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ORIGINAL PAPER

Anthropogenic effects and climate change threats on the flood diversion of Erchung Floodway in Tanshui River, northern Taiwan

Shang-Shu Shih · Sheng-Chi Yang · Huei-Tau Ouyang

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Abstract The Erchung Floodway, one of the successful measures of the Taipei Flood Prevention System, was constructed to mitigate the Tanshui River floods in the Taipei metropolitan area. The Taipei metropolitan area is the most crowded region in Taiwan. More than one-third of the total population of the country resides in this area. However, its function has changed due to urban development and natural alterations over time. The main concerns of this study are to investigate the current diversion capacity and the current vulnerability of the Taipei Flood Prevention System in accordance with influential environmental factors, including anthropogenic effects and climate change threats. Thirty-two scenarios were established for sensitivity analysis using HEC-RAS model. The results indicate that the capacity of the Erchung Floodway diversion has noticeably decreased from 9,200 to 6,300 m^3/s under a 200-year recurrence flood. Three vulnerable locations have been identified: Shihtzutou, Shezi, and Wugu. It was also found that the Taipei Flood Prevention System will encounter challenges if the roughness of the riverbed within the Erchung Floodway increases by over 50 %, the roughness of the riverbed within the Tanshui River increases by over 25 %, the water stage at the river mouth rises to 5.03 m, or the 200-year recurrence flood increases to 28,300 m^3/s. Two proposed cost-effective mitigation strategies in the present study are: (1) to remain or decrease the riverbed elevation and roughness within the Tanshui River (Taipei Bridge section); (2) to decrease the riverbed roughness by at least 25 % within the upstream and midstream of the Erchung Floodway.

S.-S. Shih
Hydrotech Research Institute, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 116, Taiwan, ROC

S.-C. Yang (✉)
Taiwan Typhoon and Flood Research Institute, National Applied Research Laboratories, 11F., No. 97, Sec. 1, Roosevelt Rd., Zhongzheng Dist., Taipei 10093, Taiwan, ROC
e-mail: shirky@narlabs.org.tw

H.-T. Ouyang
Department of Civil Engineering, National Ilan University, No. 1, Sec. 1, Shennong Rd., Yilan City, Yilan County 260, Taiwan, ROC

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1 Introduction

Population growth and improved living standards with the possession of high-value belongings have created new challenges for society and the environment and increased the vulnerability toward flood hazard (Dang et al. 2011). Following the rapid urbanization of Taiwan, approximately 80 % of the population now lives in urban areas (Huang and Hsu 2003). These urban areas are usually near large rivers due to their inherent industrial and domestic water demands. Flood inundation along riversides caused by the heavy precipitation that is associated with rainstorms or typhoons frequently occurs in lowlands and floodplains (Chen et al. 2006; Hsieh et al. 2006; Pan et al. 2012). Therefore, river floods have become a major cause of concern in Taiwan. The Intergovernmental Panel on Climate Change (IPCC 2012) indicated that the economic losses caused by weather, climate, and geophysical events in small island developing countries each year are higher than 1 % of GDP in many cases and 8 % in the most extreme cases. Understanding the impact of extreme hydrologic events is becoming essential from both a scientific and political perspective (Lehner et al. 2006).

Although Taiwan has used potential inundation maps as references to set up non-structural strategies for mitigating flood hazards (Murphy 2003; Lowe 2003; Chen et al. 2006), structural measures still play an important role in decreasing the risk of flooding. Three protection measures, including the construction of high-level protection levees, diversion channels, and detention reservoirs, have been proposed for flood mitigation (Hsieh et al. 2006). The Erchung Floodway, one of the successful measures of the Taipei Flood Prevention System, was established between 1982 and 1996 to divide the Tanshui River floods and to protect the residences living in Taipei metropolitan area. However, its function may have changed over time due to urban development, such as hydraulic facility construction and natural alterations, such as riparian vegetation succession and sediment deposition. Furthermore, climate change effects might further degrade the flood diversion function of the Erchung Floodway and increase the flood risk of the Tanshui River. Dang et al. (2011) indicated that climate changes are projected to increase the frequency and severity of extreme weather events. An observation in Central Europe shows that flood risk and vulnerability are likely to increase due to climate change (Kundzewicz et al. 2005). IPCC (2001) concluded that consequent adaptation strategies are crucial for preserving the health of human societies and a sustainable environment, because the intensity and frequency of floods may be raised due to climate change. Consequently, economic losses caused by natural catastrophes could increase significantly (Botzen et al. 2010).

