



Influence of rain pattern on flood control in mountain creek areas: a case study of northern Zhejiang

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Abstract

Mountain creek areas are a type of flood-prone area, and the flood control in these areas has not been well understood. This study aims to evaluate the impact of rain patterns on the water level and the establishment of flood control standard in mountain creek areas by conducting a case study. The case study was performed on a typical mountain creek area, called Shiliqu watershed in Hangzhou, China. A MIKE11 model was first established to analyze the required flood control standard through investigating the river level impacted by two rain patterns (the designed rainstorm and the typhoon Fitow). The results show that the designed rainstorm pattern and the typhoon Fitow rain pattern have the single-peak and multi-peak profile, respectively. The peak rainfall value of the designed rainstorm pattern is much higher than that of the typhoon Fitow. However, the large fluctuations under the typhoon Fitow rain pattern causes multi-level overtopping which threatens the safety of the flood control. Also, the typhoon Fitow could have a greater influence on the water level of the tributaries of the river than that of the mainstream. The selection of rain pattern on the design of flood control standard in mountain creek areas is discussed.

Keywords Flood control standards · Mountain creek · Rain pattern · Small watershed · Typhoon

Introduction

With the rapid urbanization, much attention has been paid to improve the flood control standard of cities, and flood control countermeasures have been continuously improved. Protection against flooding has become a national policy in the world (Brouwer and Van Ek 2004; Dircke and Molenaar 2015). The implementation of this policy is critical to the flood control management. Cruz et al. (2007) reported that people affected by flooding will rise to 94 million annually by the end of the 21st Century.

To date, many global flood damages have occurred in Asia, particularly in China (Tingsanchali 2012). China's hilly area exceeds two-thirds of the country's land area with steep riverbed slope; this is conducive to the formation of mountain flood (Liu et al. 2017). Among these areas, the mountain creek area is flood-prone where flooding could lead to large disasters. Thus, the flood control for the mountain creek area is critical to protecting people's safety and property. Floods in the creek area are difficult to discharge considering the following special characteristics: (1) The terrain varies greatly, and the geological structure is rather complicated; (2) The river slope is steep, and collecting area is small; (3) Heavy rain with large intensity is rather concentrated; (4) Having a strong sand-carrying and scouring capacity. The mountain creek area is also challenged by other factors. For example, the typhoon influences the mountain creek. The water level in the river is generally high during the typhoon season, which may cause flooding and destruction of villages, roads, bridges (Gaillard et al. 2007; Liu et al. 2009a, b). Typhoon precipitation is an important cause of heavy rain and floods. The rain pattern induced by typhoon could be different from that caused by other precipitations. The rainfall pattern is the rain intensity that shifts with time, reflecting

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the surface runoff. Liu et al. (2009a, b) reported that the occurrence of geological disasters is related to rain patterns besides rain duration and rainfall. Currently, typical historical rainstorms have often been used as the designed rainstorm patterns for the flood control standard, which is calculated by the flood frequency method. The flood control standard is the design flood of a certain return period, and the actual flood is used as the flood control standard in some places. When a flood that is not greater than the flood control standard occurs, the proper use of the flood control system can generally ensure the safety of the protected objects. The rain pattern is thus expected for being considered to design the flood control standard, but little research studied the influence of the typhoon rain pattern on the flood control in small watersheds. Most studies focus on other rain patterns. Huff (1967) proposed four types of typical rain patterns as designed rain patterns to construct storm models for hydrologic applications. Yen and Chow (1980) proposed an asymmetric triangular rain pattern, and the peak rainfall position was determined by the statistical moment method. Forestieri et al. (2016) applied a hydrological model to simulate the rainstorm-type flooding process of different design areas in the Sicilian Basin research and obtained the early warning mechanism of critical rainfall. Pedrozo-Acuña et al. (2017) researched the flood caused by the historical torrential rains of different rain patterns in the various return periods of Tabasco, Mexico. Various schemes were obtained for identifying the flooding points under various rain patterns and the countermeasures. The above studies have not discussed the impact of different rain patterns on the water level and flood control in a mountain creek. The research of different rain patterns can help us adopt a safer design of flood control standard and thus benefits flood control projects (Dale et al. 2018). It is important to analyze the flood control standard under different rain patterns in small watersheds. Besides, with the rapid urbanization, the environment of the underlying surface changes, and the hydrological conditions have changed greatly (Kang et al. 1998; Klöcking and Haberlandt, 2002; Bari et al. 2005; Bronstert et al. 2007; Lee et al. 2018). Further studies are needed for the applicability of the current rain pattern.

