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Extreme Flood Disasters: Comprehensive Impact and Assessment

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Abstract: Evaluating extreme flood disasters is a prerequisite for decision making in flood management. Existing extreme flood disaster assessments fail to either consider or evaluate comprehensive impacts from social, economic, and environmental aspects. This study first analyzes the causes of extreme flood disasters and subsequently the potential flood consequences in depth. On the basis of this comprehensive analysis, an extreme flood disaster indicator system is developed by taking into account social, economic, and environmental consequences. To assess the comprehensive impacts, we propose a refined social and economic impact evaluation method and a semi-quantitative environmental impact evaluation method, which are applied to Jingjiang Flood Diversion District (JFDD) located in the Yangtze River Basin, and analyze two extreme flood scenarios. The results show that almost all of the JFDD area is flooded with inundation areas of 901.36 km^2 and 879.49 km^2, respectively. The corresponding affected populations are 0.51 million and 0.5 million. The direct economic losses are 18.83 billion and 14.33 billion, respectively. Moreover, 5 potential pollutant sources and 11 protected areas are inundated under two scenarios. Extreme floods have relatively serious impacts on local ecology and the environment. The proposed methodology can provide effective support for decision makers.

Keywords: extreme floods; disaster chain; impact assessment; flood damage; environmental impacts

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1. Introduction

Flood is one of the most serious natural disasters worldwide [1–3], accounting for 44% of all disaster events from 2000 to 2019 [2]. Floods usually cause huge economic losses and severe human casualties. With the implementation of flood control and disaster reduction systems, the human death caused by floods is, to some extent, reduced. However, flood is still one of the main global risks according to the Global Risks Report [4] under the double pressure of climate change and socio-economic developments. With climate change, the frequency of heavy precipitation events increases [5,6]. Extreme floods are usually caused by extreme rainstorms [7], such as the one across central Europe in 2021 and the 20 July 2021 heavy storm in Zhengzhou, China. The total number of flood disaster events in 2000–2019 was more than twice as high as that in 1980–1999 [2]. In addition, with the socio-economic developments, extreme floods may also lead to more disastrous consequences, such as human injury, livelihood being seriously damaged or destroyed, and even the disruption of the global supply chains. From 2000 to 2019, floods affected 1.6 billion people worldwide [2]. Moreover, floods contributed to USD 651 billion of economic losses according to EM-DAT data [2]. Besides, floods may also have potentially adverse impacts on the environment and ecology when polluted floods flow into surface drinking water sources or other protected areas [8,9]. Therefore, it is significant to conduct refined and comprehensive extreme flood disaster assessment to better support flood prevention decision making and further lessen the negative impacts. However, the existing extreme flood disaster assessments fail to either consider or evaluate comprehensive impacts from social, economic, and environmental aspects.

Extreme and disastrous floods can cause various and comprehensive adverse consequences [10–12], including economic losses, social impacts, and environmental impacts. Previous studies of flood disaster assessments mainly focused on monetary loss evaluation and the affected population assessment. Environmental impacts are rarely assessed not only because of the lack of public awareness but also the fact that they are intangible and hard to quantify. Indeed, they are very important to society [9,13]. Therefore, it is important to integrate the social, economic, and environmental impacts together for the flood management decision making.

Compared to the rare study on floods' impacts on the environment, there are many studies on flood loss assessments [14,15]. Flood loss assessment is multidimensional, complex, and interdisciplinary. It is affected by multiple factors, including regional rainfall characteristics, geographical features, flood control systems, and socio-economic conditions [15,16]. Therefore, the assessment methods are diverse [17]. Previous efforts to estimate flood economic losses have focused on depth-damage functions [18] to integrate flood depths, land use types, and economic factors. With the fast development of GIS, spatial analysis technology has also been introduced into the loss assessment method. Then, the accuracy of the assessment employing this method is determined by the exposure data. The exposure data can be represented in terms of each affected object, such as buildings, critical infrastructures, etc., at the microscale and/or land use types, such as farmlands, urban areas, etc., at the mesoscale. However, the detailed data of each affected object are not easy to acquire. The land use data can be easily obtained through remote sensing (RS) interpretation [14], and it is effectively used to extract the spatial distribution of buildings, but it is difficult to establish the relationship between flood loss data and land use types. These problems lead to high uncertainties and disparities in flood loss assessments [19,20]. In this case, we should propose a refined method to evaluate the detailed flood loss of each affected object.

To address the above-mentioned problems, the present study analyzes the potential negative impacts caused by extreme floods and draws disaster chains, which provides a comprehensive insight into extreme flood disasters. Specifically, an extreme flood disaster assessment index system is established by incorporating social, economic, and environmental indicators. We then develop a refined method to evaluate social and economic impacts and also put forward a semi-quantitative method to assess environmental impacts. Last, the newly established methods are employed in the Jingjiang flood diversion district (JFDD) to demonstrate the effectiveness of our assessment system.

