https://doi.org/10.5194/nhess-2021-163
Preprint. Discussion started: 8 June 2021

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Assessment of the Direct Economic Losses of Flood Disasters Based on the Spatial Valuation of Land Use and Quantification of Vulnerabilities: A Case Study of the 2014 Flood in Lishui city, China

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Abstract. The refined assessment of the direct economic losses of flood disasters is important for emergency dispatch and risk management in small- and medium-sized cities. There are still great challenges in the accuracy and timeliness of the previous research methods. In this study, a single flood disaster in Lishui city in 2014 was taken as an example to study and verify a method for the rapid and refined assessment of direct economic loss. First, based on a field investigation, the inundation range and submerged depth simulated by the flooding model were verified. Next, the urban land use status map and high-precision remote sensing classification data were fused and combined with expert questionnaire surveys, thereby providing the types and values of disaster-bearing bodies. Then, the existing vulnerability curve database was summarized, and the curves were calibrated by disaster loss reporting. Finally, the spatial distributions of the flood disaster loss ratio and loss value were estimated by spatial analysis. It is found that the constructed land use map has detailed types and value attributes as well as high-precision spatial information. Secondly, the vulnerability curves after function fitting and calibration effectively reflect the change characteristics of land use loss ratio in this area. Finally, the estimated loss ratio and loss value distributions can accurately reflect the spatial pattern of flood disaster loss, which is useful for the government to formulate effective disaster reduction and relief measures.

Key words: Flood disaster, Direct economic loss, Loss assessment, Vulnerability curve

1 Introduction

Refined assessments of the direct economic losses of flood disasters are very important in disaster emergency rescue and urban flood risk management (Li et al., 2017; UNISDR, 2015). The results of a rapid quantitative assessment of disaster losses with high spatial resolution not only provide suggestions for the government to formulate emergency dispatch management measures, such as releasing disaster information, deploying rescue forces and relief materials, and the emergency resettlement of disaster victims, but also lay a data foundation for decision-makers to plan sponge cities and formulate flood risk management systems and climate change adaptation policies (Alfieri et al., 2016; Merz et al., 2010).

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As a key component of flood risk assessment, flood loss assessment has been extensively analyzed by researchers (Falter et al., 2015; Koks et al., 2015). The flood loss data obtained from a comprehensive high-quality field survey after a disaster can accurately reflect the disaster loss situation and has important reference value for the establishment and verification of flood loss models (Carisi et al., 2018). However, given that loss data can only be obtained after a flood, these data cannot provide timely guidance for disaster relief. Collecting loss data is also time-consuming and laborious, which supports the further development of flood loss assessment models.

Due to the development of existing flood loss assessment models, there are relatively mature methods and tools (EMA, 2002; Scawthorn et al., 2006), and the popularization of flood insurance provides relatively complete socioeconomic and disaster loss data; thus, disaster losses can be quickly assessed when floods occur (Hsu et al., 2011). The United States (Smith D, 1994), the United Kingdom (Stephenson and D'Ayala, 2013), Japan (Dutta et al., 2003), Canada (NRC, 2017), Australia (Hasanzadeh Nafari et al., 2016b, 2016a), Italy (Amadio et al., 2016), China (Li et al., 2012; Penning-Rowsell et al., 2013), and other flood-prone countries have carried out a large number of loss assessment studies using different classification systems of disaster-bearing bodies and then used the existing loss database and post-disaster investigation data to establish local flood vulnerability curves.

In addition, with the development and application of hydrological models and hydrodynamic models, geographic information systems (GISs), and remote sensing (RS) (Elkhrachy, 2015; Jonkman et al., 2008), flood loss assessment models based on depth-damage functions have been improved (Komolafe et al., 2018). However, there are still some problems. First, there is a lack of a depth-damage functions for use in specific areas, which need to be constructed through extensive post-disaster survey data (Albano et al., 2018). Second, the effect and accuracy of the assessment are affected by the scale of the disaster-bearing body. The microscale loss assessment model for each affected object (building, infrastructure object, etc.) has poor applicability. However, mesoscale disaster-bearing body data mainly refer to land use data obtained through remote sensing (RS) interpretation (Merz et al., 2010). Although mesoscale data can effectively be used to extract the spatial distribution of buildings, it is difficult to identify the use types of buildings. These problems lead to high uncertainties and disparities in flood loss assessments (Gerl et al., 2016).

With the introduction of fuzzy mathematics, gray system models, genetic algorithms, and other mathematical methods, the rapid estimation and prediction of regional flood direct economic loss can be realized (Qie and Rong, 2017; Zhao et al., 2014; Zhou et al., 2006), which can effectively reflect the overall situation of economic losses in a large region and reduce the investment in human and material resources. However, due to the lack of high-resolution spatial location information, this approach cannot provide timely and effective suggestions for the government to formulate targeted emergency scheduling plans.

To effectively improve the accuracy, timeliness, and practicability of flood disaster loss assessment, a refined assessment model of single-flood disaster losses in small- and medium-sized cities is explored in this paper. The heavy rainfall from 18 August 2014 to 20 August 2014 caused serious river backflow and urban waterlogging, and many houses and roads were flooded in Lishui city. Therefore, taking this flood disaster as an example, a refined assessment model for the direct economic

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losses of regional flooding disasters was constructed. The model includes flood inundation models, the spatial distribution of land use types, the quantification of land use values, vulnerability curve fitting, and optimization, as well as loss ratio and loss value estimations.

