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Joint impact of rainfall and tidal level on flood risk in a coastal city with a complex river network: a case study for Fuzhou city, China

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Abstract

Coastal cities are particularly vulnerable to flood under the combined effect of multi-variable variables, such as heavy rainfall, high sea level and large waves. For better assessment and management of flood risk the combined effect and joint probability should be considered. This paper aims to study the joint impact of rainfall and tidal level on flood risk by estimating the combined risk degree of flood and the joint flood probability. The area of case study is a typical coastal city in China, which has a complex river system. The flood in this city is mainly caused by inundation of river system. In this paper, the combined risk degree of flood is assessed by analyzing the behavior of the complex river network of the city under the combined effect of rainfall and tidal level with diverse return periods. The hydraulic model of the complex drainage network is established using HEC-RAS and verified by comparing the simulation results with the observed data during Typhoon "Longwang". The joint distribution and combined risk probability of rainfall and tidal level are estimated using the optimal copula function. The work carried out in this paper would facilitate assessment of flood risk significantly, which can be referred for the similar cities.

1 Introduction

Flood is the natural disaster occurring most frequently and the risk of flood has been rising in many parts around the globe (Adelekan, 2010; Chang et al., 2008), which prompts international flood management increasingly shifting towards a more integrated system of flood risk management (Plate, 2002; Samuels et al., 2006; Merz et al., 2010). In recent years the scope of flood risk assessment has ranged from national level (Hall et al., 2005; Ni et al., 2010) to river basin (Kok and Grossmann, 2009; te Linde et al., 2011; Mazzorana et al., 2012; Rulli and Rosso, 2002) and urban area (Dawson et al., 2008; Hadjimitsis, 2010; Pathirana et al., 2011; Wang et al., 2010), even to specific site (Dawson et al., 2005; Youssef et al., 2010; Ernst et al., 2010). Traditionally, the scenario simulation approach is employed to assess flood risk in urban areas through evaluating the physical aspect of flood like extent and depth of inundation and the loss that would occur. It is obvious that the method cannot effectively reflect the threshold conditions of flood and the probability of flood. It is therefore essential to develop an integrated approach in managing the risk of flood in coastal urban areas to tackle the problem properly.

Coastal cities are particularly vulnerable to flood in coastal urban areas caused by heavy rainfall on the inland tributary catchment or high water level of the receiving water body on downstream boundary or both (Archetti et al., 2011). That is, the flood probability or flood severity is a function of rainfall and water level of the receiving water body. The operational conditions of drainage facilities such as drainage pumping stations also influence the flood severity. However, the combined effects of rainfall and tidal level at the outfall may be interested in determining the probability of tide-locking of drains and the scale of drainage facilities in design (Hawkes, 2008). Therefore, in this paper the joint effect on flood is analyzed with the joint probability of rainfall and tidal level for an improved assessment of flood risk considering the standard of service of defence structures existing. The combined impact of rainfall and tidal level on flood is assessed through the hydraulic simulation of the urban drainage network. Moreover, the joint probability is analyzed using a multivariable probability model.

In China, the vast majority of coastal cities are located in low lying areas with a complex river network (such as Fuzhou, Wenzhou, Shanghai, etc.), and for each of the cities the directly receiving water body for flood is a tidal river. The episodes of flood in these cities are mainly river inundation due to the combined effects of rainfall runoff and high water level on downstream boundary conditions. In such cases, the hydraulic simulation model of the urban drainage network particularly should take the characteristics of complex river networks and their structures into consideration. Some numerical simulation tools for urban drainage networks, like MIKE 11 (Ngo et al., 2007), HEC-RAS (Fan et al., 2009; Knebl et al., 2005; Lee et al., 2006; Rodriguez et al., 2008), have been widely adopted presenting operational conditions of complex river systems. They are not only capable of representing flood characteristics for the surface-river interaction mechanism, but also can reflect the effects of various flood control and urban infrastructures such as dykes, culverts, bridges, pumping stations, etc.

Joint probability refers to the probability that two conditions occur at the same time, i.e. the encounter probability of two variables. The joint probability methods are used widely (Carsel and Parrish, 1988; Hawkes et al., 2002; Kuehn et al., 2011; Lele et al., 2007; Wang et al., 2009). The methods include Bayesian Networks, statistical analysis, Monte Carlo simulation and copula functions. Multivariable probability model is often employed to study joint distribution of two-dimensional variable, such as the normal distribution model (Sheng, 2000), the Gumbel mixed model (Yue et al., 1999), the Exponential model (Bacchi et al., 1994), the gamma distribution model (Skaugen, 2007), the Meta-Gaussian model (Kelly and Krzysztofowicz, 1997), the FGM (Farlie-Gumbe1-Morgenstern) model (Long and Krzysztofowicz, 1992), and copula models (Grimaldi and Serinaldi, 2006; Balistrocchi and Bacchi, 2011). Copulas have been widely employed to estimate joint distribution of two variables in hydrological applications (AghaKouchak et al., 2010; Balistrocchi and Bacchi, 2011; De Michele et al., 2007; Bárdossy and Pegram, 2009; Renard and Lang, 2007; van den Berg et al., 2011). The reason is that they can relax the restrictions of traditionally bivariate probability models. For example, using copula functions no assumption is needed for the variables to be independent or normal, or to have the same type of marginal distributions.

The purpose of this paper is to show an integrated approach to study the joint impact of several variables on flood risk for a coastal city with a complex river network. Based on a practical case study, the combined impact on flood risk is carried out by estimating the combined risk degree of flood and the joint flood probability with the different return periods of rainfall and tidal level.

2 Case study area

Fuzhou city, the site chosen as the case study, is located in the southeast coast of China and is characterized by a maritime subtropical monsoon climate. Its mean annual temperatures range from 16 to 20° and its mean annual precipitation is approximately 1320 mm. The typhoon active periods are from July to September, and typhoons land directly throughout the city twice a year on average.

