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Optimal management of the flooding risk caused by the joint occurrence of extreme rainfall and high tide level in a coastal city

Jijian Lian[1] · **Hongshi Xu**[1] · **Kui Xu**[1] · **Chao Ma**[1]

Abstract Coastal cities are more vulnerable to floods due to the joint impact of rainfall and tide level. Quantitative risk assessment of disaster-causing factors is critical to urban flood management. This paper presents an integrated method to quantify the hazard degree of disaster-causing factors, rainfall and tide level, and to investigate the optimal management of flooding risk in different disaster-causing factor areas. First, an urban flood inundation model is used to simulate inundated extents in different drainage districts. Then, formulas are put forward to calculate the hazard degree of rainfall and tide level based on inundated extents in different combinations of rainfall and tide level. According to the hazard degree, the main disaster-causing factor could be identified in each drainage district. Finally, the optimal management of flooding risk in different disaster-causing factor areas is selected by disaster reduction analysis and cost–benefit analysis. Furthermore, the coastal city, Haikou of China, is taken as a case study. The results indicate that the hazard degree increases with the increasing distance between the drainage district and the Qiongzhou Strait or the Nandu River in the eastern of Haikou. Heavy rain is the main disaster-causing factor in inland areas, while high tide level is the main disaster-causing factor in island areas. For the area whose main disaster-causing factor is heavy rain, water storage projects could effectively reduce flooding. Meanwhile, pumps are economical choices for the area where tide level is the main disaster-causing factor. The results can provide reference for drainage planning in other coastal areas.

Keywords Flood · Urban flood inundation model · Hazard degree · Drainage facilities

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1 Introduction

With the increasing frequency and intensity of extreme weather and the acceleration of urbanization, flood is considered as the most common natural disaster worldwide during last decades (Feng et al. 2001; Adelekan 2010). Floods have caused extremely severe disasters with economic losses, social impacts and personal casualties in urban cities, especially in China (Lu and Ran 2011; Zheng et al. 2013; Yin et al. 2013). For example, the July 2012 huge flood event in Beijing caused 79 deaths and at least 10 billion Yuan economic losses. Besides, according to the statistics released by the Office of State Flood Control and Drought Relief Headquarters, 1508 cities across 28 provinces in China had suffered urban flooding for the effect of super ENSO events, which caused 237 people death, 93 missing and 146.92 billion Yuan losses before July 13, 2016.

In China, coastal cities with high urbanization level and rapid economic growth are more vulnerable to floods caused by a combination of rainfall and tide level, the main disaster-causing factors in coastal cities (Zhong et al. 2012; Lian et al. 2013). Floods caused by simultaneous extremes are usually more severe than that when either variable is extreme in isolation (Zheng et al. 2014). In order to correctly estimate the flood risk of coastal areas and propose reasonable drainage planning, it is critical to investigate the joint effect of rainfall and tide level on flood events.

Current researches on rainfall and tide level mainly focus on their dependence. Coles et al. (1999) found that there was a statistical dependence between rainfall and tide level in Oxford and Worthing in southern England. Svensson and Jones (2006) proposed that the statistical dependence between rainfall and tide level should be taken into account for flood risk management. Recently, various methods have been used to quantify the dependence between rainfall and tide level in coastal cities. Liu and Chen (2011) used Copula-based models to investigate the joint distribution of rainfall and tide level, and the drainage standards in coastal cities were proposed based on the encounter probability of rainfall and tide level. Xu et al. (2014) investigated the joint probability of extreme precipitation and storm tide level and its variation under changing environment by Copulas. Zheng et al. (2013) established a bivariate logistic threshold-excess model to investigate the dependence between rainfall and tide level along the Australian coastline. Zheng et al. (2014) compared three classes of statistical methods—threshold excess, point process and conditional—in terms of their ability to quantify flood risk. Zheng et al. (2015a, b) proposed an efficient joint probability method (the design variable method) to estimate flood risk in the coastal zone. The result showed that it was critical to incorporate the dependence between extreme rainfall and storm tides to correctly estimate the coastal flood risk.

The above analyses confirm that the dependence between rainfall and tide level is significant and has a great impact on flood risk estimate (Svensson and Jones 2006; Lian et al. 2013; Zheng et al. 2013, 2014). However, few attentions have been paid to the relationship between disaster-causing factor and flood extents, such as the hazard degree of rainfall and tide level and the main disaster-causing factor in a drainage district. The main disaster-causing factor has a significant impact on flooding risk management, because different drainage facilities need to be considered in different disaster-causing factor areas. Therefore, it is important to quantify the hazard degree of disaster-causing factors and identify main disaster-causing factor (rainfall or tide level) for flood risk management in coastal cities.

The main objective of this paper is to present an integrated method to quantify the hazard degree of rainfall and tide level in different drainage districts, and investigate the

optimal management of flooding risk based on risk division of rainfall and tide level. The study would provide significant support for drainage planning decision making in coastal areas. The framework of the method is described in Sect. 2. In Sect. 3, taking a coastal city named Haikou in China as an example, the hazard degree of rainfall and tide level is calculated and two kinds of drainage facilities are compared by disaster reduction analysis and cost–benefit analysis in different disaster-causing factor areas. The conclusions are summarized in Sect. 4.

