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Flood Risk Identification and Resilience Building Strategies for Mountainous County Level City—A Case Study of Xichuan

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Abstract: China has a large number of county-level cities in mountainous areas which are very prone to rainstorm-caused floods. Moreover, as county-level city, the exposures, as well as available funding and technologies, are very limited, and flood control standards are also constrained, therefore, resilience building is essential for flood management. Taking Xichuan as an example, this paper performed the analysis on the present, future, and residual flood risks in the urban area using flood simulation and scenario analysis methods, in which several key factors were taken into account, including built-up area expansion, flood control infrastructure improvement, rainfall change due to climate warming, and changes in the hydrological characteristics of the underlying surface due to human activities. Based on these findings, the strategies were proposed and analyzed for resilience building, including (1) practicing systematic management at river basin scale to delay and cut down of peak discharge flow of floods to the city, (2) establishing a multi-level, synergistic defense system integrating gray, green, and blue infrastructures to mitigate flooding, waterlogging and river bank erosion in urban areas, (3) enhancing the resilience of key infrastructures to keep the basic functions for the city during flooding, (4) strengthening monitoring and early warning capabilities, and (5) raising public's awareness of flood risks and capacity of responding to floods, both (4) and (5) are significantly helpful for the public to timely take correct actions in case of floods.

Keywords: county level city; mountainous area; flood risk; resilience building

1. Introduction

In recent years, county level city in mountainous areas has increasingly become prone to flooding and waterlogging in China, typically, rainstorms hit Rongjiang County, Qiandongnan Autonomous Prefecture, Guizhou Province, on 24 June 2025, Guiding County, Qiannan Autonomous Prefecture, Guizhou Province, and Xuan'en County, Enshi Prefecture, Hubei Province, on 18–19 May 2026. As the world continues to warm, climate hazards are expected to increase in frequency and intensity, and the impacts of extreme events will be more severe due to the increased exposure and vulnerability of human activities [1–3]. Study indicates that warmer air can hold more water vapor, for every 1 °C increase in temperature, the atmospheric water-holding capacity increases by approximately 7%, which result in the release of more water during precipitation events [4], and also change the vegetation cover status [5,6] then change the hydrological environment; hence, climate change, with inevitable and irreversible warming trend, has intensified global flood risks through multiple channels, posing unprecedented challenges to traditional flood control systems [7,8]. Moreover, the rapid expansion of urban areas has significantly

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changed the local hydrological environment, which lead floods rise and fall abruptly, much faster than before. Studies indicate that urban hydrological processes and drainage system have greatly strengthened the challenge of water-related disasters [9], while rational designs of drainage system and green infrastructure in urban area are able to enhance the orderly discharge of excessive rainwater from extreme rainfall [10,11]. In addition to above, floods can be mitigated in some degree rather than be eliminated completely, therefore, it is necessary to enhance the resilience of social and economic systems to flood disasters [12–16], and shift innovative policies and practices to climate change and rapid urbanization [17]. As county-level cities in mountainous areas, their flood control standards, as well as economic and technical conditions, are very limited, however, the floods and waterlogging are very complicated and devasting destructive, and frequently result in heavy losses; moreover, given global climate change, it is crucial to strengthen risk identification and resilience-building to mitigate flood losses. Xichuan, a typical mountainous county-level city in Henan province, China, is characterized by a certain number of exposure values, complicated internal water system, surrounded by several external creeks, low flood control capacity, now, it has been experiencing an integrated ecological protection and environment improvement project of ADB which highlights flood risk management and resilience building since 2021 [18]. Taking this county as an example, this article concentrates on discussing the approaches on flood risk identification and resilience building strategies for county-level cities in mountainous areas.

2. Background and Methodology

2.1. Background

Xichuan County is located in the foothills of the Qinling Mountainous Areas, subtropical zone and prone to heavy rainfall. The urban areas of this county, situated in both banks of the Guanhe River (drainage area 4219 km^2, flowing into the Danjiangkou Reservoir eventually, the core water source area of China South-to-North Water Diversion Project, with very high ecological and environment protection requirements), just cover the river network area of several natural creeks and artificial ditches, the Tiemiao Creek, the Wayu Creek, the Shiban Creek, the Biaochi Creek, the Neihe River, the Gumugou Ditch and the Xiaogou Ditch, which are called as "Five Rivers and Two Ditches" for the central urban area by local people; moreover, the Dongfeng Ditch, runs through the urban area from north to south; currently, the main tributaries directly flooding into the urban areas include the Biaochi Creek, the Wayu Creek, the Shiban Creek, and the Shuitian Creek (known as the Xihe River after convergence of the Shiban Creek in the urban areas) while the Xiahe Creek will flow through the future urban area. Obviously, the urban areas are surrounded by external creeks, and the internal water system is complicated with natural and artificial waterways intersected. Figure 1 presents the layout of the current and future urban areas and the river networks while Table 1 provides the details of "Five Rivers and Two Ditches".

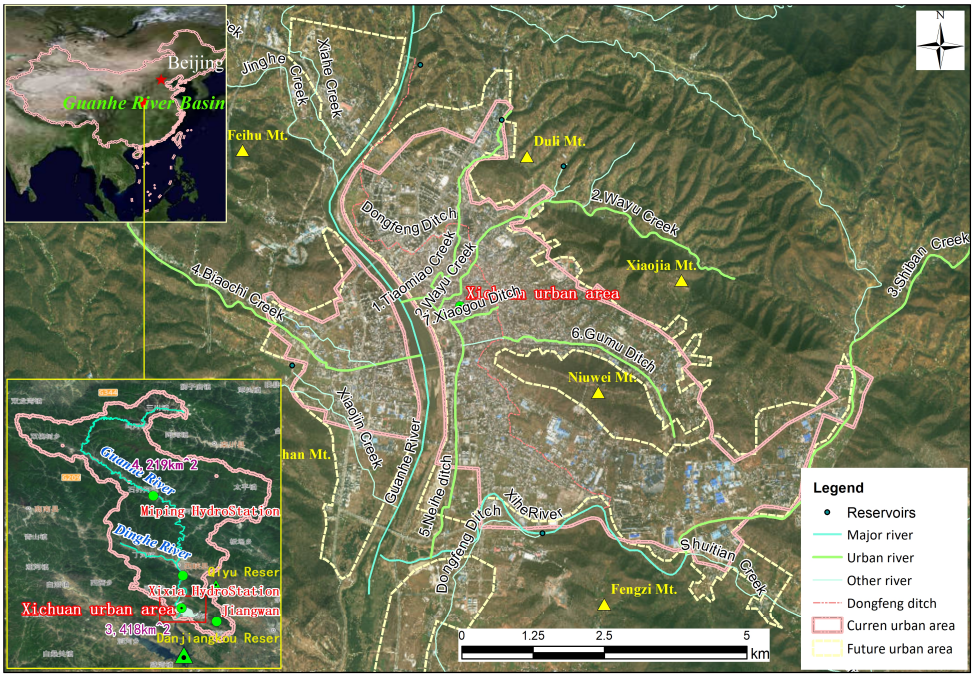


Figure 1. Xichuan urban areas and floods sources.

Table 1. Basic information of rivers/creeks runs through the Xichuan urban areas [19].

No.	Creek	Drainage Area/km^2	River Length/km	Channel Slope
1	Tiemiao	7.84	7.28	0.093
2	Wayu	11	8.14	0.100
3	Shiban	40.76	15.24	0.068
4	Biaochi	9.12	8.54	0.204
5	Neihe	28.37	30.76	0.016
6	Gumugou	8.44	5.70	0.103
7	Xiaogou	2.64	3.43	0.276

Table 1 indicates that "Five Rivers and Two Ditches" are characterized by short channel length and steep channel slope, with drainage areas ranging widely from 2.64 km^2 to 40.76 km^2, which means the urban areas are heavily threatened by flash floods. Generally, there are three types of flood sources for the urban areas: (1) floods from the main tributaries around the urban areas; (2) floods from the Guanhe River; and (3) rainstorm over the urban areas.

Therefore, the Xichuan city has been troubled by several problems, typically as follow: first, urban floods, the water levels of the urban rivers usually rise higher than the ground once rainstorm occurs, and many streets are frequently inundated; second, the limited leading time for early warning, the concentration time of flow the creeks round the urban areas are very short; third, the degraded water environment, both banks along "Five Rivers and Two Ditches" have been occupied by buildings which have heavily weakened the local drainage capacity and water environment. According to *the Flood Control Plan of Xichuan County*, the flood control standards of the urban section of the Guanhe mainstream are 20-year flood for mid-term and 50-year flood for long-term, while those for other urban creeks are only 20-year flood. However, floods exceeding design standards are always possible and pose threat to the urban areas; moreover, the built-up area is currently 25.23 km^2 with population 205 thousand and will expand to 43 km^2 [20], which means more exposure values to floods in the coming future; and climate warming, as mentioned above, is an inevitable and irreversible trend in the future, needs to be considered for urban flood management. Therefore, it is critical to verify the flood risks and take correct actions in advance for flood management in the Xichuan city.

2.2. Methodology

Flood simulation and scenario analysis are the main components of the methods in this study. First, the change of flood risk elements are detected which include the variations of flood risk elements of hazard, exposure and vulnerability [21]; second, scenarios are designed according to these changes in the future, such as rainfall change due to climate warming, urban area expansion, structural measures implementation, and underlying surface changes [19]; third, flood simulations are performed using two-dimensional shallow water modeling method for these scenarios to obtain the flooding area, flood depth; fourth, flood risk identification are conducted with Geographic Information Software packages (ArcGIS 8.1), to project the present, future and residual risks [22]; fifth and last, resilience strategies are proposed based on the analysis of the projected flood risks, as Figure 2.

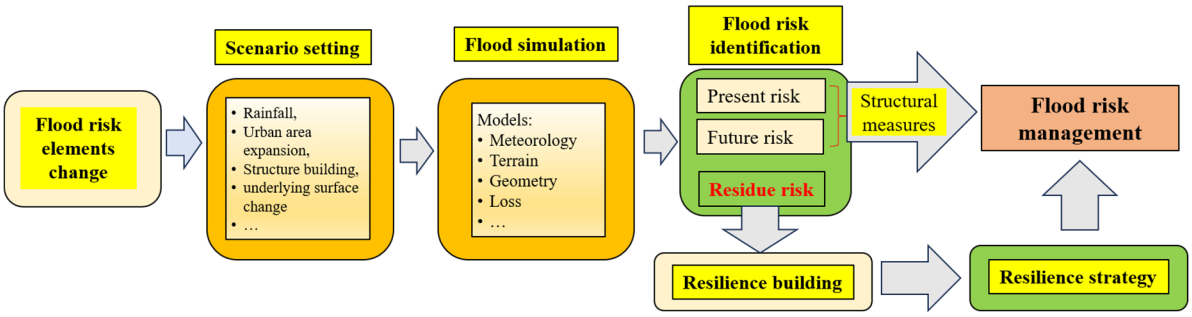


Figure 2. Methodology for flood risk identification and resilience building.