Fuzhou almost has all the typical characteristics of China's coastal cities, where the region distributes hills and plains with a complex river network, and the receiver of flood is a tidal river. The entire city is surrounded by mountains in the north, the west, the east and a tidal river, Min River in the south. The majority of land in Fuzhou city is mixed hilly area of 66.72 km^2 (41.8 %), and plain region of 90.05 km^2 (58.2 %). Dozens of rivers and conduits in the city form a complex river system with converging and diverging branches and closed loops (Fig. 1). The whole river system could be divided into two zones: the west regions with the main drainage channel, Baima River, and the east regions with Jinan River and GMG River. The city has a hydrologic station called LB, which can measure the precipitation, discharge and level in the Min River.

In recent years, the river network and its urbanized coast have been particularly vulnerable to flood during the intense rainstorms of typhoons. The direct reasons for the disasters are reportedly due to the inundation of river system under the effect of intense typhoon rainfall and high water level downstream. The disasters disrupt daily residents' activities and cause huge socio-economic loss. For example, the catastrophic flood due to Typhoon "Longwang" with 1-h maximum rainfall of 118 mm in 2005 caused the inundation of 13.69 km^2 areas, more than 62 people killed, 24 missing, 120 000 evacuated, and direct economic losses of 2.2 billion Yuan.

3 Data and methods

The data used in this study are mainly composed of quantities of precipitation and tidal level records, DEM of 5 m grid spacing, hydraulic structures materials and hydraulic parameters, sewers information, and the profiles of rivers' cross sections provided by the relevant authority. The levels in this paper are measured by Luo Zero Vertical Datum of China.

The methods in this paper consist of data collection, analysis and interpretation, as described in the following sections.

- Setting up complex river network model for the study area.
- Assessment of flood severity through a joint analysis approach.
- Joint probability analysis for rainfall and tidal level using copula functions.

3.1 Complex river network modeling

The well-known HEC-RAS hydrodynamic model is used for the simulation of the complex river network (Fig. 2). It presents a user-friendly interface for data input and visualization of results. The data sets in the model include the details of cross sections and hydraulic constructions, hydraulic parameters, scheduling mode of tide-locks, and boundary conditions. There are 1713 cross-sectional profiles of the whole river network. The distances between consecutive cross sections vary from 20 m to 50 m. The manning roughness coefficients set in the model range from 0.025 to 0.045. The boundary conditions contain two types, inflow boundary condition and outlet boundary condition. The methods for calculating the boundary conditions are introduced hereinafter.

3.1.1 Inflow boundary conditions

To simulate flood routing better, the mountainous areas and the urban areas are divided into different unit catchments (Fig. 3). SWAT and ARCGIS help divide the northern mountain areas into several units according to their distribution. Based on the existing drainage pipelines distribution and DEM data, the urban areas are separated into several units. The northern mountainous areas are divided into 16 units from n1 to n16. The rest units comprise the urban areas. For each unit, the outlet flow hydrograph is calculated as the inflow boundary condition of the model.

The inflow boundary conditions are classified into two kinds. One is the rainfall runoff from northern mountains and the other is the urban storm runoff. According to the precipitation data, the flow hydrograph of outlet is calculated for each unit in the northern mountains by Xinanjiang model. It has been widely validated and employed in China (Ren-Jun, 1992; Cheng et al., 2006; Hu et al., 2005). Surface runoff process for a unit of the urban area is generalized as a triangle process (the dashed line in Fig. 4). For this process, peak discharge Q, the summit point of the triangle, is calculated by Reasoning Formula Method. Total volume of runoff W, the area of the triangle, is derived by urban rainfall and runoff model. Then, duration of the surface runoff T is equal to 2 times of W divided by Q. In a unit with a drainage system, outflow of the pipeline network is modified as the solid line in Fig. 4 due to maximum outflow capacity (that is $Q_{p,\max}$) of the pipelines. In other units, outflow is same as surface runoff that flows into river directly.

3.1.2 Outlet boundary conditions

The outlet boundary conditions are mainly the design tidal level hydrographs at the outfall. They are derived by the data of tidal levels from 1952 to 2008 measured by LB hydrologic station. The operation condition of the tidal gate also should be considered for each outfall. In the model its opening is regulated by an automatic control based on water level on the upstream side. When this level exceeds the tidal level of outfall, the gate is open so that the drainage system is in communication with the receiving water body.

3.2 Joint impact of rainfall and tidal level on flood

The joint analysis of coastal urban flood vulnerability is estimated by the model of a complex river network established by HEC-RAS, simulating the operation conditions combined different standards of rainstorm runoff with different tidal levels at the outfalls. For each design standard rainfall, the simulation is repeated by varying the condition of the tidal level at the outfall. Considering HEC-RAS could present the visualization of results, the critical condition of flood is when the river level exceeds its bank. The extent of rivers overflowing the bank presents the flood severity of the whole drainage networks. It is hence possible to generate the curves of flood severity as a function of rainfall and tidal level.

3.3 The analysis of joint risk probability

The 1952–2008's annual maximum precipitation in 24-h and its corresponding tidal level measured by the LB hydrological station in Fuzhou city are used to analyze the joint distribution. The corresponding tidal level refers to the level when annual maximum precipitation in 24-h happened. For each maximum level corresponding to annual maximum daily precipitation, it matches a frequency in the annual maximum tidal level. Therefore, the combined probability of the maximum daily rainfall and the annual maximum tidal level can be analyzed through the joint distribution of annual maximum daily rainfall and its corresponding tidal level.

A few well-known copulas featuring a wide range of dependence, including Gaussian copula, *t*-copula, Clayton copula, Frank copula and Gumbel copula, have been selected.