From a systemic point of view, vulnerability is the relationship between a purposive system and its environment, where that environment varies over time (Green 2004). Shi et al. (2005) suggested that with rapid urbanization and climate change, flood disasters have been intensifying and threatening sustainable development, and an integrated approach to flood risk management is necessary. Few studies systematically discuss both anthropogenic effects and climate change threats for river flood mitigation. It is important to detect a decline in flood prevention ability before a potentially catastrophic flooding occurrence. This study attempts to identify the answer to the core question: Do any vulnerability exist in the Taipei Flood Prevention System due to Erchung Floodway diversion changes resulting from anthropogenic effects and climate change threats? Numerical model simulations were applied to examine the current capacity of the Erchung Floodway diversion and to conduct a sensitivity analysis of impact factors corresponding to anthropogenic effects and climate change threats. Corresponding strategies for disaster mitigation were proposed based on these results.

2 Study area

The Taipei metropolitan area, being the largest in Taiwan and including more than one-third of the total population, deserves a special attention with regard to flood prevention measures. In the past, the Taipei metropolitan area has encountered numerous severe floods with heavy losses, such as the floods caused by Typhoon Pamela in 1961 and Typhoon Opal and Typhoon Amy in 1962. To mitigate such flood disasters, a large-scale flood prevention program was implemented in 1963 and fully completed in 1999, namely the Taipei Flood Prevention System. Since 1981, dykes and levees, approximately 32 km in length, have been constructed along the major rivers in this region (Huang and Hsu 2003).

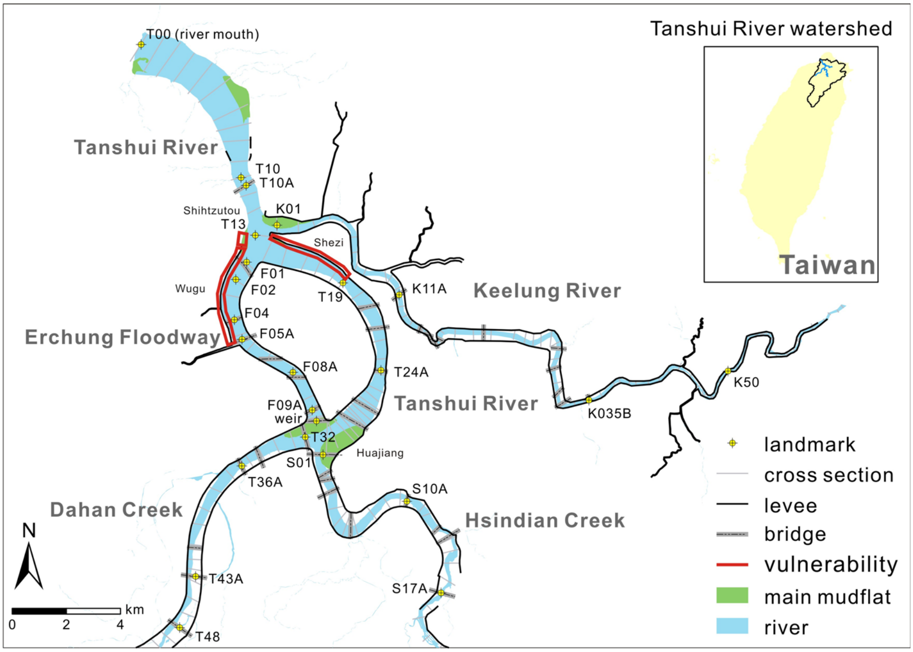

Fig. 1 Study area and current vulnerabilities of the Taipei Flood Prevention System. The Tanshui River system is located in northern Taiwan and passes through the Taipei metropolitan area. It consists of three main tributaries: the Dahan Creek, the Hsindian Creek, and the Keelung River, with a mainstream length of 158 km and a watershed area of 2,776 km^2. The study area is the downstream region of the Tanshui River System, which has high population density and has encountered numerous severe floods in the past. Three vulnerabilities were recognized according to the experiment results of the numerical model and would encounter flood inundation under Q_{200}: Shihtzutou (*left bank* from F01 to T13), Shezi (*right bank* from T13 to T19), and Wugu (*left bank* from F01 to F05A)

The specific goal of this measure was to protect the Taipei metropolitan area against the 200-year recurrence flood and reserve a 1.5 m levee height as a margin. The mitigation of floods is complicated by the bottleneck located at the smallest river width near the Taipei Bridge (section no. T24A in Fig. 1 with a river width of 450 m) which is unable to tolerate a 200-year recurrence flood. The Erchung Floodway, one of the most important measures of Taipei Flood Prevention System, was established to divide floodwaters. The specific goal of the Erchung Floodway is to divide 9,200 m^3/s of floodwater from the Tanshui River under a 200-year recurrence flood event. This allows the Q_{200}-Tanshui River to decrease from 23,500 to 14,300 m^3/s. Since its completion, the Erchung Floodway has functioned successfully during ten flood events (Table 1).

