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Research article

A nonstructural flood prevention measure for mitigating urban inundation impacts along with river flooding effects

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ABSTRACT

In recent decades, urban developments along rivers have experienced high flooding risks, elevated by increasing urbanization. Due to the expansion of urban areas, flood mitigation strategies must rely on nonstructural flood management policies. This study evaluated the impacts of pluvial floods considering fluvial flooding effects through field surveys and numerical model simulations. Nonstructural flood protection measures are provided by establishing warning water levels based on variant scenario simulations. The results reveal that the aggravated drainage system overflow induced by elevated river water is significant when considering river flooding effects. As a result, current drainage systems have failed to meet the designed flood protection standards, indicating the need to produce potential inundation maps and to establish warning water levels. To prevent the main evacuation route of each settlement from being blocked due to flooding, the proposed warning water levels support timely and effective evacuations. Public community centers and schools in noninundation areas near settlements were identified as possible shelters based on the proposed warning water levels and inundation maps. We conclude that although the riverside areas without dike protection could sustain natural environments and landscapes, they must incorporate nonstructural flood protection measures. At the same time, it must be considered that river flood levels may reduce urban drainage capacity.

1. Introduction

The extent and intensity of damage incurred due to flooding around the world have been increasing over the last few decades (IPCC, 2012). Because it is located within the most active region of tropical cyclone formation in the Western Pacific, Taiwan frequently experiences extreme precipitation events. To prevent damage associated with such events, structural flood mitigation strategies such as levees, channel improvements, and other engineering infrastructures have commonly been implemented. However, since the 1990s, flood mitigation strategies have moved toward a new paradigm in which nonstructural flood mitigation strategies are considered (UCAR, 2010). These strategies, which emphasize altering the characteristics of the structures that experience flood damage (Buss, 2005), employ various measures, including the implementation of flood warning systems in addition to flood mapping, flood emergency preparedness planning, and evacuation planning.

Urban development along rivers has resulted in a high risk of flooding, and the risk rises with increasing development (Islam, 1997; Messner and Meyer, 2006; Mustafa et al., 2018). For example, Muis et al. (2015) projected that the urban area of Indonesia would expand by 215–357% from 2000 to 2030, which may drive a corresponding increase in river flood risk of 76%. Increasing precipitation is related to an increasing risk of flood hazards. Overall, the flood risk around the globe has been projected to increase by approximately 187% by 2050 based on predicted changes in the flood peak return periods, flood frequency, and flood damage functions under climate models with different emissions and socioeconomic scenarios, such as the Hadley Centre Coupled Model, version 3 (HadCM3) and the Special Report on Emissions Scenarios (SRES) A1b (Arnell and Gosling, 2016).

Scientific knowledge supports the increasing efficiency of flood protection. Previous studies have focused on both the development of technology and simulating the performance of flood mitigation strategies. Multiple factors, such as different precipitation patterns (Chen et al., 2006) and land subsidence (Wang et al., 2018), in addition to the impacts of climate change (Wang et al., 2013), the influences of storm surges (Chen and Liu, 2014; Doong et al., 2016) and the application of adaptation strategies (Hsu et al., 2016), have been considered in analyses and simulations of flood inundation to evaluate all of the possible causes of increased flood risks. In addition, a physiographic inundation

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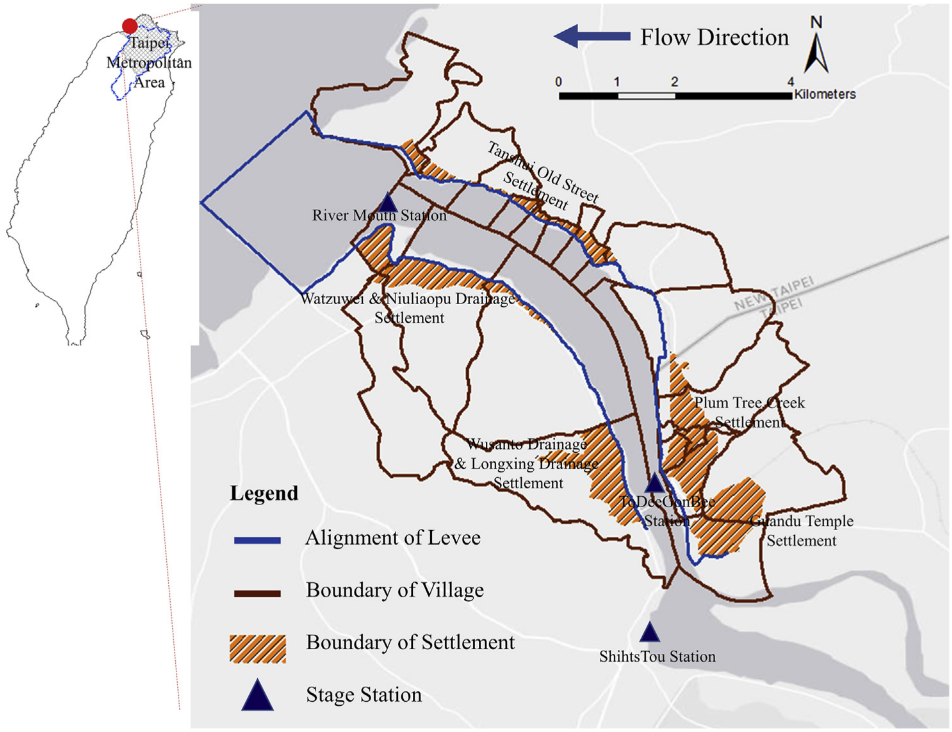

Fig. 1. The study area in the Tanshui River mouth in northern Taiwan.

model (Chen et al., 2013), spatiotemporal downscaling of rainfall and two-dimensional overland flow models (Pan et al., 2014), artificial neural networks (Liu and Chung, 2014; Fu et al., 2016), statistical models (Yang et al., 2015), a two-stage support vector machine approach (Jhong et al., 2017), and multiobjective genetic algorithms (Ouyang, 2018) have been used for the analysis and simulation of flood inundation to enhance the predictive accuracy and reduce the lead time of early warning systems.

However, there has been little discussion about the applicability of current flood mitigation strategies. Recently, Shishegar et al. (2018) reviewed more than eighty papers on stormwater management and noted the lack of research evaluating the feedback loop between the design of strategies and their application. Over the past two decades, the population of metropolitan Taipei, which was classified as an alpha city in 2018 by the Globalization and World Cities Research Network (GaWC), increased by approximately 0.4 million people. In addition to its population growth, metropolitan Taipei has experienced an increasing trend in precipitation since the 1950s and 1960s (Liu et al., 2009; Shiu et al., 2009; Chang et al., 2012; Chu et al., 2014). Accordingly, Shih et al. (2014) indicated that the downstream reach of the Tanshui River faces a high risk of river flood inundation. The potential impacts of floods caused by the increasing population and precipitation in metropolitan Taipei have attracted considerable attention. We hypothesize that river flooding effects would influence urban stormwater drainage and increase inundation impacts along riverside areas. This study attempts to examine the applicability of implementing flood mitigation in an urban area considering river flooding effects. The scope of this study is to provide a nonstructural flood prevention measure by integrating inundation maps, evacuation route maps, and warning water levels to effectively mitigate the inundation impacts of the Tanshui River mouth in metropolitan Taipei. The implications for urban inundation management will also be discussed.

