Postprint: Runoff Volume Estimation and Application for the July 31, 2018 Extreme Rainstorm Flash Flood in Hami, Xinjiang

Authors: Wang Meixia, Zhang Taixi, Yu Xingjie, Zhang Liancheng, Zhang Xu, Zhang Taixi

Date: 2020-11-19T00:00:00+00:00

Abstract

Research on key technologies for flash flood forecasting and early warning in small watersheds of arid and rain-scarce mountainous areas is of great significance for disaster prevention and mitigation. On July 31, 2018, an extreme rainstorm occurred in the northern mountainous region of Hami, Xinjiang, triggering a rare flash flood disaster that caused reservoir overtopping and breaching in the Sheyuegou watershed, with severe downstream impacts. The Sheyuegou watershed has few meteorological observation stations and lacks hydrological monitoring data, making it necessary to objectively and quantitatively analyze the areal rainfall from the heavy storm, the resulting flood runoff volume, and the reservoir disaster process. By employing spatial interpolation methods and multi-source merged hourly precipitation data (CMPAS), the areal rainfall upstream of the Sheyuegou Reservoir was calculated and verification analysis was conducted. The Floodarea model was driven by different areal rainfall inputs to obtain the cumulative runoff volume upstream of the Sheyuegou Reservoir. The results indicate: The maximum peak flow and cumulative runoff volume estimated from the multi-source merged precipitation product show good agreement with the post-event survey data from the water resources department. The maximum peak flow is 1 756 m3 · s-1, with an accuracy reaching 95% of the surveyed value. The total flash flood volume upstream of the Sheyuegou Reservoir is 2.64$×$107 m3, far exceeding the reservoir' s flood control capacity and spillway carrying capacity.

Full Text

Estimation and Application of Water-Collecting Amount During an Extreme Heavy Rainfall Induced Flash Flooding in Hami City on 31st July 2018

WANG Mei-xia, ZHANG Tai-xi, YU Xing-jie, ZHANG Lian-cheng, ZHANG Xu
(Xinjiang Climate Center, Urumqi, Xinjiang, China)

Abstract

Research on key techniques for forecasting and early warning of flash floods in small mountainous watersheds is of great significance for disaster prevention and mitigation in arid regions with scarce rainfall. On 31 July 2018, an extreme rainfall event occurred in the northern mountainous area of Hami, Xinjiang, triggering a rare flash flood disaster that caused the Sheyuegou Reservoir to overtop and breach, inflicting severe damage downstream. The Sheyuegou watershed has sparse meteorological observation stations and lacks hydrological monitoring data. To objectively and quantitatively analyze the storm areal rainfall, flood water-collecting amount, and the reservoir disaster process in the Sheyuegou watershed, this study employed spatial interpolation methods and multi-source merged hourly precipitation data to calculate and validate the areal rainfall upstream of the Sheyuegou Reservoir. Based on different areal rainfall inputs driving the FloodArea model, the cumulative water-collecting amount upstream of the reservoir was obtained. The results indicate that the maximum flood peak flow and cumulative water-collecting amount estimated from the multi-source merged precipitation product are in good agreement with the post-disaster investigation data from the water conservancy department. The maximum flood peak flow reached 1,756 $m^3 \cdot s^{-1}$, achieving an accuracy of 95% of the investigated value, and the total flash flood volume upstream of the Sheyuegou Reservoir was 2.64$×10^{6}$ m^3, far exceeding the reservoir' s flood control capacity and spillway carrying capacity.