2. Causes and Impacts of Extreme Floods

Extreme floods are caused by the interactions of atmospheric processes, basin hydrological processes [21,22], and human activities (refer to Figure 1). Heavy and/or persistent precipitations are usually the very first cause of extreme floods, which is not the case for small floods. The land use changes [23], due to fast urbanizations or geographic variations, will increase the runoff coefficient, enhance runoff generations, and then increase flood peaks and volumes in the rivers. In this case, fluvial flooding occurs when rivers flow overtop their banks or dams/dikes break. Dam overtopping is one of the main reasons for dam break [24]. Pluvial flooding occurs when rainfall volumes exceed the infiltration capacity and the drainage capacity and result in the inundation of urban areas. Besides, the collapse of the barrier lakes in mountainous areas, formed by landslides, is likely to cause extreme floods downstream.

Extreme flood disaster is a threat caused by extreme flood to human life, property, sensitive ecological and environmental areas, etc. Extreme flood is characterized by a wider inundation range, higher hazards, and therefore, probably leads to a wider range of affected areas. Correspondingly, the category of expected disaster-bearing bodies is much wider. For example, flood control structures, such as dikes and dams as part of flood disaster prevention systems, are not only flood prevention forces but also disaster-bearing bodies under extreme floods [25]. In addition, extreme floods also likely cause negative impacts on sensitive ecological areas, such as protected surface and groundwater as well as nature reserves. On this basis, we draw the extreme flood disaster chain in Figure 2. The direct impacts include economic, social, and environmental consequences. Among them, the economic impacts include the damage to houses, agriculture, industry and commercial assets, and damage to critical infrastructures, such as transportation, water supply, power supply, and communication systems. Social impacts mainly refer to people affected by the evacuation, homelessness or injury, and potential human casualties [26]. Environmental impacts include scouring the sensitive ecological and environmental areas or polluting sensitive ecological and environmental areas after extreme floods flow through potential pollutants. Moreover, in modern society, since the construction of urban flood control and drainage facilities lags behind the construction speed of urbanization, and lifeline projects, such as communication, power supply and water supply, have more weaknesses, extreme floods are likely to result in much larger flood impacts than flooded areas. Then, extreme floods probably further lead to indirect impacts beyond the geographical area or after the flood events. For example, the disastrous river floods that occurred in Thailand in 2011 seriously disrupted the global supply chains [27].

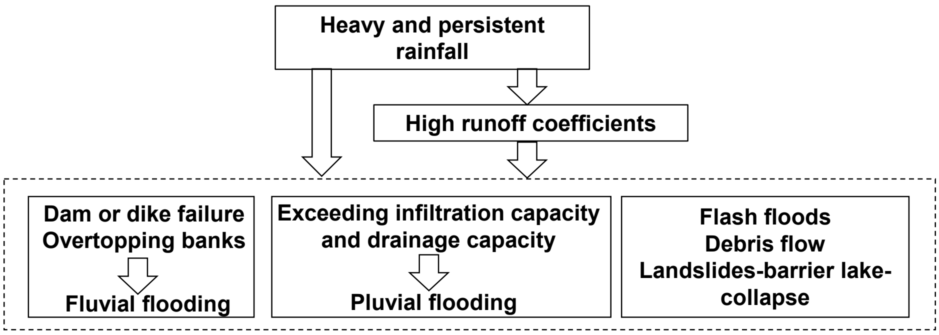

Figure 1. The causative mechanisms of extreme floods.

