

# Research on Regional Early Warning of Flash Flood Disasters in Small Watershed Based on Multi-source Early Warning Data Fusion

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**Abstract.** The research on the early warning method of flash floods serves as an important groundwork for the prediction and early warning of flash flood disasters. Being restricted by various objective factors such as lack of data and complicated formation mechanism of flash flood disasters in small watersheds, accurate and targeted early warning has consistently been a weak link within the flash flood control system. In this regard, focusing on a series of problems, such as "short risk forecasting period", "frequent missing and false reports" and "poor early warning accuracy", this research explores a hierarchical partition management system that fulfills the demands of early warning based on the analysis of watershed lag time and risk situation. Meanwhile, based on the comprehensive consideration of the characteristics of various multi-source early warning data, such as meteorological forecast rainfall and monitoring rainfall water level, this research proposes corresponding early warning modes for different types of early warning objects. On these grounds, this research applies the proposed early warning system to Xiaguan Creek in Shangyu District, Zhejiang Province. Relevant findings indicate that the effective extension of the forecasting period, coupled with the reduction of the phenomenon of "missing and false reports", provides scientific support for the early warning and transfer decision related to flash floods.

**Keywords:** Flash Flood Warning; Watershed Lag Time; Risk Situation; Hierarchical Partition Management; Multi-source Early Warning Data; Xiaguan Creek Watershed

## 1. Introduction

The flash flood induced by rainstorm is regarded as one of the most destructive natural disasters in the world because of its concentrated rainfall, significant suddenness, rapid disaster formation speed, strong destructive power, and great difficulty in prediction and prevention. Affected by climate change and increasing human activities, the frequency and intensity of extreme rainstorms in various watersheds and regions exhibit a trend of continuous enhancement [1]. Moreover, the death toll from flash floods accounts for 61% to 80% of the death toll from flood disasters [2]. In other words, flash floods have seriously affected the sustainable development of China's economy and society. Against this backdrop, the effective implementation of flash flood disaster prevention and control has emerged as a critical challenge that requires immediate attention in the development of flood control and disaster reduction systems.

In retrospect, scholars at home and abroad have implemented a plurality of research on the early warning of flash flood disasters, establishing diverse relatively perfect flash flood forecasting and early warning systems. The flash flood guidance [3] and China flash flood hydrological model [4], as typical representatives among them, have been widely applied in numerous countries and regions by virtue of their advantages, such as the excellent embodiment of the physical mechanism of flash floods, distinct structure, and easy accessibility. The existing early warning methods for flash flood disasters primarily rely on flood forecasting models and mathematical statistics analysis [5]. Specifically, flood forecasting models typically employ high-precision hydrological models to simulate the evolution process of floods induced by rainstorms in relevant watersheds. By comparing the simulated flow value with the set flow threshold, the model is able to directly

provide early warning for areas where floods may occur. Nevertheless, due to the lack of observation data in small watersheds, the inability of the flood forecasting model in effective parameter calibration and verification makes it difficult to fully apply its technical approach in

numerous small and medium watersheds. By contrast, the essence of mathematical-statistical analysis is to establish an index system related to the occurrence of flash floods, such as critical rainfall, static or dynamic critical water level, etc. Particularly, it can judge the level of flood risk through real-time rain condition and water regime monitoring, thereby deciding whether to initiate early warning. This method, however, can neither completely identify the influencing factors of flash floods nor accurately describe the physical mechanism of floods. In other terms, it solely showcases a limited degree of early warning accuracy.

In summary, the current early warning of flash flood disasters generally relies on the support of a series of detailed data, encompassing the underlying surface, water regime, and historical flash flood disasters in small watersheds, lacking consideration of the temporal and spatial differentiation characteristics of flash flood disasters in prevention and control areas at all levels. As a result, the early warning of flash flood disasters exhibits various defects worthy of attention in practical application, such as low accuracy, and missing and false reports [6]. To this end, according to the characteristics of different early warning objects in the watershed as well as the manifestations of flash flood disasters, this paper constructs a differentiated early warning system for flash flood disasters based on fully excavating the characteristics of various multi-source early warning data, such as forecasting precipitation, monitoring precipitation, and local water level. In this way, this research aims to leverage the advantages of data fusion to provide effective solutions to the severe challenges faced by the early warning of flash flood disasters, such as "disasters caused by light rain" and "extremely low success rate of disaster prevention and control".

## 2. Method

To begin with, this research makes clear the urgency and perniciousness of flash flood risk in each region of the watershed through the analysis of watershed lag time as well as the assessment of flash flood risk situation. In this foundation, this research further constructs a differentiated early warning system based on the risk forecasting period and the risk level of flash floods by integrating various multi-source early warning features, such as meteorological forecast precipitation, monitoring precipitation, and local water level.