2 Materials

2.1 Study area

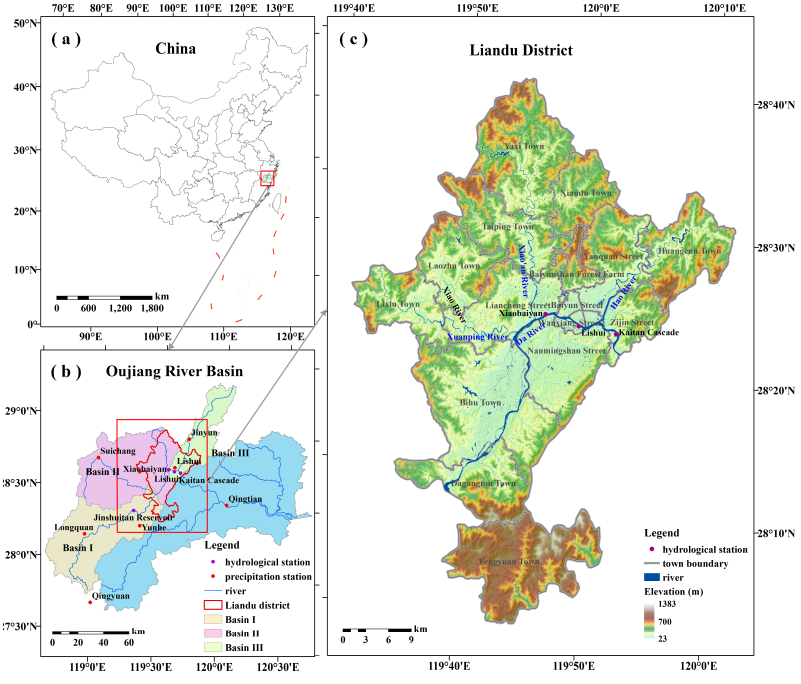

Figure 1. Location of the study area. (a. The location of Oujiang River Basin in China. b. The distribution of hydrological stations, precipitation stations, rivers and sub basins in Oujiang River Basin, and the location of Liandu District in Oujiang River Basin. c. The terrain distribution and town boundary of Liandu district.)

Liandu District is in southwestern Zhejiang Province, between 28°06′ N-28°44′ N and 119°32′ E-120°08′ E (Figure 1). This district is in the middle reaches of the Oujiang River Basin, surrounded by hills and mountains with plains in the middle, spanning a total area of approximately 1,502 km^2. Liandu District is situated within Lishui city, with a relatively concentrated population and socioeconomic status. As a result of both urban planning and topography, the flood disaster in Liandu District caused heavy losses. Because topography has a great impact on hydrology and hydrodynamics, it is easy to ignore regional

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differences based on administrative units. Considering the impact of the Jinshuitan Reservoir operation, the upper reaches of the Oujiang River Basin are divided into three sub watersheds (Figure 1).

2.2 Precipitation

The gridded precipitation data come from the hourly precipitation data set of the National Meteorological Information Center, which integrates China's automatic station data with the NOAA CDR Climate Prediction Center morphing technique (CMORPH) product with a resolution of 0.1°. The overall error is within 10%, and the accuracy in areas with heavy rainfall and sparse sites is greater than in similar international products (Shen et al., 2014). The data can effectively reproduce the spatiotemporal pattern of rainfall and are suitable for simulating flood inundation.

Based on the hourly precipitation levels, the mean accumulated precipitation of the middle and upper reaches of the Oujiang River Basin and the 3 sub watersheds were calculated (Figure 2). The precipitation change trend of each sub watershed is generally the same, with the accumulated precipitation exceeding 210 mm. The precipitation increased rapidly after 5:00 on August 18th, and the entire precipitation process basically ended at 10:00 on August 20th.

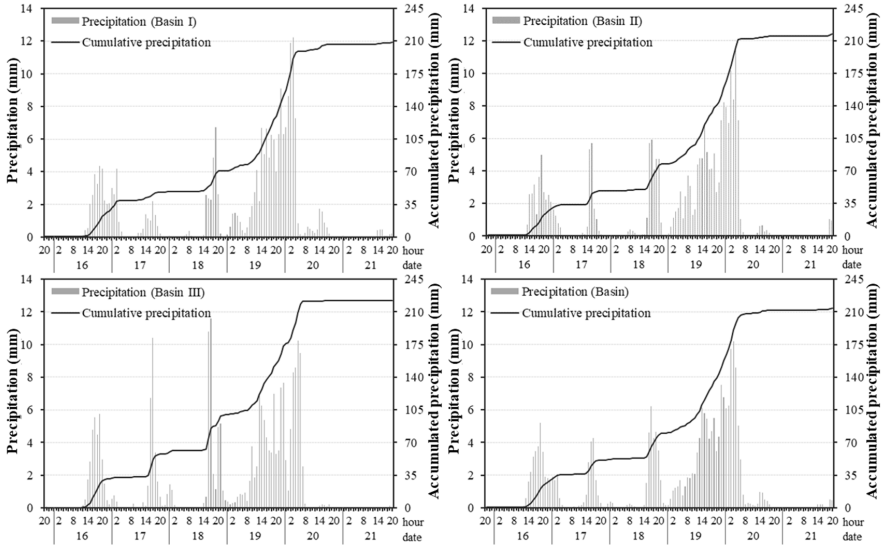

Figure 2. Distribution of hourly and accumulated precipitation in the entire basin and each subbasin. (The grey column is hourly precipitation, and the black curve is cumulative precipitation. The precipitation time is from 20:00 on August 15th to 20:00 on August 21st, 2014.)