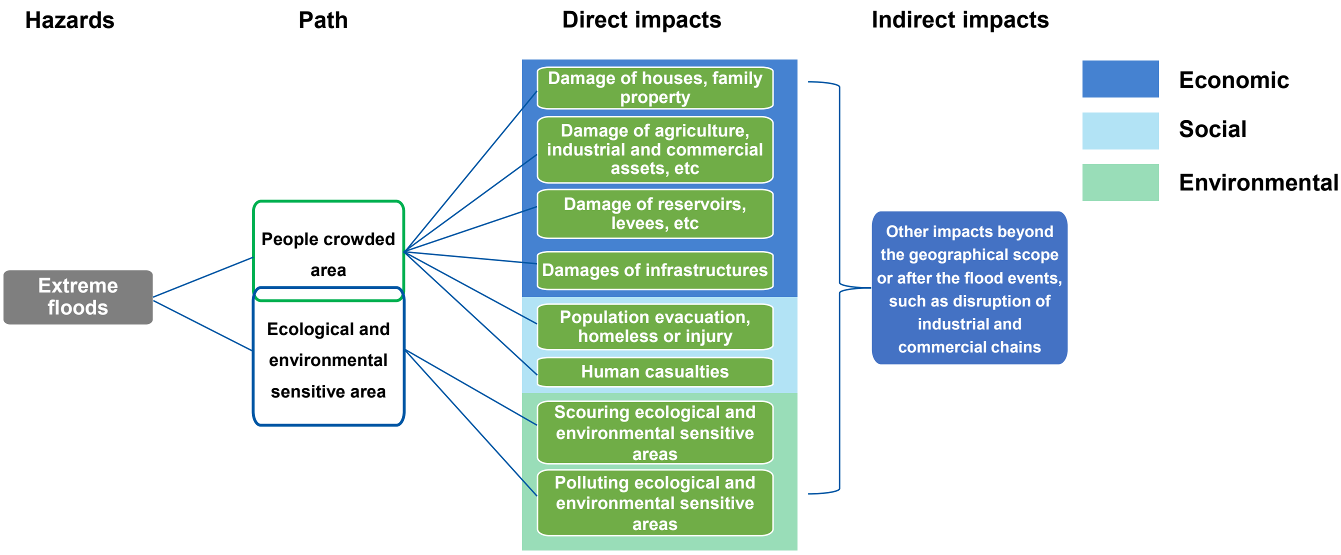

Figure 2. Extreme flood disaster chains (direct and indirect impact refer to the consequences occurring within the inundated region and far away from the flooded region during and/or after a flooding event, respectively).

3. Materials and Methods

3.1. Extreme Flood Disaster Indicator System

We establish the index system of extreme flood disasters (refer to Figure 3). The index system contains 10 assessment indicators from three aspects, i.e., social impacts, economic impacts, and environmental impacts.

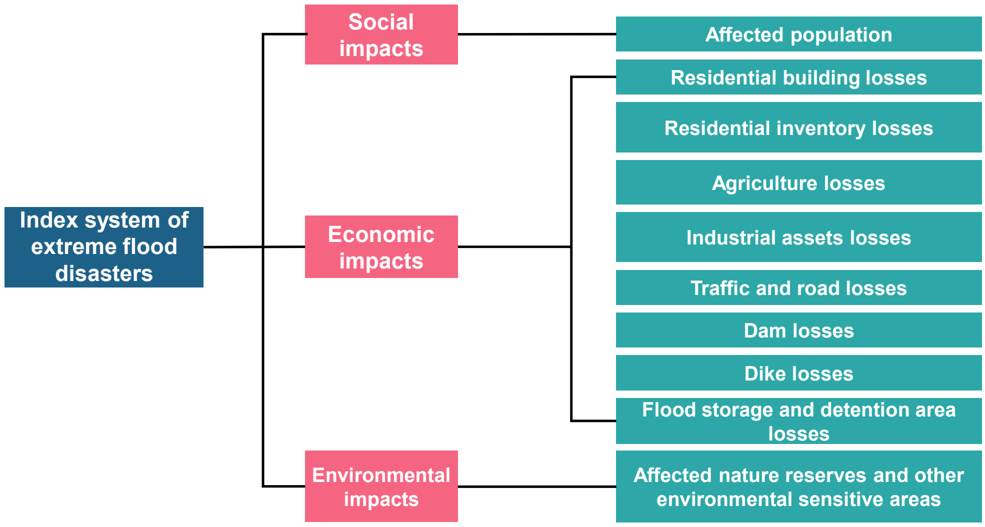

Figure 3. Extreme flood disaster indicator system.

(1) Social impacts are described by the expected number of people affected within the flooded area because ensuring the safety of people's lives is the primary task of flood prevention and emergency response. Understanding the number of affected populations is a prerequisite for flood management decision making and then providing support for personnel evacuation, emergency rescue, provision of medical and food relief, etc. In addition, various types of losses are closely related to human production and life, and the distributions of the affected population can further imply the impacts and losses of socio-economic activities and properties that are closely related to them in the floods. We do not consider the index of the number of people injured or dead because it is hard to quantify it accurately.

(2) Economic impacts are reflected by direct economic losses, including residential building losses, residential inventory damage, agriculture losses, losses of industrial enterprises, traffic and roads, as well as the losses of hydraulic engineering in the flooded area.

(3) Environmental impacts include the affected nature reserves and other affected environmental sensitive areas caused by extreme floods.

3.2. Flood Impact Assessment

3.2.1. Economic Impact Assessments

The economic impact evaluation is to measure the consequences of extreme flood disaster based on economic value data, including the losses of the residential buildings, inventories, agriculture, industry, infrastructure, etc. The assessment process is divided into 5 major steps as shown in Figure 4.

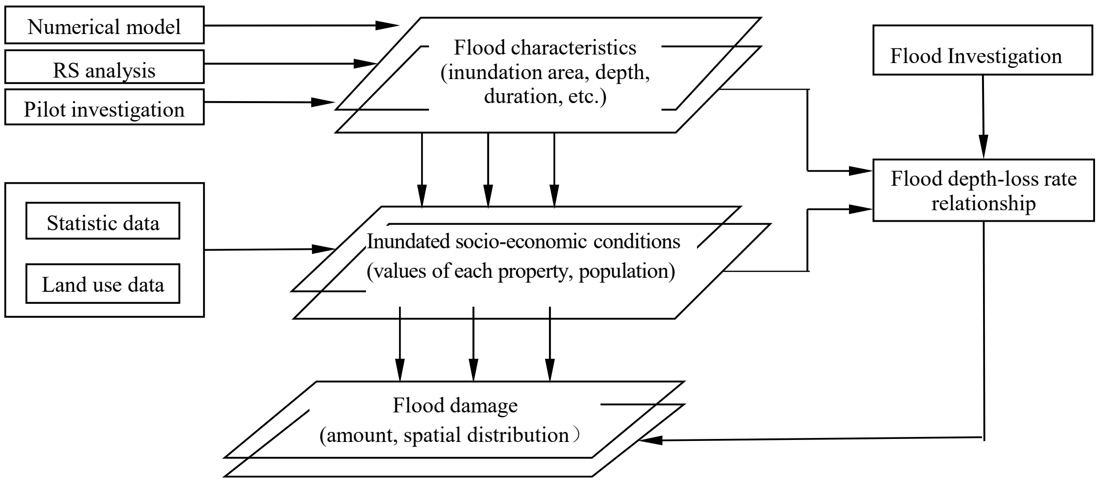

Figure 4. The flow chart of flood damage assessment.

