Article

Comprehensive Risk Assessment of Urban Waterlogging Disaster Based on MCDA-GIS Integration: The Case Study of Changchun, China

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Abstract: Urban waterlogging will harm economic development and people's life safety; however, the waterlogging risk zoning map provides the necessary decision support for the management of urban waterlogging, urban development and urban planning. This paper proposes an urban waterlogging risk assessment method that combines multi-criteria decision analysis (MCDA) with a geographic information system (GIS). The framework of urban waterlogging risk assessment includes four main elements: hazard, exposure, vulnerability, and emergency response and recovery capability. Therefore, we selected the urban area of Changchun City, Jilin Province as the study area. The Analytic Hierarchy Process (AHP) is a generally accepted MCDA method, it is used to calculate the weight and generate a result map of hazards, exposure, vulnerability, and emergency responses and recovery capability. Based to the principle of natural disaster risk formation, a total of 18 parameters, including spatial data and attribute data, were collected in this study. The model results are compared with the recorded waterlogging points, and the results show that the model is more reliable.

Keywords: urban waterlogging; analytical hierarchy process; remote sensing and GIS; risk assessment

1. Introduction

Urban waterlogging refers to continuous or heavy rainfall in a short period of time that exceeds the urban flood discharge capacity, a hazard phenomenon that causes flooding in urban areas [1]. Against a background of the increasing population, and an increasing urbanization rate, the proportion of the urban population will continue to increase. As urbanization progresses, the land cover types and hydrological conditions are altered, and impervious surfaces expand rapidly, leading to an increased risk of urban waterlogging [2–5]. At the same time, the frequent occurrence of extreme rainfall events caused by global climate change and the increase in waterlogging events on a global scale may have a serious and direct impact on the economy and humanitarianism, as well as continue to adversely affect economic development [6,7].

China is suffering from the adverse effects of climate change and rapid urbanization. According to statistics from China's Ministry of Housing and Urban-Rural Development, about 60% of the cities are affected by waterlogging, especially in large cities such as Zhengzhou, Shenzhen, and Shanghai. For example, in July 2021, Zhengzhou city in Henan Province was hit by continuous heavy rainfall, with the highest daily precipitation of 552.5 mm, resulting in 398 deaths and missing people, 380 of which were in Zhengzhou, accounting for 95.5% of the total number of deaths and missing people in the province.

Urban waterlogging caused by extreme precipitation leads to the loss of basic urban functions and huge economic losses [8]; in this case, there were direct economic losses of 120.06 billion yuan. Cities are densely populated and highly economically developed areas; urban waterlogging events will have a serious impact on social development [9]. Therefore, how to deal with and alleviate the urban waterlogging events is an important issue.

Nowadays, more and more researchers have started to pay attention to urban waterlogging [10]. The studies by scholars show that not only are environmental factors (altitude and rainfall) important causes of urban waterlogging, but also human activities [11–13]. This is mainly divided into three aspects: (1) urban drainage facilities; (2) urban micro-topography; and (3) expansion of impervious surfaces. Urban areas such as subways, lowlands, and underground parking lots benefit from precipitation accumulation, and urban flooding events often occur. The expansion of the impervious surface area caused by the urbanization process has exacerbated the problem of urban waterlogging [14,15]. In addition, urban stormwater drainage pipes in most of the developing countries are poorly designed and poorly maintained to effectively alleviate flooding in the face of extreme rainfall. In order to solve the problem of urban waterlogging, researchers have proposed engineering measures, such as "low-impact development mode" and "sponge city", to alleviate the problem of waterlogging [16–20]. These plans mainly use measures such as infiltration, stagnation, storage, purification, utilization, and drainage to absorb and utilize the rainwater on the spot, thereby reducing surface runoff. In the scholars' research, it was found that topographic factors (elevation and slope) also play a significant role in the occurrence of urban waterlogging events, and low-lying and flat areas have a greater risk of urban waterlogging [11,21,22].

At present, there is no unified standard for urban waterlogging disaster risk evaluation, and different scholars adopt different evaluation methods, according to their relative significance in their own research. In this study, according to the risk formation principle of natural disasters, the risk assessment of an urban waterlogging disaster is divided into four criteria layers, which are hazard, exposure, vulnerability, and emergency response and recovery capability, respectively. This method is also regarded as a kind of multi-criteria decision making (MCDA). In previous studies, scholars only considered the risk of urban waterlogging and rarely considered the human factors [23]. The difference between urban waterlogging disaster risk assessment and traditional urban waterlogging disaster risk assessment in this paper lies in the fact that the traditional risk assessment mainly starts from the perspective of the disaster-causing conditions, ignoring the complexity of the carrier itself in the face of the urban waterlogging disaster and the effect of people's disaster preparation on risk mitigation. This study comprehensively considered a variety of factors, including vulnerability, and disaster prevention and reduction abilities, so as to make the evaluation results more scientific and standardized. This paper takes the area within the Changchun City Ring Expressway as the research area, and mainly uses the analytical hierarchy process (AHP), remote sensing (RS), geographic information system (GIS), and field observations to create a waterlogging risk map in the Changchun urban area, to provide help for decision-makers and a theoretical basis for urban development planning.

