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A rainfall-based flash flood warning method integrating spatial stratification and multi-mode discrimination

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Rainfall -based methods are widely used for flash flood monitoring and warning. However, the conventional approach of issuing an alert based on any single associated station exceeding a threshold leads to frequent false alarms, hindering timely evacuations. This study proposes a method integrating spatial stratification and multi-mode discrimination. The method innovatively classifies rainfall stations associated with each village according to the spatial relationships among station–village, station–watershed, and station–station pairs. A multi-mode warning framework combining single-station, multi-station, and areal rainfall warnings is developed, with the appropriate warning mode determined by the station–village distance and the upstream watershed area of the village. Validation was conducted in six representative villages across Fujian Province. These villages were selected to encompass diverse watershed characteristics and varying rainfall gauge densities, thereby forming a systematic and representative testing framework. Results demonstrate that, compared to the traditional method, the proposed approach maintains high detection rates for actual disasters while significantly reducing the false alarm rate. The new method completely eliminated the three false alarms generated by the traditional approach, demonstrating a substantial improvement in warning precision. Specifically, using single-station warnings for nearby stations ensures rapid response to local heavy rainfall, while multi-station and areal rainfall warnings for more distant stations effectively capture regional events and reduce false alarms caused by gauge failures or localized convective storms. By integrating the sensitivity of point rainfall information with the stability of regional rainfall patterns, the proposed method substantially enhances the reliability and robustness of flash flood warnings, providing strong technical support for timely evacuation and disaster risk reduction in mountainous flash flood prone regions.

KEYWORDS

areal rainfall warning, false alarm rate, flash flood warning, multi-station warning, single-station warning, warning accuracy

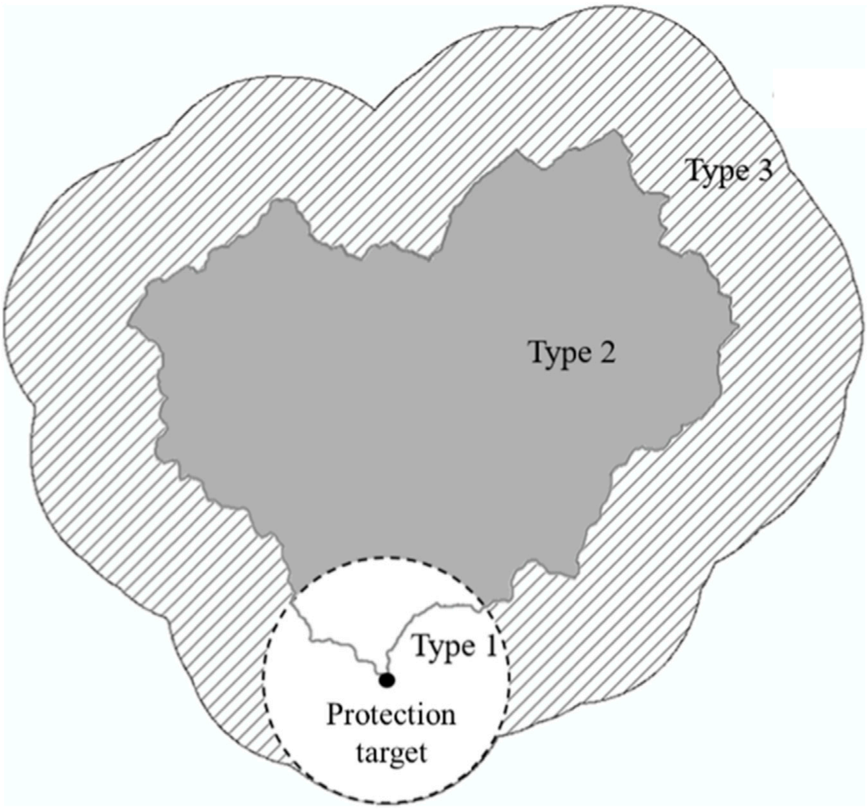


FIGURE 1
Schematic diagram of the classification of rainfall stations.

1 Introduction

Flash floods are among the most destructive natural disasters, notorious for their sudden onset and capacity to inflict severe losses on lives and property (Cheng and Li, 2020; Co, 2011; Choudhury and Haque, 2016; An and Ouyang, 2025; Manoj et al., 2024). The development of effective early warning methods is therefore critical for disaster prevention and mitigation (Ma and Hu, 2005; Luna et al., 2025; Rivera and Dela Vega, 2025).

Rainfall-based warning approaches are widely used in mountain regions because of their simplicity and real-time operability (Haijun et al., 2025). In practice, protection targets (e.g., villages) are commonly linked to a set of nearby rainfall stations, and a warning is issued once any associated station exceeds the rainfall threshold (Author anonymous, 2020; Yang P. et al., 2020). Although this single-station warning method allows for rapid response, it suffers from two major shortcomings. First, when heavy rainfall occurs in the upstream catchment but rainfall near the downstream protection target remains below the threshold, the ensuing flood may still cause flash flood disasters in the village, which the existing method fails to capture (Ye, 2019; Luo et al., 2020; Liu, 2012; Liu et al., 2024). Second, in areas with sparse gauge networks, some protection targets lack nearby associated stations, leading to missed alarms (Pirone et al., 2023; Yang Q. et al., 2020).

To address these issues, recent studies have attempted to improve this approach by expanding the association between protection targets and rainfall stations to include those located in upstream catchments (Liu et al., 2010; Yuan et al., 2019; Wang et al., 2018; Song and Kim, 2025). However, the warning principle still relies on single-station exceedance. Such fixed logic makes existing methods prone to false alarms under localized convective storms and limits their adaptability across basins of varying scales and gauge densities (Yang et al., 2025).

Considering these limitations, this study proposes a rainfall-based flash flood warning method that integrates spatial stratification and multi-mode discrimination. This method involves classifying the associated rainfall stations based on station–village distance, watershed topology, and gauge density, rather than linking stations solely by geometric proximity or watershed inclusion. Building on this classification, a unified multi-mode framework is developed that combines single-station, multi-station, and areal rainfall warnings. The proposed method adaptively selects the most appropriate warning mode according to watershed area and rainfall gauge density. In this way, the method integrates the sensitivity of point rainfall with the stability of regional rainfall patterns, thereby enhances robustness in complex mountainous terrains.