2 Methods

2.1 Overall framework

The overall framework of the method is shown in Fig. 1. Firstly, an urban flood inundation model is built by coupling 2D surface inundation model, river hydrodynamic model and pipe model. Secondly, using urban flood inundation model, flood inundation extents could be simulated under typical scenarios combining rainfall and tide level. Thirdly, according
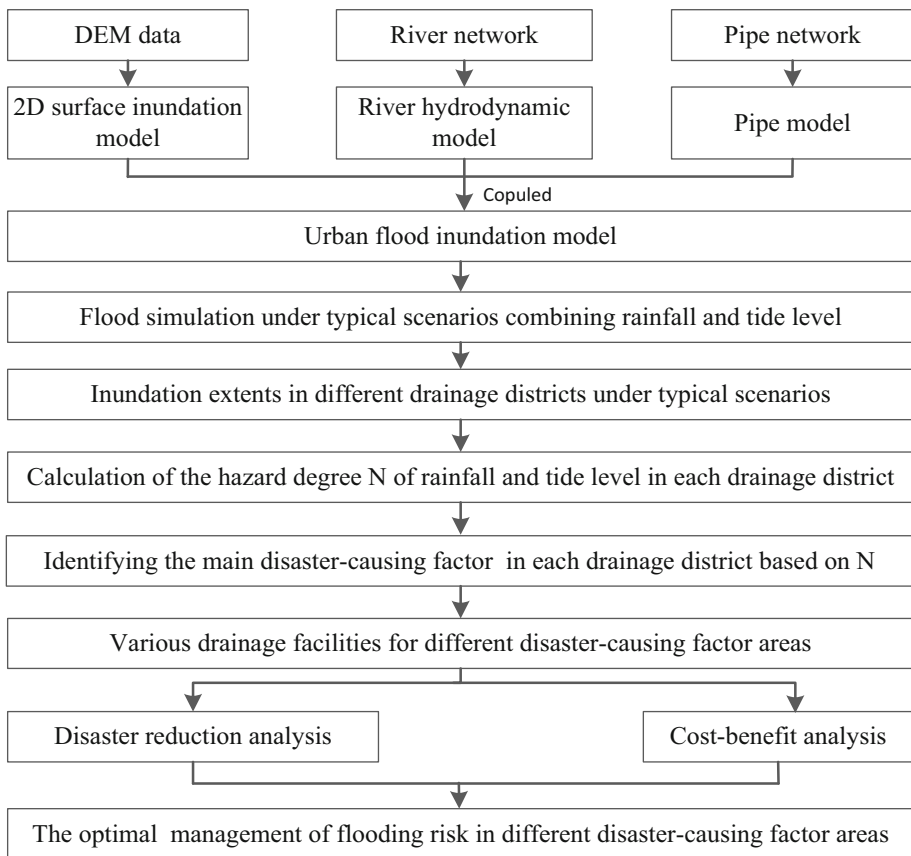

Fig. 1 The optimal management framework of flooding risk based on the hazard degree of rainfall and tide level in a coastal city

to the inundation extent, the hazard degree N and the main disaster-causing factor are calculated in each drainage district. Finally, the optimal management of flooding risk in different disaster-causing factor areas is determined by disaster reduction analysis and cost–benefit analysis, and reasonable drainage facilities are proposed for different disaster-causing factor areas.

2.2 Urban flood inundation model

In recent years, a GIS-based 1D–2D coupling model, which combines rainfall runoff, pipe and river flow, and surface flow models with a high-resolution digital elevation model (DEM), has been developed to estimate the inundation extent in urban areas at a small scale (Li et al. 2009a, b). The 1D hydraulic models, including pipe model and river hydrodynamic model, could be used to simulate pipe flow and river flow based on the Saint Venant equations (Akan and Houghtalen 2003). The 2D surface flood model could be used to simulate unsteady 2D surface flow above ground by integrating the equations of mass and momentum conservation. Large numbers of commercial software programs are available for conducting such computations. For example, HEC-RAS, MIKE11 and SOBEK can be employed to establish river hydrodynamic model. MIKE URBAN and SWMM can simulate pipe flow in sewer system. A GIS tool with DEM could be used to calculate the inundation extent of pipe network and river network. Moreover, software programs like MIKE FLOOD and PCSWMM can couple 1D and 2D hydraulic models to build urban flood inundation model precisely.

2.3 Quantifying the hazard degree of rainfall and tide level

Using urban flood inundation model, inundation extent in each drainage district can be calculated under different combinations of rainfall and tide level. The hazard degree could be quantified based on the inundation extent. For different combinations of rainfall and tide level, if the inundation extent significantly increases with the growth of rainfall and does not change with tide level, then rainfall is the main disaster-causing factor in this drainage district. On the contrary, tide level is the main disaster-causing factor. If the inundation extent significantly increases with the growth of rainfall and tide level, then both rainfall and tide level are disaster-causing factors. The following method can be used to quantify the hazard degree of rainfall and tide level.

Firstly, the relative changing ranges of rainfall ΔH and tide level ΔZ are defined as follows:

$$\Delta H = \frac{h_n - h_1}{h_n} \tag{1}$$

$$\Delta Z = \frac{z_n - z_1}{z_n} \tag{2}$$

where h_n and z_n are the maximum rainfall and tide level in design conditions, respectively. h_1 and z_1 are threshold values of rainfall and tide level, respectively, which lead to flood inundation.

Then, the relative changing ranges of inundation extent H' caused by rainfall and Z' caused by tide level are expressed as formulas (3) and (4):

$$H' = \frac{\alpha_n - \alpha_1}{\alpha_n} \tag{3}$$

$$Z' = \frac{\beta_n - \beta_1}{\beta_n} \tag{4}$$

$$\alpha_1 = (\alpha_{11} + \alpha_{12} + \ldots + \alpha_{1n})/n \tag{5}$$

$$\alpha_n = (\alpha_{n1} + \alpha_{n2} + \ldots + \alpha_{nn})/n \tag{6}$$

$$\beta_1 = (\beta_{11} + \beta_{12} + \ldots + \beta_{1n})/n \tag{7}$$

$$\beta_n = (\beta_{n1} + \beta_{n2} + \ldots + \beta_{nn})/n \tag{8}$$

where α_{11}, α_{12}, …, α_{1n} are inundation extents when rainfall is h_1 and tide level changes from z_1 to z_n; α_{n1}, α_{n2}, …, α_{nn} are inundation extents when rainfall is h_n and tide level changes from z_1 to z_n; β_{11}, β_{12}, …, β_{1n} are inundation extents when tide level is z_1 and rainfall changes from h_1 to h_n; β_{n1}, β_{n2}, …, β_{nn} are inundation extents when tide level is z_n and rainfall changes from h_1 to h_n; α_1 and α_n are average inundation extents as rainfall is h_1 and h_n, respectively; β_1 and β_n are average inundation extents as tide level is z_1 and z_n, respectively.

The definitions of N_H representing the inundation extents in unit change of rainfall and N_Z representing the inundation extents in unit change of tide level are as follows:

$$N_H = \frac{H'}{\Delta H} \tag{9}$$

$$N_Z = \frac{Z'}{\Delta Z} \tag{10}$$

Here N_H means the hazard degree of rainfall and N_Z means the hazard degree of tide level. By comparing N_H with N_Z, the hazard degree of rainfall and tide level in a district can be defined as follow:

$$N = \frac{N_H}{N_H + N_Z} \tag{11}$$

The range of N is 0–1. Drainage district with larger N value indicates that it is more strongly affected by rainfall than by tide level. Table 1 shows the relationship between N and the main disaster-causing factor.