2. Materials and Methods

2.1. The Study Area

Changchun City is the capital of Jilin Province in China, one of the important central cities in Northeast China, and an important node city on the northern route of the "Belt and Road". In the two decades from 2000 to 2019, the city underwent a rapid urbanization process, and the urban area expanded by 1.4 times [24]. Changchun City has a continental monsoon climate in the north temperate zone. The average annual precipitation is 561.6 mm. The precipitation is mainly concentrated in July and August, and the altitude is mainly distributed between 250–350 m. The geographical location of the urban area of the district of Changchun is from 125°8′12″ to 125°27′49″ east longitude and from 43°44′19″

to 44°2′10″ north latitude. The study area is shown in Figure 1, covering an area of about 522 square kilometers.
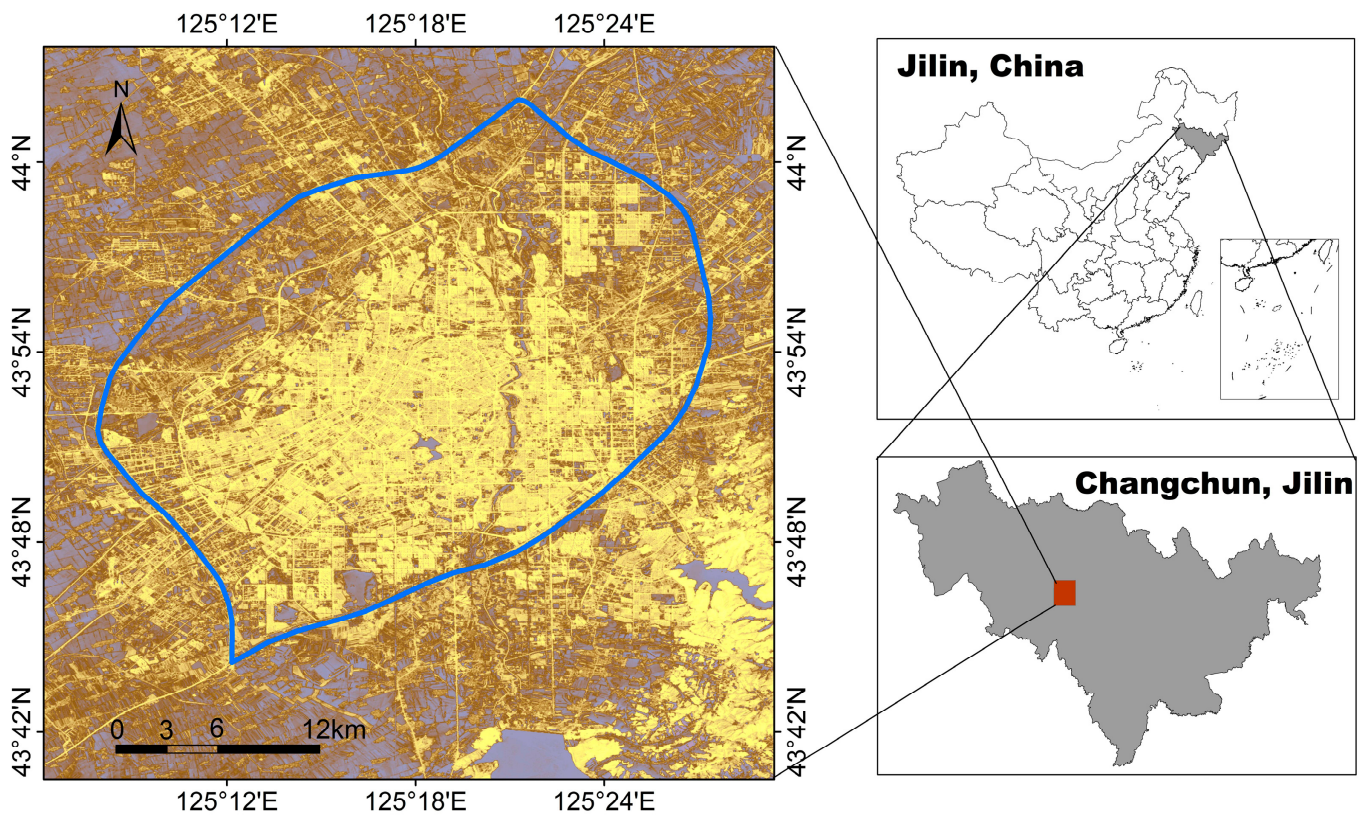

Figure 1. Location map of the study area.

2.2. Data and Methodology

2.2.1. Data Acquisition and Preparation Techniques

This study needed a large amount of non-spatial attribute data and multi-source spatial data to analyze the waterlogging disaster risk in the urban area of Changchun. After consulting several experts and reading a large quantity of relevant literature, a total of 18 indicators were selected to calculate the risk of urban waterlogging. Among them, nine indicators of altitude, slope, rainfall, geomorphology, NDMI (Normalized Difference Moisture Index), NDVI (Normalized Difference Vegetation Index), distance from waterbodies, LULC (Land Use and Land Cover), and drainage density were used to analyze the hazard of urban waterlogging. The three indicators of population density, road network density, and GDP (Gross Domestic Product) were used for exposure analysis. The proportion of the vulnerable population, commercial buildings, and residential buildings were used for vulnerability analysis. The three indicators of per capita income, institutional capacity, and education status were used for the analysis of emergency responses and recovery capability. Table 1 summarizes the selection of the indicators and data sources for this study. Figure 2 summarizes the technical route and methods of this study. In addition, all of the layers were prepared in the ArcGIS10.8 environment.

Table 1. Selected indicators of waterlogging risk model and their source.