The parameters of copulas in this paper are estimated by the maximum likelihood method. The most appropriate copula is selected by using the Kolmogorov-Smirnov

(K-S) test and Ordinary Least Squares (OLS) criteria. K-S test is a commonly used non-parametric test, whose test statistic D is defined as Eq. (1). OLS is defined as Eq. (2). Quantile-Quantile (Q-Q) plot presenting the experience frequency of the variable and the fitting situation of theoretical frequency is also employed to intuitively reflect goodness and fit.

$$D = \max_{1\le k\le n}\left\{\left|C_k - \frac{m_k}{n}\right|, \left|C_k - \frac{m_k - 1}{n}\right|\right\} \tag{1}$$

where C_k is the copula value of joint observation sample, $x_k = (x_{1k}, x_{2k})$, and m_k is the number of joint observations that meet the conditions $x \le x_k$ in the joint observations sample.

The formula of OLS is:

$$\mathrm{OLS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(p_i - p_{ei})^2} \tag{2}$$

where p_i and p_{ei} present the theoretic frequency and experience frequency of joint distribution, respectively.

The joint distribution function with the rainstorm variable H and the tidal level variables Z is assumed as $F(h,z)$, and the marginal distribution functions are $f_h(h)$ and $f_z(z)$, respectively. The joint density function is $f(h,z)$, and the marginal density functions are $f_h(h)$ and $f_z(z)$. Similarly, the density function of Copula function $C(u,v)$ is $c(u,v)$. Then:

$$f(h,z) = c(F_h(h), F_z(z))f_h(h)f_z(z) \tag{3}$$

where $c(u,v) = \dfrac{\partial^2 C(u,v)}{\partial u \partial v}$.

As long as one of the two variables, the rainfall H or the tidal level Z, exceeds a certain probability, it is denoted as $P\cup(h,z)$. When both of the two variables exceed a certain probability, it is denoted as $P\cap(h,z)$. The relationship is presented in

Eqs. (4) and (5).

$$P\cup(h,z) = P((H > h)\cup(Z > z)) = 1 - F(h,z) \tag{4}$$

$$P\cap(h,z) = P((H > h)\cap(Z > z)) = 1 - F_h(h) - F_z(z) + F(h,z) \tag{5}$$

4 Results and discussions

4.1 Verification of the complex river network model

One major flood event during Typhoon "Longwang" in 2005 is selected for verification of the complex river network model for Fuzhou. The operational conditions are simulated by the model according to the rainstorm data and the operation of flood control. The comparison of flooding scope of the rivers between simulation results and the actual measurement is plotted in Figs. 5 and 6. The comparison of level hydrograph in the midstream of Jinan River is also carried out between the observation and the result of simulation for better validation of the model (Fig. 7). The inundation scopes of the river network in Figs. 5 and 6 are basically same. Both of the simulated and the measured highest water levels in Fig. 7 are 7.0 m, and their level hydrographs have the same trend. The similarity between the simulation results and the observation indicates the model of the complex river network can be used to present the submerged scope of rivers under the joint effect of rainfall and tidal level.

The deviations between the simulation results and the observed data may be caused by two reasons: (a) the calculation results of runoffs derived from rainfall data may be probably slightly deviate from the real data; (b) the complexity of river network makes it different to accurately calibrate the manning roughness coefficients.

4.2 Joint impact of rainfall and tidal level on flood

As previously mentioned, for a coastal city the flood severity is subjected to the joint influence of rainfall, tidal level of receiving water body, and the operational conditions of drainage facilities like drainage pumping stations. Based on this, two operational conditions of drainage facilities, without and with pumping stations working, have been simulated. For each condition, the isolines of flood severity are presented as the function of rainfall and tidal level at the outfall (Fig. 8). The same results are presented in Fig. 9, shown in terms of return periods of each variable. The "start" condition represents the threshold condition before flood occurs.

Figure 8 shows that flood severity is directly affected by the rainfall, tidal level and dispatch of drainage facilities. It is interesting to note that the combination of high level and small precipitation and the combination of low level and heavy rainfall are both able to cause flood. Flood severity is more sensitive to tidal level under the combined effect of high level and small precipitation, compared with the combination of low level and heavy rainfall. That means with a slight increase in tidal level the submerged scope will be significantly expanded in the former condition. However, the chance of the slight increase is very small for high tidal level, as shown in Fig. 9b. For example, for the rainfall of 5-yr return period, if the flood severity increases from 25 % to 50 %, the return period of tidal level has to increase from 30 yr to 50 yr. It is therefore essential to analyze the joint probability of low level and heavy rainfall and high level and small precipitation.

Figure 10 shows that drainage facilities can obviously take effect on flood drainage under the low precipitation. For example, with the pumps working the standard of rainfall for flood occurring can increase return period from 10 yr to 20 yr with the tidal level of 1.9-yr return period. However, as long as rainfall intensity exceeds a certain return period, the drainage facilities do not work. This indicates that it is inadvisable to control flood with higher standards of drainage facilities irrationally, it is better to strengthen flood risk management on the basis of understanding the flood risk effectively.

4.3 Joint probability analysis

4.3.1 Marginal distributions

The Pearson Type III (P-III) distribution widely used in hydrological field of China is adopted to fit the marginal distributions of the annual maximum daily rainfall H and its corresponding tidal level Z. The distribution functions of rainfall H and its corresponding tidal level Z are denoted as $F_H(h)$ and $F_z(z)$, respectively. The parameters are estimated by the combination of Linear-moments method and Curve-fitting method. For the variable of rainfall H, the parameters u_H, C_v, and C_s are 112.51 mm, 0.38, and 1.27, respectively. For the variable of tidal level Z, u_Z, C_v, and C_s are 5.41 mm, 0.14, and 1.47, respectively.