2. Materials and methods

2.1. Study area

Among all the natural disasters that occur in Taiwan, flooding is the most damaging, with economic losses of approximately ten billion Taiwan dollars (TWD) per year (2012, the Central Weather Bureau's website: http://photino.cwb.gov.tw/tyweb/hazards/meteo-hazards-data.htm). Correspondingly, to alleviate flood damage, the Taiwanese government has greatly invested in flood mitigation strategies, particularly structural strategies. Since the 1950s, more than 2,500 km of levees and 700 km of embankments have been constructed along rivers in Taiwan, with a total construction cost of 700 billion TWD (Hsu and Lin, 2011). A large-scale flood prevention program called the Taipei Flood Prevention System was implemented in 1963 and fully completed in 1999 to prevent hazards and economic losses caused by flood events in the Taipei metropolitan area. As part of this program, approximately 32 km of levees and dikes were constructed along the Tanshui River to mitigate 200-year flood events. Then, in the 2000s, the concepts of nonstructural flood mitigation and management came into focus in Taiwan. The Regulation Project of Flood-prone Areas was proposed by the Ministry of Economic Affairs (MOEA) in 2006 with a budget of 116 billion TWD over an 8-year period (WRA and MOEA, 2006). In this study, we focused on a region of the Tanshui River mouth with a river length of 8.9 km.

The Tanshui River, whose downstream reach flows through the Taipei metropolitan area in northern Taiwan, is a major river in Taiwan. The mainstream of the Tanshui River is 158.7 km in length, covering an area of 2,726 km^2. The tidal regime of the Tanshui River is semidiurnal with mixed tides. The mean high water level tide (MHWL) EL was recorded at 1.40 m above sea level, and the mean low water level (MLWL) EL was recorded at -0.85 m. The downstream reach of the Tanshui River is remarkably influenced by tides with an approximate tidal reach of 31 km and a tidal range of 2.5 m. In 1999, 32 km of levees and dikes were constructed along the river to prevent flood damage in the Taipei metropolitan area. The study area, namely, the Tanshui River mouth, is the only downstream reach of the Tanshui

River that lacks levees or dikes because the flood risk therein is low due to its wide channel cross-section (Department of Water Resources, Taiwan Provincial Government, 1999). However, the growth of the population and economy in this area have increased the need to prevent flood hazards by improving the associated flood mitigation and management measures. Nineteen villages with a total area of 38 km^2 are situated along the Tanshui River mouth, as shown in Fig. 1. Over the past decade, the population of these villages has grown from 90,000 to 98,000.

Consequently, we focused on the capability and applicability of flood mitigation and management policies in five urban settlements among these villages along the Tanshui River. These five settlements, namely, the Tanshui Old Street Settlement, the Plum Tree Creek Settlement, the Guandu Temple Settlement, the Watzuwei and Niuliaopu Drainage Settlement, and the Wusanto Drainage and Longxing Drainage Settlement, are located on a 200-year floodplain with areas of 0.63 km^2, 1.21 km^2, 0.97 km^2, 1.07 km^2 and 1.01 km^2, respectively. The elevations of the Tanshui Old Street Settlement, Watzuwei and Niuliaopu Drainage Settlement, and Wusanto Drainage and Longxing Drainage Settlement range from 1.21 m to 16.98 m, from 1.56 m to 13.54 m, and from 2.68 m to 5.28 m, respectively, illustrating that some of these areas are below the designed water level, i.e., 2.7 m, for a 200-year flood event according to the Taipei Flood Prevention System.

2.2. Flood simulation

Understanding the characteristics of floods constitutes one of the key factors in determining flood mitigation strategies (UNISDR, 2015). We, therefore, performed a flood simulation to evaluate the capability and applicability of flood mitigation and management strategies in the study area. The characteristics, namely, riverbank overflow (i.e., fluvial flooding) and rainfall-generated overland flow (i.e., pluvial flooding), of two types of floods were taken into account through the CCHE2D model (National Center for Computational Hydroscience and Engineering, the University of Mississippi, 2017) and NTU-2DFIM model (Lai, 2012), respectively. The study area is typically subjected to the intrusion of seawater, but the impacts of downstream river water on drainage systems have not been evaluated. Hence, we examined the overland flow, both considering and not considering the impacts of downstream river water. For the scenario considering the impacts of river water, we adopted the river water level simulated using the CCHE2D model as the downstream boundary condition for the overland flow simulation in the NTU-2DFIM model (Fig. 2). The details of the simulations are described below.

2.2.1. Riverbank overflow

We applied the CCHE2D model, a two-dimensional depth-averaged numerical model, to simulate the water level in the estuary of the Tanshui River. The CCHE2D model was developed by the National Center for Computational Hydroscience and Engineering (NCCHE) based on the continuity equation (Equation (1)) and momentum equations (Equations (2) and (3)) (Zhang, 2005). The main procedures of the numerical simulation include the generation of the mesh, the specification of the boundary conditions, the setting of the parameters, and the simulation.

$$\frac{\partial Z}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial Z}{\partial x} + \frac{1}{h}\left[\frac{\partial (h\tau_{xx})}{\partial x} + \frac{\partial (h\tau_{xy})}{\partial y}\right] - \frac{\tau_{bx}}{\rho h} + f_{Cor}v \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial Z}{\partial y} + \frac{1}{h}\left[\frac{\partial (h\tau_{yx})}{\partial x} + \frac{\partial (h\tau_{yy})}{\partial y}\right] - \frac{\tau_{by}}{\rho h} + f_{Cor}u \tag{3}$$

where u and v are the depth-integrated velocity components in the x and y directions, respectively; Z is the water surface elevation; h is the local water depth; g is the gravitational acceleration; ρ is the water density; f_{Cor} denotes the Coriolis parameter; $\tau_{xx}, \tau_{xy}, \tau_{yx}, and\ \tau_{yy}$ are the depth-integrated Reynolds stresses; and $\tau_{bx}\ and\ \tau_{by}$ are the shear stresses on the bed surface.

In this study, we ran a steady state flow simulation of riverbank overflow events under 2-, 5-, 10-, 20-, 50-, 100-, and 200-year recurrence floods. For the simulation, the grids were generated by algebraic methods, and the topography of each grid was interpolated from the cross-sectional bathymetry data of the Tanshui River system from the Tenth River Management Office, Water Resources Agency (WRA) (Fig. 3).

We used the design discharge and water level under different recurrence intervals in the Regulation Master Plan at the River Mouth of the Tanshui River (Department of Water Resources, Taiwan Provincial Government, 1999) illustrated in Table 1 as the initial and boundary conditions for the discharge in the upstream reaches and the water level in the downstream reaches. Generally, a greater recurrence interval implies a greater discharge from the upstream reach and higher water levels in the downstream reach. The river flood levels would be caused by not only tidal level but also river flood discharge and both of the cases were considered in our river model simulation. Moreover, the discharge records of the Tanshui River and the water level at the river mouth station during Typhoon Soulik from 5:00 a.m. on July 13, 2013, to 11:00 p.m. on July 14, 2013, were used to calibrate Manning's roughness coefficient in the simulation. The recorded data during Typhoon Aere in August 2011 and Typhoon Morakot in August 2009 were used for the model validation. For the calibration and validation steps, the ToDeeGonBee station was selected for comparison, and the simulated water depth was compared with the recorded water depth in terms of the value of the Nash-Sutcliffe efficiency coefficient (NSE), as shown in Equation (5). In accordance with the suggestions of Ritter and Muñoz-Carpena (2013), NSE≥0.90 is classified as a very good simulation, whereas NSE values ranging from 0.80 to 0.90 indicate a good simulation, and values ranging from 0.65 to 0.80 indicate an acceptable simulation.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{i=N}(O_i - P_i)^2}{N}} \tag{4}$$

$$NSE = 1 - \frac{\sum_{i=1}^{i=N}(O_i - P_i)^2}{\sum_{i=1}^{i=N}(O_i - \bar{o})^2} = 1 - \left(\frac{RMSE}{SD}\right)^2 \tag{5}$$

where N is the number of samples; O_i and P_i represent the sample (of size N) containing the observations and the model estimates, respectively; $\bar{o}$ is the mean of the observed values; RMSE is the root mean square error; SD is the standard deviation of the observations.