2.2.1. Flood Modeling

As the base of flood risk analysis, flood modeling was performed with two-dimensional shallow water equations using HEC-RAS software package (HEC-RAS 6.6), including the creation of meteorological model, terrain model, geometry model, boundary condition and roughness coefficients. More details are presented in the Section 3: Flood Simulation.

2.2.2. Flood Risk Analysis

Flood risk is the essential of flood management and was proposed to be classified as three levels of operational, project planning and project design [22]. The concept of flood risk was currently defined as the comprehensive effect of hazard, exposure, and vulnerability [21]. In this study, the authors agree all of these conceptions, but have a restriction that only flood danger is simply analyzed, and exposure and vulnerability are not quantitatively measured. Flood risk analysis is performed as follow three categories: (1) present risk: the flood risk associated with present development and landuse; (2) future risk: the flood risk associated with projected future development and landuse, but no new flood management measures implemented; and (3) residual risk: the risk the community would be exposed to after new flood management measures have been planned and implemented in the future. Based on flooding information, the following features are taken into consideration as flood risk analysis performed, the urban area development plan, climate change, and the grey-, blue-, and green-infrastructure of the ADB project [18].

2.2.3. Scenario Analysis

Recent years, the factors of scenario analysis on flood risk have mainly concentrated on climate change [23–26], landuse change and urbanization for flood risk assessment [27,28]. Given above reasons, the following factors are taken into consideration for scenario analysis: (1) flood magnitudes: two typical frequencies (20-year flood, and 50-year flood, the flood control standards for the river sections within the urban areas and for the urban section of the Guanhe mainstream) of rainfall-runoff, on behalf of floods lower or equal flood control standards, and current urban areas, are set for flood simulation to evaluate present risk; (2) climate change: the Xichuan city is located in mountainous area where water vapor increment will play critical role in case of rainstorm-flood events; (3) two changes of underlying surface: first, the urban areas expansion in the future, second, the implementation of soil conservation measures (SCMs)[19,29], for the former will increase the exposure to floods while the latter will change the hydrologic feature of the river basin.

3. Flood Simulation

3.1. Computational Domain and Basic Method

3.1.1. Computational Domain

As mentioned before, the external flood sources of the urban areas include the Guanhe River and "Five Rivers" (the Biaochi Creek, the Tiemiao Creek, the Wayu Creek, the Shiban Creek and the Shuitian Creek) for the present urban areas, and the Jinghe Creek and the Xiahe Creek due to the expansion of urban areas in future (see Figure 1). The Guanhe River divides the urban areas into two parts, and in the upper reach very close to the urban areas there is a hydrological station (the Xixia Hydrological Station with drainage area of 3418 km^2, built in 1951), and the other rivers are the main contributors of floods for urban areas, therefore, the computational domain include the lower part of the Xixia Sation of the Guanhe River, and all the catchments of the tributaries, covering total area 363 km^2.

3.1.2. Basic Method

Flood simulation was performed with two-dimensional hydrodynamic method in which assuming that the flow is incompressible, the unsteady differential form of the mass conservation (continuity) equation is [30]:

Continuity equation:

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

Momentum equations:

$$\begin{aligned}\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}&=-g\frac{\partial Z_s}{\partial x}+\frac{1}{h}\frac{\partial}{\partial x}\left(v_{t,xx}h\frac{\partial u}{\partial x}\right)+\frac{1}{h}\frac{\partial}{\partial y}\left(v_{t,yy}h\frac{\partial u}{\partial y}\right)-\frac{\tau_{b,x}}{\rho R}+\frac{\tau_{s,x}}{\rho h}\\ \frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}&=-g\frac{\partial Z_s}{\partial y}+\frac{1}{h}\frac{\partial}{\partial x}\left(v_{t,xx}h\frac{\partial v}{\partial x}\right)+\frac{1}{h}\frac{\partial}{\partial y}\left(v_{t,yy}h\frac{\partial v}{\partial y}\right)-\frac{\tau_{b,y}}{\rho R}+\frac{\tau_{s,y}}{\rho h}\end{aligned} \tag{2}$$

where t is time [s]; u and v, the velocity components in the x x- and y-direction respectively [m/s]; q, a source/sink flux term [m/s]; Z_s, water surface elevation [m]; g, the gravitational acceleration [m/s^2]; $v_{t,xx}$ and $v_{t,yy}$, the horizontal eddy viscosity coefficients in the x- and y-directions [m^2/s]; $\tau_{b,x}$ and $\tau_{b,y}$, the bottom shear

stresses on the x- and y-directions [kg/m/s^2]; $\tau_{b,x}$ and $\tau_{b,y}$, the surface wind stresses on the x- and y-directions [kg/m/s^2]; R, hydraulic radius [m]; and h, water depth [m].

3.2. Meteorological Model

Rainfall hyetograph is the essential of meteorological model, current and future meteorological models of 24-h-rainfall hyetograph were developed to highlight the role of climate change to future flood risk. The former, current design rainfall of specific return periods, was created strictly according to the approaches of "*Henan Design Rainstorm Flood Manual for Small and Medium-sized Watersheds*" [31], while the latter considered climate change besides current design rainfall, in which, given the Guanhe River Basin being the core water source area of China South-to-North Water Diversion Project and long-term and sustainable high ecological and environmental protection requirements, the possible change on daily rainfall under RCP 4.5 scenario was used with increment of 0.9–1.1 °C and 7 percent of total rainfall within the corresponding duration [32]. As mentioned before, according to *the Flood Control Plan of Xichuan County*, the flood control standards of the river channels in the urban areas are 20-year flood, hence, the corresponding rainfall hyetographs are used as the meteorological model for flood simulation, and Figure 3 presents the results of design rainfall with duration of 24 h, in which "CC" stands for climate change considered. One thing needs to be noted, for drainage areas and channel slopes like the creeks around the urban areas (See Table 1), the rainfall duration, 24 h, is long enough to simulate rainfall-runoff process for it exceeds much the time of concentration of these creeks; moreover, the accumulative rainfall depths in Figure 3 are still less than 250 mm with duration of 24 h, the standards of extreme rainfall in China; that is, the flood control capacity of urban rivers will remain relatively limited even after the successful implementation of planned structural works of ADB meeting their flood control standards.

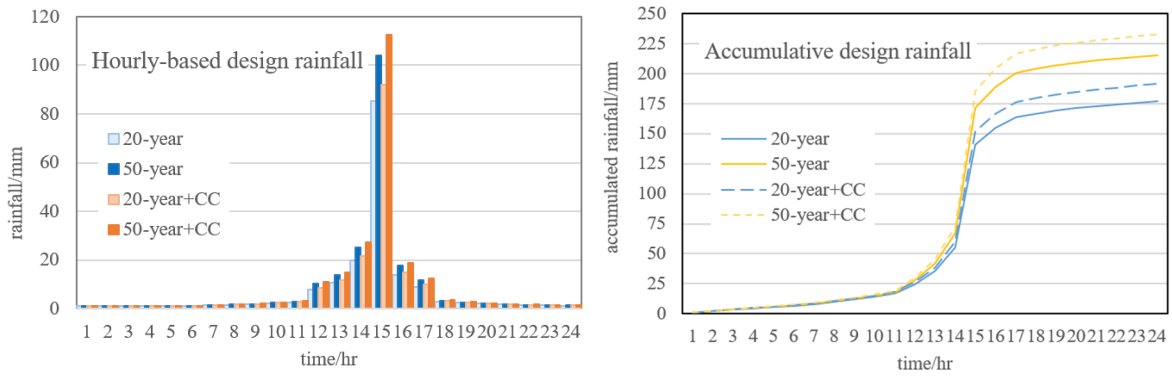


Figure 3. Hyetograph of 24-h design rainfall.

3.3. Terrain Model

The Digital Elevation Model (DEM) used to create the terrain model in this study, are obtained from ALOS PALSAR dataset (https://search.asf.alaska.edu/#, accessed on 8 October 2021), covers the whole computational domain and has a spatial resolution of 12.5 m. Based on the raw DEM data, two terrain models of the urban areas, "without-project terrain" and "with-project terrain", were used to perform flood simulation. The "without-project terrain" is the current terrain while the "with-project terrain" refers to the future terrain in which the structural measures of the ADB project for the urban areas, such as river channel dredging and widening, constructions of embankments and water storage, have been considered. The above has been presented in Figure 4, in which Figure 4A shows the whole computational domain within the yellow line, Figure 4B demonstrates a demo of with-project terrain in the urban areas while Figure 4C illustrates the current (brown line) and future (red line) urban areas.

Moreover, the change of underlying surface of the computational domain was also considered in the future terrain model (See Figure 5), especially, the implementing of SCMs within the catchments will significantly change the vegetation cover rate and improve local hydrological environment, then change the interception capacity of rainfall and resistance of surface.

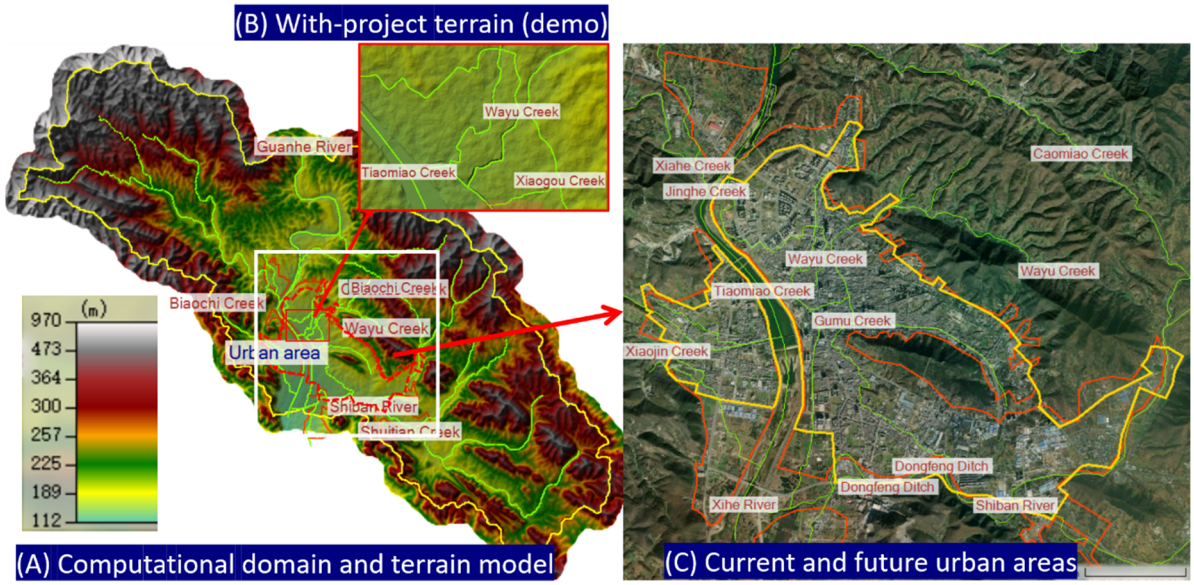


Figure 4. Computational domain, terrain model and urban areas (current-yellow line, future-red line).