4.3.2 Goodness-of-fit test

Using the maximum likelihood function, parameters of the copula functions are all calculated and thus each Copula function is obtained. Subsequently, D and OLS can be calculated according to Eqs. (1) and (2). The calculation results are shown in Table 1. With significance level of the K-S test $\alpha = 0.05$, the calculated values D of the five copula functions can all pass the examination. Table 1 shows that the Gumbel copula function better fits the joint distribution of the rainstorm and flood tidal level of Fuzhou. The Q-Q plot shows the correlation of empirical and theoretical joint distribution for the Gumbel copula function (Fig. 11).

According to Eq. (3) and Table 1, the joint distribution function of maximum daily rainfall H and its corresponding tidal level Z has been calculated, as shown in Eq. (6):

$$F(h,z) = \exp\left\{-\left[(-\ln F_h(h))^{1.0581} + (-\ln F_z(z))^{1.0581}\right]^{\frac{1}{1.0581}}\right\} \tag{6}$$

4.3.3 Joint probability analysis

The distribution of P-III is used to fit the series of annual maximum flood tidal level, where $u_Z = 7.32\,\text{mm}$, $C_v = 0.12$, $C_s = 0.45$. For the tidal level corresponding to the maximum daily rainfall, it can rank a frequency in the annual maximum tidal level series. This frequency is denoted as P_M, and the return period is denoted as T_M. For each given combination of different annual maximum daily rainfall and its corresponding tidal level, the risk probability can be obtained with Eq. (4)–(6), as shown in Table 2.

Table 2 shows that for one variable, the occurrence probability of rainfall and tidal level is getting smaller and smaller with increasing the standard of other variable. For Fuzhou city, the probability is very slight when heavy rainstorm and high tidal level occur at the same time. The occurrence probability of high level and low precipitation is smaller than the one of low level and heavy rainstorm. It can be seen in Table 2 that the encounter probability of 5-yr return period rainfall and 50-yr return period level is 0.0146 %, while the occurrence probability of 50-yr return period rainfall and 5-yr return period level is 0.0546 %. This clearly indicates the flood in Fuzhou is mainly caused by the intense rainfall, which is in agreement with practical experience. The flood caused by Typhoon “longwang” is the typical example.

It is interesting to note that the joint probability of rainfall and tidal level is always larger than the exceedance probability of corresponding return period rainfall, even though the encounter probability is very slight. This means the joint effect of rainfall and tidal level increases the risk of flood. For a coastal city, the flood probability would outnumber the design probability if the design standard only depends on the return period of rainfall without considering the choice of the downstream boundary condition. It is therefore essential for the determination of flood design standards to analyze the joint probability and joint effect of multivariate.

5 Conclusions

The work is carried out to assess the combined effect as well as the combined probability of rainfall and tidal level on flood risk in a coastal city with a complex river network. The work is split into three main parts: (a) the establishment of hydraulic model for the complex river network in Fuzhou city; (b) the joint effect analysis of rainfall and tidal level on flood severity; (c) the joint probability analysis of rainfall and tidal level for flood risk probability.

Given that the mainly flooding is river flood for Fuzhou, the model of the complex river network is established for simulating the flood routing. Base on the model, the joint effect of rainfall and tidal level on flood severity is analyzed. The results show that: (a) the flood risk in the coastal city is transformable with the changed combination of rainfall and tidal level; (b) it is better to strengthen flood risk management by understanding the flood risk effectively, rather than using drainage facilities with higher standards to control flood irrationally.

The analysis of joint risk probability of rainfall and tidal level is also carried out by the copula function. The results show that, the flood probability would outnumber the design probability without considering the choice of the downstream boundary condition, if the design standard only depends on the return period of rainfall in a coastal city.

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Table 1. Goodness-of-fit test of copulas.

Copulas	D	OLS
Gumbel Copula	0.0602	0.01603
Clayton Copula	0.0660	0.01699
Frank Copula	0.0641	0.01691
Normal Copula	0.0657	0.01784
t-Copula	0.0654	0.01699

Table 2. Risk probabilities of different encounter conditions.

Encounter conditions									
Maximum annual 24 h rainfall			Corresponding tidal level				$F(h,z)$	$P\cap(h,z)$ (%)	$P\cup(h,z)$ (%)
H (mm)	P (%)	T (a)	Z (m)	P (%)	P_M (%)	T_M (a)			
226.1	2	50	9.39	0.03	2	50	0.9798	0.0082	2.0218
226.1	2	50	8.97	0.06	5	20	0.9795	0.0147	2.0453
226.1	2	50	8.58	0.14	10	10	0.9789	0.0291	2.1109
226.1	2	50	8.13	0.32	20	5	0.9773	0.0546	2.2654
226.1	2	50	7.32	1.41	50	2	0.9674	0.1496	3.2604
194.6	5	20	9.39	0.03	2	50	0.9498	0.0100	5.0200
194.6	5	20	8.97	0.06	5	20	0.9496	0.0184	5.0416
194.6	5	20	8.58	0.14	10	10	0.9490	0.0381	5.1019
194.6	5	20	8.13	0.32	20	5	0.9476	0.0757	5.2443
194.6	5	20	7.32	1.41	50	2	0.9383	0.2416	6.1684
169.8	10	10	9.39	0.03	2	50	0.8998	0.0118	10.0182
169.8	10	10	8.97	0.06	5	20	0.8996	0.0222	10.0378
169.8	10	10	8.58	0.14	10	10	0.8991	0.0474	10.0926
169.8	10	10	8.13	0.32	20	5	0.8978	0.0979	10.2221
169.8	10	10	7.32	1.41	50	2	0.8893	0.3447	11.0653
143.4	20	5	9.39	0.03	2	50	0.7998	0.0146	20.0154
143.4	20	5	8.97	0.06	5	20	0.7997	0.0278	20.0322
143.4	20	5	8.58	0.14	10	10	0.7992	0.0612	20.0788
143.4	20	5	8.13	0.32	20	5	0.7981	0.1309	20.1891
143.4	20	5	7.32	1.41	50	2	0.7909	0.5017	20.9083