This study focuses on the understanding of rainfall pattern and its impact on water level and flood control standards. A case study in Shiliqu, a typical mountain creek area in the northern part of Zhejiang Province, China was carried out. The influences of the conventional designed rainstorm pattern and the typhoon Fitow rain pattern on the water level and flood control are investigated. These two rainstorm patterns with distinguishable features are representative. Suggestions for flood control strategies in the mountain creek area are also proposed. Our study could provide guidelines for the selection of rain pattern

on the design of flood control standard in mountain creek areas.

Methods

Study area

The Shiliqu small watershed in Yuhang District of Hangzhou is in the transition zone of the mountain plain with the mountainous hills to the west and the tidal flats to the east (Fig. 1). The drainage area is about 49.30 km². Penggongji town is in the mountainous area and surrounded by mountains in the north. Xiangpeng road and 104 national road are on the south. The terrain of Penggongji town, which is flood-prone, is similar to a small basin. Qikengxi and Banshixi are the tributaries of the Shiliqu small watershed.

Because the rainstorm and plum rain appear alternately, the occurrence of bimodal rain pattern is short. The largest peak rainfall is 152.0 mm (in June) and 155.6 mm (in September), respectively. The average annual rainfall is 1363.3 mm, the maximum rainfall is 2018.2 mm (in 1954), and the minimum annual rainfall is 837.6 mm (in 1967). The rainfall distribution during the year was uneven mainly

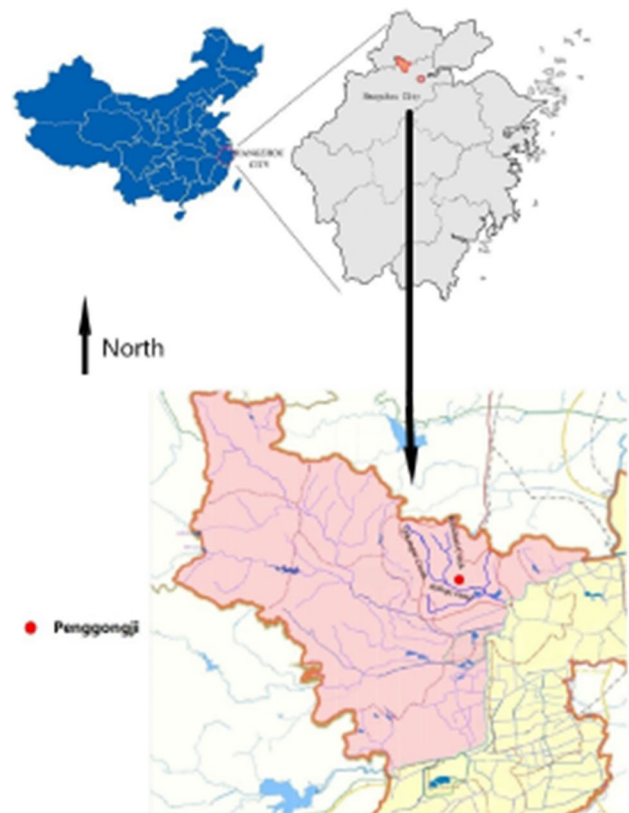


Fig. 1 Shiliqu drainage diagram

concentrated in April and September, accounting for 66% of the annual rainfall.

Establishment of river networks model

A hydraulic software developed by the DHI (Danish Hydraulic Institute), MIKE11 (Kumar et al. 2019) is used to study one-dimensional hydrodynamics, such as water quality (Cox 2003; Liang et al. 2015), rainfall runoff (Kumar et al. 2019), flood forecasting (Panda et al. 2010), reservoir operation strategies (Lee et al. 2018), and water resources management (Doulgeris et al. 2012). It is a widely used commercial hydrodynamic calculation model (Havnø et al. 1995). The HD (hydrodynamic) module in the MIKE11 software is used to calculate unsteady flow and analyze the variation of water level in each control section along the river. By using Structure Operation (SO) modules, gates, bridges and other buildings are simulated according to the position and form of the actual structures. The discharge capability of the structures coupled with hydrodynamic matrix equation is first calculated. If the highest water level of the river channel for different rain patterns is lower than the bank elevation, the flood control standard is regarded to be safe. The highest water level is thus obtained for the flood control standard.