(1) Analyze the flood inundation areas, flood depth, and durations using flood simulation model or RS analysis or field investigations.

(2) Collect economic data, statistical data, and land use spatial distribution data, and then use the area weighting method or regression analysis method to generate an economic database with spatial attributes that can reflect the distributions and differences of economic indicators.

(3) Overlay the flood inundation layer with the economic layer according to their spatial relationships using GIS analysis tools and then manage to obtain the values and distributions of economic properties under different flood depths.

(4) Collect historical flood loss data of typical regions, units, or industry sectors, etc., estimate the flood loss rate of each property under different flood depths, and establish the flood depth-loss rate relationship of each property.

(5) Based on the property type and flood depth-loss rate relationship in a flooded area, calculate flood economic losses according to Equation (1).

$$D = \sum_i \sum_j Vij\eta(i,j) \quad (1)$$

where V_{ij} is the value of ith property under jth water depth in a flooded area, $\eta(i,j)$ is the flood loss rate of ith property under jth water depth.

V_{ij} is mainly calculated using the current market value method. Housing property is calculated using the replacement cost method, i.e., based on the cost of a newly built house in the local area, and then obtaining the values after depreciation. Residential household property is discounted according to the current market value method based on the number of durable goods owned per 100 households in the administrative region involved. The values of other industrial and commercial assets are directly derived from the statistical yearbooks of the administrative regions. The cost of roads is considered in accordance with the repair costs by referring to the relevant national budgetary quotas for highway and railroad projects.

The flood loss rate represents the vulnerability of different properties impacted by extreme floods. The flood loss rate of different properties varies with flood depth. It is a relative index to depict direct economic losses and is described as the ratio of the loss values to pre-flood values of each property.

$$\eta = \frac{V_b - V_a + F}{S_b} \quad (2)$$

where η refers to flood loss rate, V_b is pre-flood properties' value, V_a is post-flood properties' value, F is rescue cost of properties.

3.2.2. Social Impact Assessments

The main assessment process is similar to that of economic impact assessment (refer to Figure 4). The total number of the affected population is estimated by overlaying the flood inundation area layer with the population distribution layer. To more accurately and comprehensively characterize the social impacts, the number of affected populations under different water depths and inundation duration can also be evaluated by overlaying the flood inundation depth/duration layer with the population distribution layer. In addition, if distribution data of the vulnerable population (the elderly, children, etc.) are available, the number of affected vulnerable populations under different depths/durations can also be estimated correspondingly.

The main focus of social impact assessment is to create a spatial distribution layer of population data. In China, the population data are usually presented in terms of administrative units, which express differences between statistical units. However, there are no differences within the statistical units. In order to conduct accurate statistical analyses of the affected population, spatial analysis of demographic data is employed.

(1) With the residential land layer

If the residential land layer is available, the spatial analysis of the demographic data is presented using the residential land method. We assume that the distribution of population is discrete and uniform within the residential land area of the administrative unit. The affected population is calculated by Equation (3).

$$P_e = \sum_i \sum_j A_{i,j} \cdot d_{i,j} \quad (3)$$

where P_e represents the affected population, $A_{i,j}$ is the flooded area of residential land in jth block of ith administrative unit, $d_{i,j}$ is the population density of the residential area in jth block of ith administrative unit.

If two administrative units are affected by extreme floods (gray part in Figure 5), we obtain the areas of flooded residential lands in each administrative unit (shaded parts in Figure 5) by superimposing the residential map layer, the flooded area layer, and the administrative division layer. It is worth noting that there is a big difference between urban population density and rural population density in a certain administrative unit. In practice, the smaller the level of an administrative unit (e.g., town/street), the smaller the differences in corresponding population densities on different rural residential plots or urban residential plots. Hence, we use the population density data of the smaller units and assume that the rural population or the urban population density of small administrative units can be considered equal.

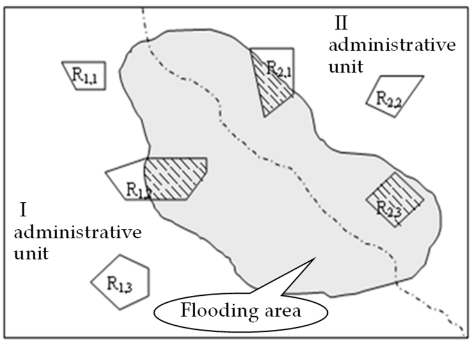

Figure 5. Diagram of flooded residential areas (the residential lands $R_{1,2}$ and $R_{2,1}$ are partially flooded, and the residential land $R_{2,3}$ is completely flooded).