### 2.1 Analysis of Watershed Lag Time

Conceptually, the watershed lag time is defined as the temporal gap between the center of gravity of the net rainfall process and the center of gravity of the watershed outlet hydrograph, which is an important factor in determining the watershed unit hydrograph and peak discharge [7]. It veritably reflects, to some extent, the disaster-causing time of hidden danger risk elements and the reference time of people's avoidance and transfer. Based on the NRCS [8].analysis method, this research divides the confluence into two stages to solve the watershed lag time, in which the first stage is the overland flow stage, denoted as  $T_{ov}$ , whereas the second stage is the river-network concentrated flow stage, denoted as  $T_{ch}$ . On these grounds, the corresponding watershed lag time is obtained according to the location of the risk area in order to estimate the urgency of early warning.

$$T_L = T_{ov} + T_{ch} \quad (1)$$

$$T_{ov} = 0.828(NL_{ov})^{0.467}J_{ov}^{-0.235} \quad (2)$$

$$T_{ch} = 0.0078L_{ch}^{0.77}J_{ch}^{-0.385} \quad (3)$$

where  $T_{ov}$  indicates the confluence time of the overland flow;  $T_{ch}$  denotes that the concentration time of the river-network concentrated flow, serving as the watershed concentration time;  $L_{ov}$  represents the longest path of the overland flow;  $L_{ch}$  is the evolution path of the

river-network concentrated flow;  $J_{ov}$  indicates the gradient of the overland flow path;  $J_{ch}$  denotes the gradient of the river-network concentrated flow;  $N$  indicates the overland flow parameter, and;  $T_L$  indicates the watershed lag time.

## 2.2 Assessment of Flash Flood Risk Situation

The assessment of flash flood risk situation reveals a comprehensive consideration of regional danger, disaster bodies, and vulnerability, involving diverse influencing factors such as topography, rainfall, river network, social economy, and land utilization [9]. Based on the typical investigation case of flash flood disasters [10], this research selects three key influencing factors, encompassing people's avoidance of danger, house's resistance to danger, and flood disaster, to construct the analytic hierarchy process (AHP) structure model, thereby determining the flash flood risks in each region.

### 2.2.1. Construction of AHP Structure Model

Within the AHP structure model [11], the target layer is defined as flash flood risk ( $R$ ), whereas the criterion layer encompasses personnel risk avoidance factor ( $A_1$ ), house risk-resistance factor ( $A_2$ ), and objective flood risk factor ( $A_3$ ). Notably, three factors, including personnel, houses, and objective flood risk, are taken into account in the criterion layer from the inside out. The three factors mentioned above are not only independent in logic but also reflect excellent objectivity in terms of influence, which fulfills the requirements of AHP for maintaining the independence of the factors involved. In addition, the index layer includes the age of defending objects ( $X_1$ ), the number of defending objects ( $X_2$ ), the distance from the center of the dangerous area to the center line of the river course ( $X_3$ ), the average safety index of the house structure ( $X_4$ ), the number of houses ( $X_5$ ), the height difference between the average elevation of the house foundation and the levee crest of the control cross-section ( $X_6$ ), and the regional flood risk level ( $X_7$ ). The AHP model is detailed in Figure 1.

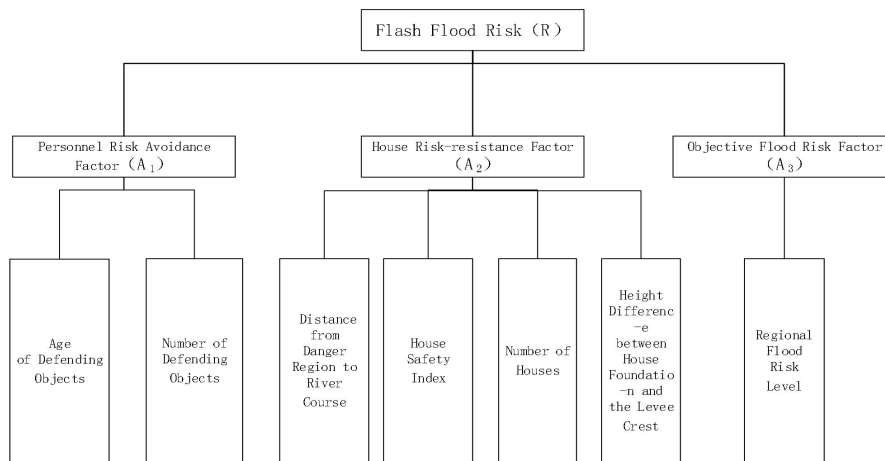


Figure 1 AHP Structure Model

### 2.2.2. Judgment Matrix Construction and Weight Analysis

According to the comparison standard, the elements within the criterion layer and the index layer are compared with their corresponding factors. On such a basis, the expert assignment scoring method is employed to establish a judgment matrix, with the weight of each index relative to the target layer being determined by solving the judgment matrix. Construction rules of AHP judgment matrix described in Table 1:

Table 1 Construction Rules of AHP Judgment Matrix

Value	Comparison Rules	Value	Comparison Rules
1	Both factors are equally important.	7	The former is more important than the latter.
3	The former is slightly more	9	The former is absolutely more

	important than the latter.		important than the latter.
5	The former is significantly more important than the latter.	2、4、6、8	Being in the middle of the foregoing importance judgment.
1/value	Both are reciprocal in importance.		

### 2.2.3. Analysis of Risk Situation

Taking into account the differences in measurement units of each index, this research introduces a normalization method to process each index in an attempt to achieve a more reasonable score for a single index. To put it another way, the normalization principle is employed to endow a single index with a value between 0 and 1 to obtain the data and relative relationship of risk factors in each region. Furthermore, the flash flood risk index of each risk region is determined comprehensively.