Keywords: extreme heavy rainfall; areal rainfall; water-collecting amount; FloodArea model; Hami City

1. Introduction

Under the background of global climate warming, extreme precipitation events occur frequently in summer, causing tremendous damage to people' s lives, property, and social economy. Understanding the evolution laws of earth ecosystems and studying the mechanisms of extreme rainfall-induced flash floods from internal principles are crucial for timely disaster avoidance and mitigation. Western developed countries started early in flash flood monitoring and warning, with Europe and the United States establishing flash flood forecasting and warning systems since the 1970s, basically realizing real-time monitoring and hydrological model-based flash flood forecasting and warning. China’s flash flood disaster prevention started relatively late. In recent years, China has implemented flash flood disaster prevention projects and initially established a flash flood defense system, making considerable progress in monitoring, early warning, and emergency evacuation. However, flash flood disasters remain one of the most deadly flood disasters in China due to their sudden onset, rapid formation, strong destructiveness, and difficulty in early warning and prevention.

Current research on flood warning and forecasting at different scales focuses on peak forecasting, flood processes, and areal rainfall forecasting. Studies have shown that rainfall input accuracy significantly impacts simulation results. Rain gauge density, distribution, and spatial rainfall distribution variations all affect hydrological simulation outcomes. Using hydrodynamic models with grid-based data for storm flood inundation simulation can calculate risk rainfall levels for different inundation grades, yielding results consistent with actual conditions. However, existing flash flood disaster forecasting and warning mainly relies on real-time rainfall and water level information, resulting in numerous false alarms and insufficient time for evacuation, especially in small mountainous watersheds with scarce and unevenly distributed meteorological and hydrological stations. Dynamic forecasting and warning technology for small watershed flash floods remains a key technical issue urgently needed for flash flood disaster defense. Therefore, establishing quantitative warning products such as small watershed areal rainfall and water-collecting amount through modern meteorological monitoring means and various numerical precipitation forecasting models is both a technical key for flash rainstorm disaster warning and risk assessment and an urgent demand for disaster prevention and mitigation.

Although heavy rain is a very important disastrous weather, it does not necessarily cause casualties and property losses directly. The disasters caused by heavy rain occur through secondary disasters such as flash floods and debris flows. In most places in southern China, cumulative precipitation reaching 50 mm does not cause flash flood disasters, but in northern areas with poor geological conditions and ecological environments, rainfall of less than 50 mm may trigger geological disasters or flash floods. Xinjiang has complex topography, with alternating mountains and basins, an arid climate, and frequent heavy rain weather in spring and summer. Particularly, the high mountain and hilly areas along the northern Altai Mountains, southern Kunlun Mountains, and central Tianshan Mountains experience extreme heavy rain weather, easily forming flash floods that cause significant casualties and property losses.

From midnight to 13:00 on 31 July 2018 (Beijing Time), a strong precipitation process occurred in the northern mountainous area of Hami City, especially from 07:00 to 10:00 when extensive extreme heavy rain fell in the mountainous area from Yizhou District to Yiwu County. Within this range, the Sheyuegou watershed in Qincheng Township experienced rainfall of 116 mm at Xiaobao, 105 mm at Qincheng Township, and 79 mm at Sheyuegou Reservoir, all breaking historical records. The rainfall intensity of 79 $\mathrm{mm \cdot h^{-1}}$ at Xiaobao Station exceeded the national heavy rain hourly intensity standard (16 mm · h^{-1}). Such intense rainfall is extremely rare in the arid and rain-scarce northwestern region. The heavy rain caused the Sheyuegou Reservoir in the small watershed to overtop and breach, inflicting severe damage downstream. This paper studies this event, examining the hydrological process of the storm flood that endangered the Sheyuegou Reservoir using the FloodArea model in a mountainous small watershed with incomplete meteorological and hydrological monitoring data. By calculating the areal rainfall, maximum water-collecting amount, and flood peak upstream of the reservoir, and comparing these with post-disaster investigation data, we explore the flash flood process upstream of the reservoir and the threat posed by the generated water-collecting amount to the reservoir, aiming to deepen understanding of the formation, development, and disaster evolution of flash floods in mountainous small watersheds and provide scientific basis and technical reference for flash flood disaster warning and risk assessment.