2.2.2. Rainfall-generated overland flow

We considered the inundation depth and inundation area of the overland flow due to heavy rainfall. The two-dimensional overland flow was simulated with the inundation depth and area in a second step using the NTU-2DFIM model based on hydrographs of the overflow rate at the manhole calculated using the Storm Water Management Model (SWMM). The impacts of downstream river water were analyzed in the two-dimensional overland flow simulation based on the river water level simulation using the CCHE2D model. Following the goal of regulating floods throughout the regional drainage system in the Taipei metropolitan area, to prevent a 5-year flood, we focused on the flood inundation under 24-h precipitation with a 5-year recurrence interval. A water depth exceeding 0.3 m was defined as inundation based on the

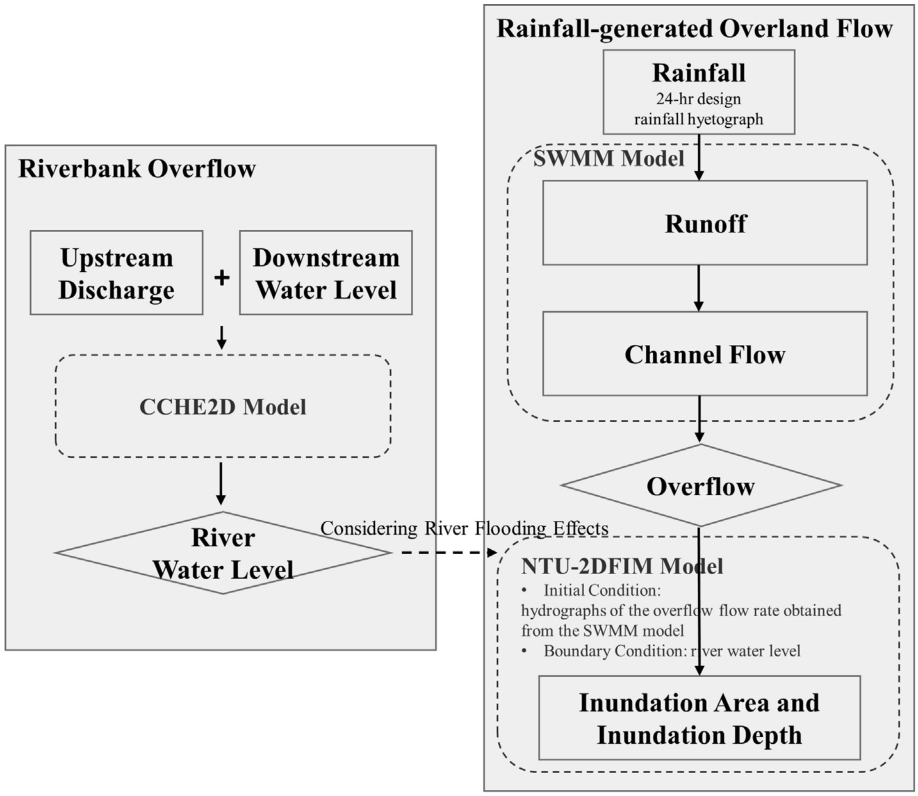

Fig. 2. Flow chart of the flood simulation and model integration.

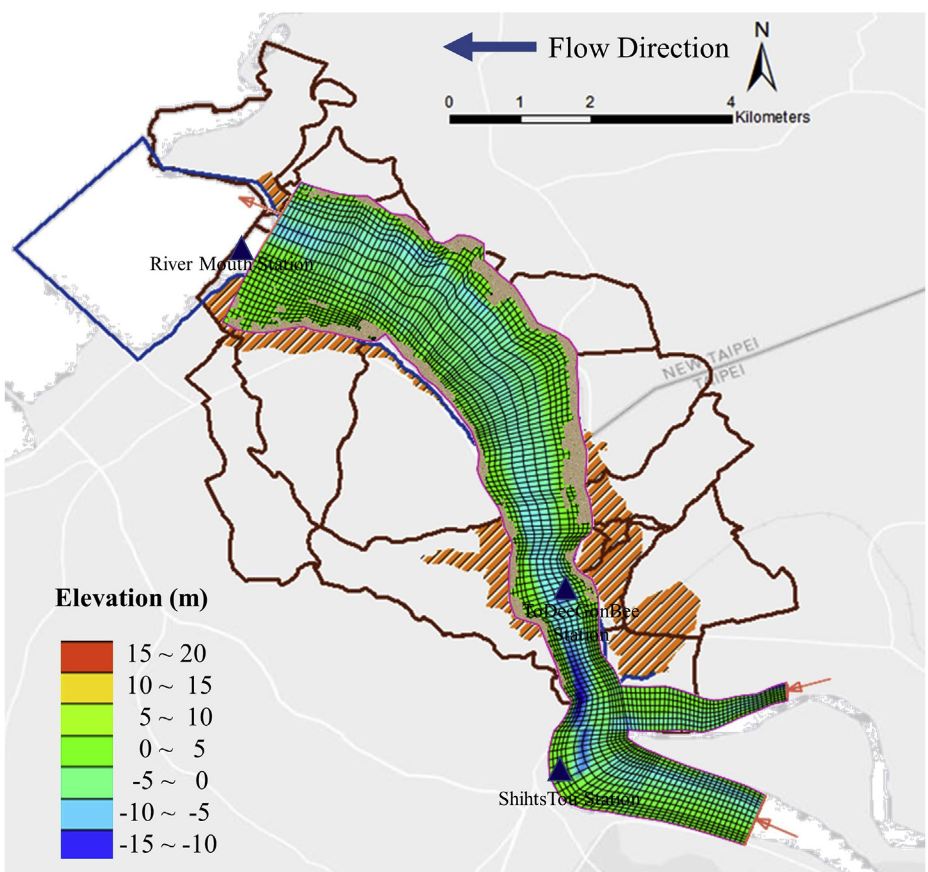

Fig. 3. The grid setup and the topography in the CCHE2D model.

Table 1
The initial and boundary conditions for the river overbank flow simulation.

Recurrence Interval (Year)	Design Discharge (m^3/s)	Design Water Level (m)
2	6,200	1.21
5	10,400	1.23
10	13,400	1.27
20	16,000	1.29
50	20,000	2.12
100	23,000	2.20
200	25,000	2.70

regulations of urban storm sewer systems in Taipei.