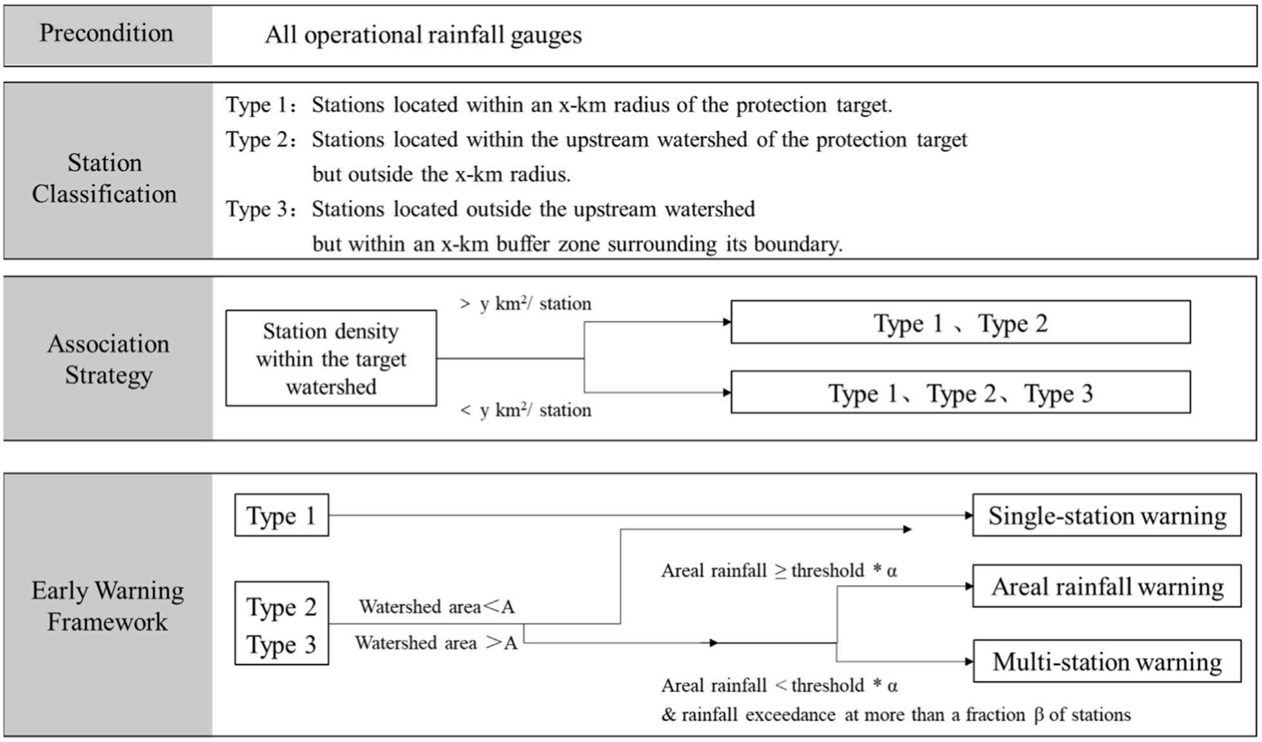


FIGURE 2
Flowchart of rainfall-based warning method for flash flood disaster integrating spatial stratification and multi-mode discrimination.

TABLE 1 Characteristics of the six representative villages and their upstream catchments.

Village	Drainage basin area (km^2)	River length (m)	Longest flow path (m)	Mean slope	Gradient (‰)
Xipian village	72.12	13,264	16952	0.380	19.1
Xiaying village	446.22	48,859	55374	0.351	3.0
Xiayang village	468.52	43,402	48272	0.377	3.6
Xiapu village	72.98	21,022	23815	0.419	21.0
Jiakui village	205.14	34,085	36878	0.432	11.4
Dongmen community	474.99	38,156	49298	0.428	5.7

2 Methodology

2.1 Rainfall-based flash flood warning method integrating spatial stratification and multi-mode discrimination

2.1.1 Classification of rainfall stations based on spatial position

All operational rainfall stations within the region of each protection target are classified according to their spatial relationships (Figure 1). The proposed spatial stratification scheme is designed to explicitly account for the distinct roles that rainfall at different locations plays in flash flood generation.

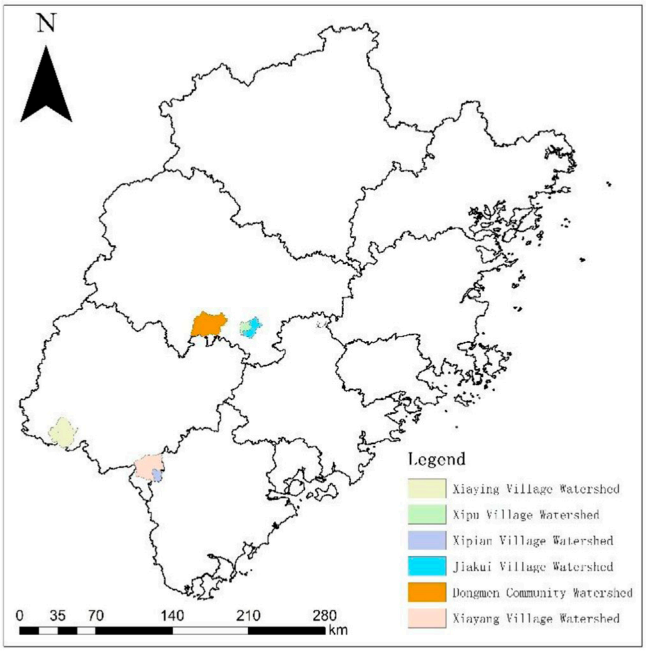
Type 1 stations are located within a circular buffer of x km radius centered on the protection target. Rainfall observed at these proximal locations predominantly drives flash flooding via direct overland flow and rapid channel response. This configuration is essential for detecting highly localized, intense convective storms capable of triggering flash floods with limited contribution from the broader catchment area. The radius x for defining station buffers is determined based on the average response time of typical flash flood-producing basins in the region and the rain gauge density. In this study, x was set to 5 km.

Type 2 stations are located within the upstream watershed of the target but outside the x km buffer. They capture rainfall from contributing areas that directly feed channel flow toward the target location. This addresses the fundamental hydrological process where upstream rainfall accumulates through the river network, potentially causing significant flooding downstream even when local rainfall is moderate.