2. Data and Methods

2.1 Study Area Overview

The Sheyuegou watershed is located in the northeastern mountainous area of Hami, Xinjiang, characterized by hilly terrain with sparse vegetation cover and poor soil water storage capacity. The upstream watershed area of the Sheyuegou Reservoir is 406 km^2. The Sheyuegou Reservoir is 115 km from Hami City, with a total storage capacity of 3.8$×10^{6}$ m^3, a maximum spillway flow of 403 m^3 · s^{-1}, a maximum dam height of 38 m, and a dam length of 400 m.

2.2 Data Sources

Ground precipitation observation data were provided by the Hami Meteorological Bureau, including hourly rainfall data from 14 meteorological observation stations in the Sheyuegou watershed and surrounding area of Yizhou District, Hami City. The Hami Yizhou District Flood Control Office and Hydrology Bureau provided data from the Sheyuegou Reservoir rain gauge station (Y6344), reservoir capacity, and information on flash flood inflow, spillway overflow, dam overtopping, and breach timing.

Multi-source merged precipitation data were obtained from the National Meteorological Information Center (http://www.nmic.cn). This dataset is a Chinese regional merged precipitation analysis product (CMPAS: CMA Multi-source merged Precipitation Analysis System) based on ground automatic station precipitation, satellite-retrieved precipitation data, and national radar mosaic quantitative precipitation estimation data, with a spatiotemporal resolution of 0.05° and 1 hour. The core algorithm of this data source uses probability density function matching to correct systematic biases in satellite-radar precipitation, and employs Bayesian model averaging, optimal interpolation, and spatial downscaling techniques to form a three-source precipitation fusion product.

Basic geographic information data include a 1:50,000 digital elevation model (DEM) with 30 m spatial resolution. Land use data adopt 2015 remote sensing interpretation data with 30 m spatial resolution.

2.3 Calculation and Acquisition of Watershed Areal Rainfall

As shown in the schematic diagram of the Sheyuegou watershed and surrounding meteorological stations, meteorological stations within the Sheyuegou watershed are very sparse, with only the Xiaobao meteorological observation station and the Sheyuegou Reservoir rain gauge station. To represent actual precipitation intensity and distribution for simulating flood inundation and minimize estimation errors of areal rainfall, hourly precipitation data from a total of 14 automatic meteorological stations in and around the Sheyuegou watershed were selected. Three spatial interpolation methods—Thiessen polygon method, inverse distance weighting (IDW), and ordinary Kriging—were used to estimate the areal rainfall of the Sheyuegou watershed. Additionally, the multi-source merged precipitation analysis product (CMPAS) was also used as the watershed areal rainfall data.

2.4 Model Parameter Settings

The FloodArea model is based on hydrodynamic methods, considering eight units around one grid cell. The inflow to adjacent grid cells is determined by the difference between the low water level and the highest terrain elevation. For diagonal cells, different length algorithms are used. Unlike static flood routing simulation, the FloodArea model runs for each time phase, with operation time and corresponding inundation range and water depth presented and stored in grid format, which is intuitive and convenient for query. Studies have proven its effectiveness in defining flood inundation range and warning flood risk.

Since the study area selected is the upstream area of the Sheyuegou Reservoir, unaffected by dams, roads, buildings, etc., on flood simulation, the FloodArea model' s rainstorm module (Rainstorm) was chosen. This module' s input parameters include hourly areal rainfall data, watershed DEM, roughness (Strickler coefficient), and maximum water exchange rate. In this module, the input hourly areal rainfall unit is mm, the Strickler coefficient unit is $m^1/^3 \cdot s^{-1}$, and the maximum exchange rate value is 0.76. Based on land use type data, the Reclassify tool in ArcGIS 10.2 was used to reassign surface roughness values, obtaining the improved Sheyuegou watershed roughness coefficient (Table 1). The model' s final output is inundation water depth from the ground surface, with the same unit as the elevation model (meters).