Figure 5. Current Landuse and roughness.

3.4. Geometry Model

For the purpose of high quality of flood simulation, as the geometry model was created (see Figure 6), much attention was paid to the follows. First, the computational meshes need to cover all of the computational domain, totally, there are 653 thousand meshes, and commonly, the size of the meshes are 50 m * 50 m for the common areas for the sake of computational time saving; second, the main channel lines of the rivers, or line structures, such as dikes and river banks, were proceeded with break line technology to capture the high ground with cell faces, and the near spacing of break line for urban area rivers or ditches was refined to 5 m (see Figure 7A); third, given the spatial resolution of 12.5 m of DEM data to create the terrain model, the urban areas were assigned as refinement regions with meshes of 10 m * 10 m for the purpose of getting more detail inundation information (see Figure 7B); fourth and last, according to the principle of worst-case scenario for risk analysis, to highlight the contribution of all tributaries, the boundary conditions are designed as follows: the upper boundary conditions include (1) the design rainfall of 24-h duration which covers the entire computational domain, and (2) the flood hydrograph of the Xixia Hydrological Station on 24 July 2010, the recorded largest flood with peak discharge of 7380 m^3/s; and for the lower boundary condition, normal depth was adopted downstream to the Guanhe River near the urban areas, the only flood outlet of the computational domain, see Figure 6.

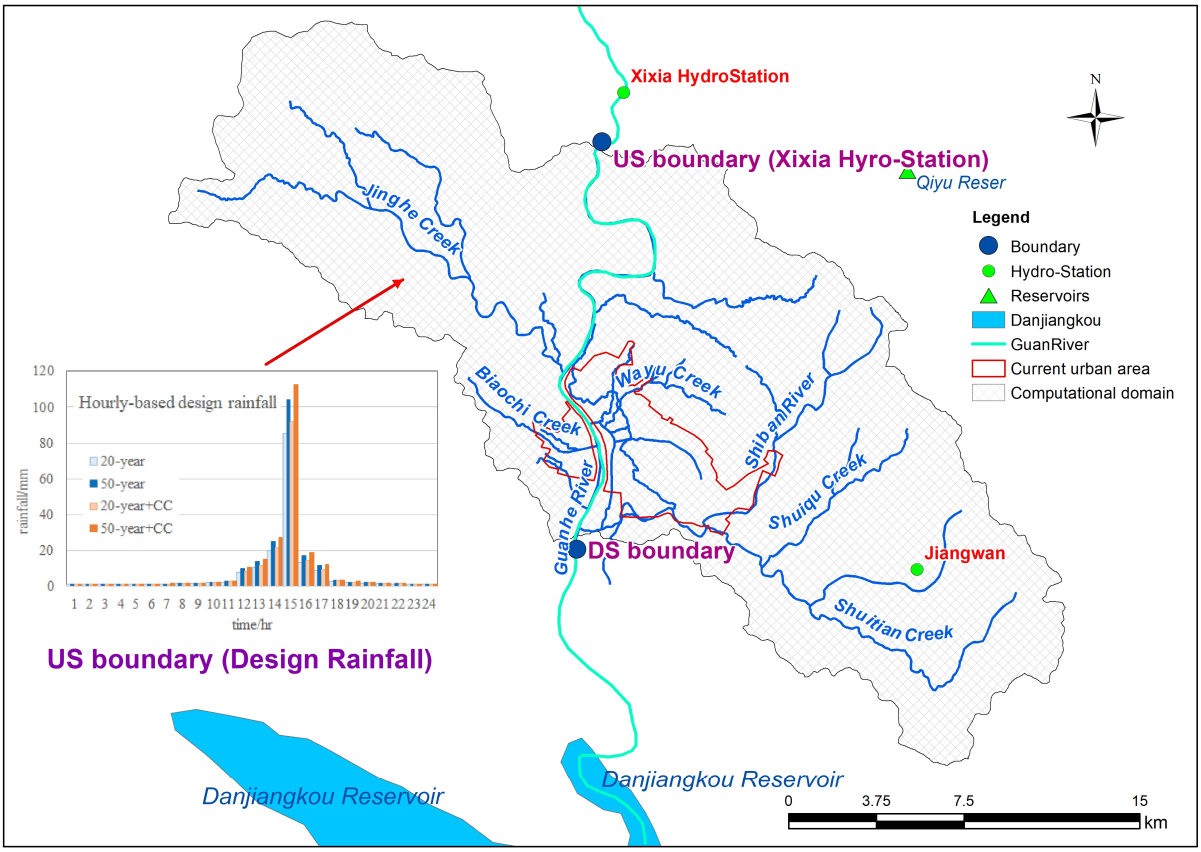
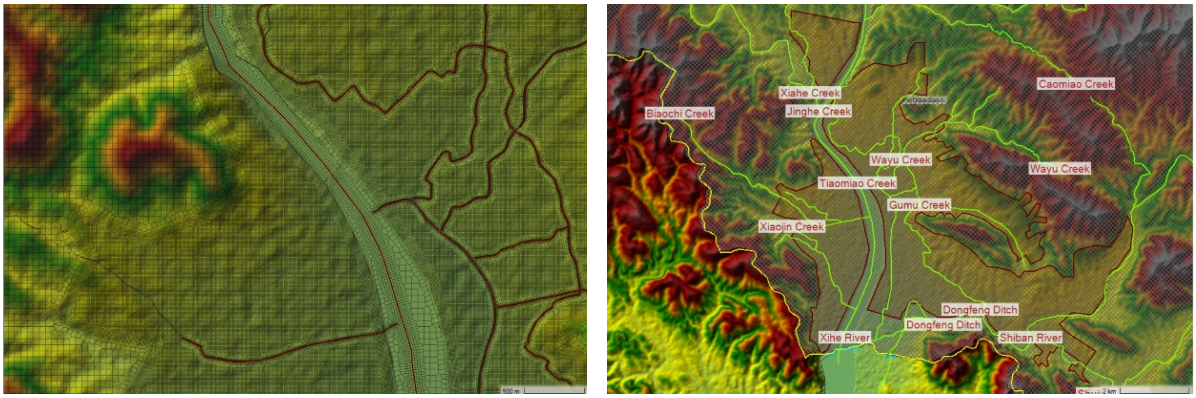


Figure 6. Geometry model.



(**A**) river and ditch as break line (**B**) urban area as refinement regions

Figure 7. Technical process in the geometry model.

3.5. Roughness Coefficients

Roughness is the important parameter reflecting surface resistance to water flow, determined comprehensively according to the river conditions where the grids located, the composition of land class, the distribution of trees and roads, etc. The assignment of roughness was conducted based on the landuse data with resolution of 30 m from the *MapWorld* (https://mulu.tianditu.gov.cn/, accessed on 1 February 2025), which consist of cultivated land, forest, grassland, wetland, water bodies, and artificial surfaces, and the corresponding assignments of roughness coefficient are based on class of landuse and shown in Table 2. And Figure 5 presents the current landuse of the computational domain.

Table 2. Landuse classification and roughness.

Code	Class	Roughness	Content
10	Cultivated land	0.065–0.08	Lands used for agriculture, horticulture and gardens
20	Forest	0.08–0.10	Lands cover with trees, with vegetation cover over 30%
30	Grassland	0.05–0.065	Lands covered by natural grass with cover over 10%
50	Wetland	0.035–0.05	Lands covered with wetland plants and water bodies
60	Water	0.020–0.025	Water bodies in the land area
80	Artificial surfaces	0.08–0.10	Lands modified by human activities

3.6. Model Rationality Analysis

The training of the Xihe River is one of the key focus of the ADB project and a typical cross-section of this river was selected to conduct model rationality analysis. Due to shortage of recorded hydrological data, full hydrograph comparison against gauge records is not feasible; the rationality test is therefore restricted to peak-discharge magnitude. In this study, model rationality was conducted by means of counterposing the two peak discharges of hydraulic analysis and rational method at the typical cross section of the Xihe River. According to the feasibility study report (FSR) of ADB [19], the flood peak discharge for 20-year-flood is 1392 m^3/s which is computed using Rational Formula Method (RFM) according to Ref. [31], a method widely used to compute design flood in China, and the computed in this study is 1452 m^3/s, the two peak discharges differ by only 60 m^3/s (4.3%), confirming the hydraulic model reproduces the RFM design peak; note that no observed gauge data are available for the Xihe cross-section, so this is a rationality rather than a validity check (See Figure 8).