### 2.2.4. Classification of Early Warning Objects

The 1-fold standard deviation classification method is utilized to divide the risk regions of flash floods in the watershed based on the flash flood risk index and the watershed time lag distribution. A total of 12 types of early warning objects were ultimately determined, with the classification method described in Table 2:

Table 2 Specific Classification of Early Warning Objects

Watershed Time Lag	Risk Index	Types of Early Warning Objects
Less than 1 hour	$<-1\sigma$	Early Warning of Emergency Class-I Risks
	$-1\sigma$ to 0	Early Warning of Emergency Class-II Risks
	0 to $1\sigma$	Early Warning of Emergency Class-III Risks
	$>1\sigma$	Early Warning of Emergency Class-IV Risks
Between 1 and 3 hours.	$<-1\sigma$	Early Warning of Relatively Emergency Class-I Risks
	$-1\sigma$ to 0	Early Warning of Relatively Emergency Class-II Risks
	0 to $1\sigma$	Early Warning of Relatively Emergency Class-III Risks
	$>1\sigma$	Early Warning of Relatively Emergency Class-IV Risks
More than 3 hours	$<-1\sigma$	Early Warning of General Class-I Risks
	$-1\sigma$ to 0	Early Warning of General Class-II Risks
	0 to $1\sigma$	Early Warning of General Class-III Risks
	$>1\sigma$	Early Warning of General Class-IV Risks

## 2.3 Research on Early Warning System with Multi-Source Data Fusion

Based on the analysis of flash flood risk situation, the research on early warning with multi-source data fusion gives full play to various characteristics, such as long risk forecasting period of meteorological forecasting rainfall, fine early warning granularity of monitoring rainfall, and high early warning accuracy of local water level. It aims to build a refined flash flood early warning system according to the regional flash flood risk characterization characteristics and the fusion of multi-source early warning data.

### 2.3.1. Early Warning Model of Flash Floods Applicable to the Upper Reaches of the Watershed

Based on the analysis of historical flash flood disasters, the early warning based on rainfall and water level monitoring fails to fulfill the needs of early transfer and risk avoidance in the flash flood risk region with a forecasting period of less than one hour. For this reason, this paper adopts an early warning model with the local water level as the criterion to determine the transfer-related early warning, the monitoring rainfall as the estimation means of soil moisture content in the early stage, and the short-term meteorological grid forecasting rainfall as the early warning threshold. Early Warning Model of Flash Floods Applicable to the Upper Reaches of the Watershed is detailed in Figure 2 as follow:

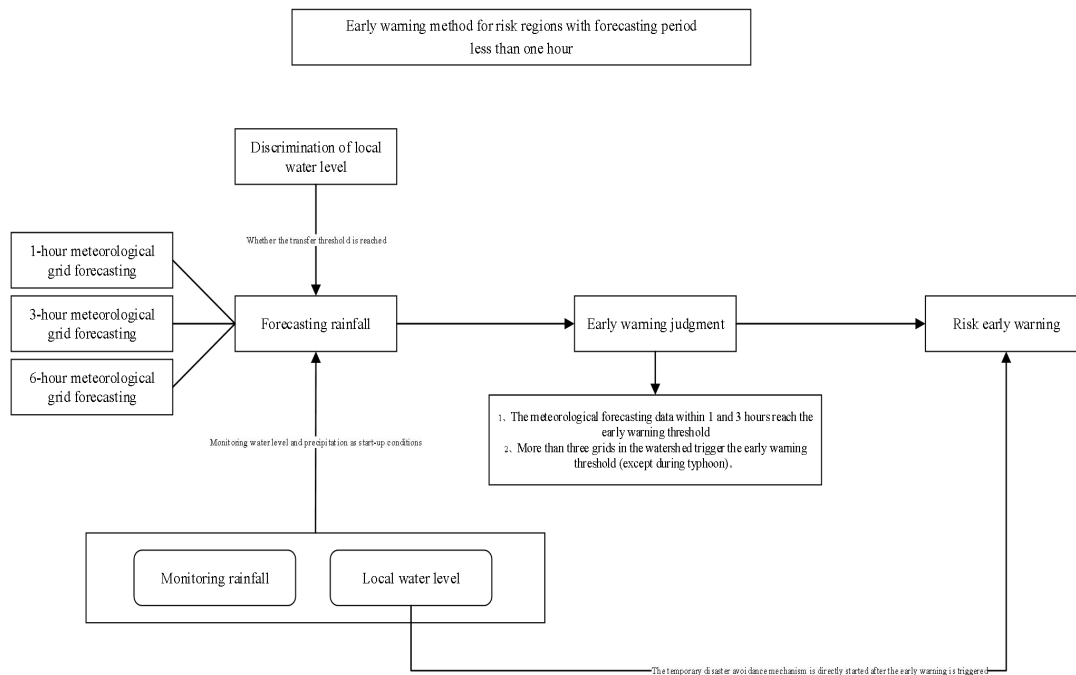


Figure 2 Early Warning Model of Flash Floods Applicable to the Upper Reaches of the Watershed

### 2.3.2. Early Warning Model of Flash Floods Applicable to the Middle Reaches of the Watershed

Regarding the flash flood risk region with a forecasting period ranging from 1 to 3 hours, not only is the early warning based on the local water level incompetent in fulfilling the needs of early transfer and risk avoidance but also the short-term meteorological forecasting rainfall can only provide limited early warning accuracy. Consequently, this paper adopts an early warning model with the local water level as the criterion to determine the transfer-related early warning, the monitoring rainfall as the estimation means of soil moisture content in the early stage, and the rising rate of the local water level as the early warning threshold. Early Warning Model of Flash Floods Applicable to the Middle Reaches of the Watershed is detailed in Figure 3 as follow:

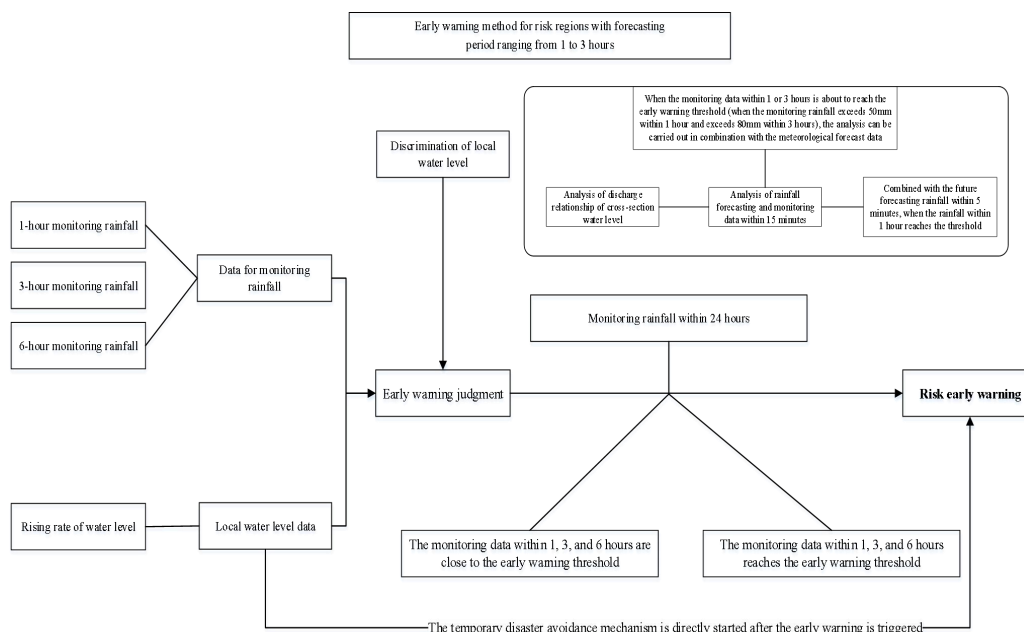


Figure 3 Early Warning Model of Flash Floods Applicable to the Middle Reaches of the Watershed

### 2.3.3. Early Warning Model of Flash Floods Applicable to the Lower Reaches of the Watershed

Regarding the flash flood risk region with a forecasting period of more than three hours, it exhibits diverse characteristics, encompassing a long forecasting period, a complex regional flood evolution environment, and poor early warning accuracy caused by difficulties in rainfall monitoring in the upper reaches. Hence, based on the hydrodynamic model, this paper adopts the early warning model featuring the linkage of upstream and downstream water levels. Early Warning Model of Flash Floods Applicable to the Lower Reaches of the Watershed is detailed in Figure 4 as follow:

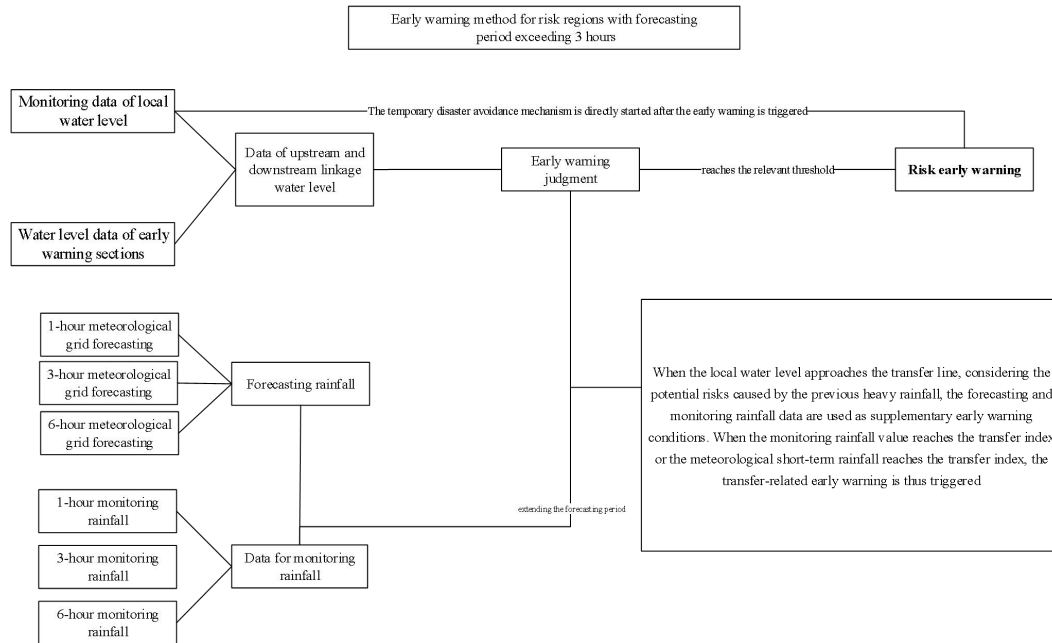


Figure 4 Early Warning Model of Flash Floods Applicable to the Lower Reaches of the Watershed

### 2.3.4. Summary

Different levels of flash flood risk regions present a progressive relationship in terms of disaster manifestations. Among them, the extremely high-risk regions (Class III) and high-risk regions (Class IV) generally exhibit low flood control capacity and more disaster-causing factors such as backwater and flood overflowing. In the period of heavy rainfall, therefore, personnel should be transferred in advance in the foregoing regions. In contrast, general-risk regions and low-risk regions present relatively high flood control capacity. Consequently, these areas can initiate the early warning according to the high-level risk early warning and the meteorological forecasting rainfall, thus avoiding excessive transfer.