The SWMM is a dynamic rainfall-runoff simulation model developed by the United States Environmental Protection Agency (USEPA). This model is used to simulate the runoff quantity and quality caused by a single or long-term (continuous) event in primarily urban areas (Rossman, 2015). The simulation is governed by the conservation of mass and momentum equations for gradually varied, unsteady flow, i.e., the Saint-Venant equations (Equation (6)). For the simulation in the SWMM model, the initial condition was the given rainfall hydrograph at each node within the watershed of the Tanshui River. Based on historical precipitation records, the 5-year precipitation at the four weather stations surrounding the study area, namely, the ShiDing-2 Weather Station, AnBu Weather Station, Taipei Weather Station, and WuDu Weather Station, is 389.9 mm, 542.7 mm, 247.8 mm and 334.7 mm, respectively (WRA and MOEA, 2010a). We further adopted the 24-h design rainfall hyetographs at the four weather stations and then applied the Thiessen polygon method to allocate the spatial rainfall distribution throughout the study area, as illustrated in Fig. 4. The Manning's n values in the simulation were based on the official design guideline of the storm sewer system in Taiwan ranging from 0.012 to 0.016 for pipes and 0.014 to 0.030 for channels (Construction and Planning Agency, 2010). A 24-h rainfall event with precipitation of 450 mm was simulated for comparison with the historical inundation locations recorded by the city government for model validation. The recorded data (precipitation and inundation locations) during three flood events caused by heavy rainfall on April 22, May 2 and June 12 in 2012 were used for the model validation.

$$Z_2 + Y_2 + \frac{\alpha_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \tag{6}$$

where Z is the elevation of the main channel inverts; Y is the depth of the cross-sections; V is the average velocity (total discharge/total flow area); α is a velocity weighting coefficient; g is the gravitational acceleration; and h_e represents the energy head loss.

The NTU-2DFIM model developed by National Taiwan University is a two-dimensional diffusive-wave model for simulating regional overland flow, determined by the topography, land cover and soil type based on noninertial surface flow dynamics. The inertial terms in the motion equations are neglected because the acceleration term of the water flow on the ground surface is small compared with the gravitational and frictional terms, and the governing equation in the model can be simplified to Equations (7)–(9). The alternating direction explicit (ADE) scheme is adopted to establish the inundation model. The NTU-2DFIM model has been applied to evaluate the effects of climate change on the drainage system in southern Taiwan (Chang et al., 2013), to establish an early warning system for 24-h inundation in eastern Taiwan (Pan et al., 2014) and to provide urban drainage flood warnings in northern Taiwan (Chang et al., 2018), among other applications. In the simulation, the overflow rate at each overflow cross-section through the SWMM model was used as the initial conditions. For the downstream boundary condition, we used the records of the water level in the downstream of the drainage system, ranging from 1.1 m to 1.6 m downstream to upstream, as the boundary condition in the scenario without river water level impact. The river water level under different recurrence intervals obtained from the CCHE2D model was used as a boundary condition for the scenario considering the downstream river water impact. The Manning's n values in the simulation were based on the land uses, which referred to the work of Chow (1959), i.e., 0.02 for roads, 0.05 for built-up areas, 0.08 for green land and parks. Similar to the simulation in the SWMM model, the 24-h rainfall event with the precipitation of 450 mm was used for the model calibration, and the heavy rainfall on April 22, May 2 and June 12 in 2012 was used for the model validation.

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = q \tag{7}$$

$$-\frac{\partial (h + Z)}{\partial x} = u\left[\frac{{n_x}^2|u|}{h^{4/3}} + \frac{q}{h \cdot g}\right] \tag{8}$$

$$-\frac{\partial (h+Z)}{\partial y} = v\left[\frac{{n_y}^2|v|}{h^{4/3}} + \frac{q}{h \cdot g}\right] \tag{9}$$

where u and v are the depth-integrated velocity components in the x and y directions, respectively; q is the rainfall intensity or pumping capacity per unit area; h is the local water depth; Z is the water surface elevation; n is Manning's roughness coefficient; g is the gravitational acceleration.

2.3. Establishing the water level

A flood warning system is the foundation of a nonstructural flood prevention measure. Following the Regulations on River Management in Taiwan, the authority in charge of the Tanshui River, the warning water level along the river was established based on historical records for early warning and evacuation purposes. The warning water level is classified into two levels, namely, alert level 1 and alert level 2. The water level may arrive at the defense flood level within two and 5 h for alert level 1 and alert level 2 (WRA and MOEA, 2015). The warning

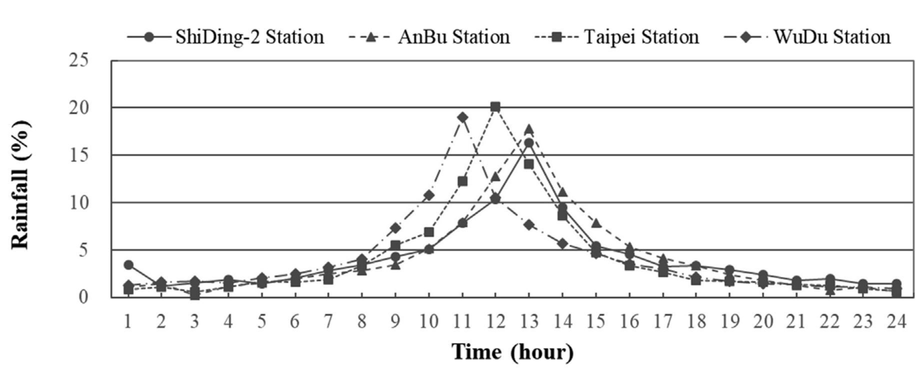

Fig. 4. The 24-hr design rainfall expressed as the percentage of total rainfall depth. For the 24-h precipitation event, the maximum hourly rainfall depth occurs at hours 13, 13, 12 and 11 at the ShiDing-2 Weather Station, AnBu Weather Station, Taipei Weather Station and WuDu Weather Station, respectively.

water levels at the ShihtsTou station are 4.5 m and 3.0 m for alert level 1 and alert level 2. However, the ShihtsTou station is the only site with a warning water level throughout the Tanshui River mouth, and this site is approximately 1–9 km from the study area, thereby reflecting the urgent need for warning water levels at each settlement. In an attempt to support an evacuation plan for each of the five urban settlements considered in this study, we established a warning water level for each settlement. Then, we performed a simple linear regression analysis between the simulated river water levels at the ShihtsTou station and each settlement. The warning water level could thus be obtained through the regression equation.

3. Results

3.1. Flood simulation

3.1.1. Riverbank overflow

The study area, namely, the Tanshui River mouth with a river length of 8.9 km, was discretized into 3,318 grids in the CCHE2D model. NSEs are 0.91 and 0.84 of the simulated and observed water depths at the ToDeeGonBee station during Typhoon Aere and Typhoon Morakot, respectively, indicating reliable simulations (Fig. 5). The spatial distributions of the river water levels under different recurrence intervals are shown in Fig. 6(a), which also shows the spatial distribution of Manning's roughness coefficient based on the model calibration. The Manning's n value ranged from 0.007 to 0.054 (Fig. 6(b)–(h)). At the settlements, the river water levels were 1.24–1.75 m, 1.35–2.67 m, 1.50–3.45 m, 1.65–4.13 m, 2.56–5.11 m, 2.73–5.51 m, and 3.24–5.94 m for the flood events under 2-, 5-, 10-, 20-, 50-, 100-, and 200-year floods, respectively (Fig. 7). Generally, an event with a greater recurrence interval resulted in a higher river water level, and the water level varied with the location; that is, settlements at higher elevations exhibited higher water levels. On the right bank, the river water inundated up to Road No. 2. Moreover, the Tanshui Old Street Settlement, Watzuwei and Niuliaopu Drainage Settlement, and Wusanto Drainage and Longxing Drainage Settlement experienced riverbank overflows with the 200-, 50- and 10-year flood events, respectively.