3 Methodology

3.1 Model descriptions and setup

An one-dimensional model, HEC-RAS 4.1 (Hydrologic Engineering Centers River Analysis System), was used in this study to estimate the bypass flow of the Erchung Floodway. Several numerical experiments were established to conduct the sensitivity analysis. The HEC-RAS model was developed by the US Army Corp of Engineers and has been applied to networking rivers under subcritical, supercritical, or mixed-flow conditions (e.g.,

Table 1 The records of the Erchung Floodway diversion for ten flood events

Typhoon	Maximum of water stage at T32 (m)	Time of occurrence	Bypass discharge[b] (m^3/s)	Water stage at T24A (m)		Difference (m)
				Without bypass[c]	With bypass	
Herb	5.27	3 a.m., August 1, 1996	1,078	4.55	4.10	−0.45
Zeb	5.16	7 p.m., October 16, 1998	900	4.23	3.86	−0.37
Xangsane	4.83	2 p.m., November 1, 2000	401	3.79	3.63	−0.16
Nari	4.91	3 a.m., September 17, 2001	516	3.87	3.67	−0.20
Aere[a]	6.62	8 a.m., August 25, 2004	3,519	–	–	–
Matsa	4.86	1 p.m., August 5, 2005	444	3.75	3.58	−0.17
Krosa	6.15	8 p.m., October 6, 2007	2,626	5.56	4.39	−1.17
Sinlaku	4.79	11 p.m., September 13, 2008	345	3.37	3.24	−0.13
Jangmi	5.13	9 p.m., September 28, 2008	853	3.88	3.54	−0.34
Saola	6.55	8 a.m., August 2, 2012	3,384	6.63	4.99	−1.64

The maximum reducing water stage at the Taipei Bridge was 1.64 m during the Typhoon Saola in 2012

[a] No data of water stage at the Taipei Bridge during Typhoon Aere

[b] Bypass discharge was estimated by $Q = 1{,}463.02\ (H - 4.50)^{1.168}$ (Water Resources Agency MOEA 2009)

[c] Water stage at the Taipei Bridge without bypass was estimated by the rating curve $Q = -1.061H^2 + 3.291H - 2.804$ (Tenth River Management Office WRA MOEA 2011, 2012)

Pappenberger et al. 2005; Rodriguez et al. 2008). The basic requirement of input data includes the networking rivers bathymetry (river connectivity, cross-sectional geometry, reach lengths, energy loss coefficients) and hydraulic data (upstream flow and downstream water level). The HEC-RAS model adopted the cross-sectional bathymetry of the Tanshui River system in 2009 as the topography data: upper boundary at T48 for the Dahan Creek, at S17A for the Hsindian Creek, and at K50 for the Keelung River as shown in Fig. 1. All bridges within this area were contained in the model. The orthographic projection was adopted to consider crossing area while the direction of all bridges is diagonal to the main stream direction. The investigation of each cross-sectional bathymetry is conducted every year by the Tenth River Management Office in WRA (Water Resources Agency) and used as the topography data in the numerical model. T00 is the first cross section of the Tanshui River and the Dahan Creek; K01 is the first cross section of the Keelung River; S01 is the first cross section of the Hsindian Creek. The upper boundaries were at T48 for the Dahan Creek, at S17A for the Hsindian Creek, and at K50 for the Keelung River. The downstream boundary is at T00 (the river mouth).

HEC-RAS provides a function, "Flow Optimizations," to optimize the division of flow at lateral structures, lateral diversions, stream junctions, and pump stations based on the energy equilibrium method (US Army Corps of Engineers 2010a, b). This function was used to estimate the bypass discharge of the Erchung Floodway. At the first iteration, this function calculates the computed energy grade lines for two cross sections just downstream of the junction under a given initial flow estimation. If the difference in the computed energy head is not within a specified tolerance, the flow would be redistributed and the profiles would be recalculated. The process proceeds until the stop criterion is met.

3.2 Scenarios setting for sensitivity analysis

A systematic sensitivity analysis from numerical model experiments is one way to investigate the impacts of environmental factors on the abilities of flood prevention measures. The variations in riverbed elevation and riverbed roughness are selected as two key factors that impact the ability of the Taipei Flood Prevention System. Furthermore, climate change threats will also lead to severe challenges for the Taipei Flood Prevention System. Two more key impact factors were selected to be examined: the water stage at the river mouth and the flow discharge of 200-year recurrence flood.

Thirty-two scenarios were examined (Table 2) considering the variation in the aforementioned key impact factors. First, the riverbed alterations within the Erchung Floodway and within the Taipei Bridge section of the Tanshui River were examined. The topography in our numerical model was further modified to measure the impact of riverbed alteration. Second, a parameter in the numerical model, Manning's n value, was modified to analyze the impact of riverbed roughness on the strength of the Taipei Flood Prevention System. The values of Manning's n within the Erchung Floodway and within the Taipei Bridge section of the Tanshui River were both further modified to −50, −25, +25, +50, and +100 %. Third, five scenarios were set to analyze the impact of water stage at the river mouth (downstream condition of the Taipei Flood Prevention System): 2.3, 2.9, 3.5, 4.03, and 5.03 m at T00. Next, considering extreme rainfall due to climate change, the 200-year recurrence flood (the total discharge of the Dahan Creek and the Hsindian Creek), that is the upper boundary condition of the Taipei Flood Prevention System, could increase from 25,000 to 28,300 m^3/s based on rain gauges records analysis of different periods (i.e., from 1954 to 1973 and from 1954 to 2008) (Water Resources Planning Institute WRA MOEA

2010). The amount of flow discharges of 200-year recurrence flood increases to 15,300 and 10,800 m^3/s for the Dahan Creek and Hsindian Creek, respectively (Table 3).