2.4 Optimal management of flooding risk based on the hazard degree of rainfall and tide level

2.4.1 Disaster reduction analysis

Drainage facilities include building water storage projects and pump stations, changing sewer systems and underlying surface conditions, etc. The inundation level can be

Table 1 The relationship between N and the main disaster-causing factor

N	0–0.4	0.4–0.6	0.6–1.0
The main disaster-causing factor	Tide level	Rainfall and tide level	Rainfall

simulated by the urban flood inundation model mentioned above. Then, the disaster reduction ΔD, defined as the reduction of inundation level after the implement of drainage facilities, can be calculated as:

$$\Delta D = D_{\text{before}} - D_{\text{after}} \tag{12}$$

where ΔD is the disaster reduction; D_{before} is the inundation level without drainage facilities; D_{after} is the inundation level after the implementation of drainage facilities.

2.4.2 Cost–benefit analysis

Cost–benefit analysis (CBA) is a well-known approach to analyze economic scenarios of projects, which compares the benefits of a project with its corresponding costs of implementation. It provides valuable information on the net benefits of a proposed project, so that it can help decision-makers to make reasonable decisions (Ashley et al. 2007; Turner et al. 1994). The formula of net present value (NPV) is defined as follows:

$$\text{NPV} = \sum_{t=t_0}^{t_e} \frac{B_t - C_t}{(1+r)^t} \tag{13}$$

$$C_t = V_t \times \text{CP} \tag{14}$$

$$B_t = B' \cdot m_t = \sum_{i=1}^{s} B_i' \cdot m_t^i \tag{15}$$

$$B' = [B_1' \, B_2' \ldots B_s'] = \text{BP} \cdot [\Delta D_1 \, \Delta D_2 \ldots \Delta D_s] \tag{16}$$

$$m_t = [m_t^1 \, m_t^2 \ldots m_t^s]^T \tag{17}$$

where B_t and C_t are the benefit and cost of a project at year t, respectively; r is the social discount rate; t_0 and t_e are the start and end year of the project lifetime, respectively; V_t is the scale of drainage facilities; CP is the unit cost of drainage facilities.

The benefit B_t in this study is defined as the reduced flood damage due to the implementation of drainage facilities at year t. It could be calculated by B' and m_t (see formula 15). B' is the reduced flood damage due to the implementation of drainage facilities in a strong rainfall event or high tide level event. m_t is the occurrence times of strong rainfall events or high tide level events at year t. For B', it could be calculated by BP and ΔD (see formula 16). BP is the flood damage in unit inundation depth which could be calculated by historical disaster loss data. And ΔD is the reduction of inundation level after the implementation of drainage facilities. It should be noted that different rainfall events and high tide level events have different inundation level reduction ΔD. So B' is also different under various conditions. Suppose there are s kinds of conditions, B' can be expressed as formula 16. For m_t, it can be calculated by following ways:

1. According to historical rainfall and tide level data, if the occurrence times of strong rainfall events and high tide level events are highest in year q, m_t is selected as m_q all the time considering the most unfavorable conditions; here m_q is the occurrence times of strong rainfall events and high tide level events in year q.
2. If the project lifetime is set to p years in the calculation, m_t is taken as the average occurrence times of each condition during past p years.

3. Assuming that rainfall and tide level would not change in future p years, the occurrence time m_t of each year in future p years is the same as that in past p years.

Through disaster reduction analysis and cost–benefit analysis, the optimal drainage facility could be proposed for each drainage district.

3 Case study

3.1 Study area

The city center of Haikou in Hainan Province, China, is chosen as the study area (Fig. 2). It is close to the Qiongzhou Strait, which is one of the frequent typhoon invasion areas. Over the past decade, about 4 typhoons affected Haikou on average every year. Typhoon rainstorm would cause severe urban waterlogging, which results in road flooding, traffic disruption, municipal drainage facility damage and many other adverse effects. For example, typhoon Rammasun attacked Haikou in July 2014, causing that all 22 towns in Haikou were flooded with 855,900 people affected and the direct economic losses of about 13.627 billion Yuan.

In addition to frequent typhoon invasion, the terrain of the study area is relatively flat (see Fig. 2), especially in Haidian Island located in the intersection of Qiongzhou Strait and Nandu River in the north of Haikou. So it exhibits high risk of flooding due to the joint impact of typhoon rainstorm and flat terrain.

The river network and drainage facilities in the study area are shown in Fig. 2. So far, four pump stations with the total design flow of 11.1 m³/s have been built, and three pump stations are under construction with the total design flow of 26.9 m³/s. Besides, there are
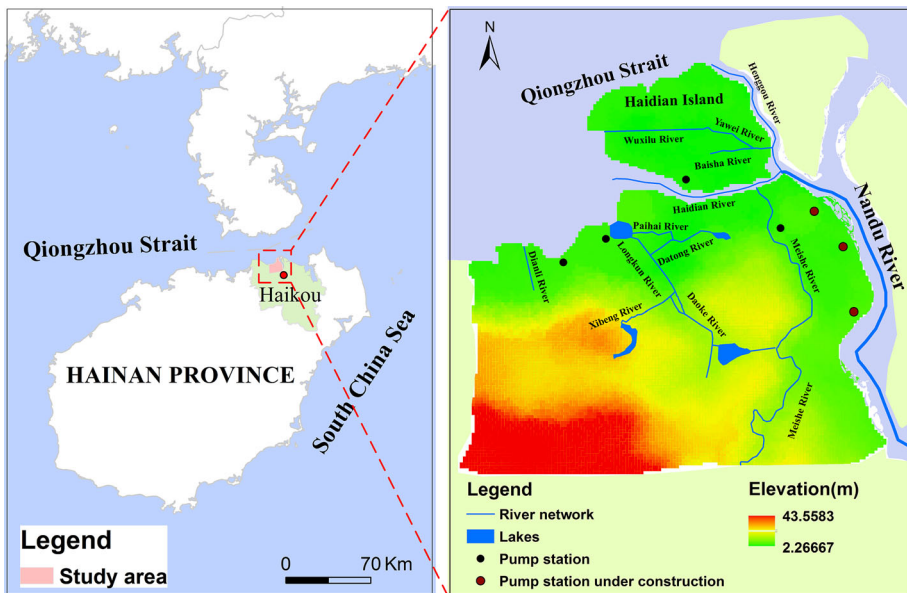

Fig. 2 The location of study area

four lakes for storing rainfall with the total storage capacity of 1,960,000 m^3 in the study area.