Sl. No	Parameters	Data Types	Date Details	Source
Waterlogging hazard indicators				
1	Altitude	ASTER GDEM	30 m × 30 m	https://www.gscloud.cn (accessed on 18 March 2022)
2	Slope	ASTER GDEM	30 m × 30 m	https://www.gscloud.cn
3	Rainfall	Raster data	2017–2021	http://data.cma.cn/ (accessed on 9 February 2022)
4	Geomorphology	Vector layer	1:4 million	https://www.databox.store (accessed on 21 April 2022)
5	NDMI	Landsat 8 OLI/TIRS	30 m × 30 m	https://www.gscloud.cn (accessed on 21 April 2022)
6	NDVI	Landsat 8 OLI/TIRS	30 m × 30 m	https://www.databox.store (accessed on 21 April 2022)
7	Distance to waterbodies	Vector layer	2021	https://www.gscloud.cn (accessed on 21 April 2022)
8	LULC	Raster data	30 m × 30 m	https://www.databox.store (accessed on 21 April 2022)
9	Drainage density	Vector layer	2021	http://www.guihuayun.com/ (accessed on 6 April 2022)
Exposure evaluation index				
1	Population density	Raster data	2020	World UN population density data set
2	Road density	Road network shape file	2021	https://www.gscloud.cn (accessed on 6 April 2022)
3	GDP	Raster data	2022	https://www.databox.store (accessed on 6 April 2022)
Vulnerability Evaluation Index				
1	Proportion of vulnerable population	Attribute data	2021	Changchun Statistical Yearbook
2	Commercial buildings	POI	2022	http://www.guihuayun.com/ (accessed on 6 April 2022)
3	Residential buildings	POI	2022	http://www.guihuayun.com/ (accessed on 6 April 2022)
Emergency responses and recovery capability				
1	Per capita income	Raster data	2021	Changchun Statistical Yearbook
2	Institutional capacity	Attribute data	2021	Changchun Statistical Yearbook
3	Education status	Attribute data	2021	Changchun Statistical Yearbook
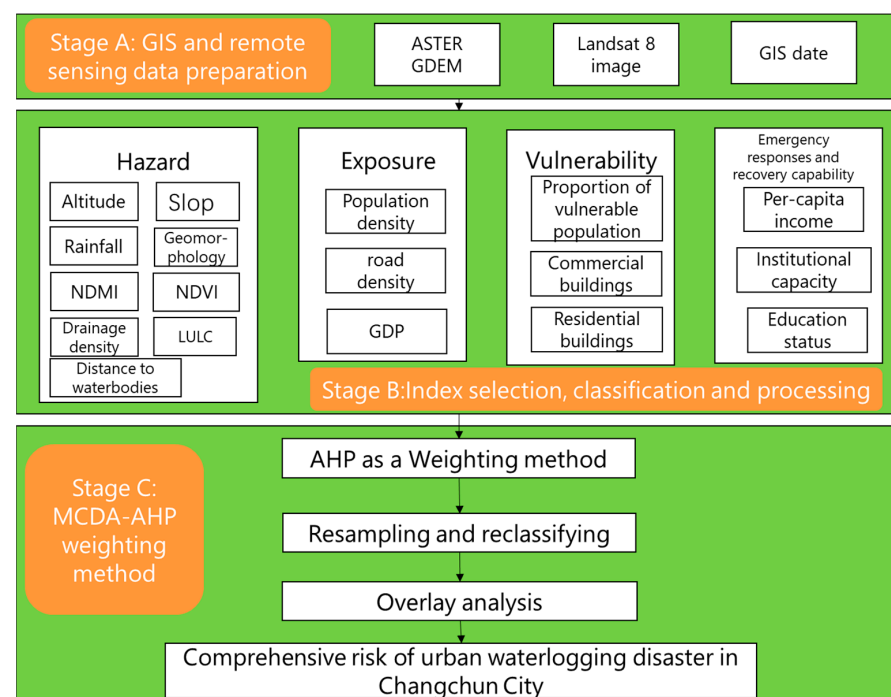
Figure 2. Workflow of the study.

2.2.2. Analytic Hierarchy Process (AHP)

As a powerful technique, the Analytic Hierarchy Process (AHP) has been widely used as a method for calculating index weights for urban waterlogging risk assessment [25,26]. The AHP focuses on a series of indicators and reduces the complexity of decision making by constructing a hierarchical structure. Therefore, we used an AHP to assign weight to each of the indicators related to the urban waterlogging risk [27]. The weight of each indicator was determined according to the pairwise comparison of the scale table (Table 2), which is based on the opinions of five experts from the Disaster Research Institute team of Northeast Normal University, a literature review [23,28,29], and field experience, and, finally, a consistency check (Table 3). If the RI (random consistency index) is less than the corresponding value in the table, the consistency check is passed; otherwise, the parameter importance needs to be corrected until it passes the test. The whole AHP process is divided into five steps: (I) establishing a hierarchical structure model; (II) constructing a judgment matrix; (III) hierarchical single ordering; (IV) checking the consistency of the judgment matrix; and (V) hierarchical total sorting. The weight calculation results for each index are shown in Table 4.

Table 2. Relative importance scale (1–9).

The Intensity of Importance/Judgments	Numeric Value
Equal importance	1
Moderate importance	3
Strong importance	5
Very strong importance	7
Extreme importance	9
The median value of two adjacent judgments	2, 4, 6, 8

Table 3. Random consistency index test (RI) table.

Umber of Criteria (n)	3	4	5	6	7	8	9
RI	0.28	0.90	1.12	1.24	1.32	1.41	1.45

Table 4. Weight of indicators.

Target Layer	Criterion Layer	Criterion Layer Weights	Indicator Layer	AHP Normalized Weight
Waterlogging risk	Hazard	0.4171	Altitude	0.2754
			Slope	0.1946
			Rainfall	0.1568
			Geomorphology	0.021
			NDMI	0.0603
			NDVI	0.0433
			Distance to waterbodies	0.0298
			LULC	0.0903
			Drainage density	0.1285
	Exposure	0.1585	Population density	0.5714
			Road density	0.1429
			GDP	0.2857
	Vulnerability	0.1294	Proportion of vulnerable population	0.1634
			Commercial buildings	0.297
			Residential buildings	0.5396
	Emergency responses and recovery capability	0.295	Per capita income	0.1929
			Institutional capacity	0.701
			Education status	0.1061

2.2.3. Modelling of Urban Waterlogging Disaster Criterion Layer

According to the theory of the four elements of natural disaster risk formation, four criterion layers were established in this study, namely, hazard, exposure, vulnerability, and

emergency response and recovery capability. The risk of urban waterlogging refers to the degree of natural variability, which directly determines whether urban waterlogging disasters will occur. Generally, the higher the risk, the greater the possibility of disasters. The risk of urban waterlogging disaster (*H*) was calculated according to the logistic regression model, and the calculation formula of the urban waterlogging disaster risk probability is shown as Equation (1):

$$H = \frac{\exp(b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_k x_k)}{1 + \exp(b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_k x_k)} \tag{1}$$

In the formula: *H* is the probability of the occurrence of urban waterlogging disasters, $H \in [0, 1]$, the smaller the value of *H* is, the lower the possibility of an urban waterlogging disaster occurring. When the value is 1, it means that 100% of urban waterlogging disasters occur. x_k for each indicator; b_k is the calculated regression coefficient.