## 3. Case Study

### 3.1 Overview of the Survey Region

The small watershed of Xiaguan Creek, which originated from the west slope of the Bogu Rock in Yuyao City, is a tributary of the middle and lower reaches of Cao'e River, encompassing a host of major branches such as Langzhuang Creek, Xun Creek, Chen Creek, Gan Creek, Shuang Creek, Qian Creek, Ren Creek, Zhang Creek, and Banong Creek. Overall, it belongs to Yuyao City and Shangyu District, with a drainage area of 234.9 km<sup>2</sup>, a main stream length of 38.3 km, and an average river gradient of 21.8‰. Due to the short riverway and rapid flow, it is seriously affected by flash flood disasters. Hence, it can be defined as a typical mountainous small watershed.

### 3.2 Data Information

The data utilized in this research encompass basic geographic information data, investigation and evaluation data of flash flood disasters, and hydrological and meteorological data related to Typhoon Muifa. More precisely, first and foremost, the geomorphic information of the watershed involved stems from DEM elevation data with a spatial accuracy of 30 m. Secondly, the investigation and evaluation data of flash flood disasters include flash flood risk zoning data, early warning index data, key risk hidden danger investigation data, and housing and population survey data. At last, the hydrological and meteorological data related to Typhoon Muifa include precipitation, water level, and meteorological data in the disaster region. Notably, all the foregoing data have been quality controlled and thus exhibit remarkable reliability.

### 3.3 Analysis of Watershed Lag Time and Risk Situation

A total of 50 villages for preventing flash flood disasters and 90 flash flood risk regions are distributed within the watershed of Xiaguan Creek, with the risk sources covering the overflow of river flood, the impact of channel flood, the blocking and backwater of slab culvert, etc. Based on the analysis of the geographical information of the watershed involved, the watershed time lag analysis method can be employed to determine the distribution of watershed lag time in each village, as illustrated in Figure 5. As can be seen from Figure 5, the distribution of watershed lag time ranges from 0.2 to 6.81 hours, which fully reflects the urgency of flood early warning in diverse regions during heavy rainfall.

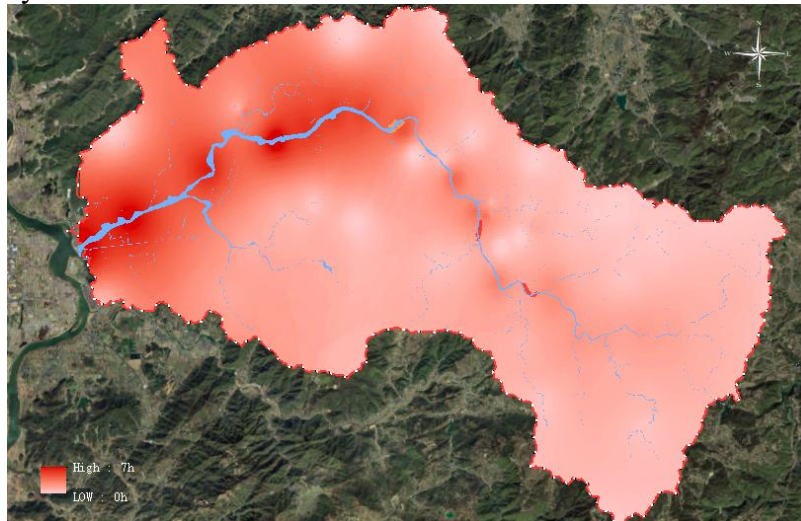


Figure 5 Distribution Diagram of Watershed Lag Time

Based on the investigation results of flash flood disasters in Xiaguan Creek, combined with the analysis of various key hidden dangers such as backwater and flood overflowing, the AHP model is leveraged to determine the risk index of flash floods in 90 regions, with the 1-fold standard deviation method utilized to divide the four-level risk regions as illustrated in Figure 7. As can be seen from the watershed risk situation depicted in Figure 8, 32.1% of the regions where historical flash flood disasters occurred are located in extremely high-risk regions, 64.4% in high-risk regions, and 3.5% in general-risk regions, implying that the risk situation analysis adopted in this research can be employed as an effective method to judge the perniciousness of flash floods. Concurrently, it fully reflects the hazard extent of flash flood disasters in different regions in Figure 6 as follow:



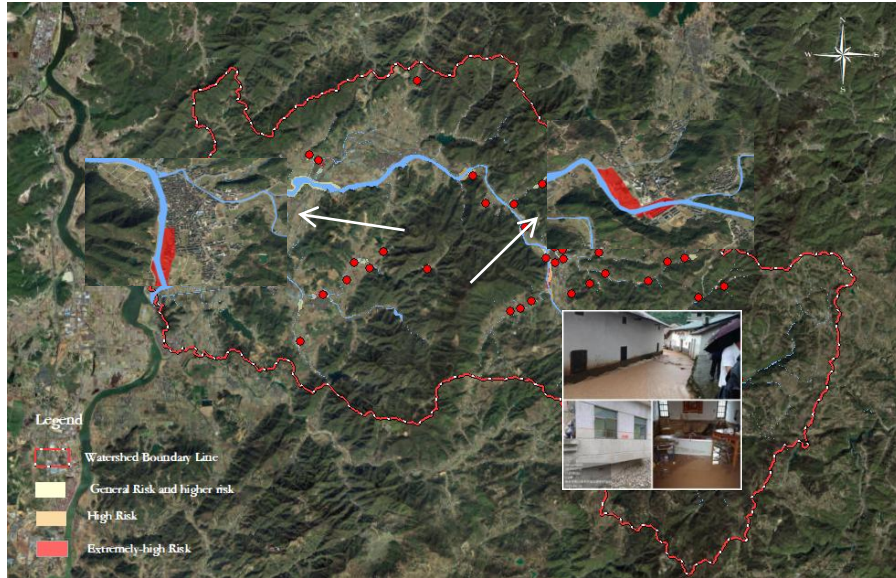


Figure 6 Risk Situation Diagram of the Watershed Involved

### 3.4 Construction of Early Warning System with Multi-source Data Fusion

#### 3.4.1. Early Warning System with Multi-source Data Fusion

According to the watershed lag time distribution of 90 risk regions within Xiaguan Creek, this research constructs three types of early warning models with multi-source data fusion based on the analysis results of typical flash flood cases.

##### 2.4.1.1. Early Warning Model of Flash Floods Applicable to the Upper Reaches of the Watershed

In the case that the water level does not reach the immediate transfer threshold, an immediate early warning will be triggered if any of the following conditions are met: a) the monitoring rainfall in the last 24 hours is more than 120 mm, with 3 or more grids in the catchment area of the defensive village in the last 1, 3, and 6 hours reaching the immediate transfer threshold of the risk region, and; b) the rising rate of water level within 10 minutes is close to the value of the immediate water level minus the constant water level divided by 2, with 3 or more grids in the catchment area of the defensive village in the last 1, 3, and 6 hours reaching the immediate transfer threshold of the risk region. Early warning will be triggered immediately when the water level is about to or has reached the immediate transfer threshold. Under this circumstance, temporary emergency resettlement can be taken on a case-by-case basis.

##### 2.4.1.2. Early Warning Model of Flash Floods Applicable to the Middle Reaches of the Watershed

In the case that the water level does not reach the immediate transfer threshold, an immediate early warning will be triggered if any of the following conditions are met: a) the monitoring rainfall in the last 24 hours is more than 120 mm, with the monitoring rainfall in the last 1 hour exceeding 30 mm and the monitoring rainfall in the last 6 hours exceeding 50 mm; b) the monitoring rainfall in the last 24 hours is less than 120mm, with the rainfall in the last 1, 3, and 6 hours exceeding the immediate transfer threshold of the risk region, and; c) the monitoring rainfall in the last 1 hour and 6 hours exceeds 30 mm and 50 mm, respectively, with the rising rate of local monitoring water level in 10 minutes being close to the value of the immediate water level minus the constant water level divided by 2.

##### 2.4.1.3. Early Warning Model of Flash Floods Applicable to the Lower Reaches of the Watershed

In the case that the local water level does not reach the immediate transfer threshold, the immediate transfer will be triggered if any of the following conditions are met: a) the water level of the upstream early-warning section reaches the immediate transfer threshold; b) the local water level is not close to the ready transfer threshold, with the monitoring rainfall or forecasting rainfall in the last 1, 3, and 6 hours reaching the ready transfer threshold; c) the monitoring rainfall of 2 or more associated rainfall stations in the upper reaches of the watershed in the last 1, 3, and 6 hours



reaches the immediate transfer threshold. In the case that the local water level reaches the ready transfer threshold, temporary emergency measures should be taken immediately.

#### 3.4.2. Analysis of the Relationship between Upstream and Downstream Water Levels

Leveraging the simulation of design flood within the watershed of Xiaguan Creek, the analysis of the relationship between upstream and downstream water levels within the watershed of Xiaguan Creek depicts the water line of flood along the flow path, thus determining the early warning threshold in the early warning model applicable to the lower reaches of the watershed.

##### 2.4.2.1. Calculation of Design Flood

The flood in the watershed of Xiaguan Creek is primarily composed of a series of branches including Langzhuang Creek, Xun Creek, Chen Creek, Gan Creek, Zhu Creek, Lu Creek, Dongli Creek, Meikeng Creek, Pailao River, Dingzhai Center River, Zhang Creek, and Ba Creek. In this regard, the reasoning formula method of Zhejiang Province is utilized to calculate the design flood of the watershed with a tributary area of less than 50 km<sup>2</sup>, whereas the instantaneous unit hydrograph method is employed to calculate the design flood of the watershed with a tributary area of more than 50 km<sup>2</sup>. The results of the design flood are presented in Table 3 as follows.