3.1.2. Rainfall-generated overland flow

A comparison of the inundation locations due to overland flow between the historical records and simulation results showed that the recorded inundation locations along the river were within the inundation locations obtained from the model (Fig. 8), thus confirming that the simulation was reliable. The inundation depths and areas at each settlement are shown in Figs. 9 and 10. Without considering the impacts of river water, the inundation areas under the 5-year precipitation event at the Tanshui Old Street Settlement, Watzuwei and Niuliaopu Drainage Settlement, Wusanto Drainage and Longxing Drainage Settlement, Plum Tree Creek Settlement and Guandu Temple Settlement were 0.07 km^2, 0.13 km^2, 0.04 km^2, 0.10 km^2 and 0.07 km^2, respectively. The average inundation depths were 0.53 m at Tanshui Old Street Settlement, 0.58 m at Watzuwei and Niuliaopu Drainage Settlement, 0.45 m at Wusanto Drainage and Longxing Drainage Settlement, 1.28 m at Plum Tree Creek Settlement, and 0.61 m at Guandu Temple Settlement. Considering the impacts of river water, we used the river water level results simulated by the CCHE2D model as the downstream boundary condition in the drainage system overflow simulation. Except at the Tanshui Old Street Settlement, higher river water levels due to greater recurrence intervals led to larger inundation areas. Upon comparing the results with and without the impacts of river water, the inundations were more severe for all settlements in the study area except for the Tanshui Old Street Settlement when the river water impacts were considered. The impacts of river water were significant for the 50-, 100- and 200-year events. Increased inundation areas of 0.02, 0.17, 0.03 and 0.03 km^2 were observed in the Watzuwei and Niuliaopu Drainage Settlement, Wusanto Drainage and Longxing Drainage Settlement, Plum Tree Creek Settlement and Guandu Temple Settlement, for 50-year recurrence events. For 200-year recurrence events, an increased inundation depth of 0.92 m was observed at the Wusanto Drainage and Longxing Drainage Settlement, and the inundation area was ten times that without considering the impacts of river water.

3.2. Warning water level establishment

Fig. 11 shows the results of the simple linear regression analysis between the simulated river water level at the ShihtsTou station and those at each settlement. The linear regression model exhibited a strong correlation among the water levels, with an R-squared value ranging from 0.96 to 0.99. Following the simple linear regression equations, the warning water levels of alert level 1 were 3.97 m, 3.22 m, 2.84 m, 2.74 m, 2.36 m, 2.20 m and 1.88 m at the Guandu Temple Settlement, Longxing Drainage Settlement, Plum Tree Cree Settlement, Wusanto Drainage Settlement, Niuliaopu Drainage Settlement, Tanshui Old Street Settlement and Watzuwei Settlement, respectively. The corresponding warning water levels of alert level 2 were 2.68 m, 2.24 m, 2.03 m, 1.97 m, 1.86 m, 1.63 m and 1.46 m. Similar to the results of the river water level simulation, the warning water levels were higher in the upper settlements than in the downstream settlements, indicating a discrepancy among the settlements. Compared with the warning water level at the ShihtsTou station, the difference in the warning water level

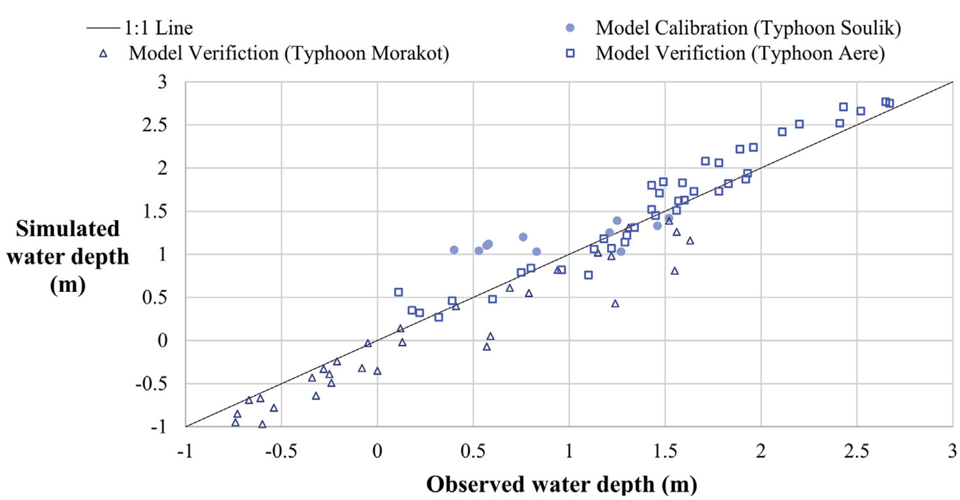

Fig. 5. The calibration and verification results of the CCHE2D model reveal the reliable prediction ability of the model, i.e., by comparing the data of the simulated and observed water depths.