The exposure (*E*) refers to all of the properties and people that may be threatened by urban waterlogging disasters and is a quantification of the value of the disaster-bearing bodies. That is, the higher the density of people and properties, the greater the potential loss. The vulnerability (*S*) refers to the degree of loss of people and properties in dangerous areas due to urban waterlogging, and it is the quantification of the bearing capacity. The higher the vulnerability, the greater the disaster losses and the greater the disaster risk. The emergency responses and recovery capability (*C*) refers to the ability to respond to and recover from disasters, mainly including disaster-resistant material reserves, emergency management capabilities, investment in disaster reduction, etc. The weaker the emergency responses and recovery capability are, the greater the disaster risk. The calculation formula of each criterion is as follows:

$$E = \sum_{i=1}^{n} W_{ei} X_{ei} \tag{2}$$

$$S = \sum_{i=1}^{n} W_{pi} X_{pi} \tag{3}$$

$$C = \sum_{i=1}^{n} W_{ri} X_{ri} \tag{4}$$

In the formula: the values of *E*, *S*, and *C* correspond to exposure, vulnerability, and disaster prevention and mitigation capabilities, respectively. *n* is the total number of indicators; *i* is the *i*th indicator; W_{ei}, W_{pi} and W_{ri} are the weights of each factor obtained by the AHP, respectively; X_{ei}, X_{pi} and X_{ri} are the quantitative values of the indicators corresponding to exposure, vulnerability, and emergency response and recovery capability.

2.2.4. Modeling of Urban Waterlogging Risk Index

In this study, the urban waterlogging risk index (*UWRI*) was positively correlated with hazard (*H*), exposure (*E*), and vulnerability (*S*), and negatively correlated with emergency response and recovery capability (*C*). The formula for calculating the Urban Waterlogging Risk Index (*UWRI*) is as follows:

$$UWRI = \frac{H \times E \times S}{1 + C} \tag{5}$$

3. Results

3.1. Parameter Introduction and Processing Results

3.1.1. Hazard Indicator

Altitude

Altitude is one of the important factors directly related to urban waterlogging [30]. Altitude affects the direction of surface runoff, with water flowing from high to low-lying areas; therefore, areas with lower elevations are more prone to urban flooding [31]. With

the help of ArcGIS version 10.8.1 (Produced by Environmental Systems Institute, Inc., Redlands, CA, USA), the DEM data of the study area were extracted, and the elevation range was 71–345 m. The overall performance of the altitude is high on both sides and low in the middle. The Yitong River and its coastal areas have lower altitudes, and the areas near the Yitong River are more prone to floods.

Slope

The urban waterlogging risk increases with decreasing slope [32]. The slope affects the speed and flow of the water. The greater the slope, the greater the surface runoff, and it is not easy to form stagnant water. The lower slopes have more water infiltration and less impact on surface runoff, and so are prone to waterlogging [33]. Taking Changchun City as an example, the slope can be divided into five categories.

Rainfall

The most direct factor affecting urban waterlogging depends on rainfall, and prolonged heavy rainfall will greatly increase the risk of urban waterlogging [34]. With the development of urbanization, human factors, and climate change affecting the global environment, urban flooding events have become more frequent, intense, and uncertain. The rainfall data in the study area selected the average annual rainfall from 2016 to 2021, and the rainfall mainly occurred from June to September.

Geomorphology

The origin of the landforms has an important impact on the formation of waterlogging [35], so this study also investigated the composition of Changchun's landforms, which are mainly composed of low-elevation alluvial–proluvial plateaus and low-elevation alluvial plains. Low-elevation alluvial plains are more prone to being submerged by flooding.

Normalized Difference Moisture Index (NDMI)

The NDMI is an updated version of the NDWI that identifies spatial differences in surface humidity. The NDMI value represents soil moisture. Areas with a high soil moisture content are prone to waterlogging disasters, so it is selected as the influencing factor of urban waterlogging [36]. The higher the NDMI value is, the higher the soil moisture content is, and the more prone it is to waterlogging. In this study, the NDMI ranged from −0.54 to 0.73.

Normalized Difference Vegetation Index (NDVI)

The NDVI is commonly used to represent the coverage of vegetation. When the value is close to 0, it means that there is no vegetation, and the closer the value is to 1, it means the coverage of vegetation is greater. Studies show that areas with higher vegetation coverage have stronger water retention and lower risk of urban waterlogging [37].

Distance to Waterbodies

Urban waterways are mainly divided into channels and rivers. The channels are man-made, the rivers are naturally formed, and the areas close to rivers are more prone to waterlogging [35]. In this study, the rivers and lakes were selected for buffer analysis, which was divided into five levels, and the density of waterlogging points was inversely proportional to the distance from the water body [21].

Drainage Density

The drainage pipe network is an important means of urban flood discharge, and areas with developed drainage pipe networks are more capable of dealing with extreme rainfall.

Land Use and Land Cover (LULC)

The change in land-use type and the increase in the impervious surfaces aggravate the occurrence of urban waterlogging events. Compared with the impervious ground, forestland can absorb more rainwater, reduce water accumulation, and is less prone to waterlogging events [36,38]. According to the supervised classification method, the land use types in the study area can be divided into five categories, of which artificial surfaces are the main component.