2.3 Water level and flood inundation

The water level data come from the hourly observations of hydrological stations of the Zhejiang Water Resources Department, including the measured water level, warning water level, and guaranteed water level. Xiaobaiyan and Lishui are river stations,

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and the Jinshuitan Reservoir and the Kaitan Reservoir are reservoir stations (Figure 1). Based on the hourly measured water level, beginning at 12:00 on August 19th, the water levels of the Jinshuitan Reservoir, Xiaobaiyan, and Lishui increased significantly, while the water level of the Kaitan Reservoir first dropped slightly and then increased significantly, and the water levels at these stations reached a peak at approximately 12:00 on August 20th. The water levels at Xiaobaiyan, Lishui, and the Kaitan Reservoir returned to normal at 00:00 on August 21st, while that at the Jinshuitan Reservoir dropped to a certain water level at 00:00 on August 22nd, and the subsequent downward trend was slow (Figure 3).

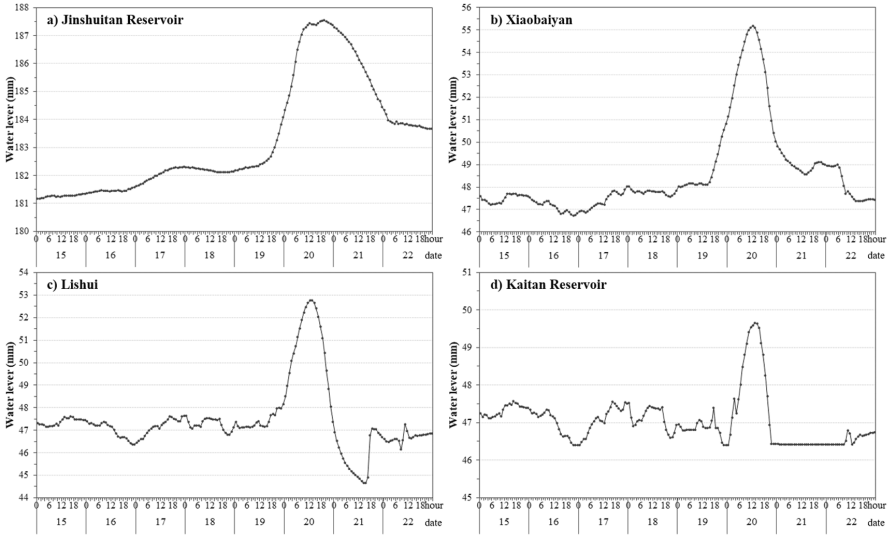

Figure 3. Distribution of hourly water levels at hydrological stations. (The time of water level data is from 00:00 on August 15th to 00:00 on August 23rd, 2014)

The flood inundation was calculated from the Yuxi to Kaitan Reservoir hydraulic model constructed by *Zhejiang Design Institute of Water Conservancy & Hydro-Electric Power*. The unsteady flow partial differential equations of the Saint-Venant open channel are used to construct a one-dimensional hydrodynamic model. Then, based on the measured channel section, water level, reservoir discharge, and high-precision topography, the implicit difference method and Gaussian principal component elimination method are used to solve the water level and discharge of each section, and then the parameters are calibrated by the measured water level (Kang and Chen, 2007). After multiple verifications, the difference between the measured and calculated water levels was between 0 m and 0.09 m. The flood volume was calculated based on the simulated water level and the elevation of the embankment (Table 1). When compared with the site survey and flood traces, the result is similar to the actual submerged depth.

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Based on the simulated maximum submerged depth distribution (Figure 4a) and real-time aerial photographs (Figure 4b, Figure 4c), the flood inundation area is mainly concentrated in the river confluence and both sides of the river, the submerged depth decreases from the river bank to both sides, and the submerged depth of the central island is generally greater than 7 m.

Table 1. Overflow volume of Liandu District in 2014 based on the hydraulic model (10,000 m^3)

	Da River South	Da River East	Da River North (Da River Section)	Da River North (Hao River Section)
Overflow volume	230.63	264.81	60.17	277.51

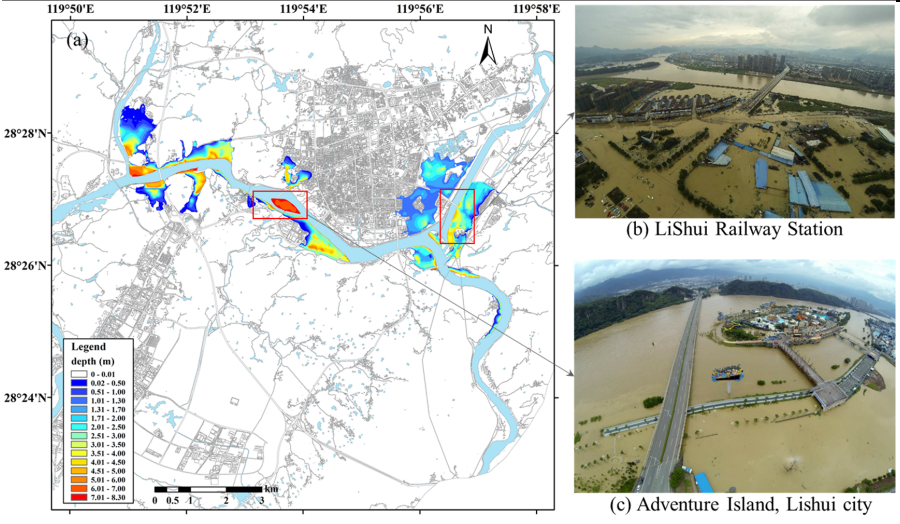

Figure 4. (a) Maximum simulated submergence depth distribution, (b, c) Aerial photographs of Liandu District in 2014.