4 Results

4.1 Verification of the numerical model

The process of verification ensures the rational estimations of the bypass discharge and water stages. Manning's n values, which are a model parameter in the HEC-RAS model, should be verified. The 100- and 200-year recurrence floods were selected for model calibration and validation. The upper boundary discharges were 11,500 and 13,200 m^3/s at T48 for the Dahan Creek, 10,200 and 10,300 m^3/s at S17A for the Hsindian Creek, and 1,300 and 1,500 m^3/s at K50 for the Keelung River (Water Resources Agency MOEA 1996) respectively. The water stage at the downstream boundary was 2.3 m at the river mouth (T00).

The difference in energy head between the Erchung Floodway and the Tanshui River was used as a threshold value to determine the bypass discharge. The tolerance of energy head difference for split flow was set to 0.02 m in this study. Table 4 shows that the difference in energy head reaches 0.01 m and the bypass flow was 6,300 m^3/s at the fourth trial. After determining the bypass discharge, the simulated water stages were compared accordingly with the physical model experiment results. If the error in the water stage was unacceptable, the Manning's n value of that cross section was adjusted, and then the process of verification returned to the previous step to check the value of bypass discharge until the bypass discharge and water stage errors were both acceptable.

The results show that the bypass discharge errors were 0.2 % for calibration and 2.0 % for validation (Table 4). Under this prerequisite, all water stage errors were <4 % (Table 5). Therefore, the numerical model can be used to simulate the mechanism of flood diversion and the variation in water stages. Some larger errors did occur around the weir and outlet of the Erchung Floodway, for example, at T32, F11, F09A, and F01. Numerical models often encounter difficulties in properly reflecting the complicated flow behavior in these areas.

4.2 Sensitivity analysis

4.2.1 Riverbed elevation

In 2010, the riverbed elevation of the Erchung Floodway was higher than it was in 1986 (i.e., it had been built-up). Perhaps this was due to early industrial area development or environmental improvement of the riparian landscape. When the topography within the Erchung Floodway in the numerical model was restored from 2010 to 1986 levels, the Q_{200}-Erchung Floodway increased from 6,314 to 6,800 m^3/s. Meanwhile, the water stage at the Taipei Bridge declined from 8.13 to 8.09 m, that is, an inverse relationship between the riverbed elevation within the Erchung Floodway and the Q_{200}-Erchung Floodway was found. In order to discuss this impact further, the Erchung Floodway was divided into three sections: the upper section (weir to F08A), middle section (F08A–F04), and lower section (F04–F01). The simulated results showed that the Q_{200}-Erchung Floodway increased by 300, 170, and 130 m^3/s when the topographies of the upper, middle, and lower sections were restored from 2010 to 1986 levels, respectively. Therefore, the impact of riverbed elevation within the Erchung Floodway was in the following order: upper section > middle section > lower section.

Table 2 The scenario settings for systematic sensitivity analysis

Impact factors	Scenarios
Anthropogenic effects	
Riverbed elevation	Modified the topography data within the Erchung Floodway (whole)
	Year 1986
	Year 2010 (current)
	Modified the topography data within the Erchung Floodway (divide into upstream, midstream, and downstream)
	Year 1986
	Year 2010 (current)
	Modified the topography data within the Tanshui River (Taipei Br.)
	Year 1970
	Year 1986
	Year 2010 (current)
Riverbed roughness	Modified Manning's n values within the Erchung Floodway (whole) (%)
	−50
	−25
	+0 (current)
	+25
	+50
	+100
	Modified Manning's n values within the Erchung Floodway (divide into upstream, midstream, and downstream) (%)
	−50
	−25
	+0 (current)
	+25
	+50
	+100
	Modified Manning's n values within the Tanshui River (Taipei Br.) (%)
	−50
	−25
	+0 (current)
	+25
	+50
	+100
Climate change threats	
Water stage at river mouth	Modified the downstream boundary condition (water stage)
	2.30 (current)
	2.90
	3.50
	4.03
	5.03
200-year recurrence flood	Modified the upstream boundary condition (flow) (m^3/s)
	25,000 (current)
	28,300

Four key impact factors affecting the ability of the Taipei Flood Prevention System were selected to be examined in this study: riverbed elevation, riverbed roughness, water stage at the river mouth, and flow discharge of 200-year recurrence flood. Thirty-two scenarios were conducted in total

Table 3 The trials of the numerical model to determine the division of flow based on energy balance