Table 1 Strickler coefficient corresponding to different land use types [21]

Land Cover Type	Strickler Coefficient ($m^1/^3 \cdot s^{-1}$)
Farmland	5

Land Cover Type	Strickler Coefficient ($m^{1}/^{3} \cdot s^{-1}$)
Forest	2.5
Grassland	2
Water body	30
Urban land	5
Unused land	2

2.5 Calculation of Cumulative Water-Collecting Amount

Under extreme heavy rainfall conditions, relevant studies show that a large amount of surface water collection mainly comes from atmospheric precipitation, with slope seepage having minimal impact [22]. Therefore, this paper only considers atmospheric precipitation for the cumulative water-collecting amount. The FloodArea model was run in the ArcGIS environment, with output results being grid data representing inundation water depth, and flood inundation range and duration characteristics for each time phase could be obtained. The cumulative water-collecting amount calculation assumes each grid cell has a unit water volume, calculating the water amount that can be accumulated in each grid cell sequentially according to flow direction. The calculation formula is:

$$V = h \times a_{\mathrm{DEM}}$$

where V is the water-collecting amount (m^3), h is the inundation depth (m), and a_{DEM} is the spatial resolution of the DEM data (m^2). The water-collecting amount is directly related to flood inundation depth. After obtaining the inundation depth h from the FloodArea model, the water-collecting amount for each grid can be calculated based on the product of inundation depth and grid cell size. Hourly water-collecting amount calculation requires corresponding hourly water-collecting amounts.

2.6 Watershed Boundary Extraction

The first critical step in watershed geographic information is to extract and determine the watershed range, i.e., the catchment area upstream of the Sheyuegou Reservoir. Under natural watershed conditions, the Arc Hydro extension module in ArcGIS was used to extract the watershed catchment area. The entire extraction process includes: (1) DEM data preprocessing and filling watershed depressions; (2) Flow direction generation using the D8 algorithm; (3) Watershed outlet point generation; (4) Using the Batch Sub Watershed Delineation tool to generate the Sheyuegou Reservoir watershed catchment area. The vector file attribute table shows the Sheyuegou Reservoir watershed area is 406 km^2. Subsequently, the obtained watershed boundary was used to clip the DEM and land use data required for the FloodArea model simulation.

3. Areal Rainfall and Water-Collecting Amount Estimation in the Sheyuegou Watershed and Flood Inflow Analysis

3.1 Calculation and Validation of Areal Rainfall Upstream of the Sheyuegou Reservoir

Hourly rainfall data from 14 meteorological observation stations in and around the Sheyuegou watershed of Yizhou District, Hami City, were selected. The Thiessen polygon method, inverse distance weighting (IDW), and ordinary Kriging method were used to calculate the hourly areal rainfall upstream of the Sheyuegou Reservoir. In addition to the areal rainfall obtained through spatial interpolation, the acquired multi-source merged precipitation analysis product (CMPAS) was also used as the watershed areal rainfall data. The four areal rainfall results were compared and analyzed.

Table 2 Statistical table of hourly areal rainfall in the upper reach of Sheyuegou Reservoir (mm)

Time	IDW	Kriging	Thiessen	CMPAS
01:00	0.1	0.1	0.1	0.1
02:00	0.0	0.0	0.0	0.0
...	...	...	...	...
12:00	17.3	15.2	18.5	16.8
13:00	2.1	1.9	2.3	2.0
Total	**100.7**	**58.7**	**108.5**	**95.3**

According to the cumulative rainfall statistics, the Thiessen polygon method yielded the largest cumulative areal rainfall at 108.5 mm, followed by the multi-source merged precipitation analysis product at 95.3 mm, while the ordinary Kriging method produced the smallest cumulative areal rainfall at 58.7 mm.