2.4 Disaster loss reporting

The disaster loss report is obtained from the Lishui Civil Affairs Bureau and is conveyed by the local government. The report records 41 statistical indicators, including the affected population, affected area of crops, agricultural losses, infrastructure losses, public welfare facility losses, household property losses, and direct economic losses. According to these statistics, a total of 167,300 people were affected in Liandu, 17,330 people were relocated in emergencies, 247 rural houses collapsed, and the direct economic loss was approximately 377.15 million yuan.

The insurance claim data come from the auto insurance list of the catastrophe "Zhejiang 0819 Rainstorm" of the Lishui branch of the People's Insurance Company of China (PICC), and the data record 19 indicators, including the policy number, the information of the insured, the estimated compensation, and the compensation paid. As of August 24th, a total of 1,045 motor vehicle insurance reports were received, with a reported loss of 50.7969 million yuan and a decided compensation of

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50.6893 million yuan. According to the analysis of the market share of various insurance types in Zhejiang Province in December 2014, PICC motor vehicle insurance accounted for approximately 48.357% of Lishui city.

3 Methods

In this study, an assessment model of the direct economic loss ratio and loss value of flood disasters was constructed by utilizing methods such as land use type fusion, land use value estimation, vulnerability curve fitting, and optimization.

3.1 Data fusion of land use types

The distribution of land use types is obtained through the fusion of current land use data in Lishui city with a high-precision remote sensing classification. The former data come from the urban and rural space development current status map of the Natural Resources and Planning Bureau in 2013, which is divided into 47 categories according to the *Urban Land Classification and Planning and Construction Land Standards* (GB 50137-2011, 2011). The remote sensing classification is derived from the Gaode map with a resolution of 2.3870768 m, including 5 categories: transportation, grassland, waters, agriculture and forest, and buildings. The steps of vector and raster fusion are as follows.

1) The unified coordinate system is adopted, the nearest neighbor method is used to resample the data onto a grid with a spatial resolution of 2 m, and geometric correction and spatial registration are performed on the vectorized land use data.

2) The building pixels in the remote sensing classification are traversed, the corresponding current land type is queried by the location, and the grid is reassigned using the type. The building pixels that have not been reassigned are assigned according to the adjacent building types. In addition, the road within 2 m of the residence is set as community parking, and buildings far from urban areas are set as rural residences.

3) The water, agriculture and forest, and road in the remote sensing classification are assigned as water, agriculture and forest, and urban road, respectively. The agriculture and forest in areas with urban buildings and the agriculture and forest and grassland in park areas are assigned as park green land.

4) Whether there are pixels in the remote sensing classification that have not been reassigned is checked. If so, the corresponding current land type is determined, and all pixels are classified.

3.2 Estimation of land use values

The value of land use obtained from expert questionnaires is relatively reliable, and the steps are as follows.

1) Based on the *Lishui Master Plan* (2013-2030), *Lishui 13th Five-Year Plan*, and *Lishui Statistical Yearbook in 2015*, reference information such as current area, planned area, planned investment, unit area budget, and description of land use types are given.

2) As to the characteristics of land use, the four major categories of residential, commercial, industrial, public management, and public services are used to estimate the value of indoor properties, and the cost per unit area is estimated for others.

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3) Questionnaires are issued to 7 experts in fields such as municipal engineering design, construction industry, water design, ecological city planning, and natural disasters, and experts are invited to estimate the land use value based on their professional background knowledge and the actual situation of the study area.

4) The value of each land use is determined by collating the questionnaires and calculating the average values.

3.3 Calibration of vulnerability curves

Although the vulnerability curves of different regions are different, there are similarities in the trend of the loss ratio with the water depth, which we can learn from. Therefore, based on the existing vulnerability curves in many countries and regions (Coto, 2002; Dutta et al., 2003; FEMA, 2017; Mo and Fang, 2016; NRC, 2017; Reese and Ramsay, 2010; Shi, 2010; Wehner et al., 2017), the steps of vulnerability curve fitting are as follows.

1) The relationship between the flooding depth and loss ratio is formulated in Liandu based on existing databases. HAZUS-Flood has a relatively complete classification, so a mapping table between the database and land use type of Liandu is established. The average loss ratio of the corresponding type of HAZUS functions as a reference for the loss ratio of Liandu. If there is no similar type in HAZUS, other databases are referenced.

2) The vulnerability curve can be fitted by a polynomial, a power function (Büchele et al., 2006), or logistic regression (Cao et al., 2016), and it can also be smoothed by nonparametric forms such as the kernel density (Merz et al., 2004). The lognormal cumulative distribution function (Limpert et al., 2001) with a high fitting degree is selected to fit the vulnerability curve, and the formula is as follows:

$$y = F(x|\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}\int_0^x \frac{1}{t} e^{\frac{-(\log t-\mu)^2}{2\sigma^2}} dt, \quad x > 0 \tag{1}$$

where F is the direct economic loss ratio, x is the submerged depth, and σ and μ are the standard deviation and mean of the logarithm of x, respectively.