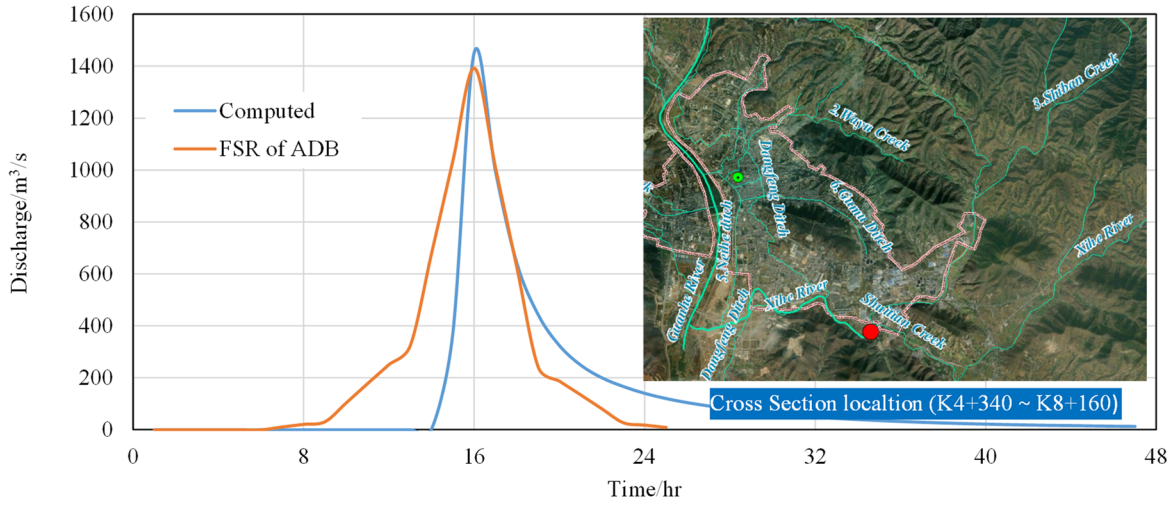
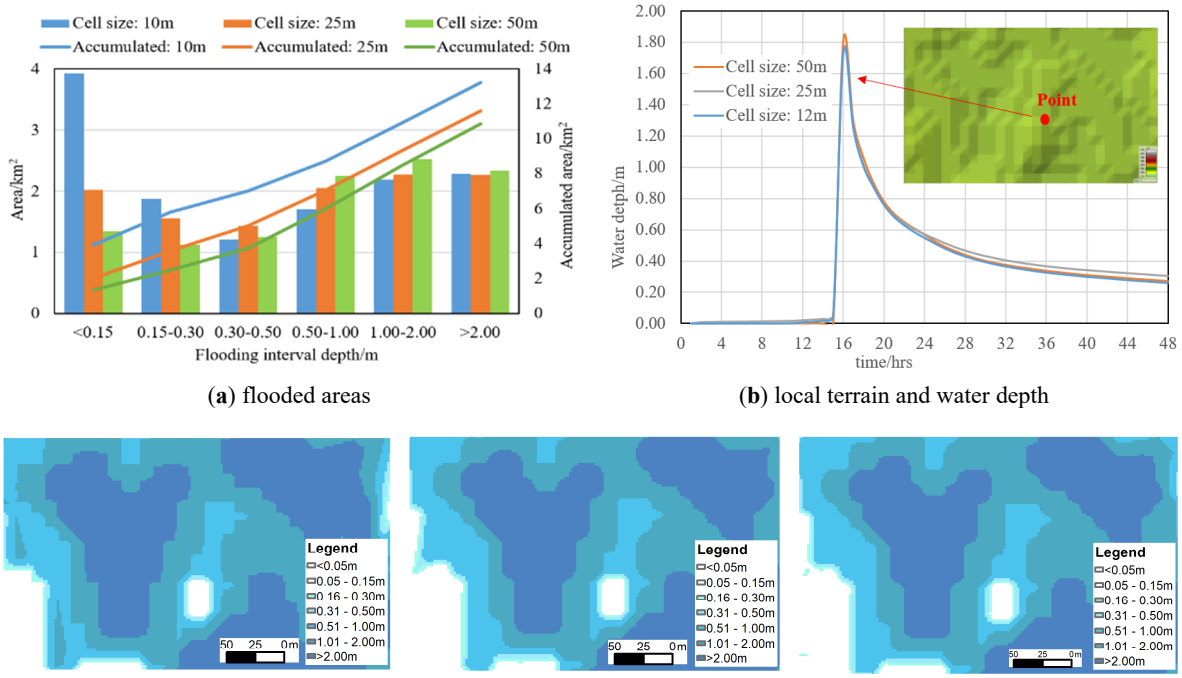


Figure 8. Model rationality analysis.

There is still more about the model to discuss. First, the input of the model is the hyetograph of 24-h design rainfall, in which, rainfall amounts and locations are hourly specified with a peak over half of the total rainfall amount concentrating within one hour (see Figure 3), obviously, most of actual rainfall events generally are not like that, but it is remarkably beneficial to the safety of flood control works and the assessment of extreme flood risk. Second, the inundation areas are sensitive to the cell sizes. A sensitivity analysis was performed for cell sizes of 50 m, 25 m and 10 m considering current urban areas and 20-year design rainfall, and Figure 9 presents the results of total flooded areas, local inundation areas and changes in water depth at a certain point for the three cell sizes. As can be seen, cell size 10 m provides higher resolution of inundation and has the most flooded areas, as Figure 9a, the general trend is larger cell size, higher water depth and more deep flooding area, as Figure 9b,c. The result of cell size 10 m was adopted to perform further analysis because it is the one most close to the spatial resolution of DEM data used to create the terrain model and the river channel width in the urban areas. Third, flow discharge is very sensitive to roughness coefficients, which are generally and experience-based assigned in this study according to the landuse categories in Table 2, and are averaged by the spatial resolution of the landuse data (30 m). It is not so accurate but an acceptable general method for two-dimensional flood simulation in large areas. Therefore, this model has accuracy limitations due to the reasons listed above, but is available to perform further flood analysis.



(**a**) flooded areas (**b**) local terrain and water depth

Cell size: 50 m Cell size: 25 m Cell size: 10 m

(**c**) local inundation areas for different cell sizes

Figure 9. Cell size sensitivity test.

4. Flood Risk Projection

4.1. Scenarios Design

Flood risk scenarios are primarily designed to assess the impact of floods from the sounding tributaries on the urban area, with extreme flood in the Guanhe River mainstream that causes backwater effects to the urban areas. Many aspects, such as landuse change in the catchment, urban area expansion, newly built infrastructure, population immigration, etc., will result in the change of exposure to flood and generate the future risk. Moreover, climate change has a certain impact and needs to be considered. In this study, flood risks are classified as three categories, present risk, future risk, and residual risk [22], and Table 3 presents the details of scenarios for risk analysis, in which, the design rainfalls (20-year and 50-year) refer to the baseline design events and the following features and their changes at current and in the future are taken into consideration, the scope of the urban area, rainfall of 24-h duration, terrains or structures of the urban area, underlying surface change due to implement of SCMs, and the major outer flood sources-the extreme flood from the Guanhe River.

The principle of worst-case scenario and the assumption of rainstorm and flood occurring with same frequency are taken into consideration as design scenarios of flood risk analysis in Table 3. For rainfall-flooding occurring with the same frequency, the floods in the surrounding creeks are computed based on the design rainfalls of 20-year and 50-year. For worst-case scenario, the recorded 2010 extreme flood event of the Guanhe River, assumed as the worst-case scenario for backwater impact to the urban areas, is used in all scenarios without consideration on climate warming. The reasons are as follows: (1) the 2010 flood event with peak discharge 7380 m^3/s is the largest flood since the construction of Xixia Hydrological Station, and the second largest recorded flood (the first one is the 1919 flood event with peak discharge 9530 m^3/s), far exceeding the flood control standard of the urban section of the Guanhe River mainstream; (2) several reservoirs have been constructed and are able to play important role in flood regulating, especially, the Shimen Reservoir (Xixia) in the upstream of the Xixia Hydrological Station (See Figure 1), completed in 2009, with drainage area of 2580 km^2 and total storage volume of 91 million m^3; and (3) as the core water source area of China South-to-North Water Diversion Project, long-term and sustainable ecological and environmental protection will be implemented in the Guanhe River Basin in the future.

Table 3. Scenario design for risk analysis.

Flood Risk	Scenario No.	Scenario Description				
		Urban Areas	Rainfall	Urban Terrain	SCMs	Guanhe Flood
Present risk	S1	Current	Design (20-year)	Current	Current	2010 extreme flood
Future risk	S2	Future	Design (20-year)	Current	Current	
	S3	Future	Design (20-year) + CC	Current	Current	
Residual risk	S4	Future	Design (50-year)	Future	Future	
	S5	Future	Design (50-year) + CC	Future	Future	
/	S6	Future	Design (20-year)	Future	Future	

(SCMs-Soil Conservation Measures; CC-Climate Change).

S1 presents the scenario for current risk, in which the components include current flood control conditions and underlying surfaces, that is, the current urban areas of the Xichuan city, the design rainfall (20-year) and terrain and soil conservation measures in the computational domain, with extreme flood from the Guanhe River.

Two scenarios, S2 and S3, are designed for future flood risk. The difference of S2 and S3 to S1 is that future urban area replaces current urban area without any new flood control measures implemented. Similarly, the change between S3 and S2 is the rainfall coming from climate change adds to the current design rainfall.

S4 and S5 are designed for residual risk. Comparing to S2 and S3, future urban terrain and soil conservation measures are used to highlight the impact of the ADB project's activities, that is, newly planned flood management measures implemented; moreover, assuming the flood control capacity of the urban river channel improved to 20-year flood, but the design rainfall changed from 20-year to 50-year. Similarly, the difference between S5 and S4 is rainfall from climate change.

As for the impacts of the ADB project activities in flood control, it was conducted by a comparison between S2 and S6, among which the differences are the change of urban terrain and SCMs.

4.2. Results Analysis

Based on the flood simulation model, flooding in the urban areas of various scenarios have been performed and Table 4 presents the results, in which, flood-depth less than 0.05 m are omitted for this depth usually has a negligible impacts for urban normal functions, and the water depth are classified as 6 levels [33]: less than 0.15 m, 0.15–0.30 m, 0.30–0.50 m, 0.50–1.00 m, 1.00–2.00, over 2.00 m. Commonly and simply speaking, the flood-depth thresholds of Ref. [33] indicate the following resilience: (1) urban flooding does not occur as flood-depth less than 0.15 m; (2) for 0.15–0.30 m flood-depth, pedestrians can walk, but the intake and exhaust ports of low-clearance cars are submerged, and residential buildings remain free of water; (3) for 0.30–0.50 m flood-depth, children and the elderly have difficulty wading through water; cars stall; roadways become impassable; and doorsteps and underground garage entrances are submerged; (4) for 0.50–1.00 m flood-depth, adults have difficulty in walking, self-rescue ability reduced significantly; side roads cut off; first-floor homes flooding; and basements and underground garages inundated; (5) for 1.00–2.00 m flood-depth, adults cannot wade through water on foot; all vehicles unable to pass; ground-floor buildings submerged up to the windowsills; underground spaces completely flooded; rescue by boat, and rescue routes severely restricted; (6) as flood-depth exceeding 2.00 m, high risk for people trapped; ground floors of multi-story buildings largely submerged; and professional rescue become difficult. As mentioned in section 3.6, due to the accuracy limitations of the flood simulation model, the calculated flooding areas are only rough basis for flood risk analysis. And the projected flood risks are briefly analyzed as follow.

Table 4. Flooding area (unit/km^2).