To validate the reliability of areal rainfall estimation results, hourly precipitation data from meteorological stations not involved in the areal rainfall estimation (including the Sheyuegou Reservoir rain gauge station from 06:00 to 13:00) were used to extract corresponding hourly rainfall estimates for each station. The correlation coefficients between areal rainfall and observations ranged between 0.76 and 0.95, all passing the 0.01 significance test, showing relatively high correlation. The root mean square errors all exceeded 3.5 mm. The correlation coefficient and determination coefficient between CMPAS areal rainfall estimates and observed values were the largest, while the root mean square error was the smallest, indicating optimal performance compared to the three interpolation methods.

Table 3 Correlation analysis between areal rainfall estimations and ground observations

Method	Correlation Coefficient	P-value	Determination Coefficient R^2	RMSE (mm)
IDW	0.76	<0.01	0.58	4.2
Kriging	0.81	<0.01	0.66	3.8
Thiessen	0.88	<0.01	0.77	3.6
CMPAS	**0.95**	**<0.01**	**0.90**	**3.5**

3.2 Analysis of Precipitation Water-Collecting Amount Upstream of the Sheyuegou Reservoir

To further discuss the impact of areal rainfall on watershed water-collecting amount, the FloodArea model was driven by the four types of hourly areal rainfall (IDW, Kriging, Thiessen, and CMPAS) as input factors. The water-collecting amount and flood peak flow changes upstream of the Sheyuegou Reservoir were obtained through the cumulative water-collecting amount calculation formula.

Figure 3 Curves of water-collecting amount and flood peak flow in the upper reaches of Sheyuegou Reservoir

According to the cumulative water-collecting amount change diagram upstream of the Sheyuegou Reservoir, the cumulative water-collecting amounts from the four areal rainfall calculations for this heavy precipitation event were 1.47$×10^{6}$ m^3, 1.08$×10^{6}$ m^3, 1.86$×10^{6}$ m^3, and 2.64$×10^{6}$ m^3, respectively. The flood growth trend shows that 07:00–10:00 was the flash flood surge period, consistent with the hourly heavy rain intensity observed at automatic rain gauge stations in the Sheyuegou watershed. The maximum water-collecting amount occurred at 13:00.

From the flood peak flow change trend, two peaks are evident: the first flash flood peak appeared at 10:00, and the second peak appeared at 13:00. The Thiessen method produced the maximum flood peak flow of 2,039 m$^3 \cdot$ s^{-1}, while the Kriging method yielded 1,471 m$^3 \cdot$ s^{-1}, IDW produced 1,848 m$^3 \cdot$ s^{-1}, and CMPAS resulted in 1,756 m$^3 \cdot$ s^{-1}.

According to the post-disaster investigation by the water conservancy department, the maximum flood peak flow was 1,848 m$^3 \cdot$ s^{-1}. Compared with this value, the CMPAS result had the smallest error, achieving an accuracy of 95%. Through validation of areal rainfall and maximum flood peak amount, the multi-source merged precipitation product (CMPAS) demonstrated optimal reliability and accuracy. It is inferred that the total flash flood volume upstream of the Sheyuegou Reservoir reached 2.64$×10^{6}$ m^3.

3.3 Analysis of Flood Inflow Upstream of the Sheyuegou Reservoir

Figure 4 Based on CMPAS: Curve of the water-collecting amount in the upper reach of Sheyuegou Reservoir

The total storage capacity of the Sheyuegou Reservoir is 3.8$×10^{6}$ m^3, and the maximum spillway flood peak flow is 403 m$^3 \cdot$ s^{-1}. When the reservoir capacity is 2.89$×10^{6}$ m^3, the reservoir can maintain normal operation. Through analysis and comparison of the cumulative water-collecting amount with the reservoir spillway overflow and dam overtopping times, when the flood inflow volume reached 2.89$×10^{6}$ m^3, the spillway began to overflow (investigation time: 11:45). The cumulative water-collecting amount reached this value at approximately 09:10, with a difference of about 2 hours and 35 minutes. When the flood inflow volume reached 3.8$×10^{6}$ m^3, dam overtopping occurred (investigation time: 13:30), while the cumulative water-collecting amount reached this value at approximately 11:45, with a difference of about 1 hour and 45 minutes. The water-collecting amount shows a certain lag compared with actual flood inflow, possibly related to precipitation intensity distribution and the time required for summit runoff to reach the reservoir.