3) Based on the fitted vulnerability curve of land use, the loss ratio is calculated by the two attributes of the submerged depth and land use type. Then, the loss value is calculated based on the loss ratio and land use value, and the formula is as follows:

$$L = DR * V \tag{2}$$

where L is the loss value of the land use, DR is the loss ratio of the land use, and V is the value of the land use.

4) Based on the mapping relationships between the disaster statistical indicators and land use types, the simulated direct economic losses are summarized, and the nonlinear equation is established with the minimum error of the disaster statistical loss and the simulated loss as the objective function. The least square method is used to solve the nonlinear equation to optimize the scale parameters, and then the optimized vulnerability curve is used to re-estimate the disaster loss.

4 Results and Analysis

4.1 Distribution of land use types

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The distribution of high-resolution land use types in Liandu is obtained by implementing the data fusion method (Figure 5a), and the names and codes of land use types are shown in Table 2. The data effectively integrate the corresponding advantages of the current urban land use and remote sensing classification. The data not only have high-resolution spatial location information but also reflect the detailed types of land use.

Agricultural and forestry land in Liandu District is the most widely distributed type. Woodlands are mainly distributed in the hilly areas of the north, east, south, and northeast. The built-up area of Liandu District is distributed along the river in a block shape, among which residential land is mainly distributed in communities near the river. Industrial land is mainly distributed in northeastern Wanxiang Street and the Economic and Technological Development Zone, which is currently in the development stage, and many industrial plants have been built.

To strengthen intraregional connections, the roads and traffic facilities are relatively complete, with an urban road area of 4.33 km^2. Commercial, warehouse, public management, and public service facilities are relatively small and scattered. They are mainly concentrated near residential and industrial land, providing various services. Park green space is distributed along the river or close to residential and commercial land, while square green space, protective green space, and public facilities are small and scattered.

4.2 Distribution of land use values

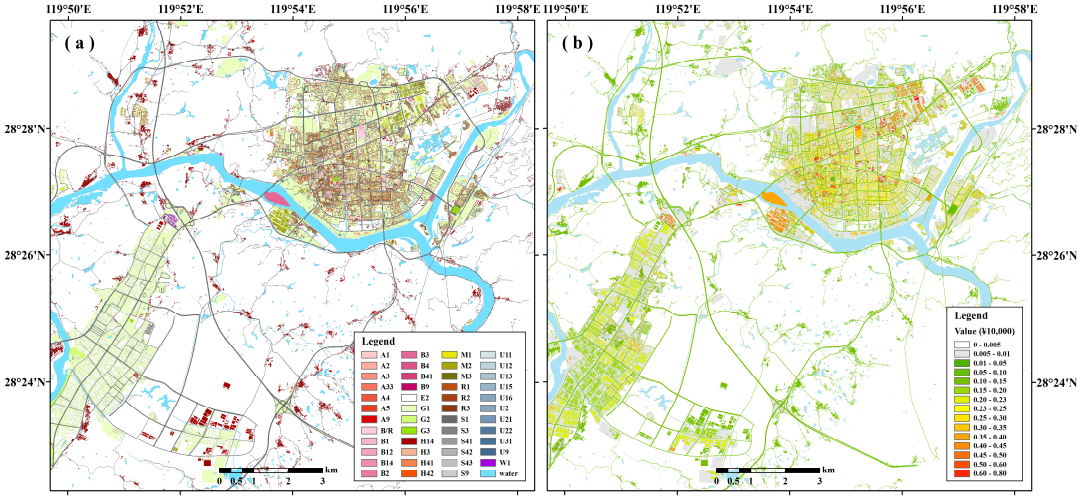

Figure 5. Distribution of land use types (a) and land use values (b) in the central urban area of Liandu District in 2013.

The asset value or cost per unit area of land use types is estimated based on expert questionnaires (Table 2). Commercial and industrial land has many internal equipment and items with the highest asset unit price. Public management and public service facilities and residential land have a higher indoor property value. The value of agricultural and forestry land is the lowest.

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The spatial distribution of land use value in Liandu in 2013 is calculated through grid assignment (Figure 5b). The value of assets per unit area in the northern city and Wanxiang Street is generally high due to the concentration of commercial, industrial, residential, public management, and public service facilities in the area. There is a water amusement project on the central island, which has a higher value per unit area. Many industrial plants are distributed in the Economic and Technological Development Zone, but due to the development stage and incomplete internal facilities, the unit price of the industrial land in this zone is calculated at half of the estimated value. Agricultural and forestry land is widely distributed and low in value, so most areas of Liandu have low values.

4.3 Fitted vulnerability curves

The vulnerability curves of all land use types are fitted by a lognormal cumulative distribution function based on the matrix of the submerged depth and loss ratio. By comparing the simulated losses and disaster loss reporting (Table 2), the scale parameter of the vulnerability curve is optimized through the least square method (Figure 6).

The loss ratios of residential, industrial, commercial, warehousing, public management, and public service land are very high, mainly due to indoor properties being soaked or washed away by floods. As the submerged depth increases, the loss ratio increases rapidly. When the depth is higher than 3 m, the loss ratio increases, and the rate of increase is unclear.

Table 2 The Classification, value, inundated area of land use types, and the comparison of simulated loss before optimization, simulated loss after optimization and statistics loss of each land use type in Liandu District.