(2) Without the residential land layer

If the residential land layer is not available, we use an approximate estimation to calculate the number of affected populations. We assume the population is evenly distributed in the whole administrative area, and the proportion of the affected population is the same as that of the flooded administrative area. The number of affected populations can then be calculated according to the total population of the administrative region using Equation (4).

$$P_e = \frac{PA_f}{A} \quad (4)$$

where P is the total population of an administrative region, A_f is the flooded area of an administrative region, A is the total area of an administrative region.

This approximate estimation method gives reasonable results only if the population is actually distributed evenly. In areas where that is not the case, the calculation results should be corrected. For example, flash floods usually occur in river valleys. However these are mountainous areas where the population is concentrated in low and flat areas on both riversides. In this case, this method usually underestimates the actual number of affected populations and should then be corrected using appropriate methods.

3.2.3. Environmental Impact Assessment

We evaluate the potential ecological and environmental impacts caused by extreme floods considering three aspects, i.e., flood inundation, the hazards of potential pollution sources, and the sensitivity of the protected areas. The assessment process concludes with 5 steps.

(1) Analyze the flood inundation areas.

(2) Collect and identify the potential pollutant sources and the protected areas within flooded areas, and then create corresponding distribution maps.

(3) Superimpose the flood inundation layer and the potential pollutant source layer to estimate the total dangerous scores of pollutant sources within inundation areas using Equation (5). Each pollutant source considers the hazard level of potential released contaminants, the numbers, and the scales of pollutant sources with the same hazard level. We analyze the typical contaminants of each pollutant source and then divide all of the potential sources into five levels according to the hazards or the toxicity of the typical pollutants (refer to Table 1).

$$S = \sum_{i=1}^{5} L_i \sum_{j=1}^{n} M_{ij} \quad (5)$$

where S is the total dangerous score of the potential pollutants within the flood extent; L_i is the hazard score of the pollutant source (see Table 1), I = 1, 2, 3, 4, 5; N_i is the corresponding number of pollutant sources with the same hazard score; M_{ij} is the scale of the jth pollutant source with the score L_i.

Table 1. Scores of potential pollutant sources with typical pollutants at different hazard levels.

Score L	Potential Pollutant Sources	Possible Typical Contaminants
5	Chemical plants	COD, NH_4^+, SO_2, toxic organic pollutants, solid waste, etc.
4	Metal plants, metal recovery works	COD, SO_2, metal, oxygen-demanding pollutants, solid waste, etc.
3	Factories	Solids, oxygen-demanding pollutants, solid waste, etc.
2	Landfills	Solids, solid waste, etc.
1	Farmlands	TN, TP, etc.

(4) Superimpose the flood inundation layer and the protected area distribution layer to estimate the total protection scores of the protected areas within inundation areas using Equation (6). We identify three kinds of protected areas, i.e., nature reserves/tourist attractions, protected surface water (e.g., surface drinking water source area), and protected groundwater (e.g., ground drinking water source area). Among them, nature reserves are divided into 3 categories according to the National Nature Reserve List, i.e., ecosystem type reserves, biological species reserves (e.g., wild animal protected areas), and natural

heritage reserves. According to their sensitivity levels, we assign a score to each protected area (refer to Table 2).

$$T = A + B + kC \tag{6}$$

where T is the total protection scores of the protected areas within the inundation area; A, B, and C are corresponding scores of nature reserves, protected surface water, and protected groundwater (refer to Table 2); k is 0.5 in this study.

Table 2. Scores of protected areas at different sensitivity levels.

Nature Reserves/Tourist Attractions		Surface Water		Ground Water	
Sensitivity Level	**Score *A***	**Sensitivity Level**	**Score *B***	**Sensitivity Level**	**Score *C***
World-class/national-level	10	Class I	10	Class I	10
Provincial-level	5	Class II	5	Class II	5
City-level	1	Class III	1	Class III	1

(5) Determine the classification criteria of dangerous level and protection level (see Table 3) and then combine the two aforementioned levels using the matrix method (see Figure 6) to determine the severity level of the environmental impacts.

Table 3. Classification criteria of dangerous level and protection level.