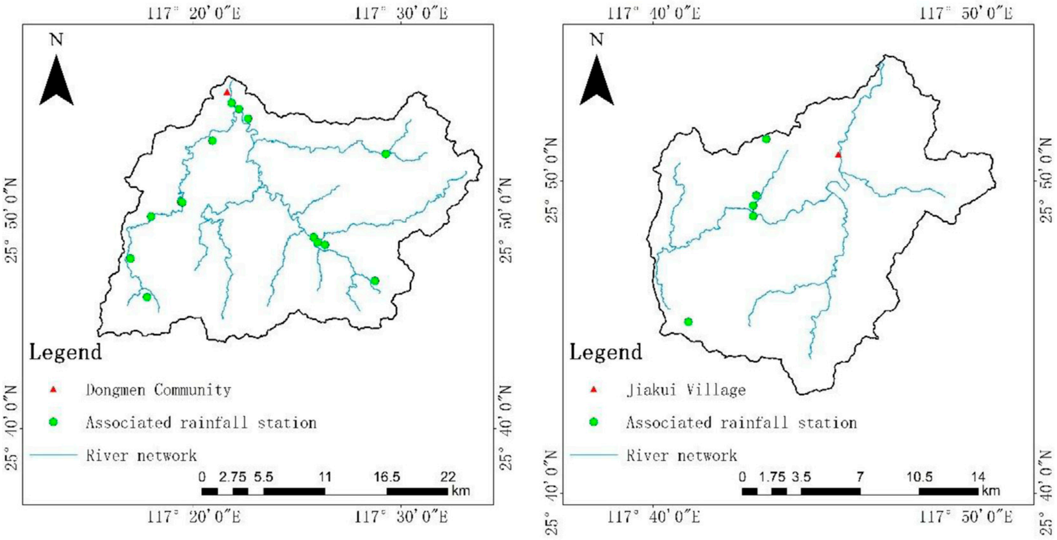
Type 3 stations are situated outside the upstream watershed but within an x km buffer zone around its boundary. Stations in this category help characterize the regional rainfall structure, which is critical for discriminating between widespread stratiform rainfall and isolated convective cells, which often produce highly localized and misleading warning signals.

2.1.2 Establishment of association between protection targets and multi-level rainfall stations

The association between protection targets and rainfall stations is categorized based on the density of rainfall stations within the watershed. When the density of rainfall stations (ρ) is less than or equal to a threshold y (km^2/station), indicating a dense distribution, the protection target is associated with Type 1 and Type 2 stations. When ρ exceeds y, indicating



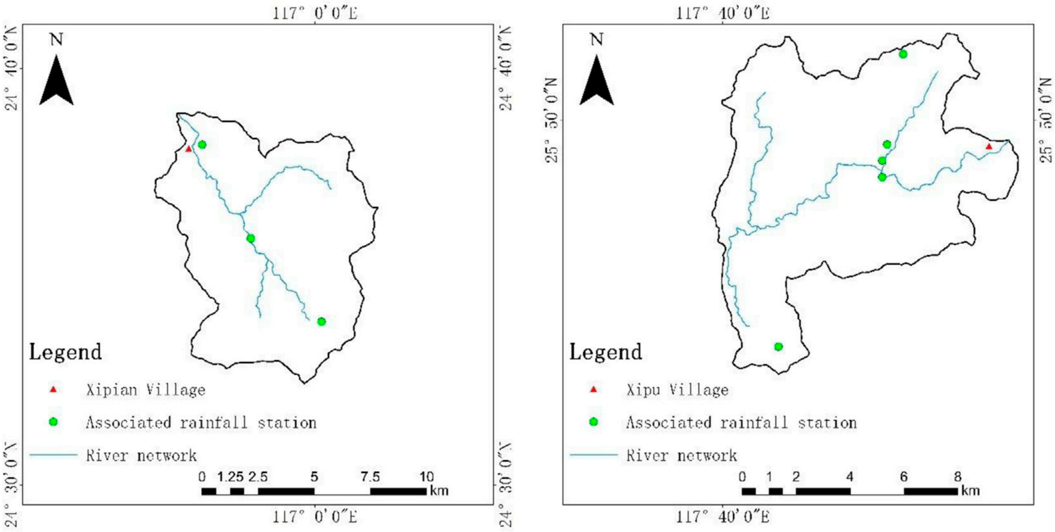
(a) Map of study area



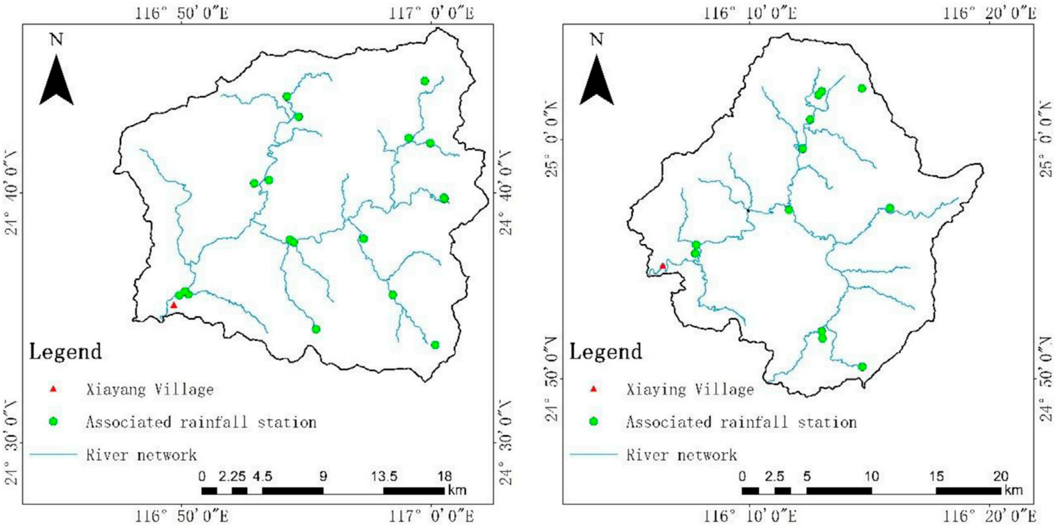
(b) Dongmen Community

(c) Jiakui Village

FIGURE 3
(Continued).



(d) Xipian Village (e) Xipu Village



(f) Xiayang Village (g) Xiaying Village

FIGURE 3
(Continued). Distribution of the study villages, upstream rivers, and rainfall stations. **(a)** Map of study area **(b)** Dongmen Community **(c)** Jiakui Village) **(d)** Xipian Village **(e)** Xipu Village **(f)** Xiayang Village **(g)** Xiaying Village.

sparse distribution, Type 1, Type 2, and Type 3 stations are all associated. The rainfall station density is calculated as shown in Equation 1:

$$\rho = \frac{F}{a} \tag{1}$$

where ρ is the station density, F is the upstream watershed area of the protection target, and a is the number of rainfall stations within the watershed. The threshold y is determined comprehensively based on regional climate, rainfall characteristics, and the provincial average station density.

2.1.3 Multi-mode rainfall warning framework

Three complementary rainfall-based warning modes are developed: single-station warning, areal rainfall warning, and multi-station warning. A single-station warning is triggered when rainfall at any associated station exceeds the rainfall warning threshold. An areal rainfall warning is triggered when the mean areal rainfall of the watershed exceeds the adjusted threshold [i.e., the point rainfall threshold multiplied by a reduction factor α, where α ∈(0,1)]. The areal rainfall is calculated using the Thiessen polygon method (Gao, 2023), and the value of α can be obtained from regional hydrological manuals. A multi-station

TABLE 2 Quantity of rain gauges and warning indicators for the study villages.