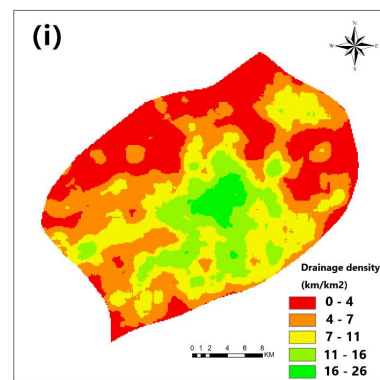The spatial distribution of hazard indicators is shown in Figure 3.
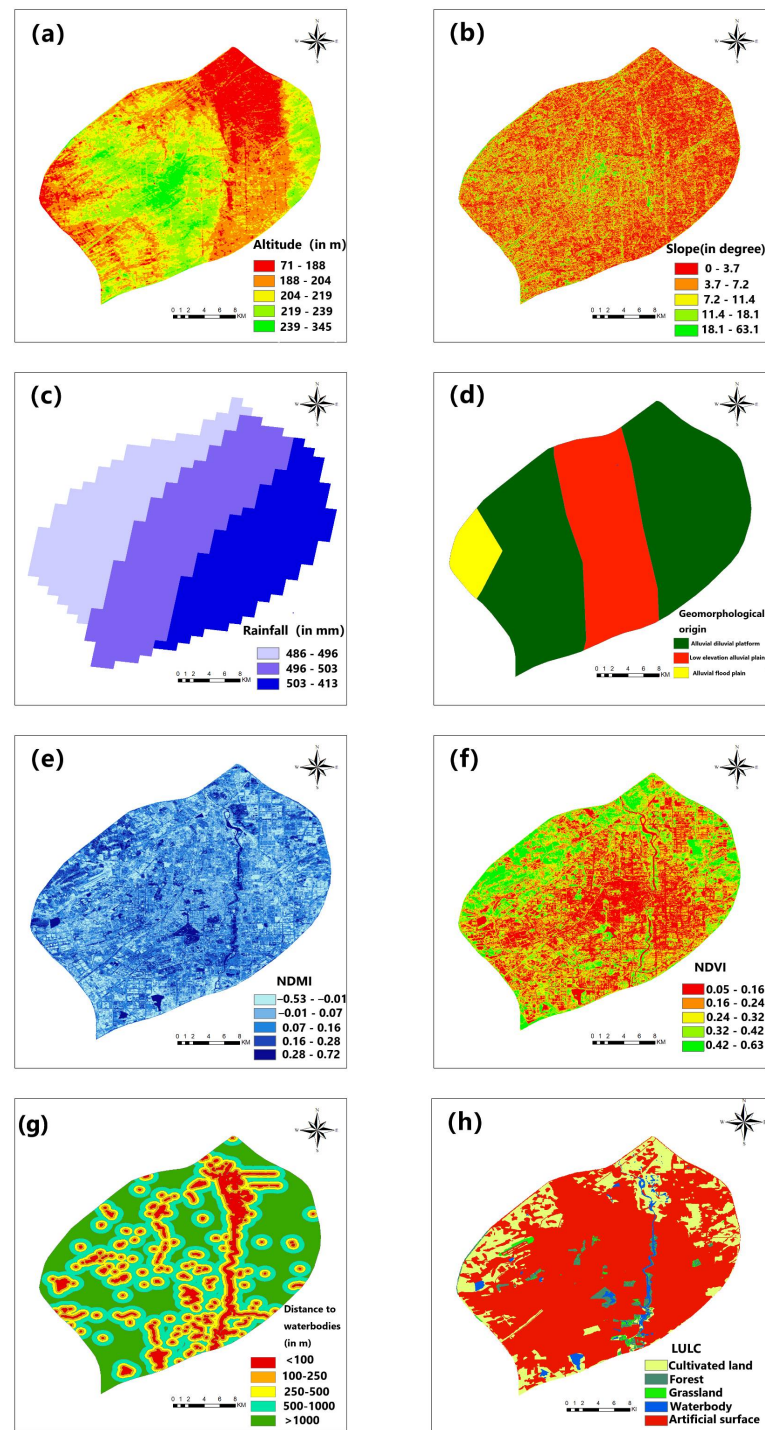
Figure 3. *Cont.*

Figure 3. Altitude (**a**); Slope (**b**); Rainfall (**c**); Geomorphology (**d**); NDMI (**e**); NDVI (**f**); Distance to waterbodies (**g**); LULC (**h**); Drainage density (**i**).

3.1.2. Exposure Evaluation Index

Population Density

The severity of an urban waterlogging disaster is related to the number of people affected. The greater the population density, the greater the potential loss and the higher the exposure [39]. The urban population density of Changchun City is very high, mainly concentrated in the central area of the city.

GDP

GDP is one of the important indicators of social and economic development, and the data used in this study are selected from China's GDP spatial distribution kilometer grid dataset. Based on the GDP statistics of all of the provinces and counties in China, the dataset also comprehensively considers the factors closely related to human economic activities, such as residential density and nighttime light intensity, and distributes the data to grid cells by using the multi-factor weighting method. The GDP value of the central area of Changchun city is relatively high, and the exposure is also high.

Road Density

The road network density is one of the indicators used to measure the development scale of urban road network and is an important exposure factor. Urban road construction is restricted by many factors, which can be divided into three levels: the economic factor; the traffic supply factor; and the traffic demand factor. In addition, the areas with dense road networks are more prone to waterlogging, due to the increase in artificial surfaces. The road network density in this study is the road length per square kilometer. The spatial distribution of exposure indicators is shown in Figure 4.

3.1.3. Vulnerability Evaluation Index

Proportion of Vulnerable Population

The proportion of vulnerable population refers to the degree of people's vulnerability to disasters. Ordinary adults are more likely to be able to protect themselves in the face of disasters, while vulnerable groups, such as the old, the weak, the sick, and the young are more vulnerable to disasters.