Trial	Reach	Flow (m^3/s)	Energy head (m)	Difference (m)
1st	Tanshui River	14,300	8.79	1.67
	Erchung Floodway	9,200	10.46	
2nd	Tanshui River	15,500	9.01	0.99
	Erchung Floodway	8,000	10	
3rd	Tanshui River	16,500	9.19	0.41
	Erchung Floodway	7,000	9.6	
4th	Tanshui River	17,200	9.33	0.01
	Erchung Floodway	6,300	9.32	

At the first trial, the difference in energy head was 1.67 m; this value is larger than the allowable tolerance. Therefore, the bypass discharge was further modified to 8,000 m^3/s and the difference in energy head decreased to 0.99 m in the second trial. The trial-and-error process proceeds until the difference is acceptable. The optimized division of the flow was 6,300 m^3/s at the fourth trial

Table 4 The results of the numerical model verification for bypass flow discharge

Flood recurrence (years)	River	Bypass flow discharge (m^3/s)		
		Physical model[a]	Numerical model	Error %
200 (calibration)	Tanshui River (Taipei Br.)	17,200	17,186	0.2
	Erchung Floodway	6,300	6,314	
100 (verification)	Tanshui River (Taipei Br.)	18,100	16,192	2.0
	Erchung Floodway	5,400	5,508	

The errors of the bypass flow discharge were 0.2 % for calibration and 2.0 % for validation. The estimated bypass flow discharges of the numerical model were slightly larger than the experimental results of the physical model. This indicates that the numerical model can be used to simulate the mechanism of flood diversion

[a] Data from Tenth River Management Office WRA MOEA (2011)

The topography within the Tanshui River (Taipei Bridge section) in the numerical model was also modified. The simulated result showed that, when the topography was restored from 2010 to 1989 levels (the year of banned sand mining), the Q_{200}-Erchung Floodway decreased from 6,314 to 5,035 m^3/s, but the water stage at T24A declined from 8.13 to 7.51 m. In addition, when the topography was restored from 2010 to 1970 levels (the reference year to design the Erchung Floodway), the Q_{200}-Erchung Floodway and the water stage at T24A were nearly the same (6,303 m^3/s and 8.21 m). The riverbed of the Tanshui River descended before 1989 due to sand mining. Thus, water stages were lower and the Q_{200}-Erchung Floodway decreased. After 1989, the riverbed elevation stopped degrading and has been rising continuously until now. This caused the Q_{200}-Erchung Floodway to decrease 1,300 m^3/s from 1970 to 1989 and recover again from 1989 to 2010.

4.2.2 Riverbed roughness

The results showed that the riverbed roughness within the Erchung Floodway obviously affects the Q_{200}-Erchung Floodway (Fig. 2). An inverse relationship was found between these two parameters. The Q_{200}-Erchung Floodway decreased to over 2,000 m^3/s when the

Table 5 The results of the numerical model verification for water stages (unit: m)

Position	Event	Q_{200} (calibration)			Q_{100} (verification)		
		Physical model[a]	Numerical model	Error %	Physical model[a]	Numerical model	Error %
Dahan Creek	T36A	9.62	9.68	0.6	9.12	9.22	1.1
Hsindian Creek	H10A	10.46	10.50	0.4	10.32	10.19	−1.3
Keelung River	K19A	7.58	7.58	0.0	7.14	7.06	−1.1
Erchung Floodway	T32	9.10	9.36	2.9	8.68	8.92	2.8
	F11	8.81	9.09	3.2	8.39	8.66	3.2
	F09A	9.01	8.78	−2.6	8.59	8.35	−2.8
	F08A	7.91	8.03	1.5	7.49	7.55	0.8
	F05A	7.58	7.66	1.1	7.12	7.18	0.8
	F01	6.98	7.24	3.7	6.56	6.78	3.4
Tanshui River	T24A	8.11	8.13	0.2	7.64	7.69	0.7
	T13	6.79	6.78	−0.1	6.36	6.33	−0.5
	T10	4.91	4.91	0.0	4.61	4.60	−0.2
	T00	2.30	2.30	0.0	2.20	2.20	0.0

The errors in the water stages were <3.7 % for calibration and 3.4 % for validation, indicating that the numerical model is able to simulate water stages, though some larger errors did occur around the weir and outlet of the Erchung Floodway, for example, at T32, F11, F09A, and F01

[a] Data from Tenth River Management Office WRA MOEA (2011)

riverbed roughness within the Erchung Floodway increased by 100 %. This indicates that it would be more difficult for floodwaters to enter the Erchung Floodway, and they would consequently flow toward the Tanshui River under the higher riverbed roughness conditions of the Erchung Floodway. The water stage at T24A rises as the riverbed roughness within the Erchung Floodway increases. This would not be conducive to flood prevention. Conversely, if the riverbed roughness within the Erchung Floodway decreases, more floods could pass by the Erchung Floodway. The Q_{200}-Erchung Floodway would increase by 1,100 m^3/s and the water stage at T24A would decline 0.09 m if the riverbed roughness of the Erchung Floodway decreased by 50 %. Moreover, the Erchung Floodway was further divided into upper (the weir to F08A), middle (F08A–F04), and lower (F04–F01) sections to reduce the riverbed roughness. The simulated results showed that the impacts of riverbed roughness within the Erchung Floodway are as follows: upper section > middle section > lower section (Fig. 3).