Village	Catchment area (km^2)	Number of rainfall stations	Station density (km^2/station)	Point rainfall warning threshold (mm)			Areal rainfall reduction coefficient α		
				1 h	3 h	6 h	1 h	3 h	6 h
Xipian village	72.12	3	24	88.86	121.62	148.26	0.872	0.900	0.934
Xiaying village	446.224	10	41	80.96	110.66	134.78	0.750	0.791	0.832
Xiayang village	468.52	19	24	88.08	120.51	146.86	0.746	0.787	0.828
Xipu village	72.98	5	14	71.03	95.1	114.32	0.871	0.900	0.933
Jiakui village	205.14	5	41	71.03	95.1	114.32	0.787	0.827	0.879
Dongmen community	474.99	12	44	76.9	101.48	120.88	0.745	0.786	0.827

The point rainfall warning thresholds for the villages are obtained from the Fujian Flash Flood Warning Platform, and the areal rainfall reduction coefficients are derived from the Fujian Province Rainfall-Runoff Charts.

warning is triggered when rainfall at multiple associated stations simultaneously exceeds the warning threshold.

2.1.4 Discrimination logic for multi-mode warnings

Real-time rainfall data from all associated stations are collected, and the appropriate warning mode is determined according to the station type and watershed characteristics. The workflow is shown in Figure 2.

If the triggering station is Type 1, a single-station warning is applied.

If the triggering station is Type 2 or Type 3, the warning mode is determined by the upstream watershed area.

- For small watersheds (≤ threshold A), a single-station warning is applied.
- For large watersheds (> threshold A), the areal rainfall is calculated. When the areal rainfall$\geq \alpha \times$ warning threshold, an areal rainfall warning is issued.
- If the areal rainfall$< \alpha \times$ warning threshold, the proportion of associated stations with rainfall exceeding the threshold is calculated. When this proportion$\geq \beta$ ($\beta \in (0,1)$), a multi-station warning is triggered.

2.2 Comparison and evaluation of warning performance

The performance of the proposed early warning method is evaluated against a traditional rainfall warning approach. The effectiveness of both methods is assessed using three standard metrics: hit, false alarm, and miss. A hit refers to a case where a village triggered a flash flood warning and a flash flood event actually occurred. A false alarm refers to a case where a warning was issued but no flash flood event occurred. A miss refers to a case where no warning was issued, yet a flash flood event occurred in the village (Wu, 2024).

3 Study area and data collection

3.1 Study area

Fujian Province is located along the southeast coast of China and lies within the mid-subtropical monsoon climate zone. The region is characterized by complex topography, where mountains and hills account for nearly 80% of the total land area. Influenced by the East Asian monsoon, rainfall in Fujian is highly uneven in both temporal and spatial distribution. The main flood season occurs from March to August, during which over 70% of the annual precipitation is concentrated. Rainfall events are often short in duration but high in intensity, and when combined with steep terrain, they make Fujian one of the provinces most prone to flash flood disasters in China.

To evaluate the proposed rainfall-based flash flood warning method that integrates spatial stratification and multi-mode discrimination, six representative villages in Fujian Province were selected as case studies. These villages are distributed across Longyan and Sanming cities, encompassing a wide range of catchment scales, topographic gradients, and rainfall station densities. Such selection enables comprehensive testing of the proposed method under diverse hydrological and geomorphological conditions. The chosen villages include both small catchments (e.g., Xipian Village and Xipu Village) and medium-to-large catchments (e.g., Xiaying Village and Guidongmen Community), ensuring the applicability and robustness of the method across different spatial scales.

The hydrological and geomorphological characteristics of the study villages and their upstream catchments are summarized in Table 1. The locations of the villages, their respective catchments, and the distribution of rainfall stations are shown in Figure 3. And the warning indicators for each village are summarized in Table 2.

3.2 Information on selected rainfall events

For the evaluation of the proposed flash flood warning method, six recent representative rainfall events were selected