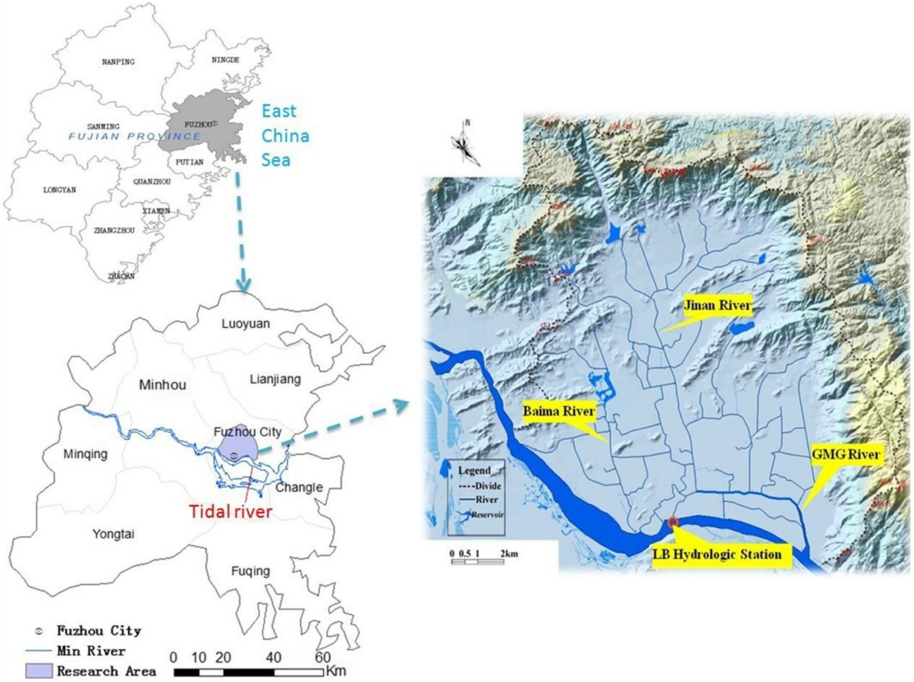

Fig. 1. Location map of the study area and its terrain map with a complex river network.

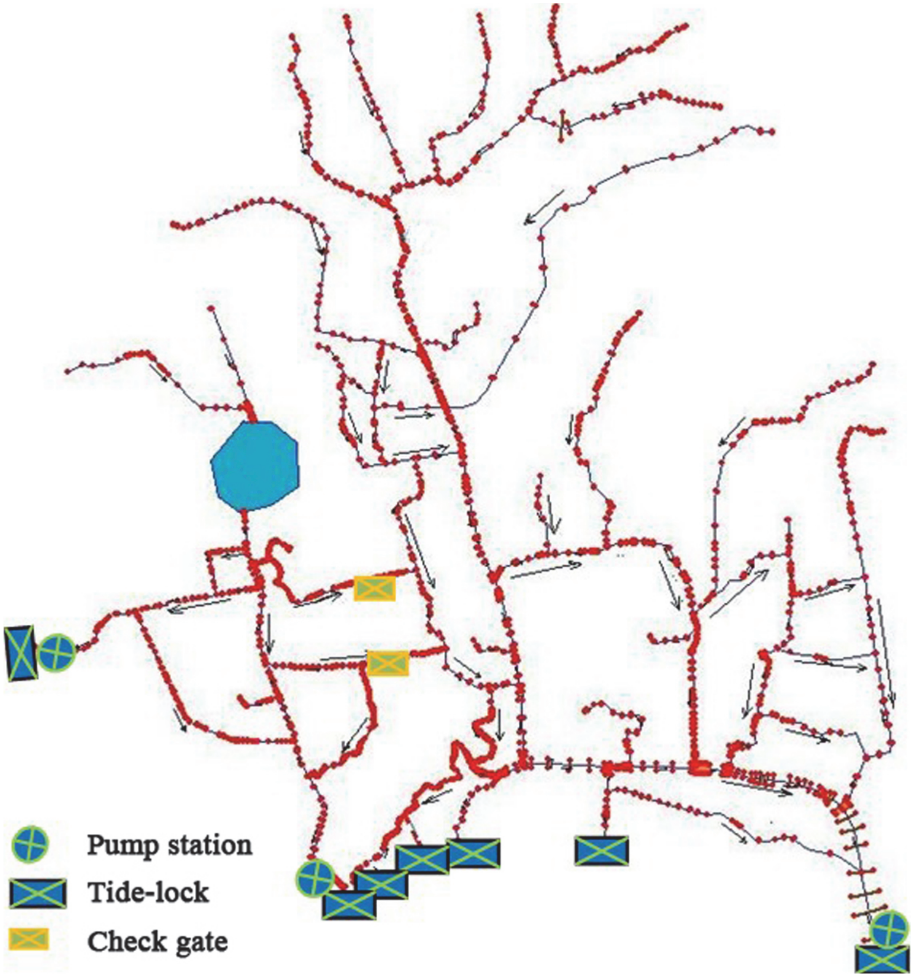

Fig. 2. River network model.