Code	Classification	Value (¥10,000/4 m^2)	Total value (¥10,000)	Inundated area (m^2)	Mean loss ratio of inundated area	Simulation loss before optimization (¥10,000)	Simulation loss after optimization (¥10,000)	Statistical loss (¥10,000)
A1	administrative office	0.40	13891.60	2020	0.79	160.41	130.81	
A2	cultural facilities	0.35	3309.60	24	0.81	1.71	1.13	
A3	educational and scientific research	0.25	13914.00	15980	0.64	639.38	499.98	
A33	primary and secondary schools	0.20	5946.60	7296	0.31	111.98	77.36	741
A4	sports land	0.30	1311.45	0	0.00	0.00	0.00	
A5	medical and health land	0.35	4601.27	568	0.80	39.82	31.72	
A9	religious land	0.10	288.70	0	0.00	0.00	0.00	
B/R	commercial and residential land	0.35	8415.99	144	0.45	5.66	1.87	
B1	commercial facilities	0.46	9944.74	5908	0.89	602.53	473.27	
B12	wholesale market land	0.50	15358.25	16252	0.48	981.98	457.98	
B14	hotel land	0.30	3247.50	2520	0.29	54.51	19.38	2940
B2	business facilities	0.60	11071.80	1100	0.10	16.17	2.00	
B4	business outlets of public facilities	0.35	18.55	148	0.47	6.15	3.20	
B41	gas station	0.44	249.70	0	0.00	0.00	0.00	

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B9	other service facilities	0.23	350.06	2308	0.64	84.37	48.19	
M1	class I industrial	0.60	20913.60	336	0.81	40.92	30.04	
M2	class II industrial	0.40	146229.20	32592	0.52	1692.03	1059.57	
M3	class III industrial	0.30	39283.50	10132	0.55	418.00	237.72	
W1	Warehouse	0.50	7500.00	7904	0.85	836.18	606.79	
E2	agriculture and forest	0.004	1398391.70	3943224	0.65	637.25	637.25	5506
R1	class I residential	0.35	3312.05	0	0.00	0.00	0.00	
R2	class II residential	0.25	104612.25	232924	0.53	7666.89	9435.06	
R3	class III residential	0.20	35893.50	78672	0.70	2756.77	3189.11	25080
H14	village construction	0.13	425820.70	176868	0.78	4507.90	5189.18	
S43	community parking	0.50	63235.50	66468	0.75	6191.58	7266.65	
H3	regional public facilities	0.15	349.80	0	0.00	0.00	0.00	
H41	military sites	0.30	629.70	0	0.00	0.00	0.00	
H42	security	0.08	467.60	0	0.00	0.00	0.00	
S1	urban road	0.12	1055377.42	931240	0.07	2047.78	2141.03	
S3	transportation hub	0.28	5559.96	4592	0.08	25.16	26.12	
S41	public transport station	0.40	0.80	0	0.00	0.00	0.00	
S42	social parking	0.60	2106.60	0	0.00	0.00	0.00	
S9	other transportation facilities	0.15	284.70	4	0.44	0.07	0.07	
U11	water supply	0.27	857.25	0	0.00	0.00	0.00	
U12	power supply	0.30	930.90	8	0.06	0.04	0.04	3448
U13	gas supply	0.40	108.40	0	0.00	0.00	0.00	
U15	communication facilities	0.80	3294.40	0	0.00	0.00	0.00	
U16	radio and television facilities	0.80	808.80	0	0.00	0.00	0.00	
U2	environmental facilities	0.50	140.50	0	0.00	0.00	0.00	
U21	drainage facilities	0.45	757.35	3352	0.25	94.22	96.50	
U22	sanitation facilities	0.15	197.40	544	0.17	3.44	3.53	
U31	fire control facilities	0.30	727.20	0	0.00	0.00	0.00	
U9	other public facilities	0.15	21.00	0	0.00	0.00	0.00	
G2	protection greenbelt	0.01	713.15	0	0.00	0.00	0.00	
G3	square land	0.08	1178.96	28192	0.41	230.11	233.69	
G1	park green space	0.01	48264.89	1608096	0.55	2211.92	2211.92	
B3	recreational and sports facilities	0.38	18234.68	161216	0.88	13540.95	13540.95	

The direct impact of floods on public facilities and roads is relatively small, and the loss ratio is generally low. However, the indirect loss caused by the suspension of roads, communications, and electricity is relatively large but is not calculated in this study. Green space and square land are less affected by floods, and the loss ratio is relatively low.