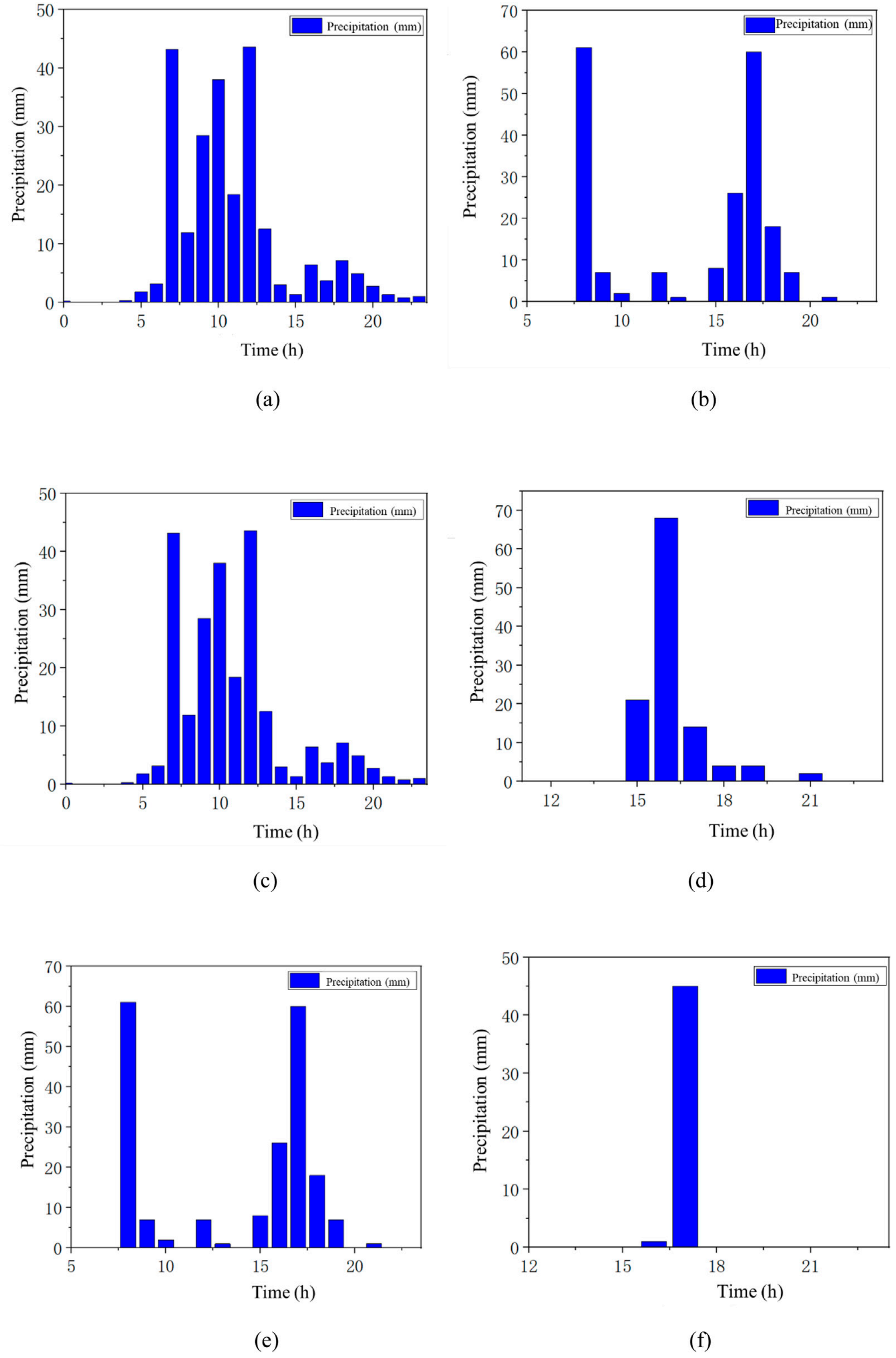


FIGURE 4
Rainfall processes recorded by the early-warning stations in study villages. **(a)** Rainfall process at the early-warning early-warning stations in Xipian Village **(b)** Rainfall process at the early-warning stations in Jiakui Village **(c)** Rainfall process at the early-warning stations in Xiayang Village **(d)** Rainfall process at the early-warning stations in Dongmen Community **(e)** Rainfall process at the early-warning stations in Xipu Village **(f)** Rainfall process at the early-warning stations in Xiaying Village.

TABLE 3 Rainfall events and disaster situations in the study area.

Village	Rainfall date	Disaster occurrence time	Disaster situation
Xipian village	20 August 2024	10:00–11:00, 20 August 2024	Flood overflowed the river channel; maximum water depth on roads: 1 m; 1 person evacuated; several landslides; 49 acres of farmland inundated
Jiakui village	4 April 2024	17:00–18:00, 4 April 2024	Flood overflowed the river channel; maximum water depth on roads: 0.3 m
Xiaytang village	20 August 2024	10:00–11:00, 20 August 2024	Flood overflowed the river channel; maximum water depth on roads: 0.7 m; 79 households evacuated
Dongmen community	4 April 2024	—	No disaster reported
Xipu village	4 April 2024	—	No disaster reported
Xiaying village	18 July 2024	—	No disaster reported

TABLE 4 Comparison of effectiveness between the proposed and traditional warning methods.

Village	Disaster situation	Proposed approach		Traditional approach		Improvement
		Warning level	Effect	Warning level	Effect	
Xipian village	Affected	Danger	Hit	Danger	Hit	Maintained effective warning for affected villages
Jiakui village	Affected	Danger	Hit	Danger	Hit	Maintained effective warning for affected villages
Xiayang village	Affected	Danger	Hit	Danger	Hit	Maintained effective warning for affected villages
Dongmen community	Not affected	—	Hit	Danger	False alarm	Avoided false alarm of traditional method
Xipu village	Not affected	—	Hit	Danger	False alarm	Avoided false alarm of traditional method
Xiaying village	Not affected	—	Hit	Concern	False alarm	Avoided false alarm of traditional method

to represent the dominant rainfall regimes and hydrological responses in Fujian across the six study villages. The rainfall processes at the associated warning stations and the corresponding disaster situations are summarized in Figure 4 and Table 3. They include both short-duration, high-intensity convective storms and longer-duration stratiform rainfall, as well as both flood-generating and non-flood-generating cases to evaluate hits and false alarms. Because the study villages span small to large catchments with varying gauge densities, the selected events also reflect differences in runoff concentration, spatial rainfall variability, and watershed sensitivity, ensuring a representative validation dataset.

4 Result and discussion

4.1 Overall comparison of warning performance

To evaluate the effectiveness of the proposed method, flash flood warnings were simulated for six representative villages and compared with those generated by the traditional approach. The selection of the key thresholds was based on regional hydrometeorological characteristics and calibration experiments. The rain gauge density threshold y is influenced by climate, spatial rainfall variability, and the provincial mean station density, and