Commercial Buildings and Residential Buildings

Both industrial and commercial buildings and residential buildings are elements that are susceptible to waterlogging, demonstrating the vulnerability of urban waterlogging [40]. These data were collected from a map's points of interest. The spatial distribution of vulnerability indicators is shown in Figure 5.
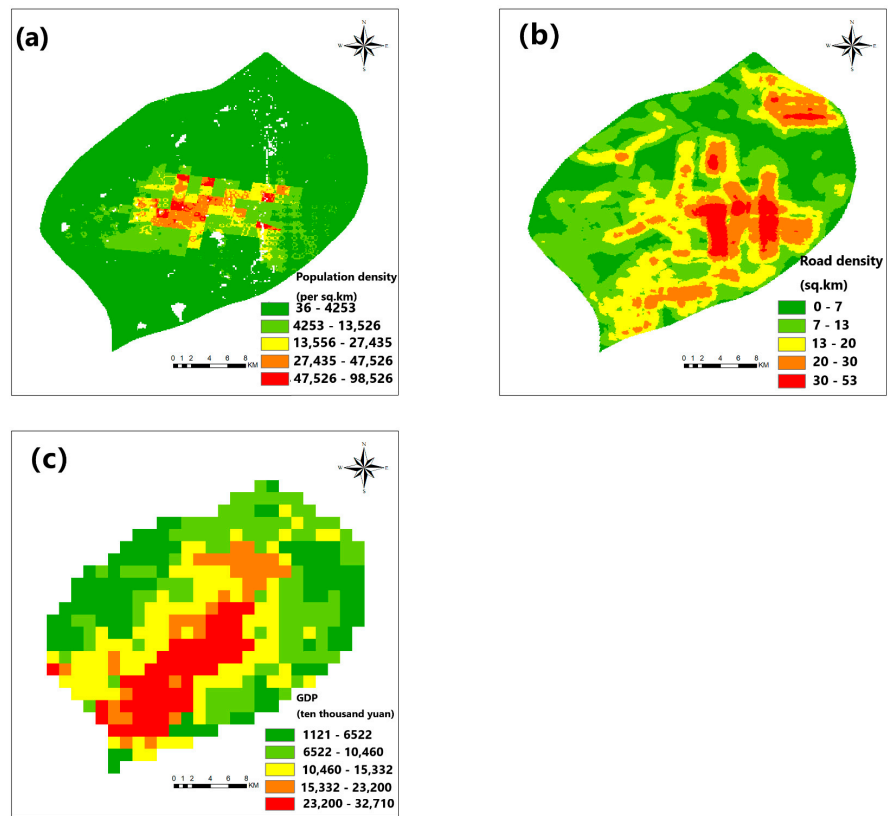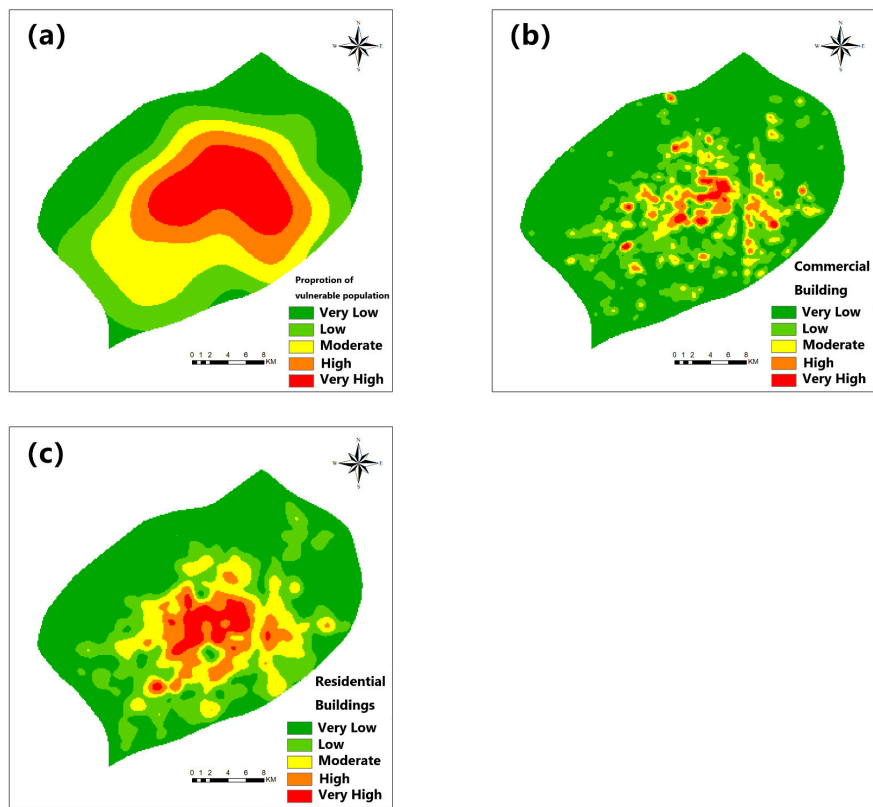
Figure 4. Population density (**a**); road density (**b**); GDP (**c**).

Figure 5. Proportion of vulnerable population (**a**); commercial buildings (**b**); residential buildings (**c**).

3.1.4. Emergency Responses and Recovery Capability

Per Capita Income

Economic ability also represents the ability to deal with disasters. Generally, wealthy families have a stronger ability to deal with disasters, and poor families are more vulnerable to disasters.

Institutional Capacity

Institutional capacity includes hospitals, fire departments, and other emergency response teams; they provide very important rescue forces, and they play a vital role in emergency response and post-disaster recovery. The areas closer to rescue services are more likely to be rescued, and as distance increases, so does vulnerability.