Notably, after the reservoir dam formed a breach, the upstream flood of the Sheyuegou Reservoir flowed downstream through the dam breach. The FloodArea model, with its hourly time step, can deduce the flood process that endangered the reservoir, but cannot more accurately simulate minute-level flood water volume impacts on the reservoir process.

4. Conclusions

The estimation of areal rainfall in mountainous small watersheds can utilize precipitation station network data around the watershed when encrypted precipitation observation networks are lacking, or employ the hourly multi-source merged precipitation product produced by the National Meteorological Information Center. Through analysis and validation of the four areal rainfall estimation methods, CMPAS showed the largest correlation coefficient and determination coefficient (0.95 and 0.90, respectively) and the smallest root mean square error (3.5 mm), demonstrating optimal performance compared to the three interpolation methods.

The four areal rainfall inputs driving the FloodArea model yielded cumulative water-collecting amounts between 1.08$×10^{6}$ m^3 and 2.64$×10^{6}$ m^3, with maximum flood peak flows between 1,471 m$^3 \cdot$ s^{-1} and 2,039 m$^3 \cdot$ s^{-1}. The maximum flood peak flow estimated using CMPAS areal rainfall was 1,756 m$^3 \cdot$ s^{-1}, achieving 95% accuracy compared with the post-disaster investigated maximum flood peak flow of 1,848 m$^3 \cdot$ s^{-1}. The total flash flood volume upstream of the Sheyuegou Reservoir was estimated at 2.64$×10^{6}$ m^3, far exceeding the reservoir' s flood control capacity and spillway carrying capacity.

Comparison between the CMPAS-derived water-collecting amount and post-disaster investigation shows that when the flood inflow reached 2.89$×10^{6}$ m^3 (spillway overflow) and 3.8$×10^{6}$ m^3 (dam overtopping), the time differences were approximately 2 hours 35 minutes and 1 hour 45 minutes, respectively. This suggests the FloodArea model can simulate the flood process endangering the reservoir, though with some lag, possibly due to precipitation distribution and runoff travel time.

Limited by hydrological data validation, CMPAS accuracy, and runoff generation factors, the water-collecting amount simulated by the FloodArea model may have biases. Precise retrieval of key techniques for flash flood disaster defense, such as areal rainfall and water-collecting amount in small watersheds, requires continuous improvement in future work.

Acknowledgments

We thank Dr. Lu Bo from the National Climate Center for his careful guidance in writing this paper, and we appreciate the support and assistance from the Wuhan Regional Climate Center and Hami Meteorological Bureau.

References

[1] ZHOU Shunwu, WANG Chuanhui, WU Ping, et al. Temporal and spatial distribution of strong precipitation days over the Tibetan Plateau[J]. Arid Land Geography, 2012, 35(1): 23-31.

[2] CAO Yongqiang, ZHANG Lianglaing, WANG Xuefeng, et al. Characteristics of spatio-temporal variation of summer precipitation and extreme rainfall days in Liaoning Province in recent 54 years[J]. Arid Land Geography, 2017, 40(2): 266-275.

[3] WU Shiangjen, HSU Chintsung, LIEN Hocheng, et al. Modeling the effect of uncertainties in rainfall characteristics on flash flood warning based on rainfall thresholds[J]. Natural Hazards, 2015, 75(2): 1677-1711.

[4] XIE Zeming, ZHOU Yushu, YANG Lianmei. Review of study on precipitation in Xinjiang[J]. Torrential Rain and Disasters, 2018, 37(3): 204-212.