Table 3 Results of Design Flood within the Watershed of Xiaguan Creek

Names of Partitions	Tributary Area (km <sup>2</sup> )	Design Flood (m <sup>3</sup> /s)				
		1%	2%	5%	10%	20%
Upstream of Xiaguan Creek	18.4	458	391	324	260	198
Langzhuang Creek	24.55	530	467	362	301	222
Xun Creek	6.34	176	152	122	99	77
Chen Creek	10.66	272	232	192	154	117
Gan Creek	10.46	240	213	169	134	108
Zhu Creek	10.02	266	237	192	156	122
Lu Creek	16.68	400	354	280	224	179
Dongli Creek	3.61	112	98	79	65	51
Meikeng Creek	4.72	126	108	87	70	54
Pailao River	10.71	297	256	206	167	129
Dingzhai Center River	20.06	559	498	388	316	245
Zhang Creek	37.05	796	707	560	446	337
Ba Creek	9.5	168	139	115	89	71

##### 2.4.2.2. Calculation and Analysis of Water Level along the Flow Path

Based on HEC-RAS software, this research implements the analysis and calculation of flood water levels along the flow path. According to the measured data of the river course, the modeling range of the watershed of Xiaguan Creek starts from the downstream of Xulin Reservoir, and incorporates a series of tributaries such as Langzhuang Creek, Xun Creek, Zhu Creek, Lu Creek, Banong Creek, and Zhang Creek, etc., with the downstream reaching the confluence of Cao'e River. Within this range, a total of 111 sections, 29 generalized barrages, and 42 bridges are laid. On these grounds, this research obtains the results of flood water line within the watershed of Xiaguan Creek at various frequencies, as illustrated in Figure 8. Ultimately, the early warning water level threshold of the upstream area to the downstream can be determined by calculating the difference of the results in Figure 7 and Table 4.

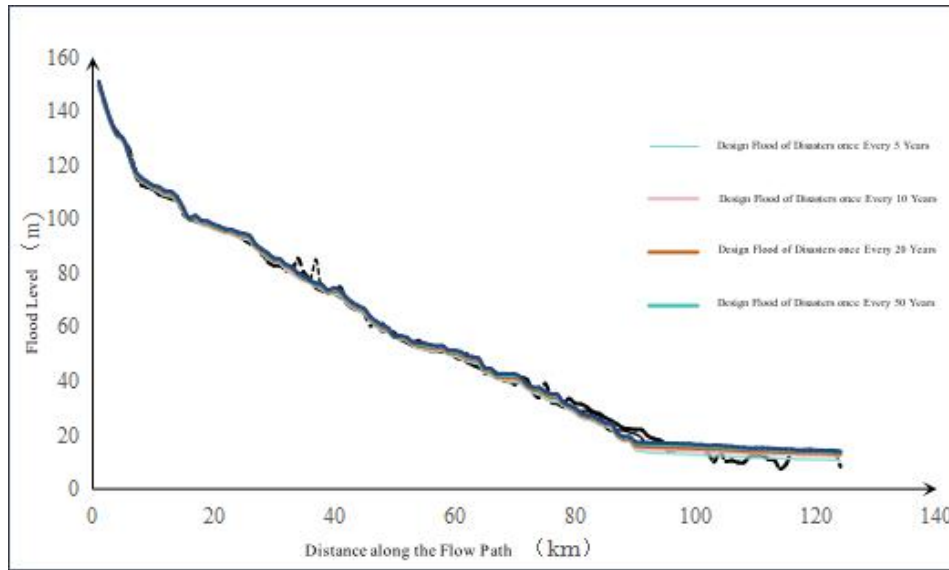


Figure 7 Water level conditions along the Xiaguan Creek

Table 4 Relationship Table of Upstream and Downstream Water Level Linkage

Serial Number	Key Villages	Disaster-causing Water Level	Early Warning Position of Water Level	Early Warning Water Level
1	Hefu Village	14.02	Miaofeng Village, Zhang Village	46.39
2	Hanzhai Village	14.39	Miaofeng Village	45.94
3	Dashibu Village	35.56	Shimen Village	46.05
4	Miaofeng Village	45.08	Hongqiao Village	100.03
5	Xiqiao Village	53.3	Hongqiao Village	100.07
6	Xinxing Village	52.86	Hongqiao Village	99.82

### 3.5 Application Case of Flash Flood Disasters during Typhoon Muifa within the Watershed of Xiaguan Creek

Taking the flash flood disasters in the Jiuzhai village within the watershed of Xiaguan Creek during "Typhoon Muifa in 2022" as a typical case(The disaster process is shown in Figure 8), this research compares and analyzes the partition-based early warning system of flash flood disasters in a small watershed with multi-source early warning data fusion with the traditional flash flood early warning system. The results indicate that the model proposed in this research can issue relevant early warnings 4.5 hours and 31 hours in advance for 2 risk periods related to the flash flood occurred. It implies that the proposed model can effectively avoid the phenomenon of missing and false reports concerning early warning while extending the risk forecasting period.

At 15:30 on September 14, 2022, a flash flood occurred in Jiuzhai Village and Sijian Village. From 12: 00 to 23: 00 on September 14, 2022, the Langzhuang Reservoir Station in Chen Creek in the upstream region showed a maximum rainfall of 32 mm in one hour (15:00 on September 14), 94 mm in three hours (approximately once every 5 years), 179.5 mm in six hours (approximately once every 10 years), and a maximum accumulated rainfall of 301.5 mm in 12 hour (approximately once every 30 years).Comparison between Partition-based Early Warning with Multi-source Data Fusion and Traditional Flash Flood Early Warning is detailed in Table 5.