3.2 Urban flood inundation model in Haikou

The data used for the urban flood inundation model include rainfall, tide level, the digital elevation model data, river data and pipe network data, which are offered by Haikou Municipal Water Authority. Based on the measured rainfall and tide level series from 1974 to 2012 in Haikou Station, different combinations of rainfall and tide level are selected as different conditions for the model. The distributions of rainfall and tide level are fitted using Pearson type-III (P-III) distribution. The comparison of empirical and theoretical distributions for rainfall and tide level is plotted in Fig. 3a, b, respectively, indicating that the theoretical distributions fit the observation data very well. Design standard rainfalls (with return periods (RPs) of 5, 10, 20, 50) are taken as typical rainfall and typical tide levels are taken as 1.88, 2.25, 2.53, 2.8, 3.17 and 3.45 m.

The one-dimensional pipe model is developed through the well-known SWMM tool with a user-friendly interface for data input and visualization of results, which can calculate runoff generation and concentration in each drainage district and also can simulate the pipe flow in different conditions. HEC-RAS software is applied to establish the river hydrodynamic model. The pipe flow calculated by SWMM can be used as flow boundary conditions in the river hydrodynamic model. Water level boundary conditions are selected as typical tide levels. Finally, a GIS tool combined elevation map of Haikou is used to extract the inundation extent of pipe network and river network, thereby forming the urban flood inundation model of Haikou.

3.3 The hazard degree of rainfall and tide level in Haikou

The study area is divided into 12 drainage districts according to pipe network distribution, river network distribution and terrain of Haikou (Fig. 4). The runoff generated by rainfall in different drainage districts flows into different areas, such as pipe network, river network and the Qiongzhou Strait. The runoff in HX district, B district and HD district flows into the Qiongzhou Strait directly. For other drainage districts, it flows into urban river network firstly and then goes into the Qiongzhou Strait.

The inundation extent of each drainage district is simulated by the urban flood inundation model under different conditions. According to simulated results and formulas (1)–(11), the hazard degree of rainfall and tide level is quantified (Table 2). Combining the
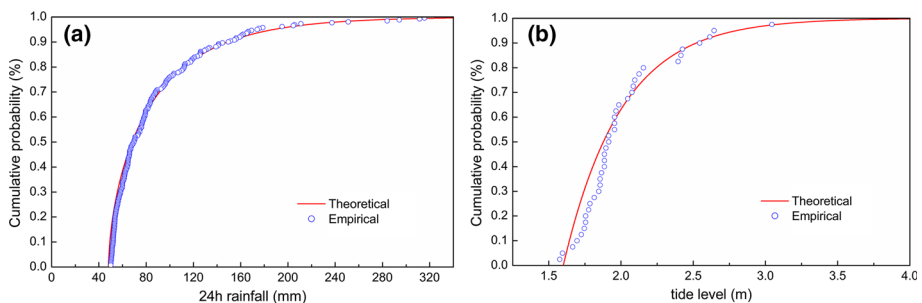

Fig. 3 Comparison of empirical and theoretical distributions for **a** rainfall and **b** tide level
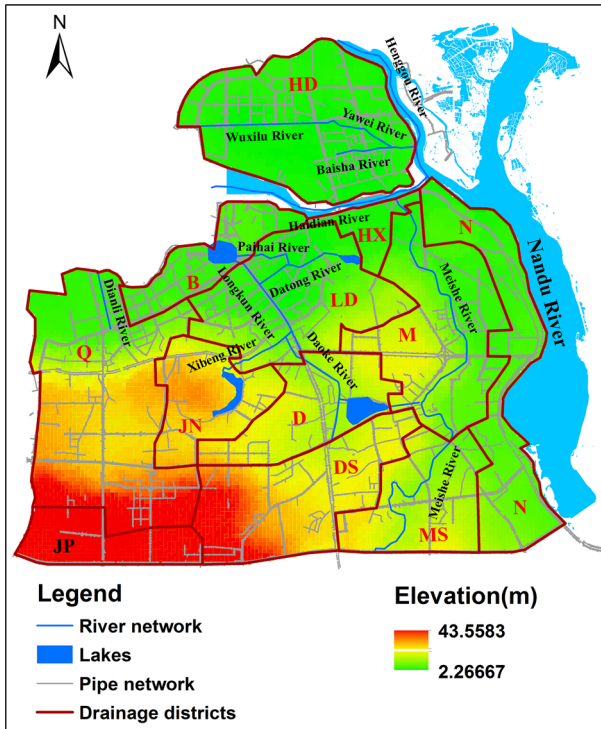
Fig. 4 The drainage districts in Haikou

Table 2 The hazard degree N and the main disaster-causing factor of each drainage district

Drainage districts	The hazard degree N	The main disaster-causing factor
HD	0.30	Tide level
HX	0.35	Tide level
B	0.38	Tide level
LD	0.41	Tide level and rainfall
N	0.48	Tide level and rainfall
M	0.49	Tide level and rainfall
Q	0.67	Rainfall
D	0.95	Rainfall
DS	0.96	Rainfall
MS	0.96	Rainfall
JN	0.97	Rainfall
JP	0.98	Rainfall

relationship between the hazard degree and the main disaster-causing factor in Table 1, the main disaster-causing factor of each drainage district is presented in Table 2. The risk zoning of rainfall and tide level is shown in Fig. 5 for the city center of Haikou.

Figure 5 shows that the hazard degree increases with the increasing distance between the drainage district and the Qiongzhou Strait or the Nandu River. Rainfall is the main disaster-causing factor in D district, Q district, MS district, JP district, JN district and DS district. Tide level is the main disaster-causing factor in HD district, B district, HX district. The other districts are affected by both rainfall and tide level. The reasons are as follows:

1. The areas where rainfall is the main disaster-causing factor are generally far away from the sea. When flood occurs, it generally flows into urban river firstly and then will be pumped into the sea. For these areas, the direct impact of tide level is slight due to long drainage channels. Urban waterlogging is mostly caused by low drainage standards of pipe network and insufficient flow capacity of urban river. For example, the flood of Q districts flows into the Dianli River through pipe network firstly and then is pumped into the Qiongzhou Strait. The drainage channel of Q district is very long, and the areas in the upstream Dianli River have the same drainage channel, which results in a lot of flood flowing into the Dianli River at the same time. It exceeds the flow capacity of the Dianli River, which causes the waterlogging in Q districts.