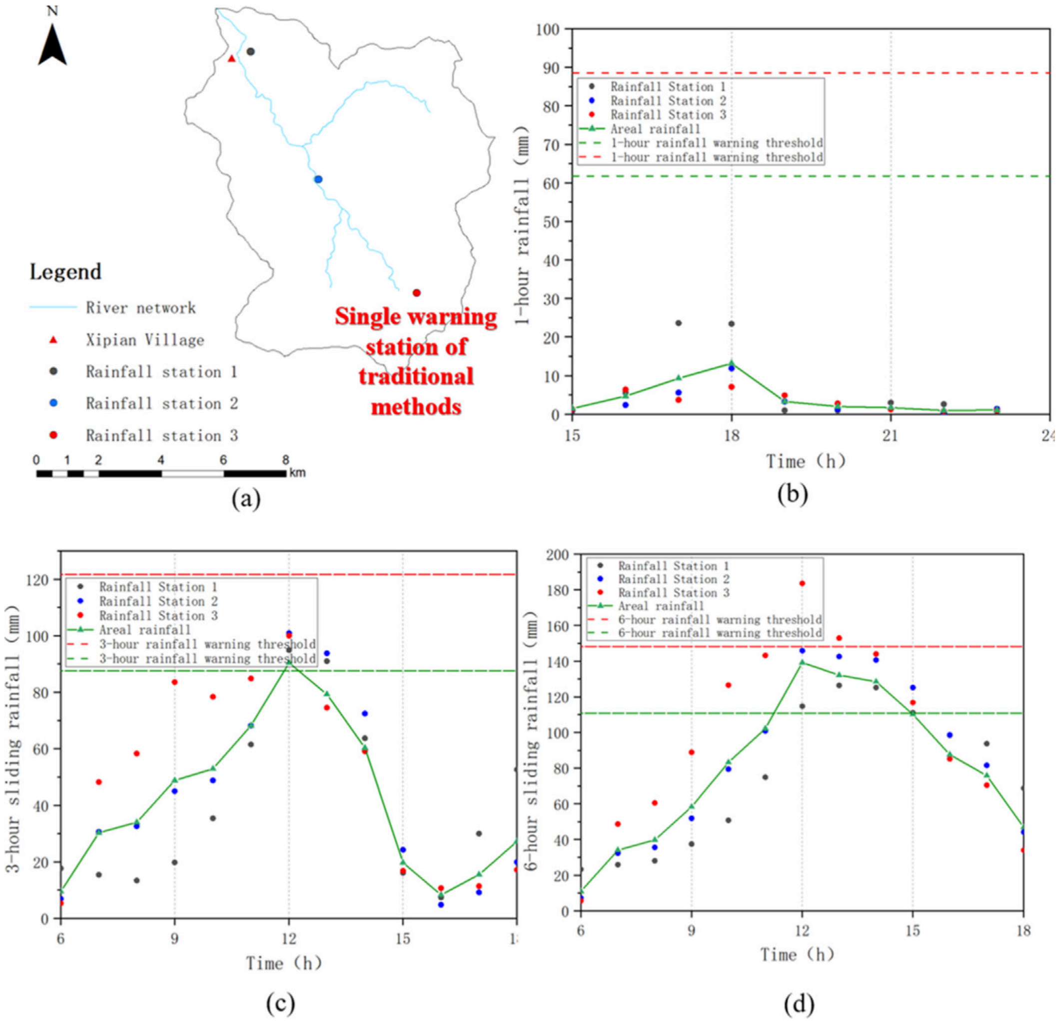


FIGURE 5
Upper catchment of Xipian Village and early warning analysis. **(a)** Map of the associated stations of the Xipian Village watershed **(b)** 1-hour rainfall process (no warning) **(c)** 3-hour rainfall process (Areal rainfall warning) **(d)** 6-hour rainfall process (traditional method of single-station warning).

typically ranges from 5 to 50 km^2/station. The watershed area threshold A generally ranges from 50 to 200 km^2, with larger values suitable for steep basins and smaller values for flatter ones. Within these ranges, y = 15 km^2/station and the A = 70 km^2 showed the best overall performance in our study. The multi-station proportion parameter β was calibrated through sensitivity tests, and β = 0.5 provided the most stable warning results.

As shown in Table 4, the proposed method achieved more accurate warnings for flood-affected villages while substantially reducing false alarms for non-affected villages. This demonstrates improved precision and reliability compared with the conventional single-station approach.

4.2 Case studies

4.2.1 Case of an affected village

Field investigations confirmed that Xipian Village was impacted by a flash flood on 20 August 2024. Warnings were evaluated based on 1-h rainfall, and moving 3-h and 6-h cumulative rainfall. The rainfall hyetographs at individual associated stations and the areal rainfall process over the upstream watershed are shown in Figure 5.

As illustrated in Figure 5a, three rainfall stations are associated with the village. Under the traditional method, only Station three recorded a 6-h cumulative rainfall of 183.6 mm, exceeding the point rainfall threshold and triggering a warning. In contrast, under the proposed method, the areal rainfall over a 3-h period reached 90.4 mm (Figure 5c), surpassing the corresponding areal threshold and activating the areal rainfall warning. This demonstrates that the proposed method effectively captures the spatially integrated rainfall pattern while maintaining rapid response capability.

4.2.2 Case of an unaffected village

Field investigations confirmed that Xipu Village was not affected by a flash flood during the studied rainfall event. This section uses Xipu Village to analyze how the proposed method avoids false alarms compared to the traditional approach. Warnings

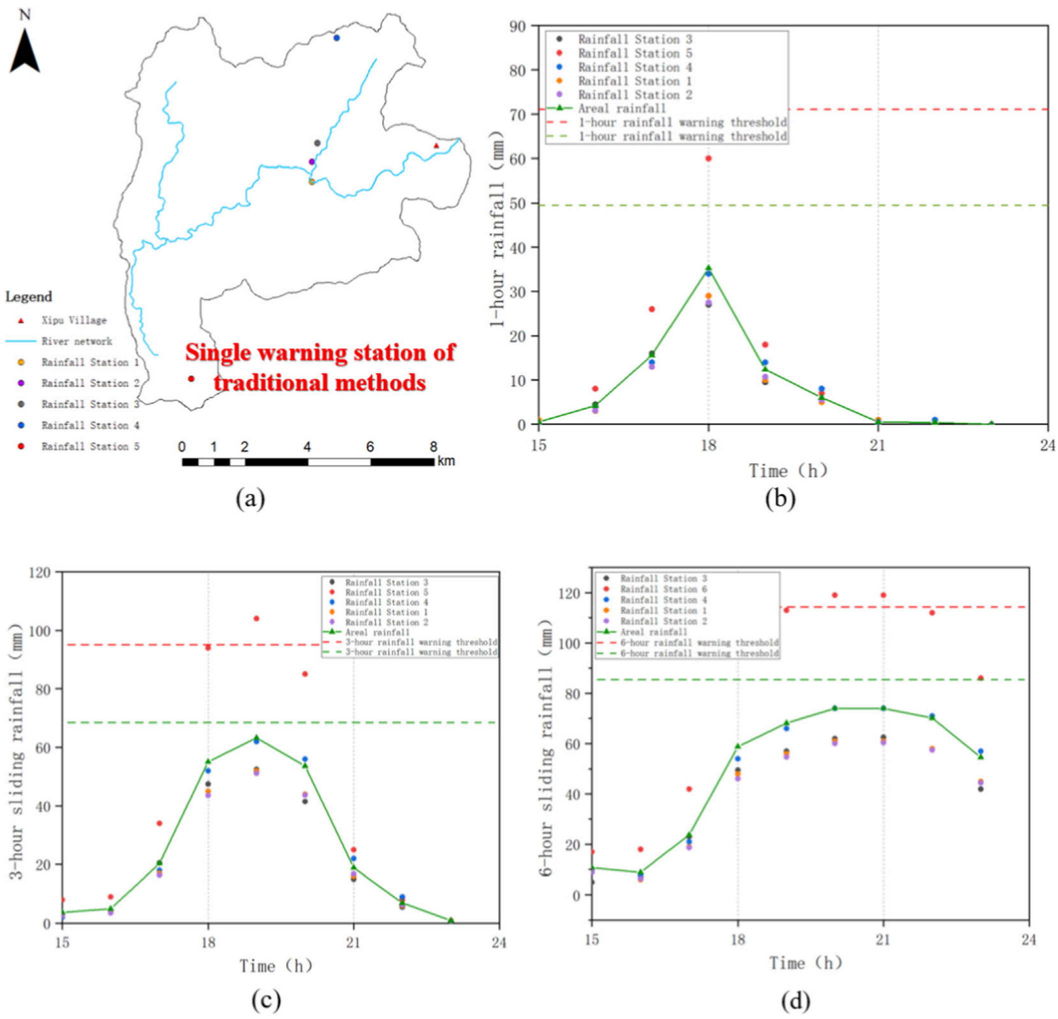


FIGURE 6
Upper catchment of Xipu Village and early warning analysis. **(a)** Map of the associated sites of the Xipu Village River Basin **(b)** 1-hour rainfall process (no warning) **(c)** 3-hour rainfall process (traditional method single-station warning) **(d)** 6-hour rainfall process (traditional method of single-station warning).