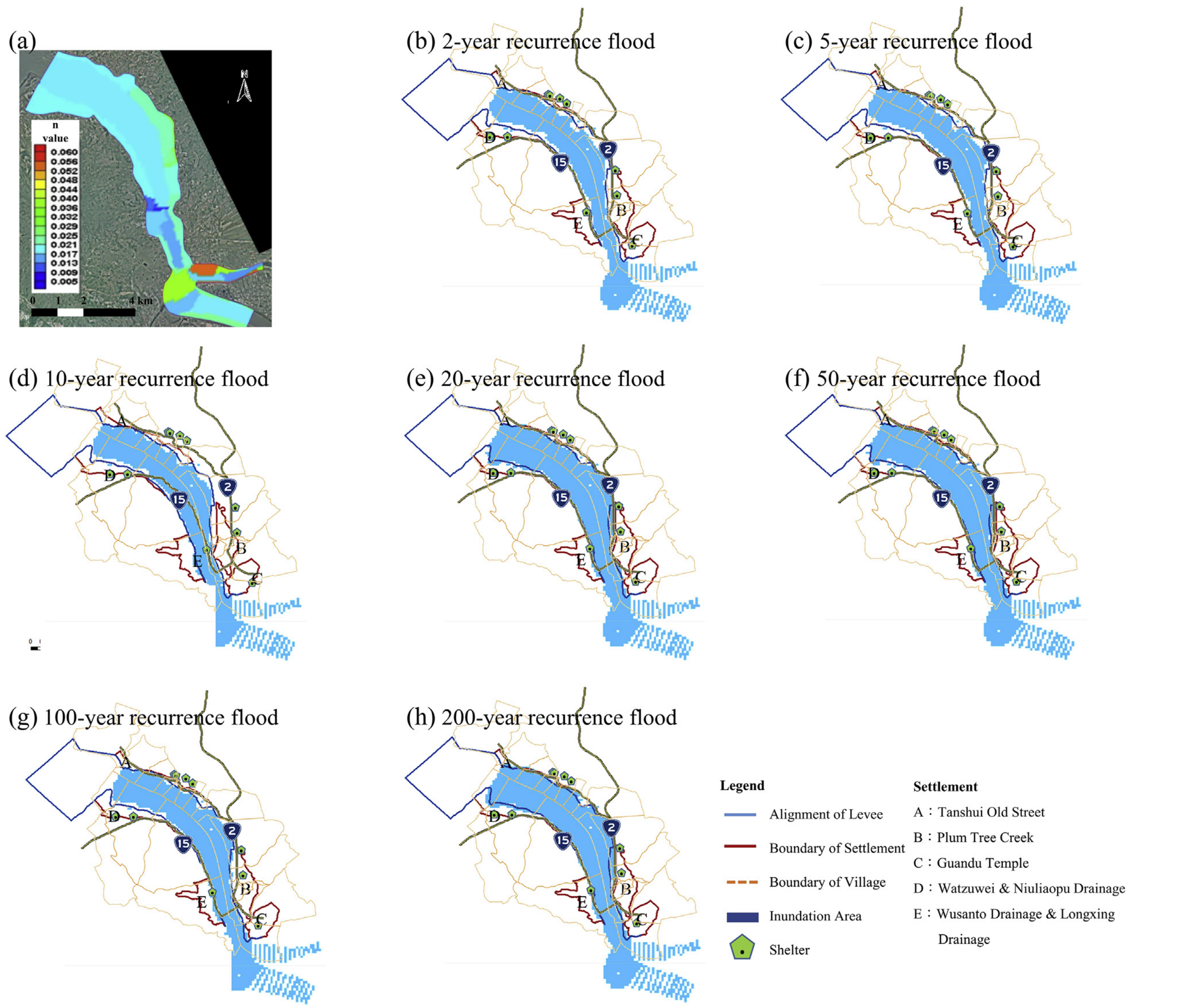

Fig. 6. (a) Spatial distribution of Manning's roughness coefficient. (b)–(h) River overbank flows for 2-, 5-, 10-, 20-, 50-, 100-, and 200-year recurrence floods and the location of the possible shelters.

varied with the distance from the settlement to the ShihtsTou station. Within a distance of approximately 9 km between the ShihtsTou station and the Watzuwei Settlement, differences of 2.62 m and 1.54 m in the warning water levels for alert level 1 and alert level 2, were observed.

4. Discussion

4.1. Capability of current flood mitigation strategies

The study area is located in a region without levee protection. To understand the real-life situation and the possible causes of floods, we conducted telephone interviews with the chiefs of the villages in the five studied urban settlements from June 2014 to October 2014. The chiefs of Minan Village in the Tanshui Old Street Settlement, Michang Village in the Watzuwei and Niuliaopu Drainage Settlement, and Longyuan Village in the Wusanto Drainage and Longxing Drainage Settlement indicated that river water had inundated the riverside areas of their villages during typhoon events. In addition, the chief of Minquan Village in the Plum Tree Creek Settlement remarked that malfunctions in the drainage system were the main cause of floods in the village.

The estimated riverbank overflows show the potential flood risks in the Tanshui Old Street Settlement, Watzuwei and Niuliaopu Drainage Settlement, and Wusanto Drainage and Longxing Drainage Settlement, thereby corroborating the overbank floods observed by the village chiefs during the typhoon events. The Tanshui Old Street Settlement, Watzuwei and Niuliaopu Drainage Settlement, and Wusanto Drainage and Longxing Drainage Settlement are located in relatively low-lying areas, where the topography is below the designed water level during a 200-year flood event according to the Taipei Flood Prevention System. Thus, a possible explanation for fluvial floods may be topography. When the river water level exceeds the ground level, river water spreads over the settlements and prevents drainage by gravity. Except for the Plum Tree Creek Settlement and Guandu Temple Settlement, in which fluvial flooding protects against 200-year flood events, the capability of overbank flow prevention at the Tanshui Old Street Settlement, Watzuwei and Niuliaopu Drainage Settlement, and Wusanto Drainage and Longxing Drainage Settlement is limited for events below 200-, 50- and 10-year floods, respectively. Settlements have extended along the alignment of levees within the Tanshui River, indicating that limited extents of the surrounding areas can be protected by structural flood mitigation measures. Therefore, these results highlight the need for a nonstructural flood mitigation policy in the study area due to the insufficiency of fluvial flood prevention and the

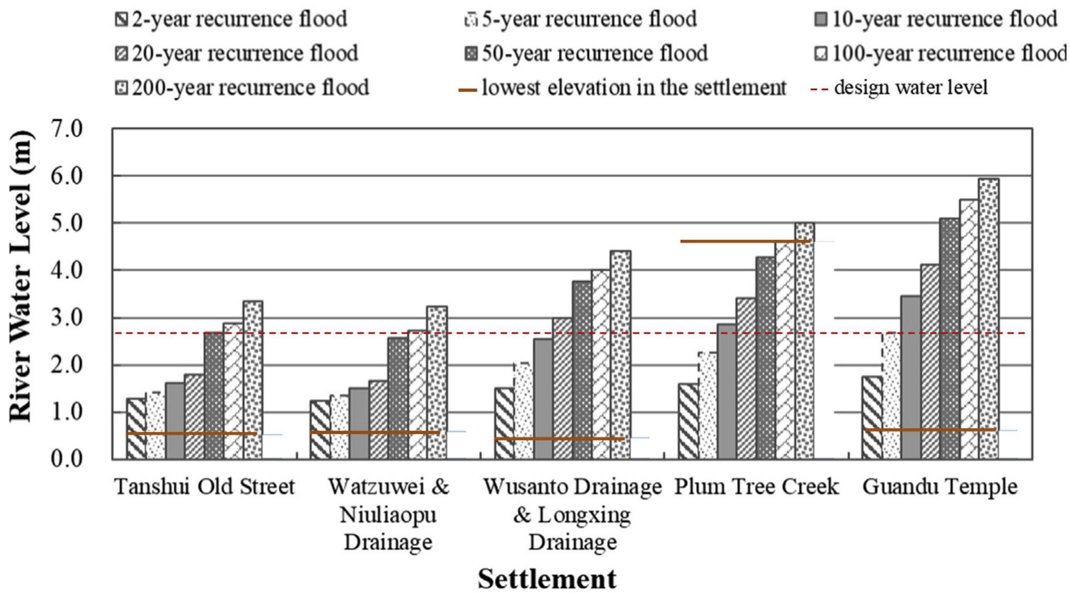

Fig. 7. The river water level at each settlement under different recurrence intervals. Except at the Plume Tree Creek Settlement, the lowest elevation in the settlements is below the simulated river water level for a 200-year flood event and the designed water level, i.e., 2.7 m, for a 200-year flood event according to the Taipei Flood Prevention System.

limitations on the surrounding areas for the construction of structural flood mitigation measures.

Insufficient or poor urban drainage systems are the main causes of overland flow. The burdens of increased urbanization and the increased intensity and duration of precipitation on urban drainage systems have been validated (Tingsanchali, 2012). Inundation due to drainage system overflow was observed without considering the impacts of river water in all of the settlements in the study area, implying that the current capacity of the pluvial flood protection system cannot protect against a 5-year flood event. Similar to many urban areas that suffer from pressing pluvial flooding due to changing precipitation patterns, expanding urban areas and aging drainage infrastructure (Webber et al., 2018), the insufficient urban drainage system in the study area raises the flood risk. Moreover, downstream river water aggravates the inefficiency of the drainage system. However, due to the lack of data, the tide cycle variation was ignored in this study. Further research considering the tide cycle in flood simulations is therefore suggested.