Flood Depth/m	Present Risk	Future Risk		Residual Risk		/
	S1	S2	S3	S4	S5	S6
<0.15	3.93	6.59	6.54	6.35	6.38	6.28
0.15–0.30	1.87	2.25	2.31	1.43	1.47	2.10
0.30–0.50	1.22	1.33	1.37	1.95	1.98	1.26
0.50–1.00	1.71	1.82	1.85	2.11	2.21	1.48
1.00–2.00	2.19	1.89	1.98	1.02	1.09	1.29
>2.00	2.29	2.14	2.37	1.75	1.93	1.41
sum	13.21	16.01	16.42	14.61	15.06	13.82

4.2.1. Present Risk

Present risk is the risk associated with present development and land use. The features are current urban areas and its terrains, with 20-year-design rainfall and extreme flood in the Guanhe River. The inundation areas in the

current urban areas are 3.93 km^2 (<0.15 m), 1.87 km^2 (0.15–0.30 m), 1.22 km^2 (0.30–0.50 m), 1.71 km^2 (0.50–1.00 m), 2.19 km^2 (1.00–2.00 m), and 2.29 km^2 (>2.00 m). See Figure 10.

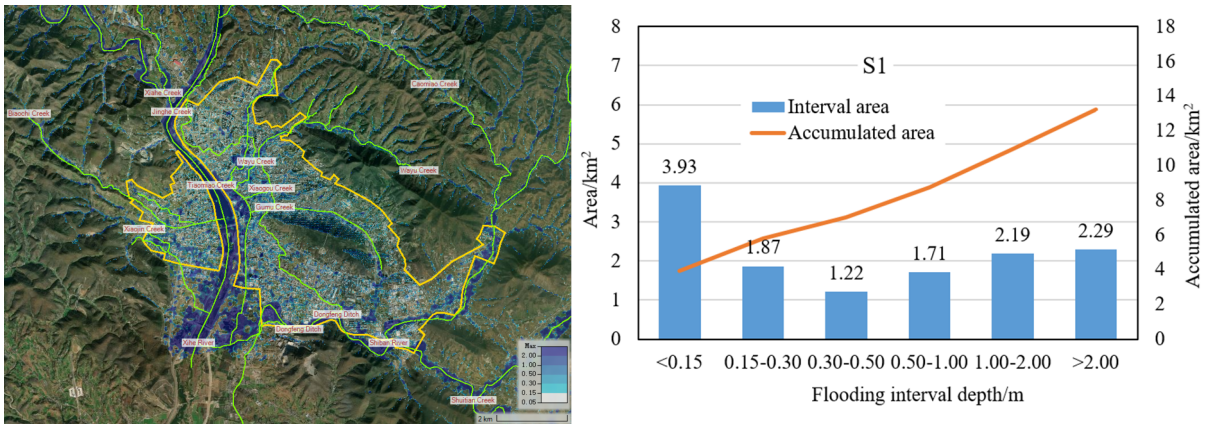
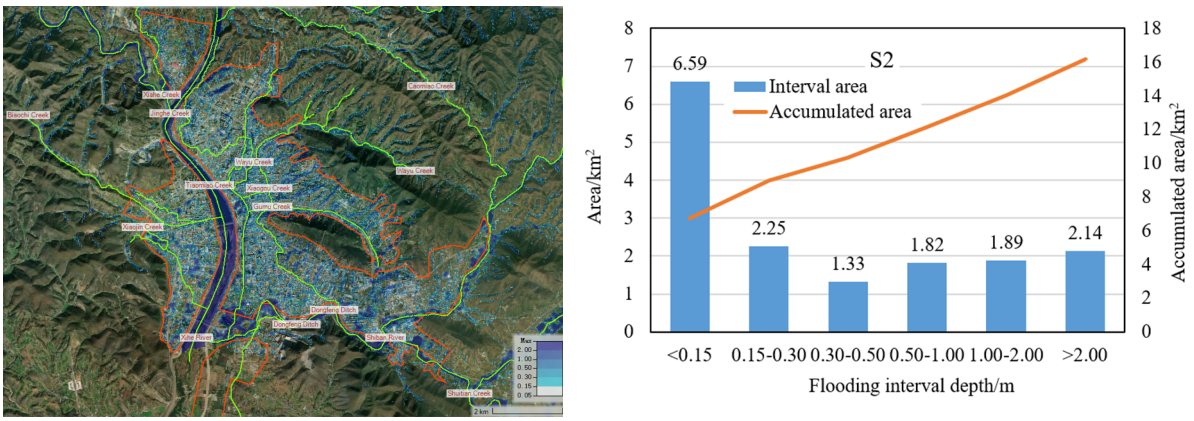


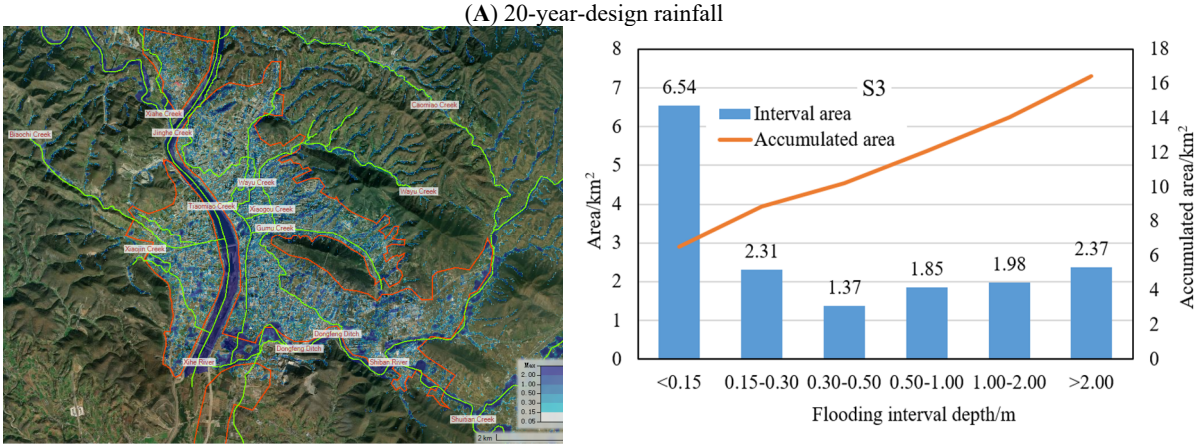
Figure 10. Urban areas present risk projection.

4.2.2. Future Risk

This is the risk associated with future development and land use, but no countermeasures are taken to reduce the impacts of floods. There are more possible extreme rainfall-flood for future risk, as example, the features are future urban area and terrain, with 20-year-design/plus climate change rainfall and extreme flood in the Guanhe River. The inundation areas in the future urban areas will be 6.59 km^2 (<0.15 m), 2.25 km^2 (0.15–0.30 m), 1.33 km^2 (0.30–0.50 m), 1.82 km^2 (0.50–1.00 m), 1.89 km^2 (1.00–2.00 m), and 2.14 km^2 (>2.00 m) as Figure 11A, while for 20-year-design rainfall plus climate change, the inundation areas will be 6.54 km^2 (<0.15 m), 2.31 km^2 (0.15–0.30 m), 1.37 km^2 (0.30–0.50 m), 1.85 km^2 (0.50–1.00 m), 1.98 km^2 (1.00–2.00 m), and 2.37 km^2 (>2.00 m), see Figure 11B.



(**A**) 20-year-design rainfall

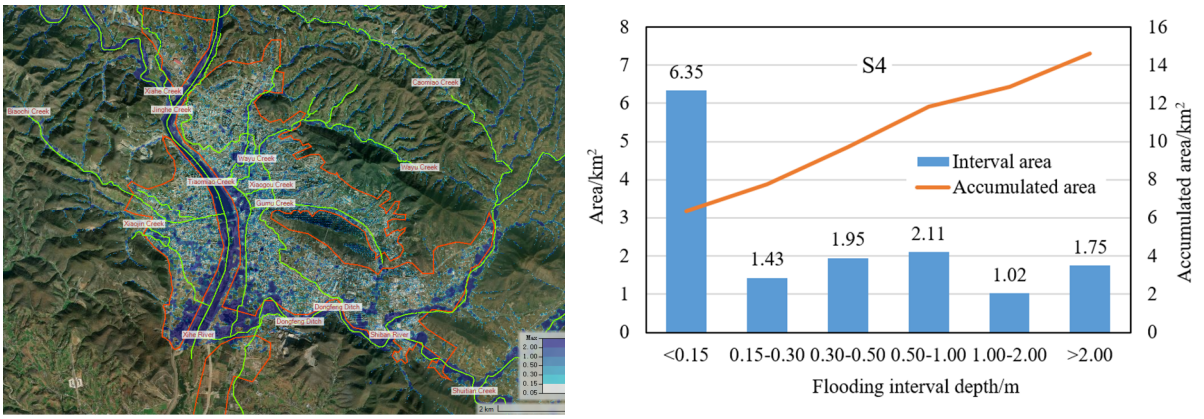


(**B**) 20-year-design rainfall plus climate change

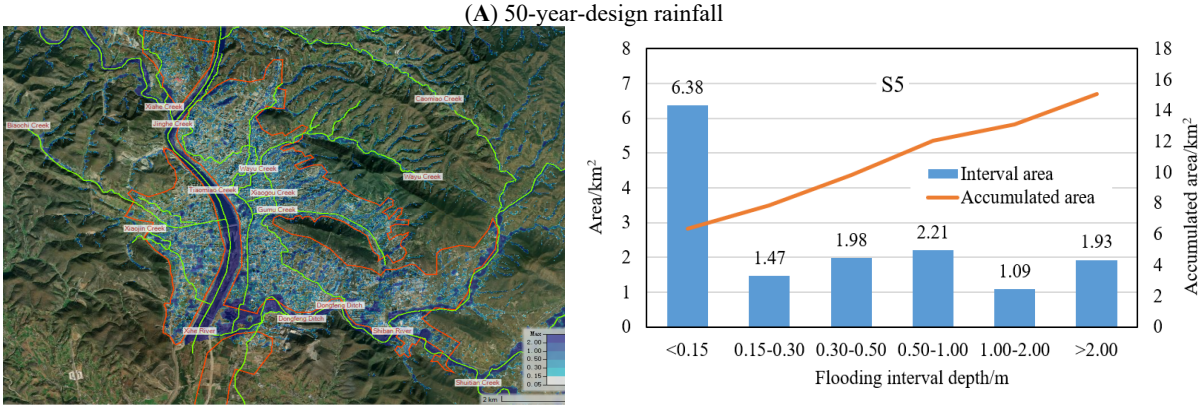
Figure 11. Urban areas future risk projection.

4.2.3. Residual Risk

Residual risk is the risk the community would be exposed to after flood management measures have been implemented, associated with future development and land use [22]. There are more possible extreme rainfall-flood for residual risk, as example, the features in this study are future urban area and terrain, and 50-year-design/plus climate change rainfall and extreme flood in the Guanhe River. Figure 12 presents the results of this scenario, the inundation areas in the future urban areas will be 6.35 km^2 (<0.15 m), 1.43 km^2 (0.15–0.30 m), 1.95 km^2 (0.30–0.50 m), 2.11 km^2 (0.50–1.00 m), 1.02 km^2 (1.00–2.00 m), and 1.75 km^2 (>2.00 m), see Figure 12A, while climate change considered, the inundation areas will be 6.38 km^2 (<0.15 m), 1.47 km^2 (0.15–0.30 m), 1.98 km^2 (0.30–0.50 m), 2.21 km^2 (0.50–1.00 m), 1.09 km^2 (1.00–2.00 m), and 1.93 km^2 (>2.00 m), as Figure 12B.