Education Status

The literature shows that education can improve disaster awareness and knowledge, and help people make correct decisions and mitigate losses when faced with disasters [41]. The level of education improves people's ability to cope with the impact of urban waterlogging disasters, and educated people have higher disaster response abilities. The spatial distribution of emergency responses and recovery capability indicators is shown in Figure 6.
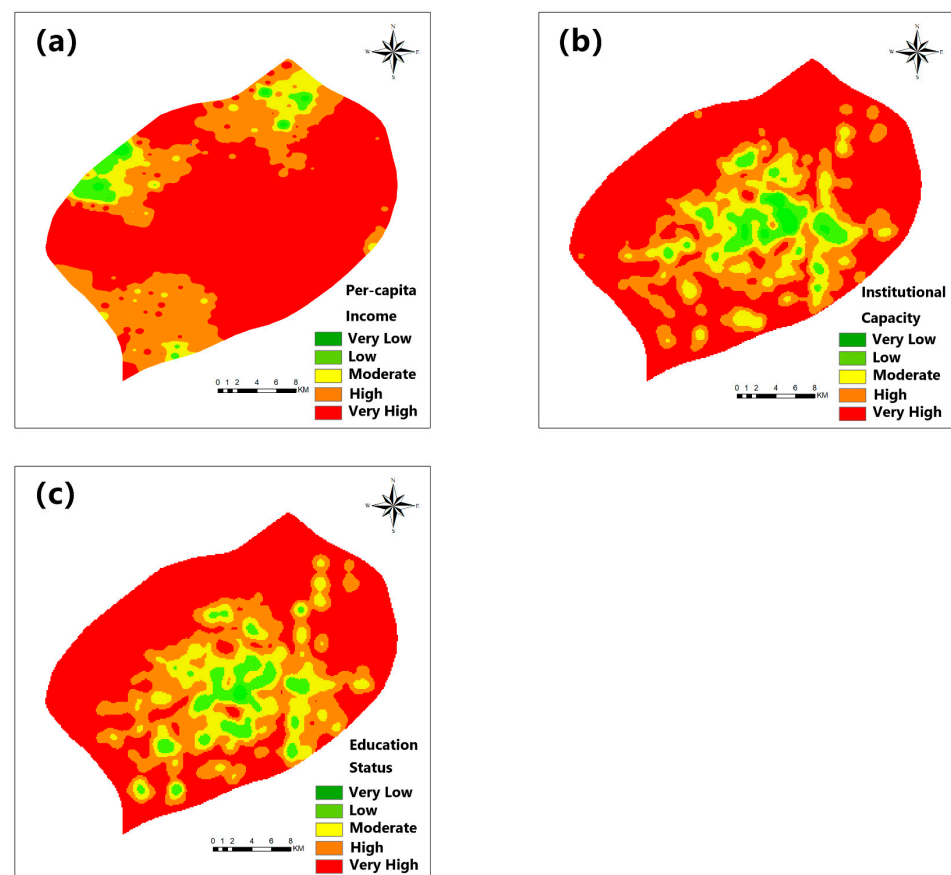

Figure 6. Per capita income (**a**); institutional capacity (**b**); education status (**c**).

3.2. *Hazard, Exposure, Vulnerability, and Emergency Responses and Recovery Capability Map*

Combined with the weight of the indicator system, the calculation results of each criterion layer are shown in Figure 7. In this study, the hazard (H) was measured with nine sub-factors. The study analyzed the influencing factors of urban waterlogging, and their impact mechanism on urban waterlogging. As shown in the results, urban waterlogging can easily occur in the east of the city, mainly because the terrain in the east of the city

is lower and there are more impervious surfaces. It is difficult for excess precipitation to pass through the impermeable surfaces, and the sewers designed earlier cannot meet the new drainage needs, which leads easily to runoff confluence. The exposure is measured with three sub-factors. The study also analyzed the exposure to urban waterlogging to confirm the list of bearing bodies in the prone area. The high exposure areas of the city are mainly concentrated in the urban center; high population density is the main factor that exacerbates the impact of flooding in communities. Three indicators were taken to evaluate urban waterlogging susceptibility. The results show that the regions closer to urban centers are more susceptible, which led us to conclude that the proportion of vulnerable, commercial buildings, and residential buildings are the major factors contributing to urban waterlogging susceptibility. This study measured the disaster prevention and reduction capacity with three indicators. The closer the area was to the city center, the stronger the area's ability to prevent and mitigate disaster. Because there are more rescue institutions and more capital investment here, the urban center also has a higher disaster prevention and reduction capacity.
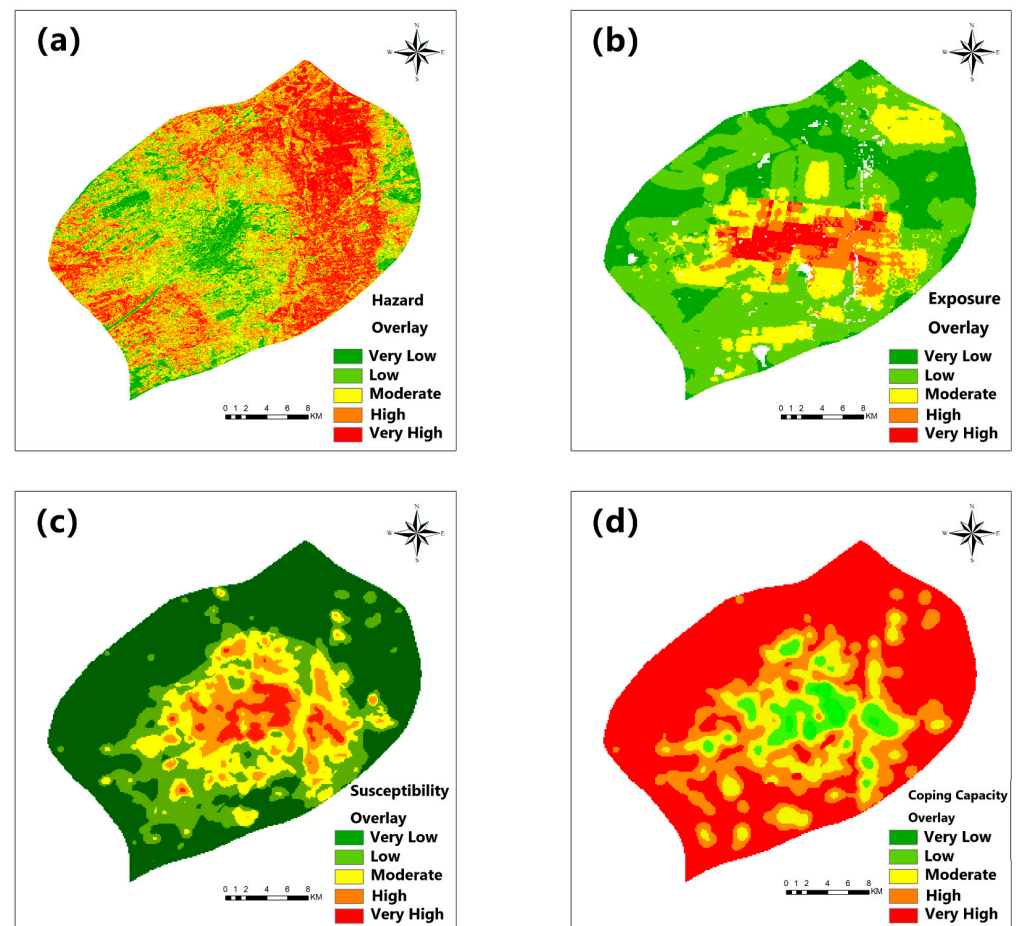