4.2. Applicability of nonstructural flood management strategies

The findings of this study demonstrate that current flood mitigation measures are incapable of preventing flood disasters caused by either riverbank overflow or rainfall-generated overland flow. In addition, the limitations on the surrounding area due to the establishment and expansion of settlements limit the construction of further structural flood mitigation measures. Accordingly, to supplement these structural mitigation strategies, disaster management mechanisms, including measures for preparedness, response and recovery, have been implemented since the Disaster Prevention and Response Act was formulated in Taiwan in 2000. In 2006, an integrated approach was implemented in the flood regulation plan in Taiwan (WRA and MOEA, 2006). For example, the potential inundation maps of 19 cities and counties in Taiwan were completed between 2007 and 2010 by the WRA (August 10, 2012, MOEA's website: http://140.116.77.34/DPRC/02.html). In 2014, a flood warning notification system was implemented by the WRA to support flood preparedness (WRA and MOEA, 2014). Also, the construction of flood prevention communities has been promoted since 2010 to raise awareness and improve the capacity for self-care and

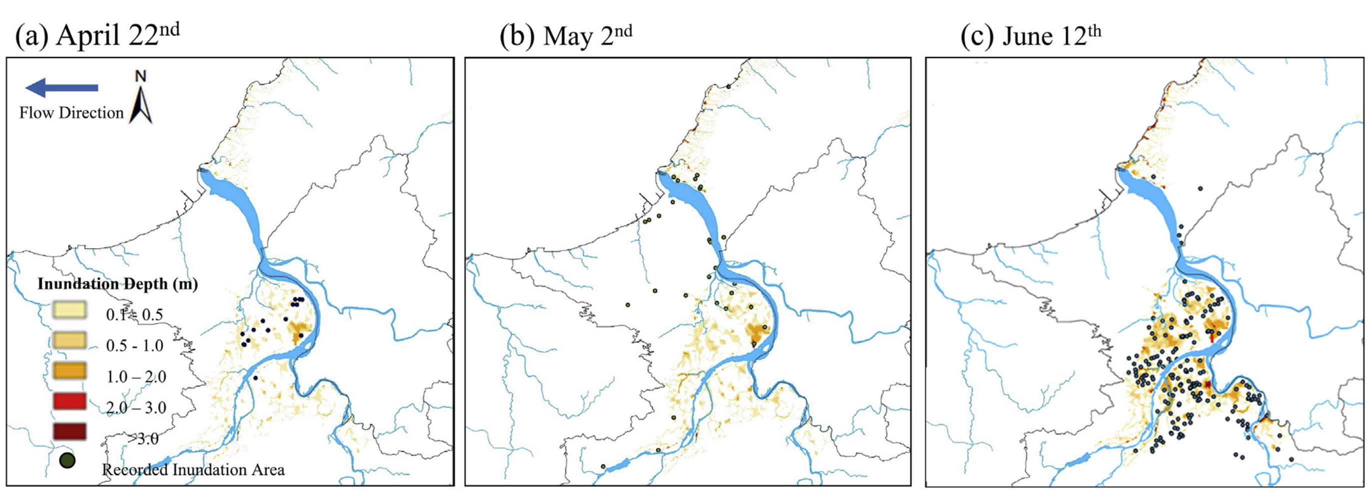

Fig. 8. The overflow simulation for the heavy rainfall on (a) April 22, (b) May 2 and (c) June 12.

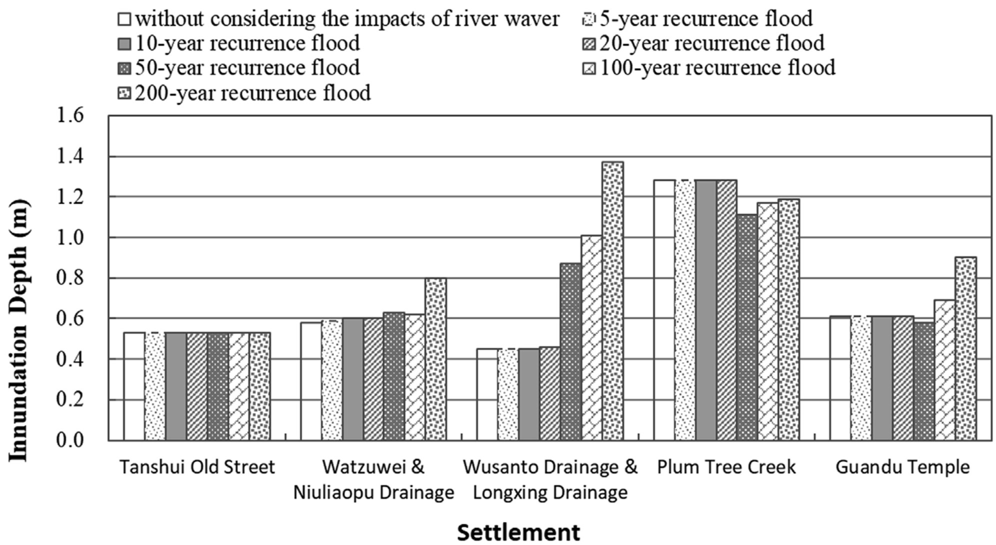

Fig. 9. The average inundation depth at each settlement with and without considering the impact of the river water under the different recurrence intervals.

mutual assistance for flood disaster prevention in the community (WRA and MOEA, 2010b). To date, approximately 400 flood prevention communities have been built throughout Taiwan. Within this plan, the potential inundation map supports the development of evacuation routes and the identification of shelter locations. Meanwhile, the warning system initiates preparations for evacuation and relocation. Considering the important roles of potential inundation maps and warning systems in nonstructural flood management strategies, we further discuss the applicability of these tools following the official guidelines based on the simulation results.

The National Science and Technology Centre for Disaster Reduction (NCER) (2016) guides the production of potential inundation maps based on the spatial distribution of rainfall. In conjunction with the rainfall patterns, the simulation results show that the aggravated drainage system overflow induced by elevated river water downstream is significant. Accordingly, if the impacts of downstream river water are not considered, taking a 50-year flood event as an example, the inundation areas will be underestimated by 0.02 km^2, 0.17 km^2, 0.03 $km^2$and 0.03 km^2 in the Watzuwei and Niuliaopu Drainage Settlement, Wusanto Drainage and Longxing Drainage Settlement, Plum Tree Creek Settlement and Guandu Temple Settlement, respectively. Therefore, to improve the applicability of current nonstructural flood management strategies, the impacts of downstream river water must be taken into account in the production of potential inundation maps.

Warning systems provide timely and effective information that supports actions for avoiding and reducing hazard risks (UNISDR, 2004), and their potential for reducing damage is well known (Lustig et al., 1988; Thieken et al., 2005; Meyer et al., 2012; Molinari et al., 2013). The warning water levels at the official water level observation stations along the Tanshui River were established following the Regulations on River Management. However, differences ranging from 0.53 m to 2.62 m and from 0.32 m to 1.54 m for alert level 1 and alert level 2, respectively, between the ShihtsTou station and the settlements within distances from 1 km to 9 km indicate that establishing a warning water level at each settlement is necessary to ensure timely and effective responses to riverbank overflows. Previously, warning systems with warning water levels intended to prevent inundation caused by riverbank overflow at each settlement were lacking because of the absence of water level records along the riverside. Therefore, we inserted the warning water level at the ShihtsTou station into the simple linear regression equations of the simulated river water level at each settlement to establish a warning water level for each settlement. The high R-squared values (ranging from 0.96 to 0.99) indicate the reliability of the regression model. However, these warning water levels should be revised based on practical experience to support actions that avoid and reduce fluvial flooding damage.