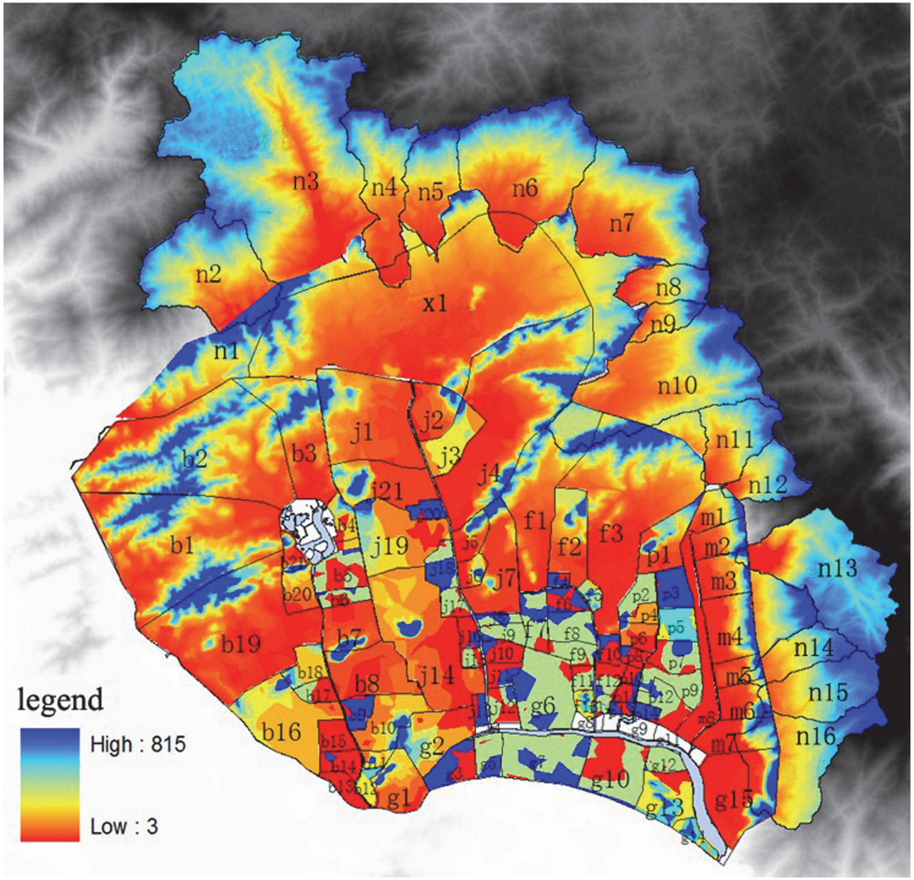

Fig. 3. District division and its numbers.

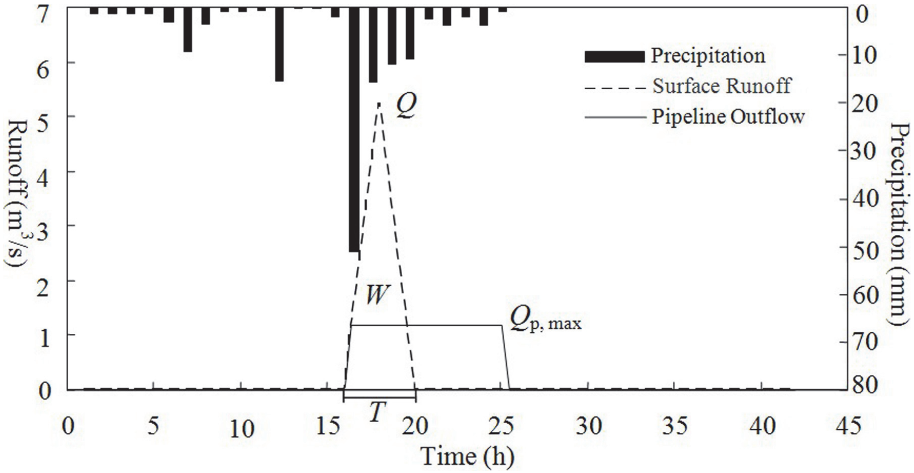

Fig. 4. Runoff process for a unit of the urban area.

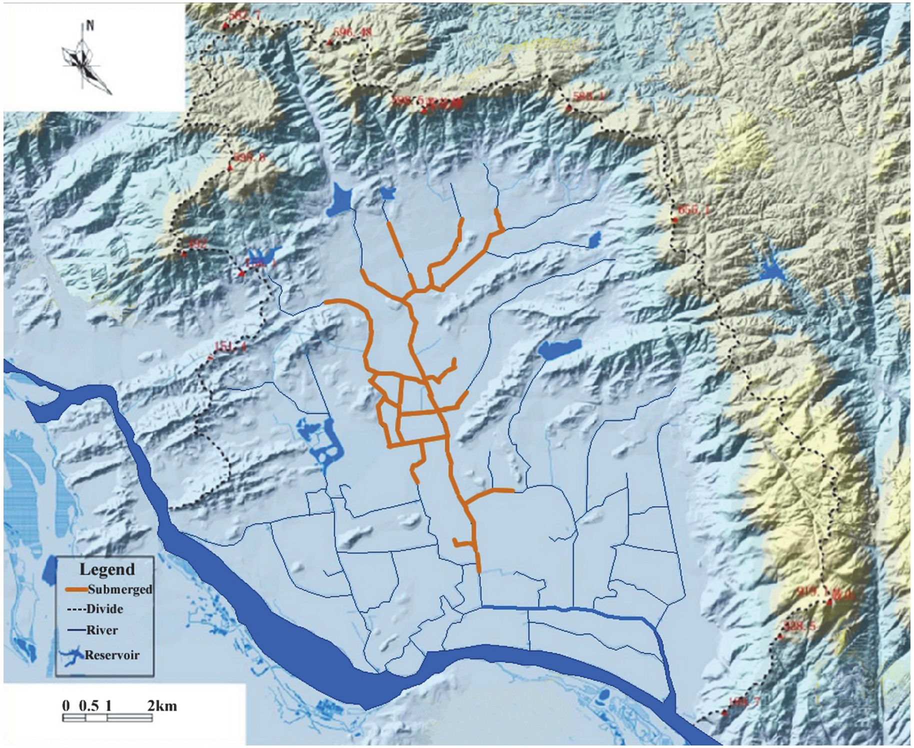

Fig. 5. Observed data of the flooded area.