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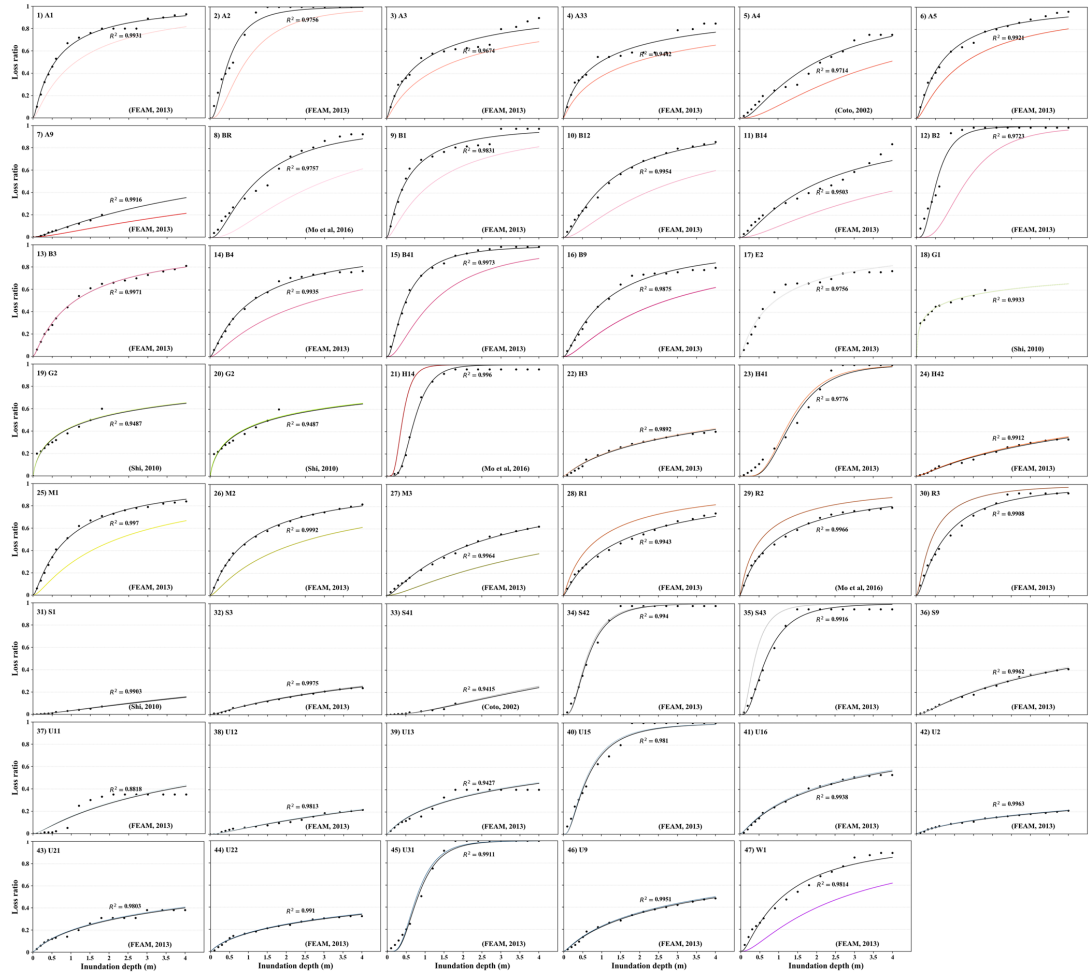

Figure 6. Fitting and optimization of vulnerability curves of land use in Liandu District (The black curve is the fitting result, and the color curve is the optimized result).

The same optimization coefficients are selected for the scale parameters of the same type of land use vulnerability curve and are obtained by solving nonlinear equations. The vulnerability curve of family property is stretched, that of infrastructure is stretched slightly, and those of public welfare facilities, industry, and commerce shrink. This comparison shows that the simulated loss after optimization is consistent with the disaster loss reporting, and the optimization effect is good (Table 2).

4.4 Distributions of the loss ratio and loss value

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Discussions

The loss ratio (Figure 7a) and loss value (Figure 7b) distributions of the flood disaster in Liandu District are obtained based on a spatial analyst algorithm.

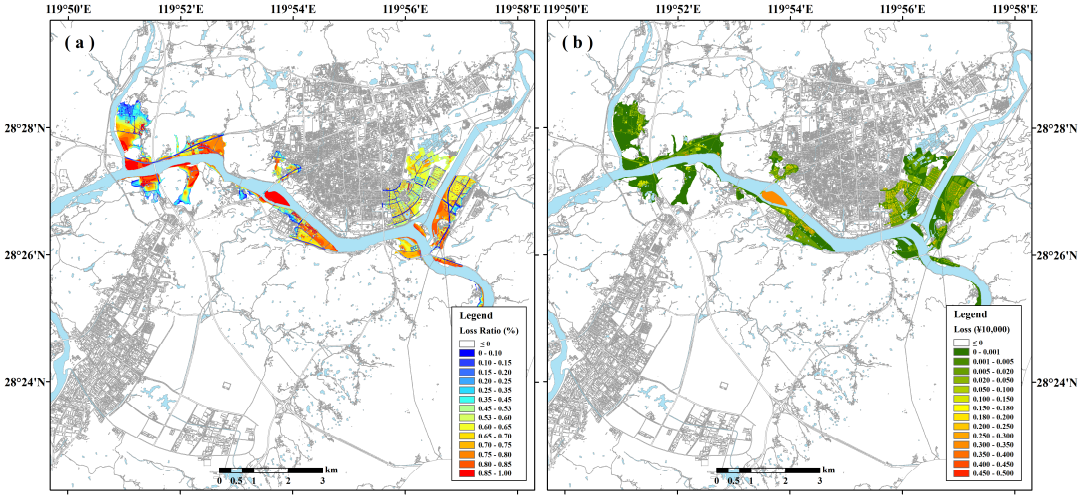

Figure 7. Spatial distribution of the flood loss ratio (a) and loss values (b) in the central urban area of Liandu District in 2014.

Due to the high inundation depth at the river confluence and both sides of the river as well as the wide distribution of agricultural land in the area, the mean loss ratio of these areas is approximately 0.63. The submerged depth of the island is more than 7 m, and there are entertainment facilities on it, so the loss ratio is more than 0.6. In addition, the submerged depth on both sides of the Hao River is more than 1 m. The west side of the river is mainly residential land, and the east side is the Lishui railway station, so the indoor property loss ratio is high. However, traffic land is less directly affected by floods, so the loss ratio is less than 0.2 (Figure 7a).