(**A**) 50-year-design rainfall



(**B**) 50-year-design rainfall plus climate change

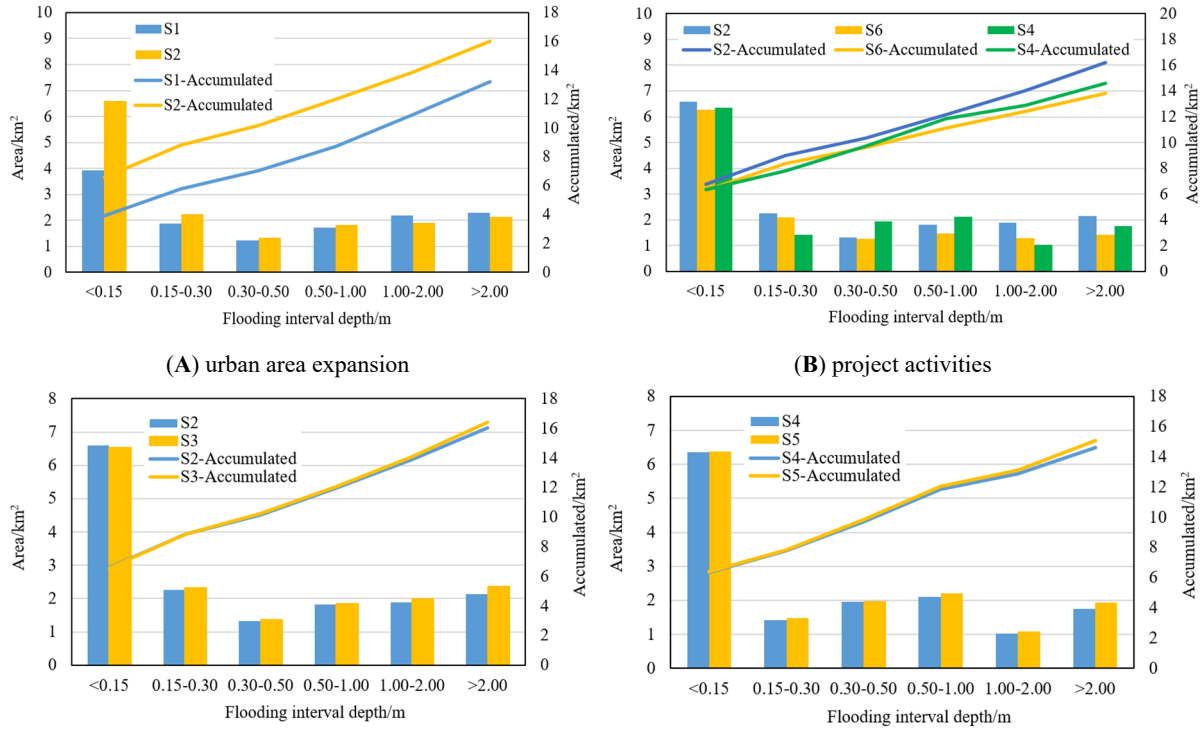
Figure 12. Urban areas residual risk projection.

The above scenarios are only some design rainfall-based flood risk projections. As mentioned before, the rainfall change from climate change are based on reference [32], in which the possible change on daily rainfall under RCP 4.5 scenario with temperature increment of 0.9–1.1 °C was recommended and drew the conclusion that seasonal flooding and storm will be as moderate risk to the Xichuan county, then the assumption of 7 percent of total rainfall within the corresponding duration due to climate warming was used in this study. In China, the standard of extreme rainfall means the total rainfall amount of 24-h-duration reaches or exceeds 250 mm, larger than the design rainfall amounts (see Figure 3), and, at the same time of 2010 flood event in the Xixia Hydrological Station, on 24 July 2010, an even more extreme storm of rainfall amount 329 mm hit the Qiyu Reservoir that lies in the northeast of the Xichuan city, about 15 km away. Therefore, actual floods may be more severe than those simulated in the future, and more extensive and in-depth strategies and measures are needed to find out to manage standard-exceeding floods.

4.3. Flood Risk Change

Comparisons among different scenarios are conducted and the main results are as follow. First, due to urban area expansion, the total flooding area will almost increase linearly, in particular, the growth of deep-water area is very significant, which indicate, if no measures are taken, there will be a greater risk of flooding for the urban areas, as Figure 13A (S1 vs. S2). Second, the project activities, typically, channel dredging or widening, embankment construction and SCMs in the catchments, will play positive role in decreasing the deep flooding area

for floods within the flood control standard, deep flooding area decreasing significantly, as Figure 13B (S2 vs. S6); however, once floods exceed the flood standard, heavy flooding will happen and deep flooding areas (in this case 0.3–1.00 m) will go up obviously, see Figure 13B (S2 vs. S4), in other words, flood risk are still exist even flood control works are implemented. Third, Figure 13C,D presents the same going up trend of flooding area due to climate warming, while deep flooding area will increase slightly without project activities, as Figure 13C (S2 vs. S3), but both the deep flooding area and total flooding area will decrease significantly with project activities, as Figure 13D (S4 vs. S5). Generally speaking, (1) project activities will play significant role for floods within flood control standard, (2) the impact of climate warming needs to be seriously considered in the future flood management, as Figure 13C,D, and (3) the inundated area will inevitably increase in the future despite various activities for flood control capacity enhancement, more strategies and countermeasures need to be taken into consideration to address residual flood risk beside structural measures.



(**A**) urban area expansion

(**B**) project activities

(**C**) climate warming (S2 and S3)

(**D**) climate warming (S4 and S5)

Figure 13. Flood risk change.

5. Resilience Building Strategies

As mentioned above, residual flood risk is always an objective and inevitable reality, no matter how high the flood control standards may be, and resilience strategies are practical and effective measures to address this risk. The traditional "structure-based defense" approaches struggle to address the growing number of extreme floods while the core of resilience building is to shift from the traditional approach of "flood control" to "living with floods", with focus on the capabilities of prevention, adaptation, recovery and learning. The combination of resilience strategies of ecology, structure, space, and society, are widely used in the flood management in the urban area of Xichuan county. As a mountainous city, the urban areas are vulnerable to multiple hazards including floods from the Guanhe River, flash floods from the tributaries, and waterlogging. Based on the flooding information analyzed above, the strategies include river basin strategy, urban area strategy and early warning strategy, and public's awareness strategy.

5.1. River Basin Strategy

The core of this strategy is that resilience building should be performed at river basin scale. There are two significant specific options of this strategy for the Xichuan city, namely, underlying surface improvement and flood control regulation by structural measures, typically, reservoirs and sluice gates.

5.1.1. Strategy on Underlying Surface Improvement

As one of the crucial ecological resilience measures, soil conservation plays important role in changing vegetation cover and rainfall interception, and then reducing and retarding flood peak discharge. Researches indicate the interception effect of canopy layer on rainfall is related to many factors, such as canopy density, tree species, forest type, and the ground layer of dead branches and leaves, fluctuating greatly at low rainfall and reaches a constant value at high rainfall, up to 13–17 mm for small catchments with a large forest coverage [34], and reducing flood peak discharge [35]. As mentioned before, the Guanhe River Basin is the core water source area of China South-to-North Water Diversion Project and much attention has been paid to ecological environment protection, including soil conservation measures at river basin scale. In the ADB project, a demonstration of SCMs with area of 11.55 km^2 was performed in the Shiban Creek Catchment. The demonstration area was zoned as four subareas: ecological restoration subarea, ecological governance subarea, ecological agriculture subarea and livable environment subarea, with objective of significant soil conservation capacity enhancement in the demonstration area, in detail, forest-grassland cover reaching over 80% of the afforestation and grassland suitable area, forest-grassland cover rate increasing by more than 15%, and the preservation rate exceeding 85% [19]. Comparison of floods between "with SCMs" and "without SCMs" at XS (K4 + 340 ~ K8 + 160) was conducted using the flood simulation model, and Figure 14 presents the difference is very obvious, flood peak discharge and flood volume reducing significantly, which indicates the river basin strategy will be remarkably effective once the soil conservation measures are completed in the future.