Basic equations and discrete formats

The hydrodynamic calculation model is based on the Saint–Venant’s equations to simulate the river flow state:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = x \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial t} \left(\alpha \frac{Q^2}{A} \right) + gA \frac{\partial h}{\partial x} + g \frac{Q|Q|}{C^2AR} = qV_x \quad (2)$$

where x (m) is the distance coordinate; t (s) is the time coordinate; A (m²) is the area of the river section; Q (m³/s) is the discharge of the river section; q (m²/s) is the discharge of the lateral inflow per unit of length; inflow is positive and outflow is negative; α is the dimensionless correction factor of momentum; g (m/s²) is the gravity acceleration; h (m) is the water level; C is the Chézy coefficient, $C = R^{1/6}/n$; n is the roughness coefficient of the river; R (m) is the hydraulic radius; V_x (m/s) is the inflow rate along the flow direction. The Abbott six-point central implicit difference method (Liang et al. 2015) was used to numerically discretize the Saint–Venant equation, and the “catch-up method” was applied to solve the difference equation. The water level and flow value are calculated at different grid points with alternative order. The position of each measured section is the water level calculation point, and the midpoint of the two water level calculation points is the discharge calculation

point. As the Abbott six-point difference method is unconditionally stabilized, select 2 min as the time step.

Boundary conditions

The discharge boundary is adopted for the upstream area of the model. The 10% frequency-designed rainstorm flood discharge was used as the discharge boundary according to the flood control standard in Banshixi, Qikengxi, Shiliqu. The flood calculation was applied for the Banshixi, Qikengxi tributary, and the calculated discharge was imported to the entry point of the tributaries in the model through the inflow boundary. The directly measured stage-discharge curve is adopted for the downstream area.

Parameter calibration

The water level change of the Banshixi hydrological station during the landfall of the typhoon Fitow was used for the parameter calibration, considering the lack of floodplain survey data in the river channel. The discharge calculated from the flooding data during the landfall of the typhoon Fitow is adopted for the boundary condition in the upstream. The stage-discharge curve (Darby and Thorne 1996) is adopted for the downstream. The calculation results of the water level and the measured data of the Banshixi hydrological station are shown in Fig. 2a and consistent with the measured data and the verification requirements. The main-channel bed roughness of the Shiliqu mainstream, Qikengxi and Banshixi tributary is set as 0.026–0.032, 0.03–0.036 and 0.025–0.03, respectively.

Design of the rain patterns

Design rainstorm pattern

There is no general rainfall data of the Shiliqu small watershed. The atlas method was applied to obtain the designed rainstorm pattern. The rainstorm distribution pattern can be calculated according to the rainfall ranking rules of the “Zhejiang Short-Term Rainstorm” period.

Typhoon Fitow rain pattern

Two major floods in Penggongji town during the typhoon landfall occurred, “Rosa” in 2007 and “Fitow” in 2013 (Wang et al. 2017). “Fitow” caused the most dangerous flooding. To obtain the data under extreme conditions, the typhoon Fitow rain pattern is used from the data measured in the Penggongji automatic water level gauge station.

Figure 2b shows the comparison between two rain patterns. From 1 to 13 o’clock, the rainfall of the typhoon Fitow rain pattern is close to that of the designed rainstorm pattern.