2. The areas where tide level is the main disaster-causing factor are generally close to the sea. The flood of these areas flows into the sea directly, or it flows into urban river firstly and then is pumped into the sea and the Nandu River. In these areas, the drainage channels are relatively short and it is fast to drain. However, these areas are easily attacked by flood due to tide jacking, low pumping capacity and low drainage standards of pipe network. For example, HD district is in the intersection of
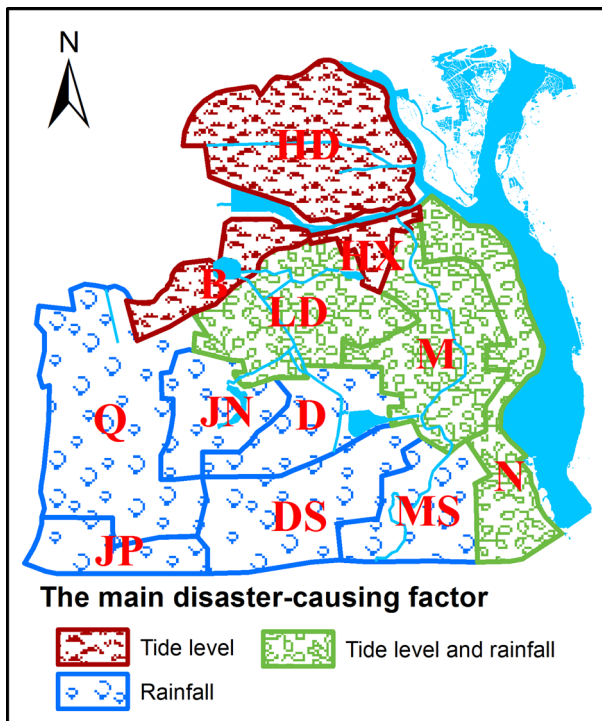

Fig. 5 The risk zoning of rainfall and tide level in Haikou

Qiongzhou Strait and Nandu River. So it is easily affected by tide jacking due to its geographical location and flat terrain. Besides, the drainage pipe network standard is low, and there is only a pump station with the design flow of 5.79 m³/s. The waterlogging occurs frequently due to tide jacking and poor drainage facilities in HD district.

To mitigate the waterlogging, lots of drainage facilities should be taken. For areas mainly affected by rainfall, the source reduction (like water storage project) and interception method (like LID infrastructures) should be adopted. And the waterlogging should be alleviated by increasing the volume of water storage. For areas mainly affected by tide level, the drainage capacity of pump station should be improved.

3.4 Optimal management of flooding risk based on the hazard degree in Haikou

Based on the results of hazard degree of rainfall and tide level, typical district where rainfall is the main disaster-causing factor and the district where tide level is the main disaster-causing factor are taken as examples to investigate the optimal management of flooding risk in different disaster-causing factor areas. In our study, drainage facilities include water storage projects and pump station projects. The process of evaluation can be described as follows. Firstly, the disaster reductions of two drainage facilities are calculated by urban flood inundation model. Then cost–benefit analysis is conducted to evaluate the economic benefit of drainage facilities. Finally, reasonable drainage facility is proposed based on disaster reduction analysis and cost–benefit analysis in different disaster-causing areas.

3.4.1 Disaster reduction analysis of drainage facilities

3.4.1.1 Disaster reduction analysis in districts mainly affected by rainfall   Taking Q district where rainfall is the main disaster-causing factor as an example, different combinations of rainfall and tide level are selected as simulation conditions. In different conditions, design standard rainfalls (with return periods (RPs) of 5, 10, 20 and 50 year) are selected and tide level is chosen as average high tide level for many years. The storage capacity of water storage project is taken as 500,000 m³. The design flow of pump station project is taken as 20 m³/s, and the amount of pumping water is also taken as 500,000 m³ in order to compare the disaster reduction of the two drainage facilities under the same condition.

The disaster reduction analysis of drainage facilities is shown in Fig. 6a. The figure shows that inundation level is significantly reduced after the implementation of drainage facilities, and the reduction of water storage project is higher than that of pump station project. The average inundation levels of two drainage facilities decrease from 3.67 to 2.97 and 3.41 m, respectively. Therefore, the disaster reduction of water storage project is obviously higher than that of pump station project in districts where main disaster-causing factor is rainfall.

3.4.1.2 Disaster reduction analysis in districts mainly affected by tide level   Taking HD district where tide level is the main disaster-causing factor as an example, in different simulation conditions, typical tide levels are selected as 1.88, 2.25, 2.53, 2.8, 3.17 and 3.45 m. The return period of rainfall is selected as 5 years. According to the runoff
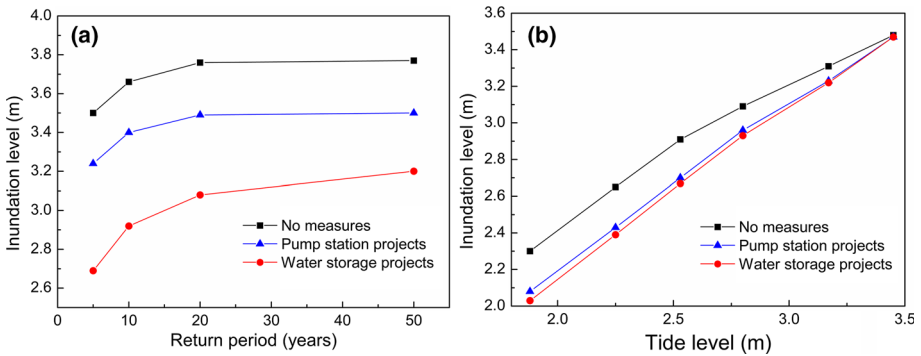
Fig. 6 Inundation level changes in **a** Q district and **b** HD district

generation and concentration calculation in HD district, the storage capacity of water storage project is taken as 200,000 m³ and the design flow of pump station project is taken as 10 m³/s.