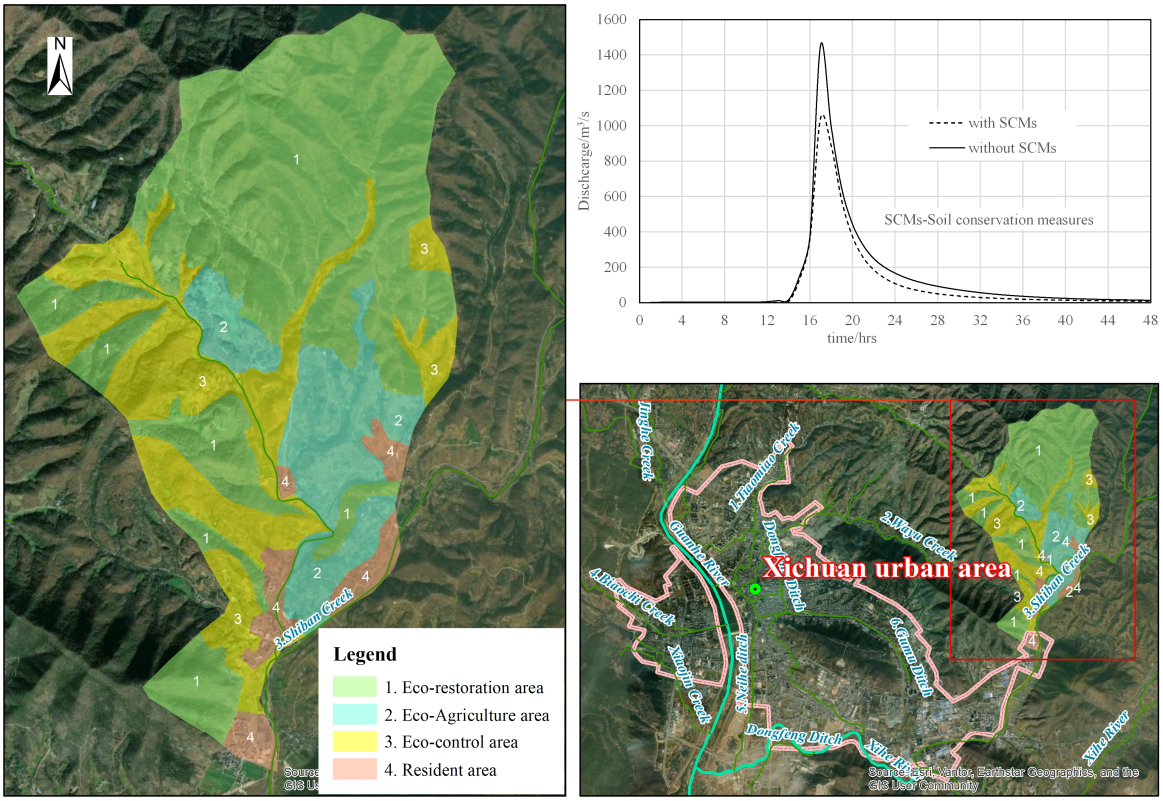
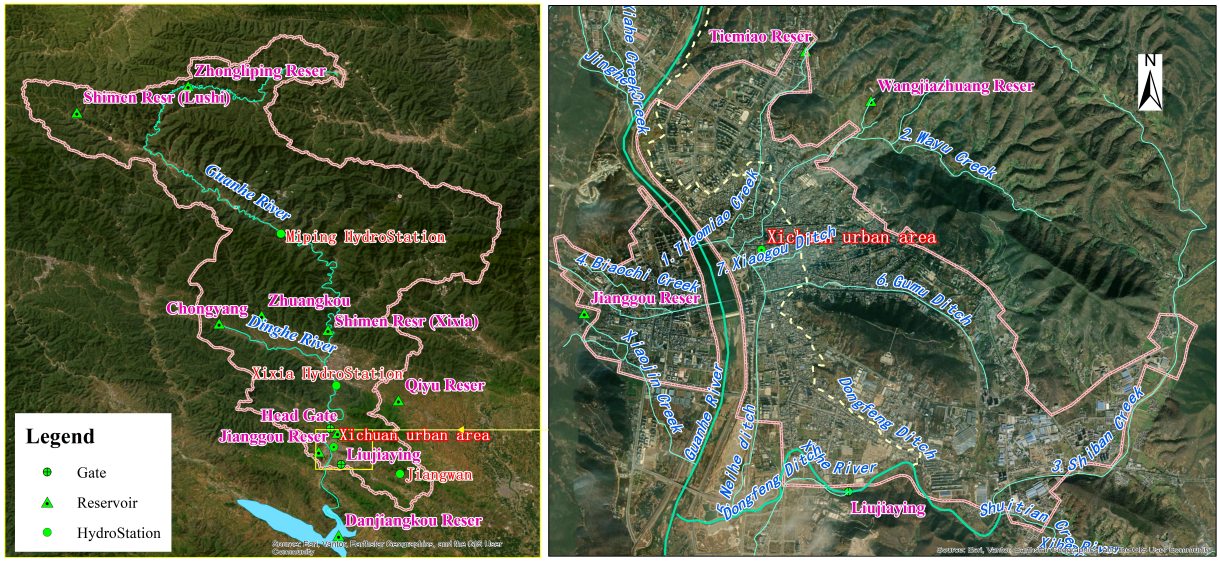


Figure 14. Soil conservation enhancing flood resilience for the urban areas.

5.1.2. Reservoir and Sluice Gate Regulation

Water storing or regulating structures, such as reservoirs and sluice gates, contribute much to enhance the resilience of flood control in the urban areas. For the Xichuan city, there are two sides of flood control structures contributing much to this. The first one is the five main reservoirs in the upper reaches of the Guanhe River basin, Shimen (Lushi), Zhongliping, Chongyang, Zhuangkou, and Shimen (Xixia) with volume capacity of 1.13 million m^3, 12.48 million m^3, 30.94 million m^3, 5.1 million m^3, and 91 million m^3, respectively, all of them are able to play a role in controlling the mainstream floods, see Figure 15A. The second one is the reservoirs and sluice gates near to or within the urban areas, directly controlling the floods from the tributaries. Currently, there are three reservoirs within or near to the urban areas, the Jianggou Reservoir, the Tiaomiao Reservoir and the Wangjiakeng Reservoir;

as mentioned in Section 1, the Dongfeng Ditch, runs through the urban area from north to south, the two sluice gates in this ditch play important role in controlling floods through the urban areas, see Figure 15B.



(**A**) main reservoirs in Guanhe River Basin (**B**) reservoirs and sluice gates surrounding the urban areas

Figure 15. Reservoir and sluice gate enhancing flood resilience for the urban areas.

5.2. Urban Area Strategy

Several countermeasures, urban drainage zoning, flood conveyance capacity enhancement, and water storage facility, and key infrastructure improvement, are taken to enhance the resilience in the urban areas.

5.2.1. Urban Drainage Zoning

Zoning urban drainage area is one of the important measures for resilience enhancement which requires each of them to address urban flooding within their own jurisdiction. Currently, the stormwater pipe networks in the urban area mainly concentrate in the built-up areas on both sides of the Guanhe River. Based on the topography and water system, the built urban areas are divided into 8 drainage subareas, with total area of 25.23 km^2 (See Figure 16).

For each drainage subarea, flood discharge and waterlogging should be addressed within their own areas, and the following activities are performed: assessment of urban flooding risks, optimizing drainage pipeline networks, and construction of separate stormwater and wastewater sewer systems. The proposed drainage project involves 8 roads, including 2 roads with stormwater and wastewater separated systems, and 6 roads installed supporting municipal drainage facilities [19].

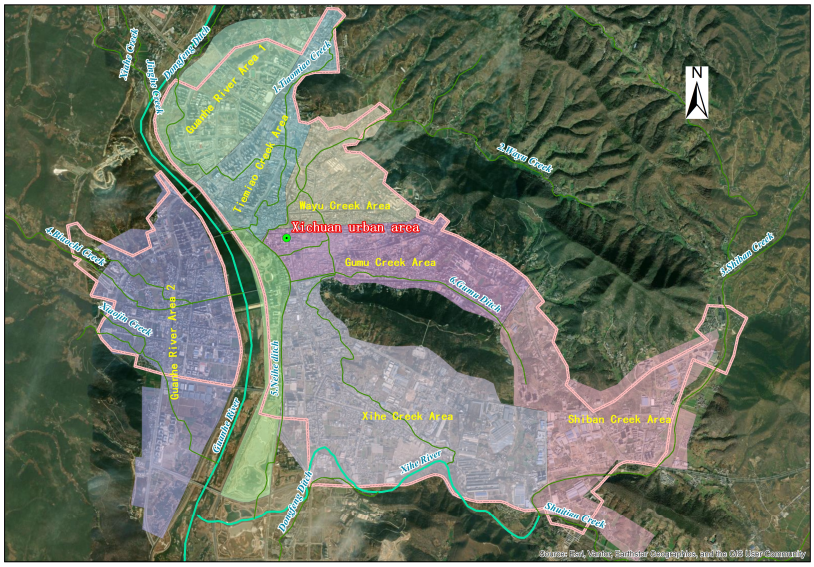
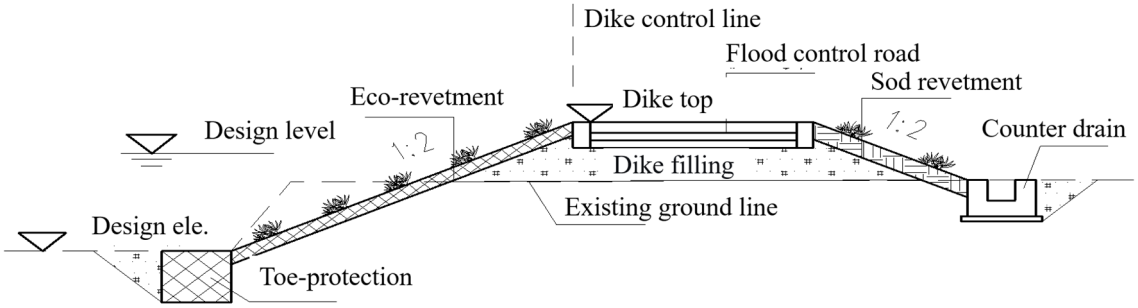


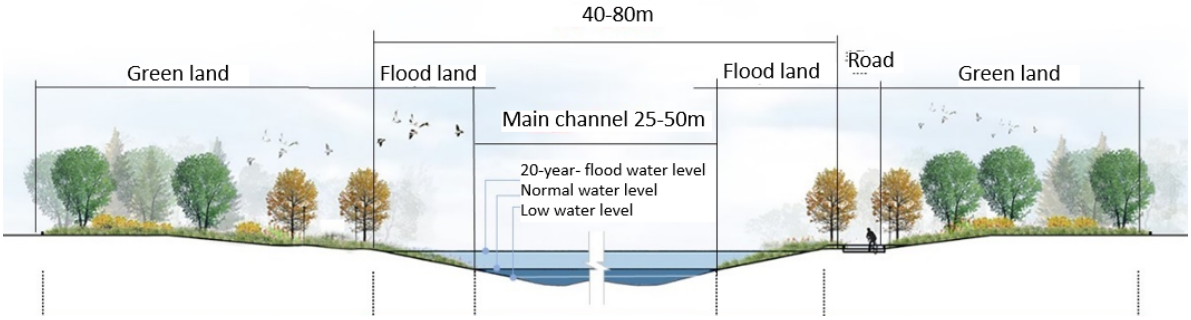
Figure 16. Urban area drainage zoning.

5.2.2. Enlarging Flood Discharging Capacity

Enhancing flood discharging capacity contributes much to resilience in urban areas. Currently, the measures mainly include dredging and silt removement works, existing bridges demolition and reconstruction works, ecological water storage works, etc. Based on flood risk and flooding information analyzed above, much ecological measures have been taken into consideration as the river embankment designs were conducted, for instance, ecological revetments, blue- or green-, are adopted for the new embankment where flood flow is relative mild while the traditional grey-means type is selected for those severely eroded river section; it is proposed to adopt foundation protection combined with first-grade gentle slope type for slope section, with flood control road (Figure 17A). This design plan for river channel covers relatively large area, but it is easy to create a variety of ecological landscape riverbank, and have buffer zone of flood land and green land, which is an important consideration on flood resilience building (Figure 17B) [19].



(**A**) typical cross-section of embankment



(**B**) typical cross section of river channel

Figure 17. Enlarging flood discharging capacity.