The values of Manning's n of the Tanshui River (Taipei Bridge section) in the numerical model were also modified to −50, −25, +25, +50, and +100 %. The simulated results showed that the riverbed roughness within the Tanshui River (Taipei Bridge section) apparently affects not only the Q_{200}-Erchung Floodway, but also the water stage at T24A (Fig. 4). This indicates that the riverbed roughness within the Tanshui River (Taipei Bridge section) is a sensitive environmental factor that influences the Taipei Flood Prevention System. The Q_{200}-Erchung Floodway increased by about 800, 1,600, and 3,000 m^3/s when the riverbed roughness increased by 25, 50, and 100 %, respectively. However, the water stage at T24A would exceed the planning water stage at 8.40 m if the riverbed roughness increased by over 25 %.

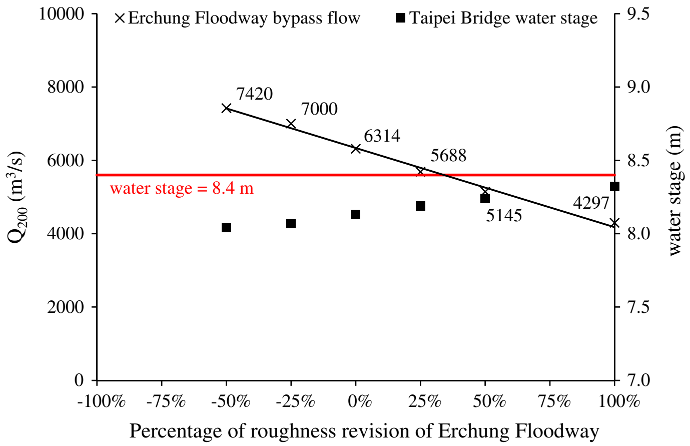

Fig. 2 The relationship among the riverbed roughness of the Erchung Floodway, the Q_{200}-Erchung Floodway, and the water stage at T24A. The simulated result showed that the riverbed roughness within the Erchung Floodway obviously affects not only the Q_{200}-Erchung Floodway, but also the water stage at T24A

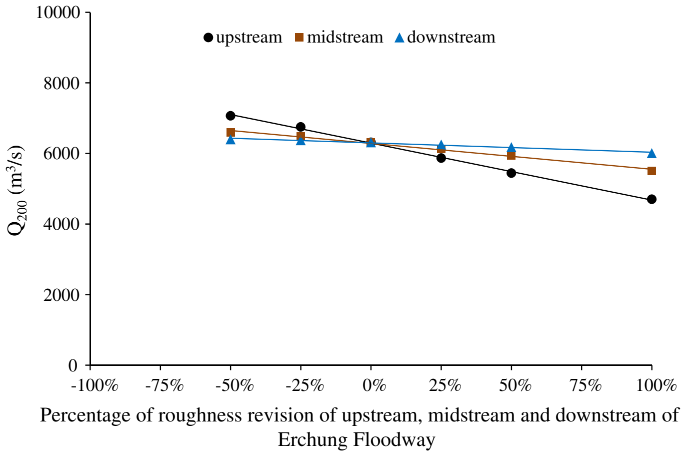

Fig. 3 The relationship between the riverbed roughness of different sections of the Erchung Floodway and the Q_{200}-Erchung Floodway. The simulated results showed that the impacts of riverbed roughness within the Erchung Floodway are as follows: upper section > middle section > lower section

4.2.3 Mean sea level

As shown in Fig. 5, a rising water stage at T00 (river mouth) would not only increase the Q_{200}-Erchung Floodway, but also raise the water stage at T24A. A higher water stage at T24A (the bottleneck) would increase flood pressure on the Taipei Flood Prevention System, though the Q_{200}-Erchung Floodway may improve. For instance, the water stage at T24A was 8.57 m, higher than the planning water stage, when the water stage at T00 was set to 5.03 m. The influence of sea-level rise on bypass flow appears to be relatively insignificant compared with the influence of the riverbed roughness variation.

4.2.4 *Amount of flood discharge*

The Q_{200}-Erchung Floodway increased about 1,200 m^3/s, which is from 6,456 to 7,659 m^3/s. However, the water stage at T24A rose to 9.00 m, which was higher than that of the planned water stage. The Taipei Flood Prevention System would encounter a severe challenge in this scenario.

