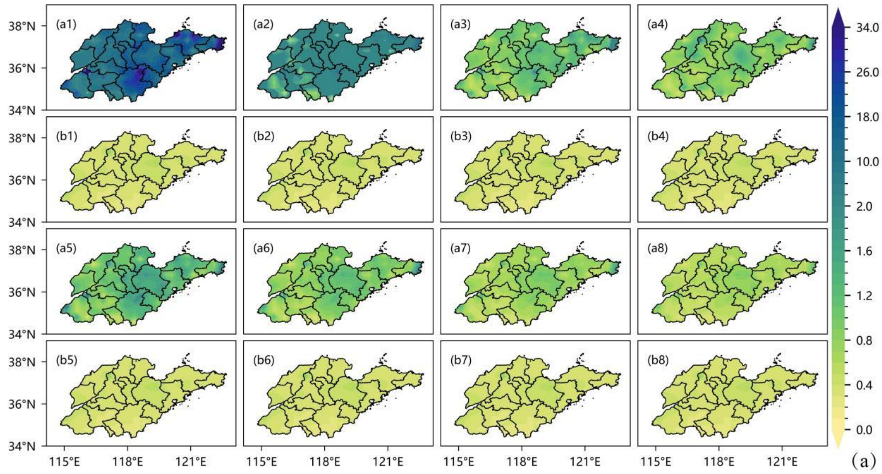

Figure 7. Spatial distribution of process precipitation ≥ 50 mm for durations ≤ 1 h (a1,b1), durations ≤ 2 h (a2,b2), durations ≤ 3 h (a3,b3), durations ≤ 4 h (a4,b4), durations ≤ 5 h (a5,b5), durations ≤ 6 h (a6,b6), durations ≤ 7 h (a7,b7) and durations ≤ 8 h (a8, b8) the spatial distribution of joint and univariate return periods of heavy precipitation

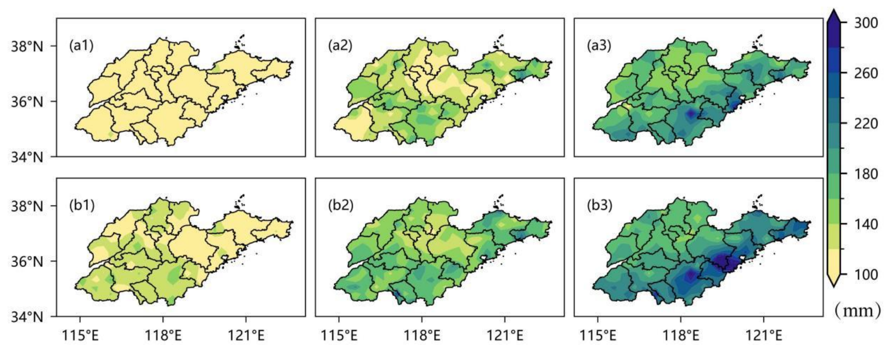

Figure 8. Precipitation (mm) thresholds (a1, b1 duration ≤ 6h, a2, b2 duration ≤ 12h, a3, b3 duration ≤ 24h) for 1 in 10 years (a1, a2, a3) and 1 in 30 years (b1, b2, b3) joint return periods

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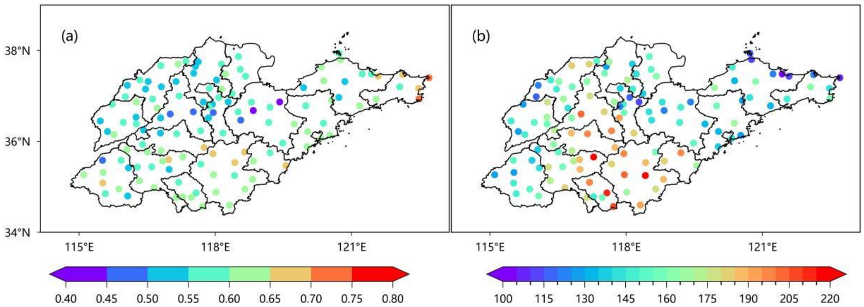

Figure 9. Spatial distribution of kendall correlation coefficients (a) and number of heavy precipitation (b) between precipitation duration and precipitation, 1990-2023

Table 1. Three Candidate Copula Distribution Functions

Copula style	distribution function	parameters
Frank	$C_{Frank}(u,v) = -\frac{1}{\theta}\ln\left(1+\frac{(e^{-\theta u}-1)(e^{-\theta u}-1)}{(e^{-\theta u}-1)}\right)$	$\theta \in (-\infty,\infty)\{0\}$
Gumble	$C_{Gumble}(u,v) = \exp(-\left[(-\ln u)^{\frac{1}{\theta}}+(-\ln v)^{\frac{1}{\theta}}\right]^{\theta})C_{Gumble}(u,v) = exp(-\left[(-ln\ u)^{\frac{1}{\theta}}+(-ln\ v)^{\frac{1}{\theta}}\right]^{\frac{1}{\theta}})$	$\theta \in (0,1]$
Clayton	$C_{clayton}(u,v) = (u^{-\theta}+v^{-\theta}-1)^{-\frac{1}{\theta}}$	$\theta \in (0,\infty)$

Table 2. Six marginal distribution functions

Marginal distribution type	Probability Density Function (PDF)	parameters
Generalised Extreme Value (Gev)	$f_{GEV}(x) = \frac{1}{\sigma}e^{-\left(1+\omega\frac{x-u}{\sigma}\right)^{-\frac{1}{\omega}}}(1+\omega\frac{x-u}{\sigma})^{-1-\frac{1}{\omega}}$	$^{\omega}$ ω is the shape parameter, u is the position parameter, σ^{σ} is the scale parameter $(1+\omega\frac{x-u}{\sigma}>0$

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		$\omega \neq 0^{1+\omega\frac{x-u}{\sigma}>0,\ \omega \neq 0}$)
Lognormal (Ln)	$f_{LN}(x)=\frac{1}{xv\sqrt{2\pi}}e^{-\frac{(lnx-u)^2}{2v^2}}, (x>0)$	u is the mean$(-\infty < u<+\infty)^{(-\infty < u < +\infty), v}$, ν is the standard deviation
Gamma (Gam)	$f_{Gam}(x)=\frac{1}{\beta^{\alpha}\Gamma(\alpha)}x^{\alpha-1}e^{-\frac{x}{\beta}}, (x>0)$	$^{\alpha}$α is the shape parameter, β is the scale parameter
Weibull (Wbl)	$f_{\mathrm{Wbl}}(x)=\frac{\beta}{\alpha^{-\beta}}x^{\beta-1}e^{-(\frac{x}{\alpha})^{-\beta})}, (x \geq 0)(x \geq 0)$	$^{\alpha}$ α is the shape parameter, β is the scale parameter
Exponential (Exp)	$f_{Exp}(x)=\frac{e^{-\frac{x}{u}}}{u}$	^{u} u is the mean$(0 < u<+\infty)^{(0 < u < +\infty)}$
Generalised Pareto (Gp)	$f_{Gp}(x)=\frac{1}{\sigma}(1-\omega\frac{x-u}{\sigma})^{\omega}$	ω is the shape parameter, u is the position parameter, σ is the scale parameter