Inundation level reductions of water storage project and pump station project are shown in Fig. 6b. The figure shows that inundation level significantly reduces in low tide level conditions. The reduction of water storage project is slightly higher than that of pump station project. However, in high tide level conditions, inundation level reductions of two drainage facilities are both slight. There are two reasons: (1) HD district is situated at Haidian Island where the terrain is extremely low and flat, and it is located in the intersection of Qiongzhou Strait and Nandu River. When tide level is high, most of areas in Haidian Island will suffer from severely floods due to the impact of tide jacking and flat terrain, which would result in the difficulty to reduce flood inundation no matter what drainage facilities are taken. (2) When pump station project is located at downstream river, it may have a limited effect on reducing flood due to the low flow capacity of rivers. This is in line with the result of Lian et al. (2013).

3.4.2 Cost–benefit analysis of drainage facilities

In this study, the benefits are defined as the flood damage reductions due to the reduction of inundation level after the implementation of drainage facilities; the costs are defined as the investment costs of water storage project and pump station project. The NPVs of two drainage facilities can be calculated by formulas (13)–(19).

$$C_{\text{storage}} = V \times CP_{\text{storage}} \tag{18}$$

$$C_{\text{pump}} = V \times CP_{\text{pump}} \tag{19}$$

where C_{storage}, CP_{storage} are the investment cost and the unit cost of water storage project, respectively; C_{pump}, CP_{pump} are the investment cost and the unit cost of pump station project, respectively.

CP_{storage} and CP_{pump} are selected as 5 million Yuan per 10,000 cubic meters and 3 million Yuan per quantity of flow, respectively, according to market price. The project lifetime is taken as 10 years. The social discount rate r is taken as 8%. In order to estimate the unit flood damage BP accurately in Haikou, Table 3 shows the inundation depth and economic loss in four rainfall events, RE-1 (October 12, 2008), RE-2 (August 05, 2009),

Table 3 Inundation depth and economic loss for different rainfall events

Year	Rainfall events	Inundation depth (m)	Economic loss (million Yuan)
2008	RE-1	1.5	331.188
2009	RE-2	0.5	57.702
	RE-3	0.7	38.810
	RE-4	0.5	30.330

RE-3 (September 28, 2009), RE-4 (October 12, 2009). The unit flood damage BP in formula (14) is selected as the average economic loss in unit inundation depth of the four rainfall events.

Considering calculation conditions in Sect. 3.4.1, m_t in Q district is the occurrence times of design standard rainfalls (with return periods (RPs) of 5, 10, 20 and 50 year) at year t. In HD district, it is the occurrence times of typical tide levels when the rainfall return period is 5 years. Table 4 shows the occurrence times of different rainfall events and high tide level events during 1974–2012. Considering the most unfavorable conditions, m_t in Q district is selected as occurrence times of various conditions in 2010, and m_t in HD district is selected as occurrence times of various conditions in 2011.

The cost–benefit analysis in Q district and HD district is presented in Table 5. For Q district, the NPV of water storage project is 2307.246 million Yuan, which is much higher than that of pump station project due to its high disaster reduction benefit. For HD district, the pump station project has better economic benefit than that of water storage project. This is because the cost of pump station project is lower than that of water storage project and the benefits of pump station project and water storage project are nearly the same.

It can be concluded that the comprehensive benefit of water storage project is superior to pump station project in districts mainly affected by rainfall through disaster reduction analysis and cost–benefit analysis. Pump station project is more economical in districts mainly affected by tide level.

3.4.3 Sensitivity analysis of parameters in cost–benefit analysis

The parameters such as the unit flood damage BP, the unit cost CP of drainage facilities and the discount rate r are all critical in cost–benefit analysis. When these parameters change, it may lead to the change in suggested decisions. The sensitivity analysis of the unit flood damage, the unit cost of drainage facilities and the discount rate are illustrated in Fig. 7.

3.4.3.1 Sensitivity analysis of the unit flood damage   From Fig. 7a, d we can see that when the unit flood damage changes from 100 million Yuan to 200 million Yuan, both the NPVs of two drainage facilities increase. For Q district where rainfall is the main disaster-causing factor, the NPVs of water storage projects are much higher than those of pump station projects, and it is more and more obvious with the increase of the unit flood damage (Fig. 7a).

For HD district where tide level is the main disaster-causing factor, when the unit flood damage is less than 160 million Yuan, the economic benefit of pump station project is superior to water storage project (Fig. 7d). It can be explained that the unit flood damage has positively linear correlation with the benefits of drainage facilities (formula 16). When

Table 4 The occurrence times of different conditions during 1974–2012 in Haikou

Year	Return period of rainfall (year)				Typical tide level (m)					
	5	10	20	50	1.88	2.25	2.53	2.8	3.17	3.45
1974	1	0	0	0	0	0	1	0	0	0
1975	1	0	0	0	0	0	0	0	0	0
1976	1	0	0	0	0	0	1	0	0	0
1977	0	0	0	0	0	0	0	0	0	0
1978	0	1	0	0	0	0	1	0	0	0
1979	1	0	0	0	0	1	0	0	0	0
1980	2	0	0	0	0	1	0	0	0	1
1981	0	0	0	0	0	0	0	0	0	0
1982	3	1	0	0	2	1	1	0	0	0
1983	0	0	0	0	0	0	0	0	0	0
1984	1	0	0	0	0	0	1	0	0	0
1985	1	0	0	0	0	0	1	0	0	0
1986	1	0	0	0	1	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0
1988	0	1	0	0	0	0	0	1	0	0
1989	4	0	0	0	1	1	0	2	0	0
1990	0	0	1	0	1	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0
1992	0	0	1	0	0	1	0	0	0	0
1993	1	0	0	0	1	0	0	0	0	0
1994	1	1	0	0	0	2	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0
1996	0	2	0	1	0	2	0	0	0	1
1997	0	1	0	0	0	0	0	1	0	0
1998	0	1	0	1	0	2	0	0	0	0
1999	1	0	0	0	0	1	0	0	0	0
2000	1	1	1	0	0	0	2	1	0	0
2001	1	1	0	0	0	0	2	0	0	0
2002	1	0	0	0	0	0	0	1	0	0
2003	1	0	0	0	0	0	1	0	0	0
2004	0	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0	0	0
2006	0	0	1	0	0	0	1	0	0	0
2007	0	0	0	0	0	0	0	0	0	0
2008	1	3	0	0	1	1	2	0	0	0
2009	0	0	0	1	0	0	1	0	0	0
2010	*1*	*2*	*0*	*1*	0	0	3	1	0	0
2011	1	1	0	1	*0*	*0*	*1*	*1*	*1*	*1*
2012	0	1	1	0	0	2	0	0	0	0