TABLE 5 Scheme design under different parameter settings.

Parameter	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Rain gauge density threshold y (km^2/station)	15	50	15	15
Catchment area threshold A (km^2)	70	70	200	70
Proportion of stations exceeding threshold β	0.5	0.5	0.5	0.25

were evaluated based on 1-h rainfall, and moving 3-h and 6-h cumulative rainfall. The rainfall hyetographs at individual associated stations and the areal rainfall process over the upstream watershed are shown in Figure 6.

As shown in Figure 6a, five rainfall stations are associated with the watershed of Xipu Village. Under the traditional method, Station five recorded a 3-h cumulative rainfall of 104 mm, exceeding the threshold and falsely triggering a warning. Under the proposed method, the 1-h, 3-h, and 6-h areal rainfalls did not exceed the corresponding thresholds (Figures 6b–d), and the proportion of stations exceeding the threshold was below β = 0.5, thus no warning was issued. In summary, the proposed method correctly issued no warning for Xipu Village during this event, thereby successfully avoiding a false alarm. This demonstrates the method’s capability to filter out localized rainfall events that do not pose a watershed-scale flood threat.

TABLE 6 Comparison of associated stations under Scheme 2

Village	Scheme 1, 3, 4		Scheme 2	
	Station types	Count	Station type	Count
Xipian village	Type1, Type2, Type3	12	Type1, Type2	6
Xiaying village	Type1, Type2, Type3	16	Type1, Type2	9
Xiayang village	Type1, Type2, Type3	31	Type1, Type2	20
Xipu village	Type1, Type2	5	Type1, Type2	5
Jiakui village	Type1, Type2, Type3	14	Type1, Type2	6
Dongmen community	Type1, Type2, Type3	17	Type1, Type2	8

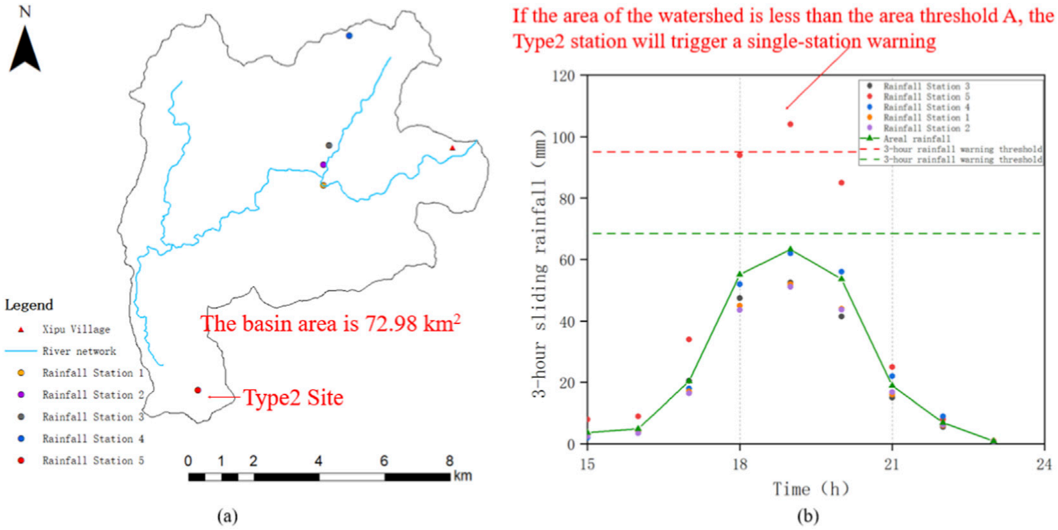


FIGURE 7
Early warning analysis under Scheme 3 in Xipu Village. **(a)** Map of the associated sites of the Xipu Village River Basin **(b)** 3-hour rainfall process chart.

4.3 Impact of parameter variations on method performance

A sensitivity analysis was conducted to evaluate the impact of key parameters on the performance of the proposed warning method. Following the principle of controlling variables, four different parameter schemes were designed for comparative experiments, as outlined in Table 5. Scheme 1 represents the baseline configuration determined in Section 3.1.

1. Scheme 2: As y increased, the number of associated stations per village decreased (Table 6), retaining only Type 1 and Type 2 stations. Reduced coverage made the method more prone to false alarms during localized heavy rainfall events.

2. Scheme 3: When A was enlarged, some small watersheds (e.g., Xipu Village) were misclassified, causing single-station warnings to be triggered despite the absence of flooding (Figure 7). This indicates that an excessively high A can raise false alarm rates.

3. Scheme 4: With station associations unchanged, a lower β value reduced the threshold for triggering multi-station warnings, making the system more susceptible to false alarms, especially in basins with heterogeneous rainfall distribution.

4.4 Discussion

While the proposed method demonstrates improved warning accuracy, its performance is subject to certain limitations. Sensitivity analysis indicates that the method's effectiveness critically depends on proper parameter calibration, particularly the rainfall station density threshold (y) and the watershed area threshold (A). The framework assumes a reasonably dense rainfall gauge network; in data-sparse regions or areas with complex terrain, its ability to accurately capture rainfall spatial heterogeneity may be limited. Future work should focus on developing adaptive parameterization schemes to enhance applicability across diverse hydrological settings.

5 Conclusion

This study proposes a rainfall-based flash flood early warning method that integrates spatial stratification and multi-mode discrimination, validated through six representative villages in Fujian Province. Comparative analysis under varying watershed conditions demonstrates the method's enhanced applicability and effectiveness.

By combining the rapid responsiveness of traditional single-station warnings with the robustness of areal rainfall and multi-station collaborative analysis, the proposed approach dynamically selects the optimal warning mode based on the spatial relationships between stations and villages, watershed area, and rainfall gauge density. For flood-affected villages such as Xipian, Jiakui, and Xiayang, the proposed method maintains equivalent detection timeliness and accuracy to the traditional approach. Meanwhile, for villages prone to false alarms in conventional systems (e.g., Dongmen Community, Xipu Village, and Xiaying Village), it effectively mitigates false alerts by considering both the spatial heterogeneity and temporal synchronization of rainfall across multiple stations, thereby improving both the accuracy and reliability of early warnings.