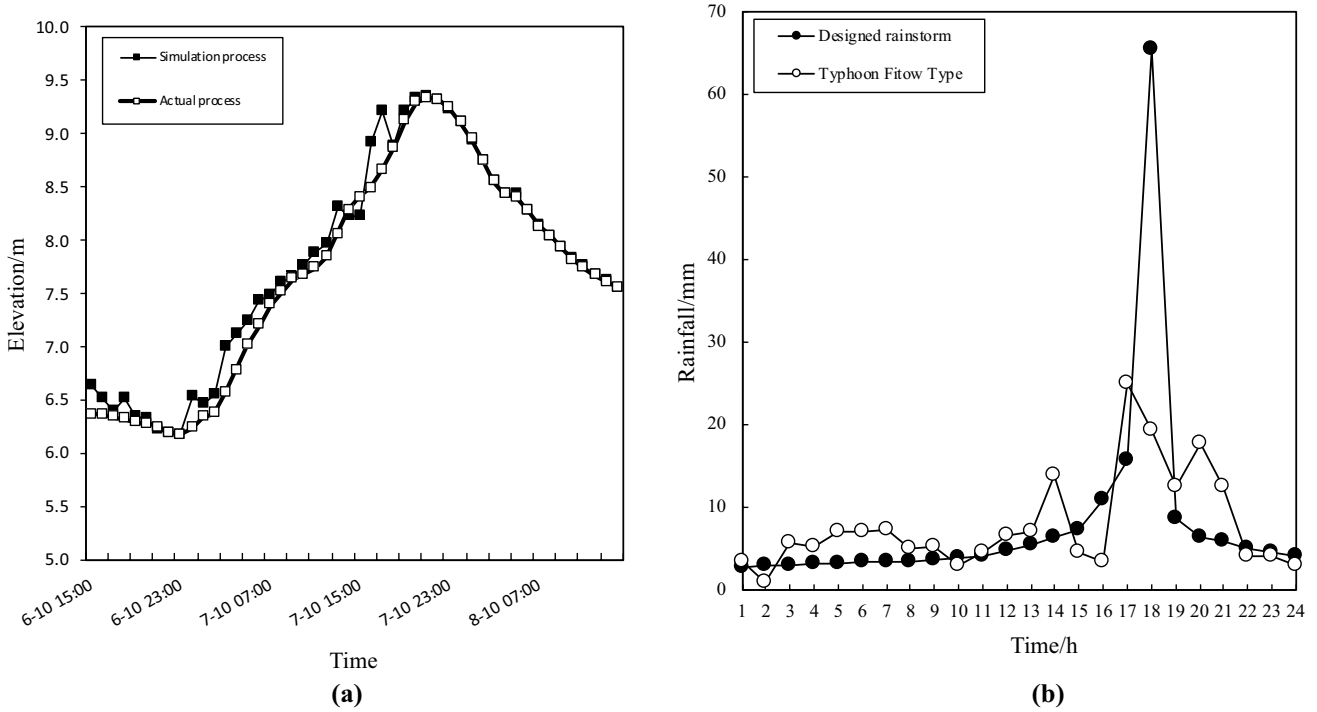


Fig. 2 a Evaluation of Shiliqu hydrodynamic model and b comparison of the designed rainstorm and the typhoon Fitow rain pattern

The designed rainstorm pattern is single-peak, and the main rainfall is concentrated around 18 o'clock. The peak value of the designed rainstorm pattern is higher than the typhoon Fitow rain pattern about 40 mm, which leads to safer flood control standards. The typhoon Fitow rain pattern shows

a multi-peak shape, and the main rainfall is concentrated around 14–22 o'clock. The peak value of the typhoon Fitow rain pattern is much lower than the designed rainstorm pattern. However, rainfall fluctuations under the typhoon Fitow rain pattern are large and consistent with the actual situation.

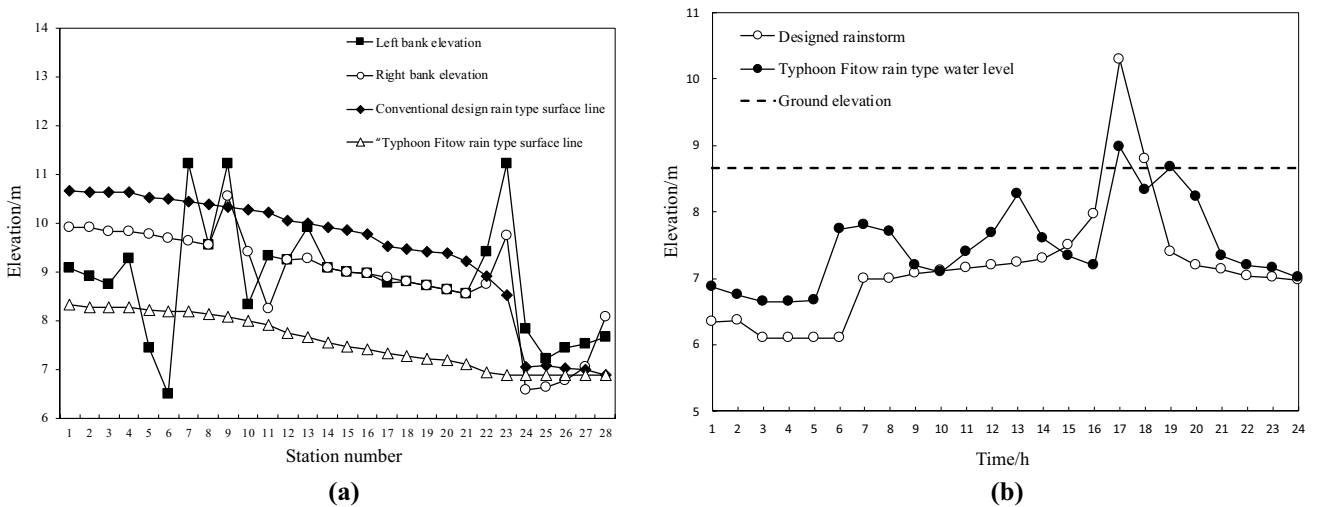


Fig. 3 a Calculated water surface curve under different rain patterns and b water level changes of Banshixi tributary station