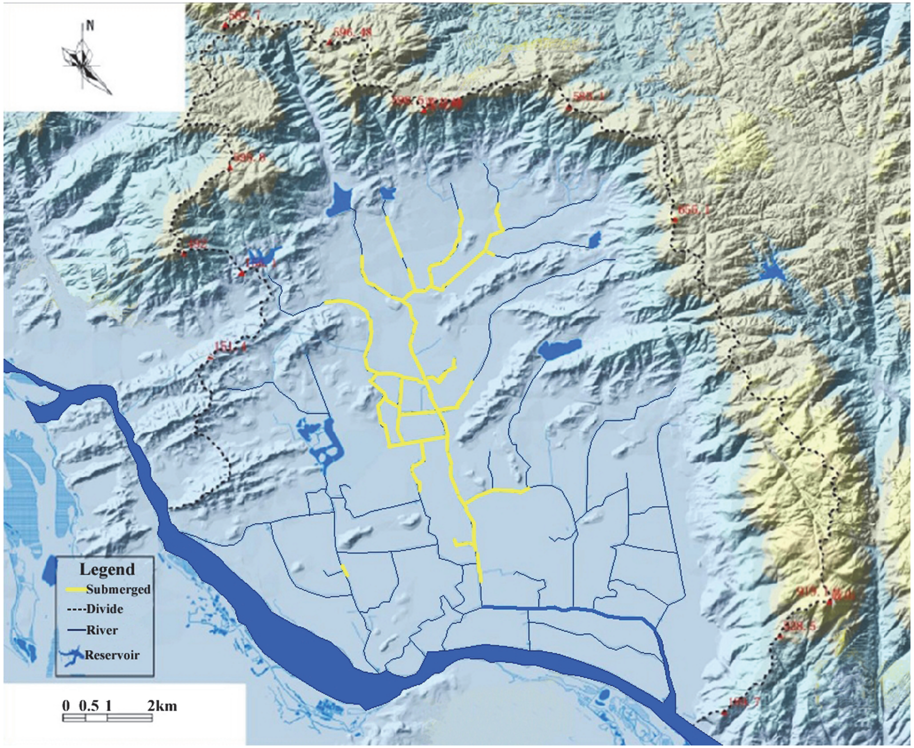

Fig. 6. Simulation results of the flooded area.

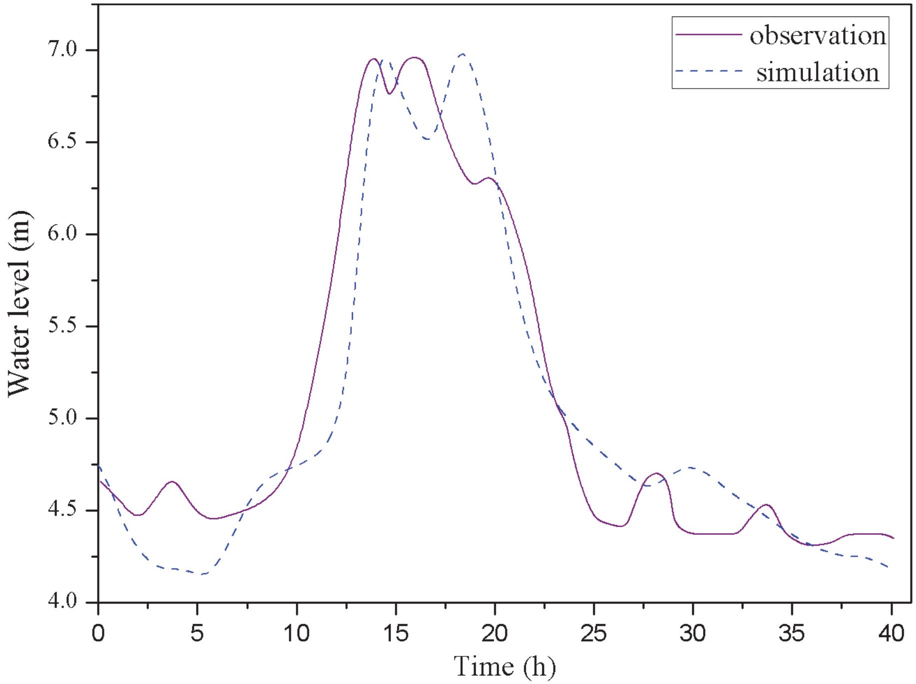

Fig. 7. Comparison of level hydrographs.

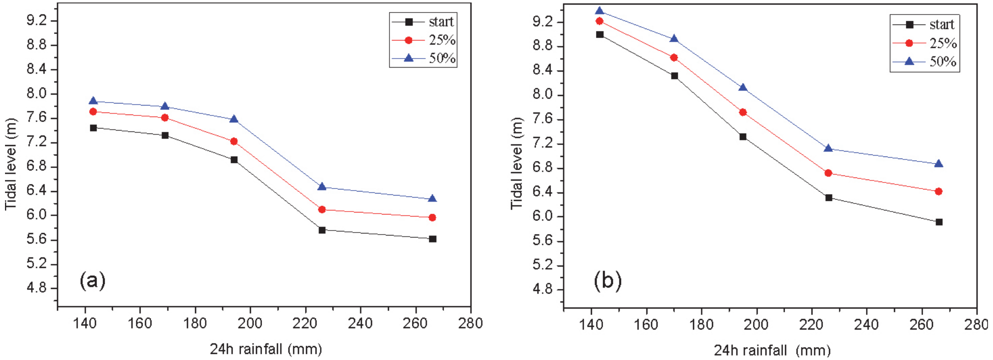

Fig. 8. Isolines of flood severity under two conditions: **(a)** without pumps working; **(b)** with pumps working.