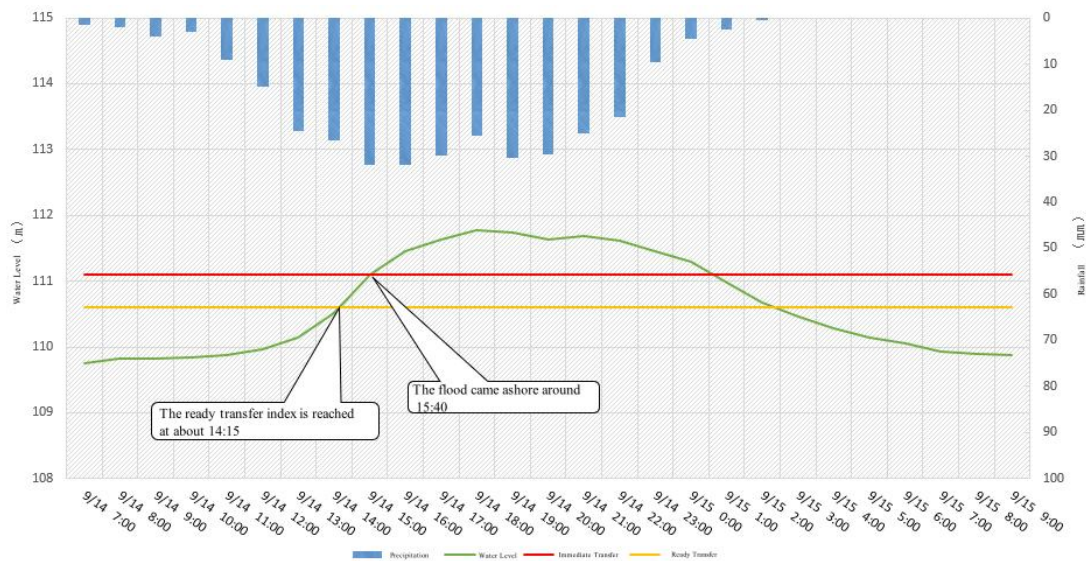


Figure 8 Rain Condition and Water Regime Process in Jiuzhai Village during Typhoon Muifa

Table 5 Comparison between Partition-based Early Warning with Multi-source Data Fusion and Traditional Flash Flood Early Warning

Risk Regions	Disaster Situation	Early Warning Based on Traditional Rainfall	Early Warning Based on Traditional Meteorological Forecast	Partition-based Early Warning with Multi-source Data Fusion
Extremely high-risk regions of Jiuzhai Village	Flood impact at 15: 30 on September 14, 2022	The early warning was not triggered in time, with the disaster being formed after the early warning.	The third-phase early warning was issued from September 13 to 14.	The early warning was issued 31 hours in advance.
High-risk regions of Jiuzhai Village	Flood impact at 15: 42 on September 14, 2022	The early warning was not triggered in time, with the disaster being formed after the early warning.	The third-phase early warning was issued from September 13 to 15.	The early warning was issued 4.5 hours in advance.
Extremely high-risk regions of Sijian Village	Flood impact at 16: 11 on September 14, 2022	The early warning was not triggered in time, with the disaster being formed after the early warning.	The third-phase early warning was issued from September 13 to 16.	The early warning was issued 29 hours in advance.
High-risk regions of Sijian Village	Flood impact at 16: 14 on September 14, 2022	The early warning was not triggered in time, with the disaster being formed after the early warning.	The third-phase early warning was issued from September 13 to 17.	The early warning was issued 4 hours in advance.
General-risk regions of Sijian Village	Disaster not formed.	No early warning triggered.	The third-phase early warning was issued from September 13 to 18.	No early warning triggered.

#### 4. Conclusions

Previous early warning systems for flash flood disasters are generally based on static or dynamic early warning indexes and hydrological and hydrodynamic models to implement related early warning work. Subject to numerous problems such as the lack of basic data related to small

watersheds and the strong spatio-temporal heterogeneity of flash flood disasters, these traditional models consistently expose various defects, such as poor early warning accuracy, frequent missing and false reports. In contrast, from the perspective of the forecasting period of flash flood risk as well as the risk-related perniciousness, this paper constructs a partition-based early warning system based on multi-source early warning data fusion by comprehensively taking into account the spatial-temporal variability of flash flood disasters. Meanwhile, the application research conducted in the pilot watershed of Xiaguan Creek has achieved excellent outcomes, which provides a novel idea for the research on the early warning system and mechanism of flash flood disasters in the southeast coastal areas. As a whole, several conclusions are drawn as follows:

Specifically, first of all, based on the AHP, this research constructs a hierarchical partition management system that fulfills the needs of flash flood early warning. Particularly, the zoning results can fully reflect the risk forecasting period and disaster-related perniciousness of risk regions in different locations within the watershed.

Secondly, this research constructs three types of early warning models by combining diverse multi-source early warning data, encompassing 24-hour meteorological forecasting rainfall, short-term meteorological forecasting rainfall, early 24-hour monitoring rainfall, short-term monitoring rainfall, local monitoring water level, and rising rate of water level. Notably, the proposed three models are suitable for the upstream, middle, and downstream of the watershed, and thereby addressing the early warning difficulties caused by the spatial heterogeneity of flash floods through the characteristics of early warning data.

In closing, by applying the proposed early warning system to the case of flash flood disaster within the watershed of Xiaguan Creek during Typhoon Muifa, this research further effectively solves the problem of missing and false reports in early warning. Most importantly, the proposed early warning system not only extends the risk forecasting period but also provides valuable time advantages for personnel transfer and risk avoidance.

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