Pollutant Sources		Protection Areas	
Dangerous Level	**Score *S***	**Protection Level**	**Score *T***
5	20 and above	5	10 and above
4	15~19	4	8~9
3	10~14	3	5~7
2	5~9	2	3~4
1	0~4	1	0~2

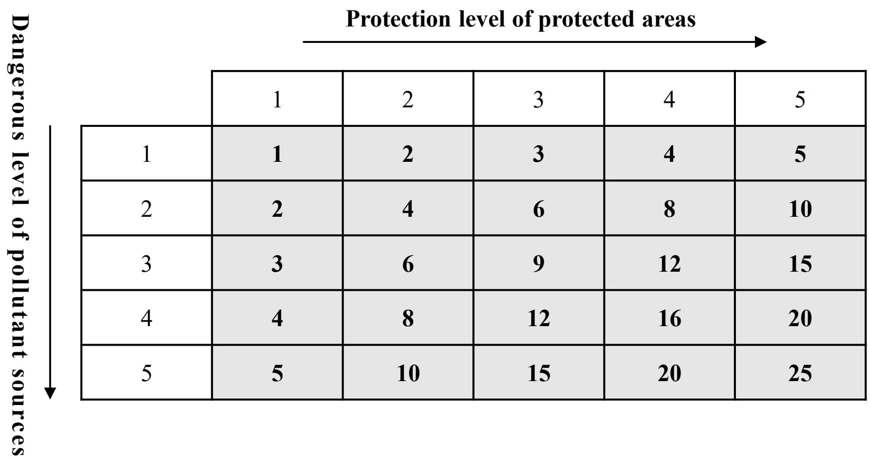

Figure 6. Matrix method used to determine the severity level of environmental consequences.

4. Case Study

4.1. Study Area

JFDD is a flood storage and detention area (FSDA), the low-lying area for the temporary storage of floods outside the river levees, along the Yangtze River. It is located in Gongan County, Hubei Province (Figure 7), covering 920.6 km^2. The topography within JFDD is higher in the north and lower in the south. The average width from north to south is about 70 km and 13 km wide from east to west. The narrowest width is 2.7 km at the neck area. JFDD, constructed in 1952, is one of the most important flood control works in the Yangtze

River Basin. Its function is to temporarily store floods from the Yangtze River. The design flood storage level at the golden mouth is 42.00 m, the design flood storage volume is 5.4 billion m^3, and the flood diversion flow is 7700 m^3/s [28]. JFDD was used only once in 1954 to prevent extreme floods of the Yangtze River. With the socio-economic development, JFDD has become the political, economic, and cultural center of Gongan County. There are 8 towns and 211 villages in JFDD [29], and the whole population is about 0.61 million up to 2019. There are more than 70 large-scale enterprises in the county, and most of them are located in the JFDD.

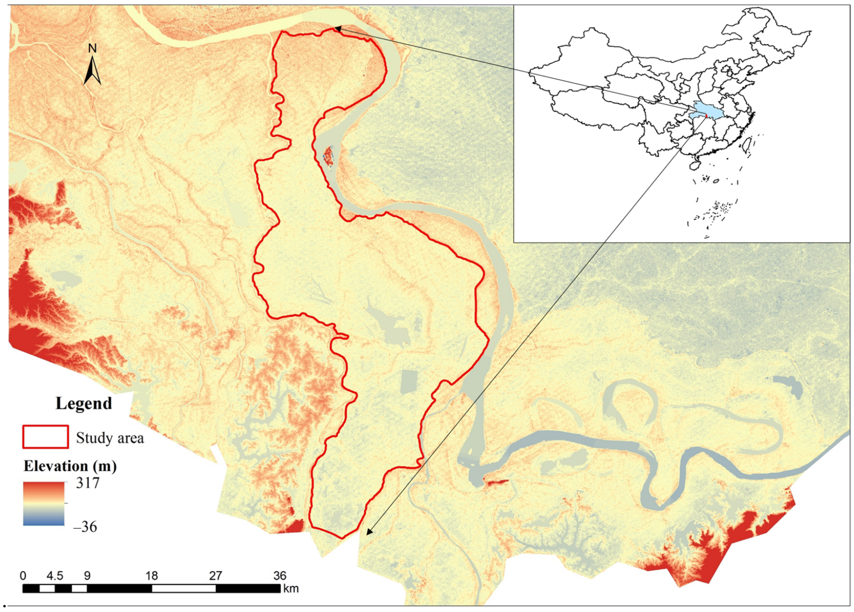

Figure 7. Location of the study area (JFDD), which is located in Hubei province (the light blue area on the map of China) and along the Yangtze River. The reference coordinate system is WGS84.

4.2. Data

The town-level socio-economic data in the study area were collected from open data and field investigation (Table 4). The economic classification data considered the main affected types, namely residential buildings and inventories, agriculture, industrial and commercial assets, and roads. The spatial distribution of socio-economic statistical data was based on 1:50,000 geographic data. The environmental data, including pollutant sources and protection levels, were collected from investigation and open data.

Table 4. Socio-economic and environmental data.

Data	Sources
Geographic data	Investigation
GDP	Statistical Yearbook of Hubei Province
Population	Statistical Yearbook of Hubei Province Statistical Yearbook of Gongan County
Industrial and commercial assets, agriculture areas and productions, and other socio-economic data	China County (City) Socio-economic Statistics Yearbook Statistical Yearbook of Gongan County Field Investigation
Pollutant sources (names, types)	Field Investigation
Protected areas (names, types, and sensitivity level)	National Nature Reserve List Field Investigation

5. Results

In this study, we set two extreme flood scenarios, i.e., 1000-year return period flood under 1954 flood type (hereinafter referred to as 54_1000) and 1000-year return period flood under 1998 flood type (hereinafter referred to as 98_1000). Under these two scenarios, we evaluated the number of affected populations, direct economic losses (residential building and inventory losses, agriculture losses, industry and commercial assets losses, and road losses), and potentially affected nature reserves and other sensitive areas. The flood hazards, including flood depths, durations, and velocities, were simulated using a 2D hydro-hydraulic model. Since flood hazard evaluation is not the focus of this paper, it was not elaborated on.