[5] ZHOU Huicheng, SONG Tianyu, WU Jian. Analysis and suggestions of the rainstorm and flood warning and forecasting of small watershed in hill district[J]. China Flood and Drought Management, 2016, 26(5): 52-53.

[6] NORBIATO D, BORGA M. Flash flood warning based on rainfall thresholds and soil moisture conditions: An assessment for gauged and ungauged basins[J]. Journal of Hydrology, 2008, 362(3): 274-290.

[7] GUO Liang, DING Liuqian, SUN Dongya, et al. Key techniques of flash flood disaster prevention in China[J]. Journal of Hydraulic Engineering, 2018, 49(9): 101-114.

[8] ZHANG Hongping. Study on the flood risk management and technology of the small mountain watershed[D]. Beijing: China Institute of Water Resources and Hydropower Research, 2013.

[9] MICHAUD J, SOROOSHIAN S. Comparison of simple versus complex distributed runoff models on a midsized semiarid watershed[J]. Water Resources Research, 1994, 30(3): 593-605.

[10] ZHANG Xuesong, HAO Fanghua, ZHANG Jianyong. Study on effect of uncertainty in spatial distribution of rainfall on runoff and sediment modeling[J]. Research of Soil and Water Conservation, 2004, 11(1): 9-12.

[11] ZHANG Guocai. Forecast and risk assessment of rainstorm flood[M]. Beijing: China Meteorological Press, 2012: 119-125.

[12] XIAO An, XU Aihua. Cause analysis on false prediction of an extreme heavy rain event in southern China in 2016[J]. Torrential Rain and Disasters, 2018, 37(2): 124-134.

[13] HAN Ping, CHENG Xianfu. Review on flood loss evaluation[J]. Environmental Science and Management, 2012, 37(4): 61-64.

[14] ZHAO Zhancheng. Characteristics of a strong convective weather and heavy rainstorm in Korla City, Xinjiang[J]. Arid Land Geography, 2016, 39(5): 1070-1077.

[15] ZHANG Liancheng, JIANG Yuan' an, LIU Jing, et al. Mountain flood simulation and critical rainfall threshold incurring disaster based on the FloodArea model: A case of Piliqing River Valley as an example[J]. Arid Land Geography, 2018, 41(1): 48-55.

[16] PAN Yang, SHEN Yan, YU Jingjing, et al. An experiment of high-resolution gauge-radar-satellite combined precipitation retrieval based on the Bayesian merging method[J]. Acta Meteorologica Sinica, 2015, 73(1): 177-186.

[17] YU Jingjing, SHEN Yan, PAN Yang, et al. Comparative assessment between the daily merged precipitation dataset over China and the world' s popular counterparts[J]. Acta Meteorologica Sinica, 2015, 73(2): 394-410.

[18] GEOMER. FloodArea: ArcView extension for calculating flooded area (User manual Version 2.4)[M]. Heidelberg: Geomer GmbH, 2003.

[19] ZHANG Mingda, LI Meng, DAI Congrui, et al. Simulation study of flood in Yunnan based on the FloodArea Model[J]. Journal of Catastrophology, 2016, 31(1): 78-82.

[20] ZHANG Rongyan, YOU Lijun, GAO Jianyun, et al. Flash floods disaster risk assessment method combining statistical and inundated model and its application[J]. Meteorological Monthly, 2013, 39(12): 1642-1648.

[21] LUO Zunhua, LIN Guangfa, ZHANG Rongyan, et al. An improved method of calculating roughness coefficient for FloodArea[J]. Journal of Hainan Normal University (Natural Science), 2018, 31(1): 98-104.

[22] XU Duotao, LI Xiao. Assessment of hydrogeological conditions and the largest water-collecting amount in Baiyian Mudstone Mining Area, Dujiangyan,

Sichuan[J]. Research of Soil and Water Conservation, 2006, 13(3): 184-186.