5.2.3. Water Storage Facilities

Water storage facilities are also the important strategy to enhance flood resilience in the urban areas. The new-build weirs were designed to maintain the ecological impoundment and landscape functions, such as water storage weir in Shiban Creek (rolling weir, mainly composed of forebay, weir body section, stilling pool and outlet anti-scouring channel section.), water storage weirs at villages of Shengshuisi and Liuyingba, and the dam of the Dongfeng Ditch. It is proposed to adopt the masonry gravity retaining wall type for the current water storage facilities and newly built water storage facilities, branch ditch inlet and the upstream and downstream embankment of the river reach with severe scouring position of concave bank. For the rest of river section, ecological retaining wall type is adopted [19].

5.2.4. Key Infrastructure Improvement

Moreover, the resilience building for key infrastructures is planned to be enhanced. The typical activities include: (1) reinforcing and reconstructing of lifeline infrastructures, such as power-water-gas supply, and communication networks, (2) using overhead or elevated installation methods if they are located in flood high-risk areas, and (3) establishing backup power systems and emergency communication links to ensure basic operational functions during flooding time [19].

5.3. Early Warning Strategy

Early warning is one of the most important strategies for resilience building, especially for emergency rescue. An early warning system has being built and improved for flood management in Xichuan county which serves the whole county and includes three subsystems of rainfall-flood monitoring, warning triggering and warning issuing: (1) rain-flood monitoring, with 252 rain gages, 133 water stage stations, and 27 video cameras, all of these devices obtaining and transmitting the real information of rainfall and flooding information to the subsystem of thresholds estimation; (2) warning triggering, once the observed rainfall depth or water level reaching or exceeding the corresponding thresholds, this subsystem will trigger red-, orange-, yellow- or blue-level warnings; and the rainfall thresholds are derived through rainfall-runoff inversion while water level thresholds are computed using water level correlation method for up- and down-stream cross sections; (3) warning issuing, with 536 wireless broadcasts, 960 hand-cranked alarmers, and 1479 handheld speakers, all of them used to disseminate warning messages once warning are triggered.

In order to mitigate flooding in the urban area, both the municipal drainage networks and road water trapped conditions have been significantly enhanced in this system based on flood risk and flooding information analyzed before, including 7 rainfall gages near the urban areas, 8 cameras for urban waterlogging supervision, and 4 sluice gages for flooding, with purpose of obtaining real-time information for the public, decision-makers, and emergency rescue. Figure 18 presents the newly installed monitoring devices in the urban areas in this system.

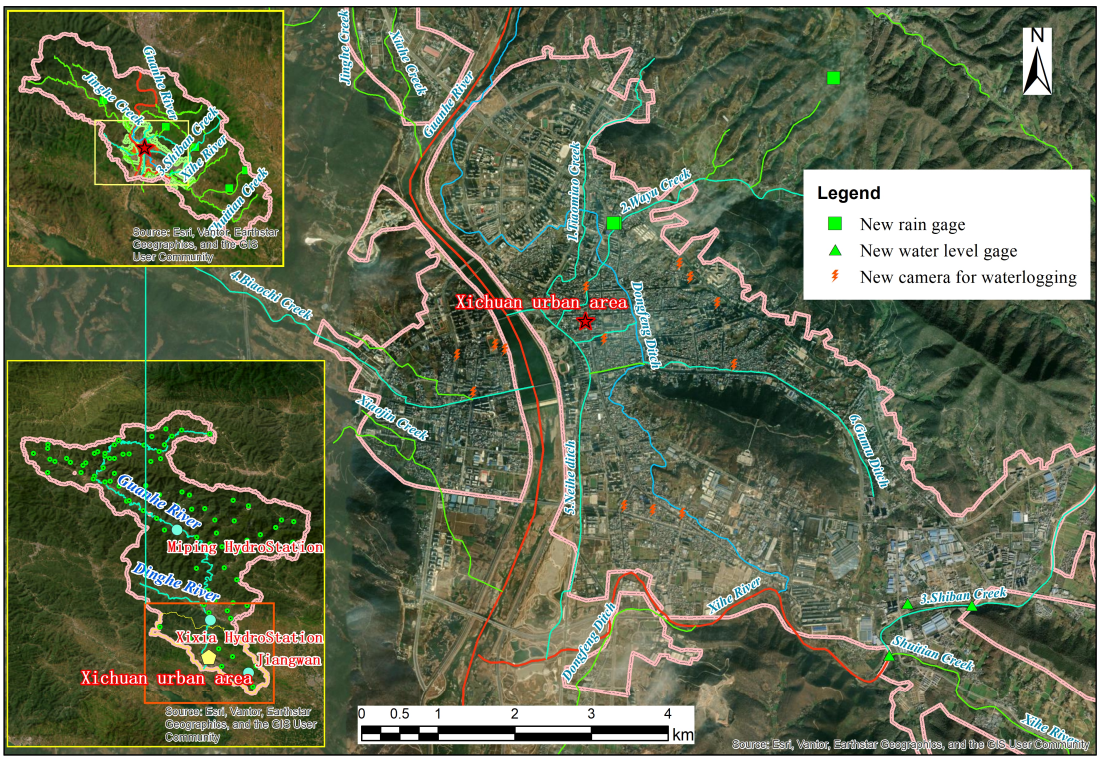


Figure 18. New monitoring devices for urban areas of the early warning system.

5.4. Public Awareness Strategy

As an integral part of social resilience, numerous measures have been implemented, such as developing emergency plans at the grassroots level, conducting public awareness campaigns, training sessions, and drills, with purpose of raising public's awareness of flood risks and capabilities. Based on the emergency plans, the tightly following main activities are as follows: (1) publicity campaigns, are often conducted through various channels, which covers the causes and hazards of flood disasters, methods and measures for evacuation and self-rescue, local disaster response command and coordination mechanisms, early warning systems and sources of personal information, infrastructure and supplies storage, and so on; (2) technical trainings, are annually performed with the trainees of village officials, militia members, volunteers, and village representatives, and the training skills to take correct actions during flood event, such as getting early warnings, evacuation routes selection, duties and responsibilities, and key points for self-rescue and mutual aid; (3) scenario-based drills, are annually conducted at village-level with various scenarios, typically, midnight, rainstorm, flash floods, transportation disruptions, and power

off; and (4) public volunteer participation mechanisms, including members of village mutual-aid-teams, youth volunteers, and small companies, to foster a culture where "everyone participates and everyone shares responsibility."

6. Conclusions

Cities at county level in mountainous areas, usually having a certain number of population and significant assets, are usually prone to rainstorm floods due to steep terrain, and short and steep river channel, and shortage of technologies and funds to flood management. Taking Xichuan County as a case, this article conducts a systematic analysis on flood risk identification and resilience building for county level cities in mountainous area under climate change. The main conclusions are drawn as follow.

(1) A practical approach on flood risk identification has been proposed for mountainous county-level cities in this study, whose core is the flood risk three levels of operational, project planning and project design, and scenario analysis based on flood simulation. In this approach, it is important to take the key elements into consideration for flood risk classification and scenario design, such as the expansion of urban areas, variation of rainstorm due to climate change, hydrological feature change of underlying surface due to implement of soil conservation measures, and the change of flood conveyance capacity from structural building activities. Flood risk analysis can identify areas prone to flooding and erosion, pinpoint weaknesses in flood management, and clarify where flood risks lie. Based on the information, the scope and approach of resilience-building will be more clearly defined and targeted.

(2) County level cities like Xichuan will continue to face a risk of flooding even various structure measures have or will be implemented, and resilience building is vital for flood management in the future. On one hand, project activities for flood control will play important role in managing floods within flood control standards, but for over-standard floods, deep flooding areas may increase due to the expansion of the urban area and climate warming, and these cities will continue to face flood risks; on the other hand, due to limited exposure values, available funding and technologies, flood control standards for county level cities like Xichuan, cannot be very high, therefore, resilience building is one of the inevitable and best options for residual flood risk management.

(3) Typical strategies to enhance the resilience were proposed for the Xichuan city and their effects were analyzed in this study; furthermore, for cities like Xichuan, with characteristics of a certain number of exposure values, steep mountainous area, complicated internal water system, surrounded by several external creeks, maybe divided into different parts by large rivers, these strategies are valuable. Generally, the proposed main strategies include: Strategy 1—river basin scale strategy, such as underlying surface improvement by soil conservation measures, reservoir and sluice gate regulation, which can play an important role in delaying and cutting down of peak flow of floods to the urban areas; Strategy 2—urban area improvement strategy, such as urban drainage zoning, construction of compound channels for widening, erosion-resisting, and flood detention and storage facilities, which will contribute much to reduction of waterlogging, erosion and flooding in urban areas; Strategy 3—early warning strategy, of which the main activity is to build a smart early warning system, covering the flood source areas and the most prone areas; and Strategy 4—public awareness strategy, aiming to raise public risk awareness and enhance public capacity. Strategy 3 and strategy 4 are very important for specific individuals or neighborhoods to take correct actions timely in case of floods.

(4) More research needs to be conducted on flood risk identification and resilience building strategies in the future. First, only flood danger was considered, flood depth in this study, but exposure and vulnerability, important components of flood risk, were not quantitatively measured, the features of exposure and vulnerability may be quite different for different urban areas. Second, structure failure and sediment issues need to be taken into consideration for flood risk identification. In fact, as global climate change intensifying, rainstorm caused floods, often carrying large amounts of sediment and debris, will be more intensive, more random, and more destructive, hence, cities in mountainous areas will face various threats besides floods, even with debris flow or landslides. Therefore, more hazard factors, such as structure failure, sedimentation needs to be considered as flood risk identification performed. Third, the impact of climate change. It is an indisputable fact that extreme weather events have become increasingly frequent in recent decades. In the field of climate change impact research, both RCP4.5 and RCP8.5 scenarios are often used for analysis, given the ecological protection and environment improvement activities in the Guanhe River Basin, only RCP4.5 scenario is used in this study; however, this remains a hypothetical scenario, and the true impacts of climate change still require further study. Fourth and last, resilience strategy needs to be considered from a more extensive and in-depth perspective. For county level cities in mountainous areas, resilience building strategy should be integrated in an overall flood management plan, focusing and persevering the conception of "ecological protecting in the upstream areas, engineering stabilizing the foothills,

drainage strengthening within the urban areas, making necessary room for floods, and awareness raising among all residents".

Author Contributions

C.L.: Conceptualization, methodology, flood modeling and analysis; X.P.: Writing—reviewing and editing; J.S.: Original draft preparation; J.W.: Data curation, mapping. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

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Informed Consent Statement

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Data Availability Statement

All of the underlying research data in this study are from the feasible study report (FSR) of ADB (PRC-53053-001). This report Ref. [19] is not publicly accessible, but the key hydrology/design inputs and the rationality benchmark are derived from the publicly available Henan Design Rainstorm Flood Manual for Small and Medium-sized Watersheds Ref. [31], and the climate-change increment follows Ref. [32].

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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