5.1. Social and Economic Impacts

We analyzed the historical data regarding flood economic losses in 1954 and referenced nearby or similar areas to determine the flood depth-loss rate relationship. In addition, we adjusted the flood loss rate according to the socio-economic conditions and disaster characteristics of the study area. On this basis, we established the flood loss rate relationship between flood depths and different affected objects in JFDD (refer to Table 5). The flood economic losses and affected populations are shown in Table 6.

Table 5. Flood depth-loss rate (%).

Flood Depth	Residential Building	Residential Inventory	Agriculture	Industry Assets	Commercial Assets	Railway	National and Provincial Roads	Roads below Provincial Level
0.05~0.5m	2	3	8	5	7	3	3	3
0.5~1.0m	10	15	41	10	27	12	9	15
1.0~1.5 m	18	22	49	15	34	17	15	20
1.5~2.0m	24	29	60	21	42	22	20	25
2.0~2.5m	30	34	72	30	49	27	23	30
2.5~3.0m	36	42	78	39	57	32	26	35
>3.0m	45	60	88	55	64	40	33	42

Table 6. The assessment results of social and economic impacts.

Scenario	Inundation Area (km^2)	Affected Population (million)	Economic Losses (billion RMB)				
			Residential Building and Inventory	Agriculture	Industry and Commercial Assets	Roads	Total
54_1000	901.36	0.51	13.27	3.88	1.13	0.54	18.83
98_1000	879.49	0.5	9.45	3.52	0.94	0.42	14.33

When facing extreme floods, almost the whole area of JFDD was flooded (see Table 6). Hence, the difference between the inundation areas is not obvious. However, the flood depth differences are obvious. The inundation area under the 54_1000 scenario is 901.36km^2, and the inundated area with a flood depth of more than 3m accounts for 95.6%. By contrast, the inundation area under the 98_1000 scenario is 879.49 km^2 and 62.4% flood depths area deeper than 3 m.

Almost all the population in the JFDD has been affected by floods, except those who live in some upland areas and safety zones. The floods also caused serious economic losses of RMB 14.332 billion and RMB 18.828 billion in the 98_1000 flood and the 54_1000 flood, respectively. The flood losses caused by the 54_1000 flood were more severe than the 98_1000 flood because the 54_1000 flood caused more severe inundation in the more densely populated and asset-rich areas.

5.2. Environmental Impacts

There are five potential chemical enterprises located in JFDD. All of them were flooded under the two scenarios. The hazard score of each pollutant source is 5 according to Table 1, and the corresponding hazard levels under two flood scenarios are 5, respectively. Besides, there are two national-level protected areas, i.e., Chonghu national wetland park and Jingjiang flood diversion project, and nine city-level protected areas within the flooded areas. Hence, the expected sensitivity levels of protected areas are 5 under the two scenarios according to Table 3. In this case, the severity levels of environmental impacts under the two scenarios are 5. Hence, extreme floods have relatively significant impacts on local ecology and the environment in JFDD (refer to Table 7).

Table 7. The assessment results of environmental impacts.

Scenario	The Hazard Level of Pollutant Sources			The Sensitivity Level of Protected Areas			Severity Level
	The Number of Pollutant Sources within the Flooded area	Hazard Scores	Hazard Level	The Number of Protected Areas	Protection Scores	Protection Level	
54_1000	5	25	5	2 national-leve l9 city-level	29	5	25
98_1000	5	25	5	2 national-level 9 city-level	29	5	25

6. Discussion

Several reasons explain the serious social, economic, and environmental impacts under two extreme flood scenarios. First, JFDD's function is to temporarily store floods and then lower the flood levels in the Yangtze River. If extreme floods exceed the flood prevention standard of the Yangtze River levees, the JFDD will be used and divert a large number of flood volumes. Floods will soon fill the whole area, except for the safety areas and other highlands [29]. Second, socio-economic development has been fast in the past few decades, since JFDD has never been used since 1954. The population density was 668 people/km^2 and the GDP per capita was 3.05 RMB per person in 2019, higher than in the surrounding areas, according to our investigation. The average annual growth rate of GDP in JFDD was 14.6% from 2004 to 2018. In this case, despite the management methods to restrict polluting enterprises, there are still several enterprises with potential contaminants, such as chemical plants and wastewater treatment plants. Extreme floods may lead to contaminant leakage or a release of organic loads [9] when flowing through those exposed potential pollutant sources. The polluted floods can result in surface and groundwater pollution, as well as soil contamination [8]. Hence, the population living or working, the assets, and the protected surface/groundwater in JFDD, exposed to extreme floods, are vulnerable. They are seriously affected when experiencing extreme floods.