Results and discussion

The calculated water surface curve under the designed rainstorm pattern and the typhoon Fitow rain pattern, left and right bank elevation of the mainstream of the Shiliqu watershed are compared in Fig. 3a. The bank elevation of the mainstream shows large fluctuations, especially in the left side bank, and the maximum difference is about 4.8 m. The calculated water surface profile under the designed rainstorm pattern experienced a rapid downward trend from the upstream to downstream. The maximum gradient was observed in the No. 23 pile. The downward trend of water surface profile is slower under the typhoon Fitow rain pattern than under designed rainstorm pattern. The water surface profile height is lower under the typhoon Fitow rain pattern than under designed rainstorm pattern. The water surface profiles are close from the No. 24 pile to the No. 28 pile under two rain patterns. Most water surface profile under the designed rainstorm pattern is higher than the bank elevation. Most water surface profile under the typhoon Fitow rain pattern is lower than the bank elevation. The comparison shows that it is safer to use the designed rainstorm pattern than the typhoon Fitow rain pattern for formulating the flood control standard.

To display the different water levels caused by the two rain patterns, data from the Station of Banshixi tributary were analyzed and shown in Fig. 3b. When the town encounters a ten-year flood under the designed rainstorm pattern, the water surface profile displays a single-peak shape and the maximum water level is 10.3 m, which exceeds the ground elevation by 1.7 m. The water level exceeds the ground elevation at 4:25 pm and the overtopping time is about 2 h. Under the typhoon Fitow rain pattern, the water surface profile displays a multi-peak shape and the maximum water level is 9 m, which exceeds the ground elevation by 0.4 m at around 16 o'clock. The second peak at 18 o'clock reaches the ground elevation at 8.6 m again. The water level fluctuates intensely from 6 to 21 o'clock. Figure 3 shows the comparison of different rain patterns. The water level under the designed rainstorm pattern is lower than that under the typhoon Fitow rain pattern from 1 to 13 o'clock in the tributaries, and its water level's fluctuation is less than that of the Fitow rain pattern. Larger fluctuations under the Fitow rain pattern may result in multi-level overtopping which threatens the safety of the flood control. Therefore, different rainstorm patterns should be considered in the actual flood control design.

Given that most river banks and channels in mountain creek area are not well designed and properly maintained, the protection of river bank and remediation of river channels are necessary to avoid the water level exceeds the ground elevation under the impact of typhoon rain. The

analysis shows that the tributary water level fluctuates greatly under the typhoon Fitow rain pattern and reaches the ground elevation twice. If the channel is blocked or damaged, the water level of the narrow channel significantly increases and exceeds the flood control standard. The effect of the typhoon rain pattern on the water level and the flood control design should be considered. The flood discharge capacity of the river channel should meet the minimum requirement because the water level rises rapidly under the designed rainstorm pattern.

Currently, the typical single-peak rainstorm pattern is mostly used for flood control. Our study shows that the multiple-peak typhoon is an important cause of flood disasters besides single-peak rainstorm. The typhoon rain pattern should be considered for establishing the flood control standard. The mountainous area may encounter a second heavy rainstorm during a bimodal rainstorm, which would cause an accumulated rainfall higher than the designed rain pattern. An efficient flood control system that considers terrain shape, ground elevation, surrounding road traffic, and rain pattern could improve the discharge capacity and prevent floods (Cheng 1999; Perry and Benet 2000; Wittenberg et al. 2004; Chang et al. 2008).

Conclusions

The hydrodynamic mathematical model of the river network was established to analyze the influence of rain patterns (typically designed rainstorm and the typhoon Fitow) on the flood control of the mountain creek area. The following conclusions are obtained:

- The large fluctuations under the typhoon Fitow rain pattern cause twice overtopping which threatens the safety of the flood control. Different rain peaks may overlap, and the water level could be rather high and exceed the ground elevation.
- The typhoon Fitow rain pattern has a greater impact on the tributary water level but less impact on the mainstream water level than the designed rainstorm pattern.
- The maximum water level varies under different rain patterns in the mountain creek areas. The water level under the designed rainstorm pattern is significantly higher than that under the typhoon rain pattern.
- Strong typhoon rain could produce accumulated high-water levels that exceed the ground elevation and cause large losses. Considering the multi-peak rain pattern in the flood control design can enhance flood resistance.

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Compliance with ethical standard

Conflict of interest The authors declare that they have no conflict of interests.

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