5 Discussion

5.1 Current vulnerabilities

The Q_{200}-Tanshui River increased from 14,300 m^3/s (planning) to 17,200 m^3/s when the Q_{200}-Erchung Floodway decreased from 9,200 m^3/s (planning) to 6,300 m^3/s (approximately −32 %), but the water stage at T24A was 8.13, <8.40 m (planning) (Table 5). Three areas would encounter flood inundation under Q_{200}: Shihtzutou (left bank from T13 to F01), Shezi (right bank from T13 to T19), and Wugu (left bank from F01 to F05A) (Fig. 1). The levee of Shihtzutou, which is approximately 930 m long, is one of the vulnerable levees of the Taipei Flood Prevention System. Shezi and Wugu were designed to serve as detention basins for containing flood volumes in the event of a disaster. However, inundation at these two districts is no longer affordable now. Both of them have dense populations (population density was 20,154 persons/km^2 for Shezi and 2,270 persons/km^2 for Wugu in 2009) and have faced pressure from development recently. Due to our findings and economic development concerns, these three vulnerable areas would be reinforced and improved by Water Resources Agency MOEA. The levees would increase from about 6 to 9.60, 9.65, and 9.50 m for Shihtzutou, Shezi, and Wugu, respectively. All of them can prevent the overbank flood inundation of 200-year recurrence flood.

5.2 Flood threats in the near future

Based on the sensitivity analysis results of the numerical model, the following situations would raise the water stage at T24A and increase the flood risk to the Taipei Flood Prevention System: (1) riverbed accretion within the Erchung Floodway; (2) riverbed accretion within the Tanshui River; (3) increasing riverbed roughness within the Erchung Floodway by over 50 %; (4) increasing riverbed roughness within the Tanshui River by over 25 %; (5) increasing the water stage at the river mouth to 5.03 m; and (6) increasing the 200-year recurrence flood to 28,300 m^3/s.

Increasing riverbed roughness within the Erchung Floodway or within the Tanshui River may be due to anthropogenic change, such as riverside park construction, or natural succession, such as plant vegetation development. This can be controlled or even be improved by appropriate management strategies. However, a rising water stage at the river mouth and the increase in quantity of 200-year recurrence floods are due to climate change. These two phenomena are not easy to prevent and are highly uncertain. This means that systems using levees and pumps to prevent urban flooding, such as the Taipei Flood Prevention System, could encounter severe challenges in the near future.

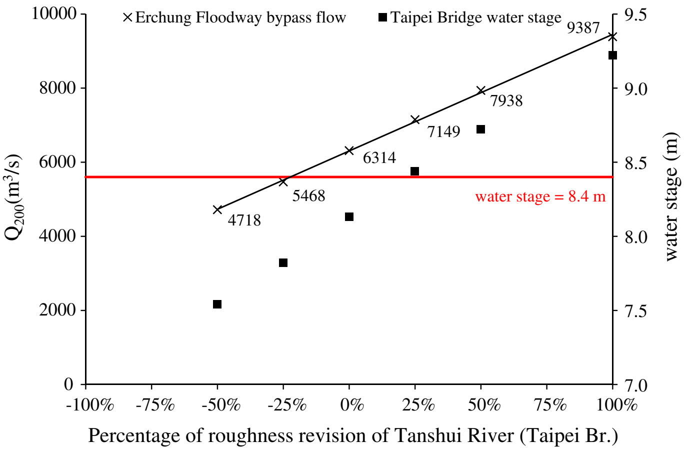

Fig. 4 The relationship among the riverbed roughness of the Tanshui River (Taipei Bridge section), the Q_{200}-Erchung Floodway, and the water stage at T24A. The simulated results showed that the riverbed roughness within the Tanshui River (Taipei Bridge section) apparently affects not only the Q_{200}-Erchung Floodway, but also the water stage at T24A

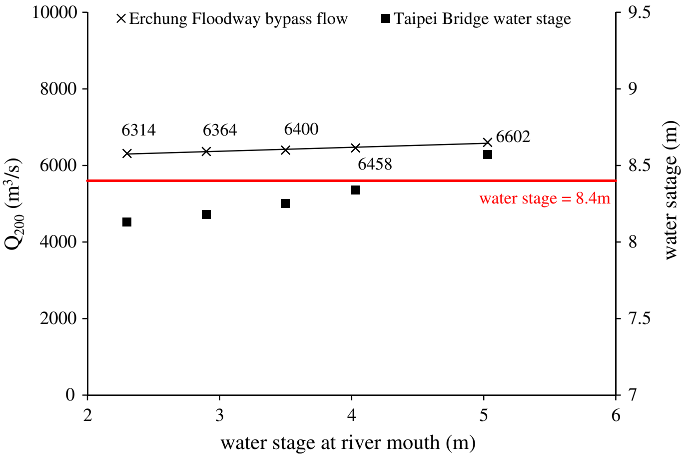

Fig. 5 The relationship among water stage at river mouth (T00), the Q_{200}-Erchung Floodway, and Taipei Bridge water stage (T24A). The simulated results showed that a rising water stage at T00 (river mouth) would not only increase the Q_{200}-Erchung Floodway, but also raise the water stage at T24A

5.3 Mitigation and adaptation strategies

According to the above simulation results, two proposed cost-effective mitigation strategies to restore the Q_{200}-Erchung Floodway and decrease flood stages are: (1) to remain or decrease the riverbed elevation and roughness within the Tanshui River (Taipei Bridge section) and to dredge silt or trim vegetation if necessary and (2) to decrease the riverbed roughness by at least 25 % within the upstream and midstream of the Erchung Floodway.