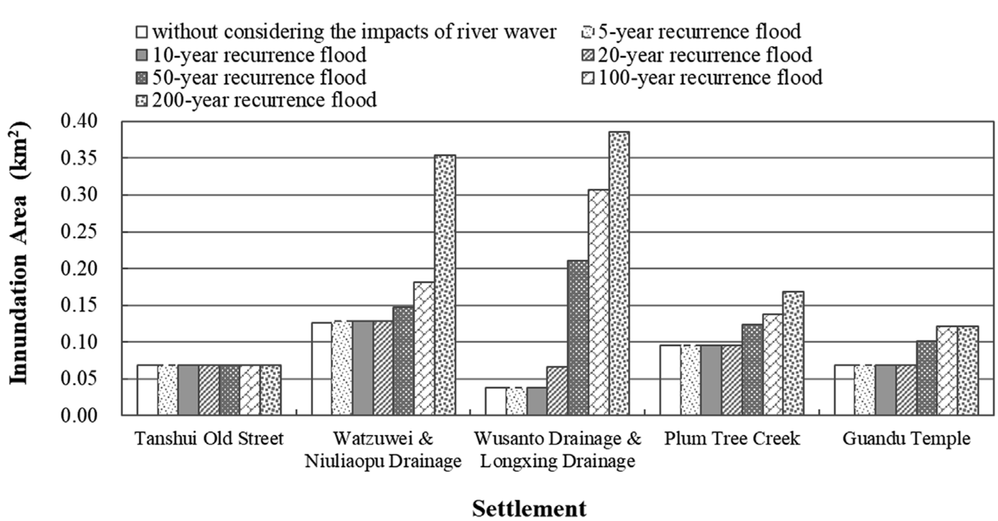

Fig. 10. The average inundation area at each settlement with and without considering the impact of the river water under the different recurrence intervals.

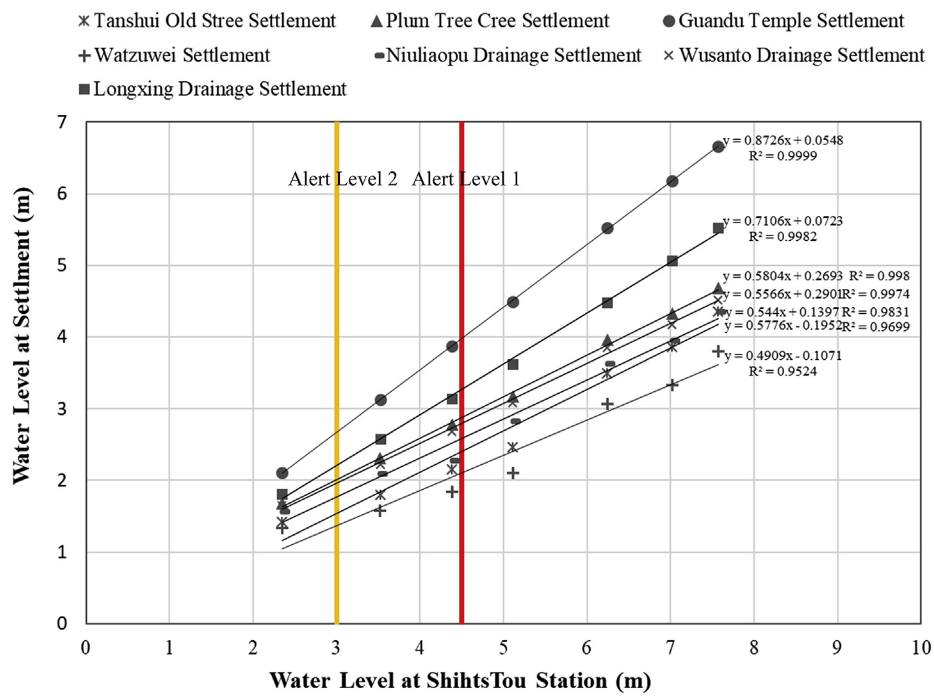

Fig. 11. The spatial relationship and simple linear regression equations between the simulated river water level for developing the alert water levels of each settlement.

An alert prompts evacuation and thus enables people to be transferred from potential disaster areas to safe areas (Stepanov and Smith, 2009). We identified possible shelters, i.e., public community centers and schools in noninundation areas near the settlements, based on the inundation map obtained in this study (Fig. 6). Road No. 2 on the right bank and Road No. 15 on the left bank play important roles in the evacuation routes linking the potential inundation areas to shelters. Considering that inundation may block the evacuation routes, we further compared the topography of the main evacuation routes with the alert level to evaluate the applicability of the evacuation actions we proposed at each settlement. The elevations of the main evacuation routes at the settlements exceed the corresponding alert level 1. Thus, it is unlikely that the main roads along the evacuation routes in each settlement would become blocked due to inundation. Consequently, the warning water levels proposed in this study may support timely and effective evacuations. Our examination of these strategies also showed that the application of flood mitigation strategies should take into account the local ecology, environment, landscape and socioeconomic factors, which is consistent with the findings of previous studies (Richards and Carter, 2008; Sayers, 2010; McBain, 2012; Shah et al., 2012) and might thus meet the demand of the ecosystem-based disaster risk reduction (Eco-DRR) approach (UNEP and CNRD, 2014).

5. Conclusions

The current flood mitigation strategies were designed based on past climate conditions and land use patterns. Considering increases in the population and precipitation, we evaluated the capability of these strategies to protect against flood inundation in the Tanshui River estuary. The results of simulations showed that the decrease in the drainage system capacity induced by elevated river water is significant when considering river flooding effects. Taking the 200-year recurrence event as an example, an increased inundation depth of 0.92 m was observed at the Wusanto Drainage and Longxing Drainage Settlement, and the inundation area was ten times that without considering the impacts of river water. The capacities of the current flood mitigation strategies to prevent riverbank overflow and drainage system overflow do not reach the designed flood protection standard.

As a consequence of the establishment and expansion of numerous settlements, the current flood mitigation strategies must rely on nonstructural flood management. We enabled an assessment of the applicability of implementing nonstructural flood management policies in the settlements along the Tanshui River estuary to help provide insights into the design of corresponding strategies. The simulation results, along with the simple linear regression model, helped establish the warning water level at each settlement. The results highlighted the need to improve the official guidelines for producing potential inundation maps and establishing warning water levels. Unfortunately, there are no gauging stations to acquire water level data with which to establish the warning water level in the warning system in most of the settlements along the river. Two suggestions were proposed: (1) the impacts of downstream river water should be considered to identify all potential inundation areas, and (2) a warning water level should be established at each settlement to enable appropriate and prompt reactions in those settlements. Also, our study suggests that future research could utilize the Eco-DRR approach by incorporating environmental and socioeconomic factors, and the flood prevention and mitigation strategies presented in this study.

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