In this study, we only estimated the total number of affected populations within the inundation areas and used this indicator to represent the social impact due to the special characteristics of JFDD. Once JFDD, as an FSDA, is decided to be used, most of the population living or working in it will be evacuated to the safety zones, highlands, or outside the JFDD, according to the plan. In addition, the duration of flood diversion will last for more than 120 h. In this case, the total number of affected populations can represent the social impacts in this study area.

Flood loss rates are influenced by many factors, such as topography, flood characteristics (flood depth and duration, etc.), property categories, flood season, and emergency measures. Generally, the flood depth-loss rate relationship is established according to the conditions of study areas and property categories. A certain number of flood-affected regions (or similar areas affected by the flood disasters in recent years) should be selected to investigate the flood loss rate of different properties under different inundation ranges. Since JFDD was only used in 1954, it lacks historical data of extreme flood disasters in the past few decades. Hence, the flood depth-loss rate relationship in this paper was established by referring to the data from similar areas. In addition, we adjusted and verified the flood depth-loss rate relationship by consulting stakeholders, such as construction engineers, enterprises owners, and related managers. Besides, we further compared the flood economic losses with those in similar areas. For example, in terms of the classification of flood economic losses, residential building and inventory losses account for the largest share of the total economic losses, followed by agriculture losses, which is consistent with other studies in similar areas [30]. The comparisons show that the flood consequences of this study are basically scientific and reasonable, which can provide a reference for the flood regulation decision making of JFDD.

One of the aims of this study is to propose a methodology that can assess the comprehensive consequences, social impacts, economic losses, and environmental impacts, caused by extreme floods. Limited by data, there are several limitations both in the social and economic impact evaluation and the environmental impact assessment.

This study established the relationship between flood depth and flood loss rate. Other characteristics of flood hazards, such as flood velocity, duration, and arrival time, may also influence the final flood economic losses, which should be studied in depth and be incorporated into the loss evaluation model as future work. In addition, with the variations in characteristics of flood economic losses, underground space, vehicles and other seriously affected properties in recent flood disasters should also be involved in flood economic losses evaluations. In terms of social impacts, the human casualty assessments based on the assessment method of the affected population should be studied in the future as well.

The environmental impact assessment is based on the assessment of potential contaminant release from pollutant sources and the sensitivity of protected areas with a semi-quantitative method. A more accurate simulation requires a micro-scale approach [9] to describe the transport of pollutants. Such evaluation needs detailed data on each pollutant source. However, these data are not open and are hard to acquire in practice. The micro-scale evaluation methods of environmental impacts will be studied when detailed data are available. In addition, the distances between the potential pollutant sources and the protected objects have different levels of impact on the protected areas, which is not considered in this study. For example, the pollutant sources within the flood extent located in the vicinity of the protected areas or close to aquifers used for domestic water supply have a greater impact than those located far away. The pollutant sources within the flooded area located upstream of the protected areas have a greater impact than those located downstream.

7. Conclusions

The causes of extreme floods and subsequently caused potential comprehensive influences of extreme flood disasters were analyzed in depth in this study. The causative mechanisms and extreme disaster chains were drawn. Heavy and/or persistent precipitations are usually the very first cause of extreme floods. Extreme flood disasters form when extreme floods cause human life loss, property loss, and sensitive ecological and environmental area damage. The potential consequences can be divided into three categories, i.e., social impacts, economic impacts, and environmental impacts. Social impacts are the potentially affected (injured, homeless, etc.) or dead people caused by extreme floods. Economic impacts reflect the direct/indirect economic losses, including residential building losses, agriculture losses, industrial losses, as well as the losses of hydraulic engineering caused by floods. Environmental impacts reveal that the protected areas are polluted due to possible contaminants spread from different types of pollutant sources, or extreme floods directly scouring the sensitive ecological and environmental areas.

On this basis, an extreme flood disaster index system and the corresponding evaluation methods, i.e., a refined social and economic impact evaluation method and a semi-quantitative environmental impact evaluation method, were proposed. The proposed methods were then applied to the JFDD to evaluate the economic impacts, social impacts, and environmental impacts under two extreme flood scenarios. The result indicates that almost all of the JFDD area is inundated by extreme floods with inundation areas of 901.36 km^2 and 879.49 km^2, respectively. The potentially affected populations are 0.51 million and 0.5 million. In addition, the possible direct economic losses are RMB 18.83 billion and RMB 14.33 billion, respectively. Among them, the residential building and inventory losses are the largest, followed by agriculture losses. It is likely that the nature reserves within JFDD are seriously influenced due to possible contaminant spread from five potential pollutant sources. The detailed analysis results provide effective information for decision making in flood management.

We focused mainly on the direct flood impact assessments. However, under rapid socio-economic developments, indirect impacts become more and more significant. Therefore, we intend to study indirect flood impacts in future work. Furthermore, we could explore artificial intelligent technology to assess flood impacts in a data-driven manner, such as learning about the relationship between flood hazards and flood losses. In addition, future work should also include underground space, vehicles, and other seriously affected properties during recent extreme flood disasters in flood damage assessments.

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