After the year of banned sand mining, i.e., 1989, the riverbed elevation within the Taipei Bridge section has been rising continuously until now. Indeed, the topography in 2010 is getting close to the level in 1970 (the reference year to design the Erchung Floodway). The increase in riverbed elevation would accelerate due to the overloading of sediment delivered from the sediment bypass tunnel of the Shihmen Reservoir. The rise of riverbed in the Taipei Bridge section is unfavorable to the strength of the Tanshui Flood Prevention System. On the other hand, the mangrove *Kandelia obovata* is spreading rapidly in the Tanshui River and has a competitive growth advantage within approximately 14.5 km (T21) from the river mouth along the Tanshui River. The riverbed roughness would obviously increase due to mangrove tree invasion into the mudflats. The capability of the mangrove invasion is expected to increase due to salt intrusion enhanced by rising sea levels, and riverbed roughness within the Tanshui River would increase consequently (Shih et al. 2011). As Yang et al. (2013) mentioned, "These mangrove forests need not only protection projects but also further management projects." Therefore, the riverbed elevation and roughness within the Tanshui River should be monitored. Silt dredging or mangrove trimming should be carried out to reduce riverbed elevation or roughness if it becomes necessary.

The riverbed roughness within the Erchung Floodway should also be managed. Because the upstream and midstream areas obviously affect the Q_{200}-Erchung Floodway, we suggest that the riverbed roughness should be decreased by at least 25 %. The riverbed roughness were tuned and determined with the value of Manning's n in this study through numerical model calibration and validation. The initial value of Manning's n was estimated by using empirical formula with different vegetation type, shape, height, density, and water depth (Woody 1956; Chow 1959). The current situation in the upstream and midstream sections was covered by grasses, distributed trees, farmlands, and parking lots. In order to decrease the riverbed roughness, the trees nearby the bridges and farmlands shall be removed. On the other hand, the riverbed of the downstream section is covered by grass, wetlands, or water. The current riverbed roughness of the downstream section is relatively low. In addition, there are a number of constructed wetlands in operation and *Mortonagrion hirosei Asahina*, an endangered species (the International Union for Conservation of nature and nature Resource, IUCN), inhabit the lower section. Thus, we suggest that the downstream section should be maintained by limited development not only for flood conveyance but also for *Mortonagrion hirosei Asahina* conservation.

6 Conclusions

Rivers in Taiwan are short with steep slopes that are favorable for the occurrence of midstream and downstream flooding. The Tanshui River basin suffers frequently flooding and inundation along riversides and surrounding lowlands by heavy precipitation associated with storms or typhoons. It took 37 years to complete the Taipei Flood Prevention System since 1963 for flood mitigation under 200-year return period flood. The implementation of structural measures was the major solution for flood defense in Taiwan. However, these measures are always limited to the design standards and cannot prevent damage when floods exceed certain scale. In addition, recently, rapid urbanization without sufficient floodplain management resulted in highly developed and densely populated zones along riverbanks. The existing hydraulic facilities were thus unable to provide adequate flood protection. The riverbed elevation and roughness changes apparently threat the strength of the Taipei Flood Prevention System.

According to the results of the sensitivity analysis, six scenarios would raise the flood stage in Tanshui River: (1) riverbed accretion in the Erchung Floodway; (2) riverbed accretion in the Tanshui River; (3) increase in riverbed roughness in the Erchung Floodway; (4) increase in riverbed roughness in the Tanshui River; (5) increase in 200-year flood return period; and (6) increase in the water surface elevation of the river mouth. We conclude that the degrading of Taipei Flood Prevention System due to rapid urbanization and climate change threats. For sustainable development and environmental protection, non-structural measures have become popular solutions for worldwide (Changnon 1998; Harman et al. 2002; Klijn et al. 2004). They are also indispensable complements to structural solutions for flood hazard mitigation (Chen et al. 2006; Li et al. 2005). Our study indicated that non-structural measures are necessary to restore the function of the Erchung Floodway. These non-structural mitigation techniques should include manipulation of decreasing the riverbed roughness and the riverbed elevation in critical regions. However, water stage variations at the river mouth and the increase discharge of the 200-year return period flood may be induced by rising sea level and climate change, respectively. These two phenomena are not easy to be predicted and overcome. It means that a system in which installs levees and pumps to prevent urban flooding, such as the Taipei Flood Prevention System, could encounter severe challenges in the near future. A comprehensive monitoring system and an effective evacuation program are suggested to establish and launch as soon as possible.

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