The numbers in bold italics are selected as occurrence times of various conditions in the calculation of cost–benefit analysis

Table 5 The NPVs of two drainage facilities in Q district and HD district

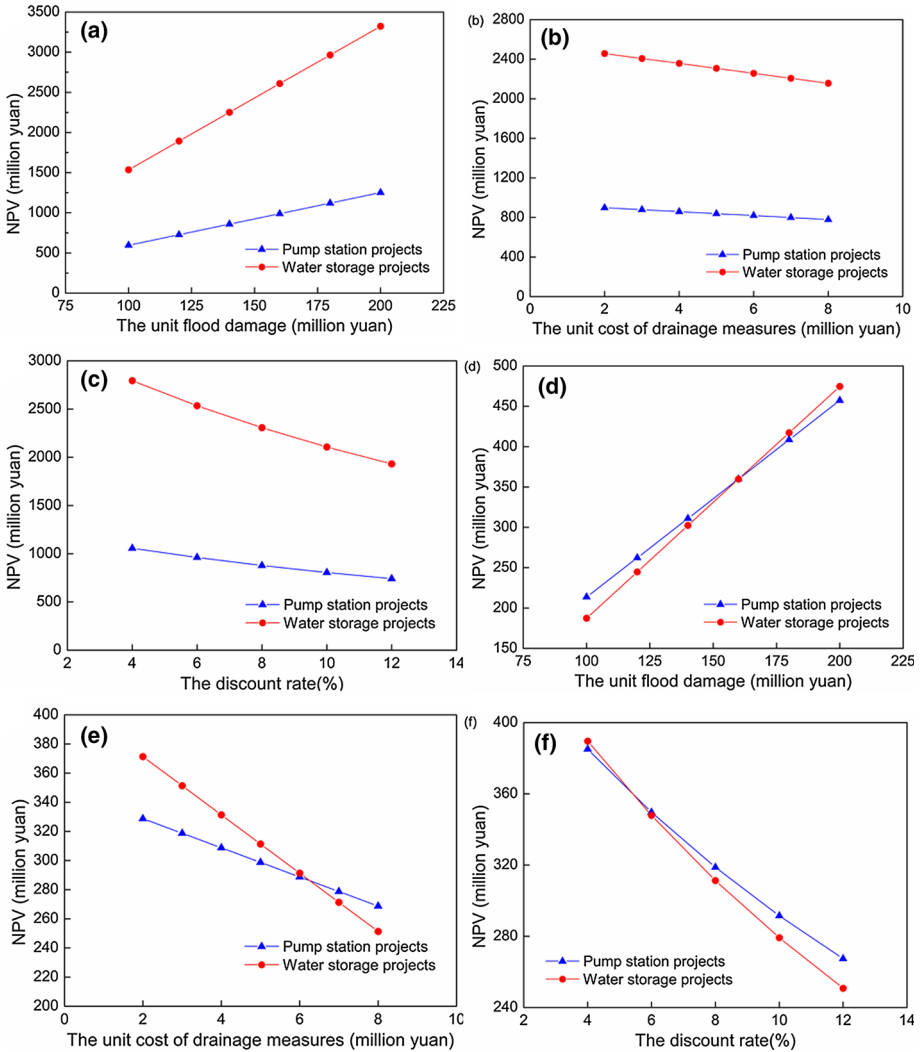| District	The NPV of water storage project (million Yuan)	The NPV of pump station project (million Yuan)
Q district	2307.246	878.849
HD district	311.305	318.715

Fig. 7 The sensitivity analysis of **a** the unit flood damage in Q district **b** the unit cost of drainage facilities in Q district **c** the discount rate in Q district **d** the unit flood damage in HD district **e** the unit cost of drainage facilities in HD district **f** the discount rate in HD district

the unit flood damage is low, the difference of the benefits of two drainage facilities becomes small, and the NPVs are determined by the investment cost. Therefore, pump station project is an economical choice due to its low investment cost. However, when the unit flood damage is more than 160 million Yuan, the NPV of water storage project is higher than that of pump station project with the increase of the unit flood damage. So water storage project is more economical in this condition.

3.4.3.2 Sensitivity analysis of the unit cost of drainage facilities When the unit cost of drainage facilities is taken from 1 million Yuan to 7 million Yuan, the NPVs of water storage project and pump station project are shown in Fig. 7b, e. From the figures, we can see the NPVs decrease with the increase of the unit cost of drainage facilities. For Q district (Fig. 7b), the economic benefit of water storage project is better than that of pump station project. It is mainly because that the inundation level reduction of water storage project is much larger than that of pump station project, which means that water storage project has much higher benefit than pump station project though the cost of pump station project is lower than that of water storage project.

For HD district (Fig. 7e), since the benefits of two drainage facilities are nearly the same (Sect. 3.4.1.2), the NPVs become very sensitive to the unit cost of drainage facilities. When the unit cost is less than 6 million Yuan, the NPVs of water storage project are greater than that of pump station project. In contrast, pump station project has better economic benefits. It is noteworthy that the above discussion is taken under the same unit cost of two drainage facilities. However, the unit cost of water storage project is usually higher than that of pump station project. When the unit cost of water storage project is 2 million Yuan higher than that of pump station project, pump station project is more economical all the time in HD district.

3.4.3.3 Sensitivity analysis of the discount rate As the discount rate increases from 4 to 12%, both the NPVs decrease in Q district and HD district. The NPV of water storage project is much larger than that of pump station project in Q district (Fig. 7c). In HD district (Fig. 7f), when the discount rate is higher than 6%, pump station project is superior to water storage project. Otherwise, water storage project is more economical.

4 Conclusions

This paper presents an approach to quantify the hazard degree of rainfall and tide level and to investigate the optimal management of flooding risk in different disaster-causing factor areas through an integration of urban flood inundation model, the method of quantifying the hazard degree and cost–benefit analysis. A coastal city, Haikou in China, is taken as an example, and several conclusions are obtained as follows.

1. Through building urban flood inundation model, the inundation extents have been simulated in different combinations of rainfall and tide level. Then, the hazard degree of rainfall and tide level in each drainage district is quantified. The result shows that different drainage districts have different hazard degree. In general, the hazard degree increases with the increasing distance between the drainage district and the Qiongzhou Strait or the Nandu River in the eastern of Haikou. Heavy rain is the main disaster-causing factor in inland areas, while high tide level is the main disaster-causing factor in island areas.