In conclusion, this method successfully integrates the sensitivity of point-based rainfall information with the stability of areal rainfall assessment, achieving a balanced, adaptive, and scientifically grounded early warning mechanism. The proposed framework demonstrates significant potential for generalization beyond the study area. By building on universally available geographic attributes, the method can be readily transferred to other regions, with key thresholds calibrated to local conditions. Furthermore, its modular design facilitates its integration as a robust decision-support layer within existing operational flash flood warning systems, enhancing their precision without requiring fundamental restructuring. This method thus offers a practical and scalable technical foundation for advancing the precision and efficiency of flash flood early warning systems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

XL: Writing – review and editing, Project administration, Methodology, Formal Analysis, Data curation, Conceptualization. YD: Supervision, Resources, Funding acquisition, Formal Analysis, Writing – original draft, Methodology. TL: Validation, Data curation, Writing – original draft, Visualization, Formal Analysis. MX: Funding acquisition, Resources, Writing – original draft, Validation, Data curation, Investigation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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References

An, H., and Ouyang, C. (2025). A hybrid framework for real-time flash flood forecasting in small ungauged catchments: integrating hydrodynamic simulations with LSTM networks. *J. Hydrology* 661, 133688. doi:10.1016/j.jhydrol.2025.133688

Author anonymous, (2020). *Tenth anniversary of flash flood prevention and control. China flood and drought management,* 7–10.

Cheng, J., and Li, G. (2020). Research on the dynamic extraction method of flash flood disaster information based on surveying and mapping geographic information technology. *West. Resour.* (06), 118–9+27. doi:10.16631/j.cnki.cn15-1331/p.2020.06.041

Choudhury, M.-U.-I., and Haque, C. E. (2016). "we are more scared of the power elites than the floods": adaptive capacity and resilience of wetland community to flash flood disasters in Bangladesh. *Int. J. Disaster Risk Reduct.* 19, 145–158. doi:10.1016/j.ijdrr.2016.08.004

Co, BXHIT (2011). Application of the "Beidou-1" satellite system in the monitoring and early warning of flash flood disasters. *China Flood and Drought Manag.* 2104, 84–86. doi:10.16867/j.cnki.cfdm.2011.04.035

Gao, F. (2023). Application of thiessen polygon method in area rainfall calculation of small basin. *Jianghuai Water Resour. Sci. Technol.* 05, 45–48. doi:10.20011/j.cnki.JHWR.202305010

Haijun, Q., Yijun, Li, Zhu, Y., Ye, B., Yang, D., Liu, Ya, et al. (2025). Do post-failure landslides become stable? *CATENA* 249, 108699. doi:10.1016/j.catena.2025.108699

Liu, Z. (2012). Research and application of flash flood early warning and forecasting technology. *China Flood and Drought Manag.* 2202, 41–5+50. doi:10.16867/j.cnki.cfdm.2012.02.014

Liu, Z., Yang, D., and Hu, J. (2010). Dynamic critical rainfall-based torrential flood early warning for medium-small Rivers. *J. Beijing Normal Univ. Sci.* 4603, 317–321.

Liu, Z., Haijun, Q., Zhu, Y., Wenchao, H., Bingfeng, Ye, Yingdong, W., et al. (2024). Increasing irrigation-triggered landslide activity caused by intensive farming in deserts on three continents. *Int. J. Appl. Earth Observation Geoinformation* 134, 104242. doi:10.1016/j.jag.2024.104242

Luna, C. C., Zambrano Nájera, J., and Vélez Upegui, J. J. (2025). Lessons learned from flash floods early warning system in a mountainous rur-urban region of Colombia. *Environ. Challenges* 20, 101199. doi:10.1016/j.envc.2025.101199

Luo, Q., Liu, L., Zhao, Y., Zhao, Y., and Guo, H. (2020). Application mechanism and practice of Mountain torrent disaster analysis and evaluation for early warning rainfall. *Water Resour. Power* 3810, 52–55. doi:10.20040/j.cnki.1000-7709.2020.10.013

Ma, J., and Hu, W. (2005). The situation of China's flash flood disaster prevention and control countermeasures. *Yangtze River* (06), 3–5. doi:10.16232/j.cnki.1001-4179.2005.06.002

Manoj, J. A., Loritz, R., Villinger, F., Mälicke, M., Koopaeidar, M., Göppert, H., et al. (2024). Toward flash flood modeling using gradient resolving representative hillslopes. *Water Resour. Res.* 606, e2023WR036420. doi:10.1029/2023WR036420

Pirone, D., Cimorelli, L., Del Giudice, G., and Pianese, D. (2023). Short-term rainfall forecasting using cumulative precipitation fields from station data: a probabilistic machine learning approach. *J. Hydrology* 617, 128949. doi:10.1016/j.jhydrol.2022.128949

Rivera, A. T., and Dela Vega, J. B. G. (2025). From vulnerability to resilience: addressing the causes, impacts, and solutions for recurrent flash floods in the Philippines. *Trop. Cyclone Res. Rev.* 143, 301–310. doi:10.1016/j.tcrr.2025.08.005

Song, J.-H., and Kim, H. (2025). Impact of precipitation station density and homogeneous regions on hydrological modeling performance. *J. Hydrology* 661, 133618. doi:10.1016/j.jhydrol.2025.133618

Wang, W., Sang, G., Yan, C., and Zhang, l (2018). Formulation of rainfall warning indicators for disaster prevention objects in hilly area based on NAM model. *IOP Conf. Ser. Earth Environ. Sci.* 2081, 012016. doi:10.1088/1755-1315/208/1/012016

Wu, W. (2024). *A comparative study of early warning methods for flash floods - taking Fujian province as an example*. Jinan: Shandong Jianzhu University. [master's thesis.

Yang, P., Xu, Z., Yan, X., and Wang, X. (2020a). Comparative study on methods of early warning index of flash flood disaster induced by rainstorm. *Adv. Eng. Sci.* 5204, 157–165. doi:10.15961/j.jsuese.202000057

Yang, Q., Dai, Q., Han, D., Zhu, Z., and Zhang, S. (2020b). Uncertainty analysis of radar rainfall estimates induced by atmospheric conditions using long short-term memory networks. *J. Hydrology* 590, 590. doi:10.1016/j.jhydrol.2020.125482

Yang, G., Qiu, H., Wang, N., Yang, D., and Liu, Ya (2025). Tracking 35-year dynamics of retrogressive thaw slumps across permafrost regions of the Tibetan Plateau. *Remote Sens. Environ.* 325, 114786. doi:10.1016/j.rse.2025.114786

Ye, Z. (2019). Association analysis between early warning indicators of Mountain flood disasters and rainfall stations in huazhou City, Guangdong Province. *Guangdong Water Resour. Hydropower* 04, 39–43.

Yuan, W., Song, H., and Liu, M. (2019). An early warning model for flash floods based on random rainfall patterns. *Adv. Water Sci.* 3004, 515–527. doi:10.14042/j.cnki.32.1309.2019.04.007