The loss value of a flood disaster is affected by the unit value and loss ratio of the land use. Therefore, the distribution characteristics of the loss rate and loss value are different. The loss ratio of this flood is relatively high, but due to the wide distribution of agricultural land in the submerged area, the loss value per unit area is low. The loss ratio and unit area value of recreational and sports facilities, residential, industrial, commercial, public management, and public service facilities are high, so the loss values are also high. The loss ratio of traffic facilities is very low, yet the loss value is relatively high due to the high construction cost (Figure 7b).

Liandu District is surrounded by high mountains, and the overland flow, affected by the topography, was formed by rainfall flowing into the Da River through the rivers in the north. The occurrences of heavy rainfall in the middle and upper reaches of the Oujiang River are similar, causing the whole basin to experience the flood peak period at the same time, which is not conducive to flood diversion efforts. To relieve the flood pressure on the basin, the Jinshuitan Reservoir was opened twice. At the same time, rapid urbanization has brought about great changes in the morphology of river channels and waters. These

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factors caused the river's water level to rise rapidly, overtopping the flood dyke and submerging low-lying areas along the riverbed. In addition, due to the high population density and highly concentrated economy in the northern area of Liandu District, serious economic losses will inevitably occur when floods exceed the fortification standard.

5 Conclusion and discussion

The research and verification of the refined assessment of single-flood disaster loss was carried out by utilizing the refined types and values of land use and quantitative vulnerability curves, and the main conclusions are as follows.

The land use type data obtained by the fusion of vector and raster data overcome the limitations of the original data. This procedure not only refines the data into detailed urban land use types but also has a high spatial resolution. In addition, the unit area costs or asset values obtained through the collection of written sources and a survey of experts via a questionnaire are more reasonable. The land use types and values constructed by the above methods provide fine and reasonable disaster-bearing body data for a refined assessment of disaster losses, thus laying a data foundation.

Based on lognormal cumulative distribution function fitting and scale parameter optimization, the vulnerability curves of 47 types of disaster-bearing bodies accurately reflect the characteristics of the loss ratio of the disaster-bearing bodies varying with the submerged depth in Liandu District and provide a reliable stage damage function curve for refined loss assessment. Among these disaster-bearing bodies, residential, industrial, commercial, public management, and storage land are seriously affected by flooding. Other land uses are relatively less affected, and the loss ratio increases slowly. In the absence of a large amount of post-disaster field survey data, the method proposed in this study can be used to construct vulnerability curves in accordance with the regional situation.

A refined assessment model of the direct economic loss of a single flood disaster is constructed in accordance with the regional characteristics based on the refined research and verification of each link in the disaster loss assessment. The estimated spatial distributions of the loss ratio and loss value of the flood disaster accurately reflect the spatial pattern of disaster loss and provide scientific guidance for disaster prevention, mitigation, and emergency rescue. In addition to park green space, recreational and sports facilities, and agricultural and forestry land, the losses of other land use types after optimization are consistent with the loss reporting, indicating that the loss assessment model of this study can be effectively applied to this area.

The loss assessment model constructed in this study can be used to estimate flood disaster losses under different climate change and economic development scenarios, providing a basis for flood risk assessment and management in small- and medium-sized cities. This, in turn, will help the government formulate reasonable climate adaptation policies and sponge city planning.

In this study, only the inundation and disaster loss reporting of one precipitation event are collected, thereby affecting, to a certain extent, the optimization results of the vulnerability curves. In the future, the data of several precipitation events will be collected to better calibrate the vulnerability curves and render the final optimized vulnerability curves more suitable for the region. Furthermore, the flood disaster caused serious direct economic losses to Liandu District. The disaster also stimulated

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a large amount of disaster relief investment, even as it disrupted public services and traffic, caused production losses for companies outside the flooded area, reduced agricultural production, and affected related industries (Jonkman et al., 2008). Therefore, it is necessary to carry out further research regarding the refined assessment of the indirect economic losses of flood disasters.

Code and data availability. The data used in the study are available at https://github.com/Haixia-Zhang/Flood-loss-assessment.git

Author contributions. ZHX and FWH conceived the research framework and developed the methodology. ZHX was responsible for the code compilation, data analysis, graphic visualization, and first draft writing. FWH managed the implementation of research activities and revised the manuscript. ZH collected data for this study. All authors discussed the results and contributed to the final version of the paper.

Competing interests. The authors declare that they have no conflict of interest.

Special issue statement. This article is part of the special issue "Advances in flood forecasting and early warning". It is not associated with a conference.

Acknowledgements. This work was mainly supported by the National Key Research and Development Program of China (grant nos. 2018YFC1508803 and 2017YFA0604903), and the Key Special Project for Introduced Talents Team of Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou) (No. GML2019ZD0601). The authors would like to acknowledge Kang Ying and Lin Song of the *Zhejiang Design Institute of Water Conservancy & Hydro-Electric Power* for providing the simulation inundation of flooding model in Liandu District.

Financial support. This research has been supported by the National Key Research and Development Program of China (grant nos. 2018YFC1508803 and 2017YFA0604903), and the Key Special Project for Introduced Talents Team of Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou) (grant no. GML2019ZD0601).

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