2. Taking the typical districts where rainfall or tide level is the main disaster-causing factor as examples, the optimal management of flooding risk in different disaster-causing factor areas is determined by disaster reduction analysis and economic benefit analysis. From the perspective of the disaster reduction analysis, for districts mainly affected by rainfall, water storage project is superior to pump station project, which means that impoundment measures are more effective than drainage measures in these districts. For districts mainly affected by tide level, when tide level is low, the inundation level decreases obviously after the implementation of drainage facilities. However, in high tide level conditions, the disaster reductions of two drainage facilities are both slight due to the impact of tide jacking and flat terrain. The results of cost–benefit analysis show that the economic benefit of water storage project is greater than pump station project for districts where rainfall is the main disaster-causing factor, while pump station project is an economical choice for districts where tide level is the main disaster-causing factor.

3. Through disaster reduction analysis and cost–benefit analysis, the comprehensive benefit of water storage project is superior to pump station project in districts where rainfall is the main disaster-causing factor, whereas pump station project is more suitable for districts where tide level is the main disaster-causing factor. The results can provide reference for drainage planning in other coastal areas.

4. Furthermore, the sensitivity of the unit flood damage, the unit cost of drainage facilities and the discount rate, is analyzed in cost–benefit analysis. For districts where rainfall is the main disaster-causing factor, water storage project is superior to pump station project all the time with the change of the unit flood damage, the unit cost of drainage facilities and the discount rate. For districts where tide level is the main disaster-causing factor, pump station project is very sensitive to the parameters in cost–benefit analysis. The reasonable drainage facilities should be determined by accurate parameters in other cities.

Due to the location, topography and climatic conditions, flood hazards of coastal cities are complex and multi-dimensional. For coastal cities, rainfall and tide level are two disaster-causing factors, which both have significant impact on flood events. The flood control planning should be given priority to drainage facilities for the main disaster-causing factor and supplemented by other prevention measures. Besides the drainage facilities mentioned above, low impact infrastructures (such as depressed green, green roofs and permeable paving) can provide not only a blue/green environment but also an efficient way of controlling flood hazard in the future in China (Yin et al. 2016).

As mentioned above, when heavy rain and storm tide co-occur, the potential for flooding in low-lying coastal zones is much greater than from either in isolation. Wahl et al. (2015) pointed out that the number of these compound events had increased significantly and the risk of compound flooding from storm surge and rainfall was increasing for major US cities over the past century. Knowing the changes of these compound events and extreme rainfall (Zheng et al. 2015c) with the climate changing is essential to mitigate the associated high-impact risks. Therefore, the investigation of the impact of climate change on compound events and flood risk estimation in coastal zones is an important research focus in the future.

References

Adelekan IO (2010) Vulnerability assessment of an urban flood in Nigeria: Abeokuta flood 2007. Nat Hazards 56:215–231

Akan AO, Houghtalen RJ (2003) Urban hydrology, hydraulics, and storm water quality: engineering applications and computer modeling. Wiley, Hoboken

Ashley R, Garvin S, Pasche E, Vassilopoulos A, Zevenbergen C (2007) Advances in urban flood management. Taylor & Francis Group, London

Coles SG, Heffernan J, Tawn JA (1999) Dependence measures for extreme value analysis. Extremes 2:339–365

Feng P, Cui G, Zhong Y (2001) On the eveluation and prediction of urban flood economic loss. J Hydraul Eng 8(3):64–68

Li W, Chen Q, Mao J (2009a) Development of 1D and 2D coupled model to simulate urban inundation: an application to Beijing Olympic Village. Chin Sci Bull 54:1613–1621

Li X, Wang L, Tan LZ, Zheng Y (2009b) Study on regional risk assessment of flood disaster in catchment area along Weihe river. Sci Geogr Sin 29(5):733–739

Lian JJ, Xu K, Ma C (2013) Joint impact of rainfall and tide level on flood risk in a coastal city with a complex river network: a case study of Fuzhou city, China. Hydrol Earth Syst Sci 17(1):679–689

Liu Z, Chen Z (2011) Study on the standard of waterlog prevention based on two waterlog-inducing factors. J Hydroelectr Eng 30(3):39–44

Lu X, Ran L (2011) China flood havoc highlights poor urban planning. Nat Hazards 56:575–576

Svensson C, Jones DA (2006) Joint probability: dependence between extreme sea surge, river flow and precipitation: a study in South and West Britain. R&D Technical Report FD2308/TR3, DEFRA

Turner RK, Pearce D, Bateman I (1994) Environmental economics: an elementary introduction. Prent Hall/Harvest Wheatsheaf Cornwall Person Commun Bryman A 34(2):200–204

Wahl T, Jain S, Bender J, Meyers SD, Luther ME (2015) Increasing risk of compound flooding from storm surge and rainfall for major US cities. Nat Clim Change. doi:10.1038/NCLIMATE2736

Xu K, Ma C, Lian J, Bin L (2014) Joint probability analysis of extreme precipitation and storm tide level in a coastal city under changing environment. PLoS ONE 9(10):e109341–e109341

Yin J, Yu D, Yin Z, Wang J, Xu S (2013) Multiple scenario analyses of Huangpu River flooding using a 1D/2D coupled flood inundation model. Nat Hazards 66:577–589

Yin J, Yu D, Yin Z, Liu M, He Q (2016) Evaluating the impact and risk of pluvial flash flood on intra-urban road network: a case study in the city center of Shanghai, China. J Hydrol 537:138–145

Zheng F, Westra S, Sisson SA (2013) Quantifying the dependence between extreme rainfall and storm surge in the coastal zone. J Hydrol 505(21):172–187

Zheng F, Seth W, Michael L, Sisson SA (2014) Modeling dependence between extreme rainfall and storm surge to estimate coastal flooding risk. Water Resour Res 50(3):2050–2071

Zheng F, Leonard M, Westra S (2015a) Efficient joint probability analysis of flood risk. J Hydroinform 17(4):584–597

Zheng F, Leonard M, Westra S (2015b) Application of the design variable method to estimate coastal flood risk. J Flood Risk Manag. doi:10.1111/jfr3.12180

Zheng F, Westra S, Leonard M (2015c) Opposing local precipitation extremes. Nat Clim Change 5(5):389–390

Zhong H, Van Overloop PJ, Van Gelder P, Rijken T (2012) Influence of a storm surge barrier's operation on the flood frequency in the rhine delta area. Water 4(2):474–493