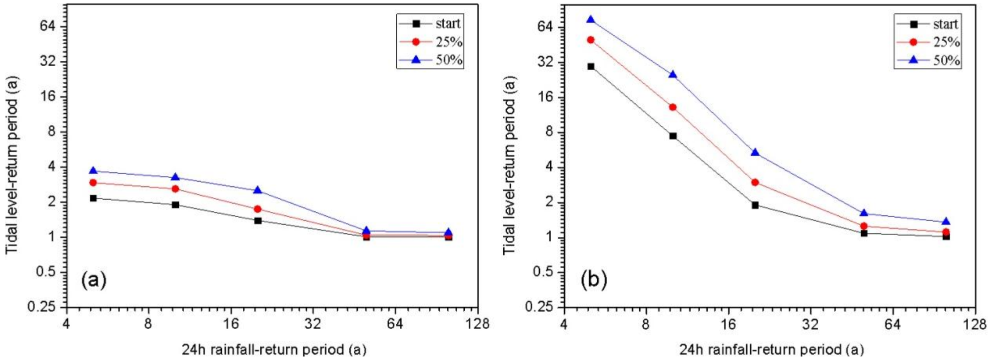

Fig. 9. Isolines of flood severity under two conditions represented by return periods: **(a)** without pumps working; **(b)** with pumps working.

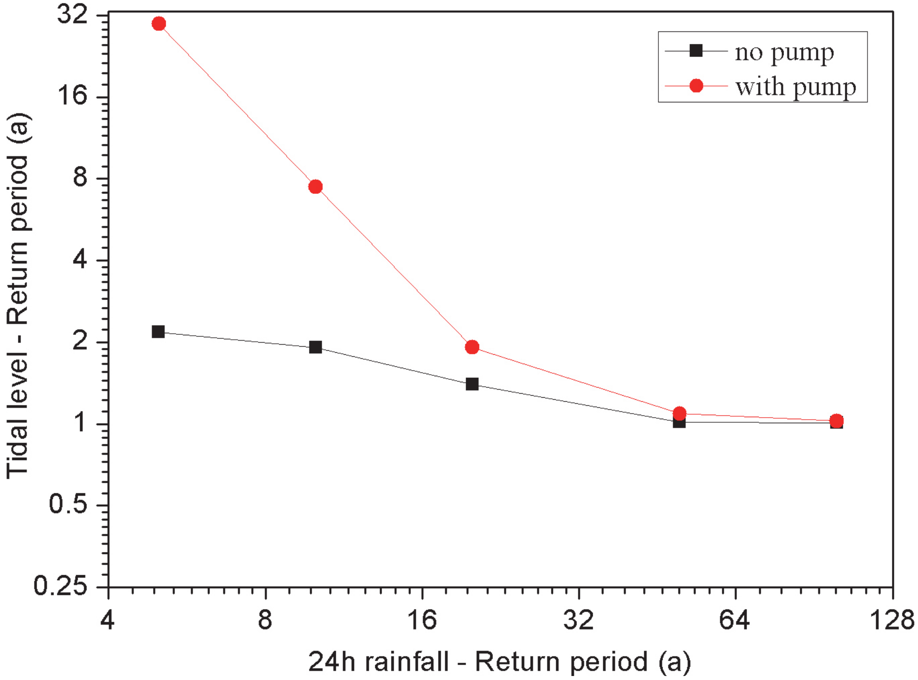

Fig. 10. Comparison of the threshold state before flood occurs.

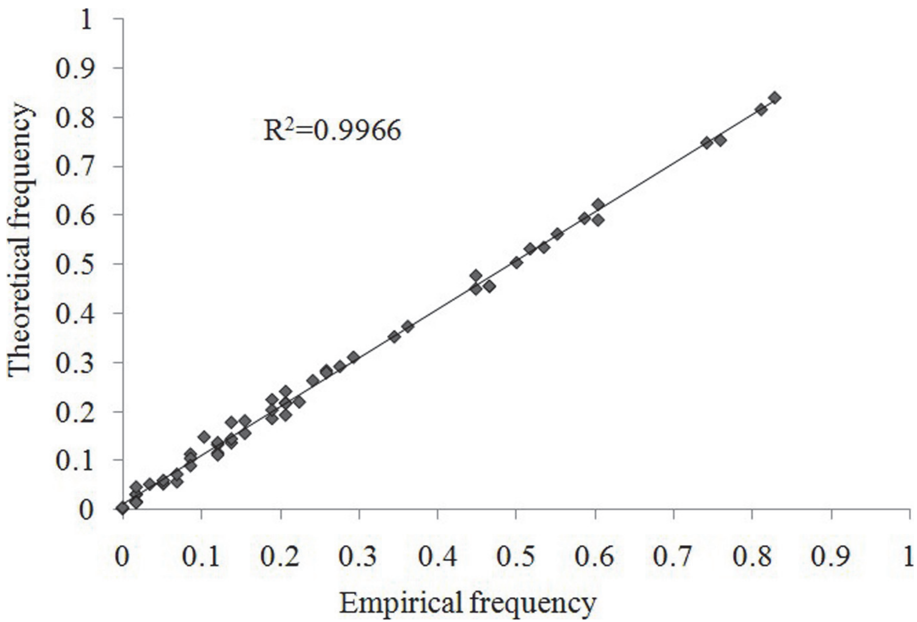

Fig. 11. Correlation between the empirical distribution and theoretical distribution.