Figure 7. Hazard (**a**); exposure (**b**); vulnerability (**c**); emergency response and recovery capability (**d**).

3.3. Waterlogging Risk

According to the results calculated by the model, the natural breakpoint method is used to classify the waterlogging risk; thus, the waterlogging disaster-risk zoning in the urban area of Changchun is formed, as shown in Figure 8. It can be seen from the figure that the extremely high-risk areas are mainly distributed in the eastern part of Changchun City. According to the national early warning grade classification standards, the waterlogging risk map of Changchun city can be categorized into four classes viz.: very low (22.4%); low (30.0%); moderate (30.7%); and high (16.9%).
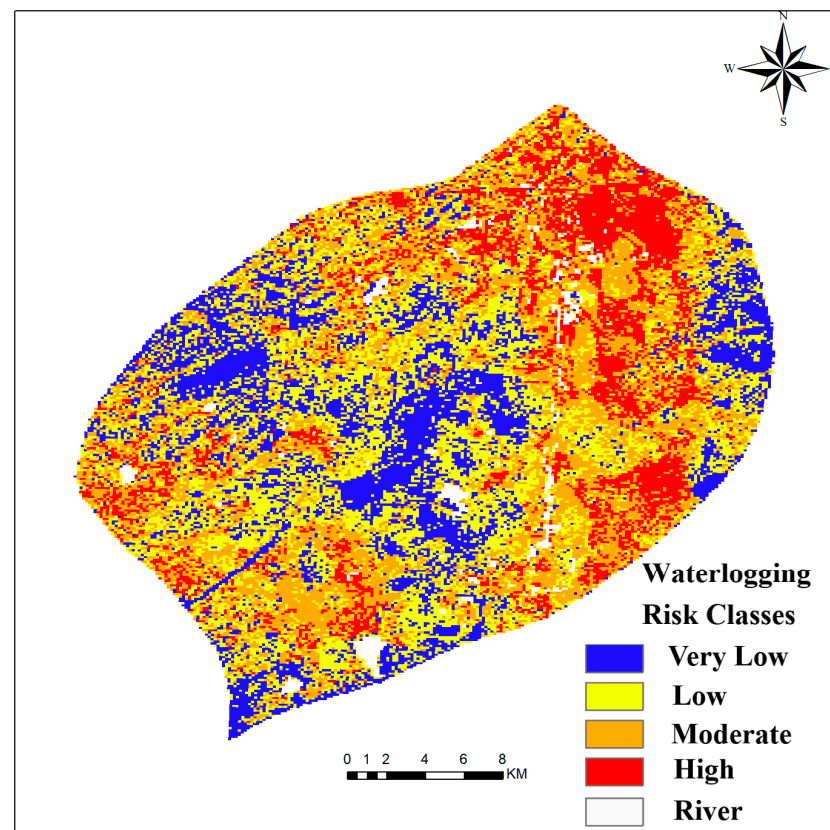
Figure 8. Urban waterlogging disaster risk zoning map.

4. Discussion

4.1. Waterlogging Point Verification

Changchun in the rainy season is plagued by waterlogging problems. In recent years, the occurrence of instantaneous heavy rainfall has brought a series of obvious problems. Many roads in the urban area are impassable, and there are endless water spots, some of which are even deeper than the waist. This paper collected a total of 49 waterlogging points in the five years from 2017 to 2021, which were mainly from government reports, field survey results, and news information. The waterlogging points were used to verify the risk zoning, the results were consistent, and the model was reliable. These waterlogging points are shown in Figure 9.

According to the reports of the water spots released by relevant departments, they are mainly concentrated in the southeast of the city, which belongs to the Erdao District of Changchun City. The model calculation results also show mainly extremely dangerous areas.

The reasons for the formation of waterlogging points are complex and can be mainly divided into the following points:

1. The drainage pipe network in the old city of Changchun was built earlier, and the design drainage standard is relatively low. At present, it is difficult to reform the drainage pipe network, and waterlogging occurs easily with the increase in impervious ground;

2. Due to the age of the drainage pipes and serious levels of deposits on them, the bottom pipe network cannot accommodate a large amount of sudden rainfall. Generally, heavy rainfall over time can be drained in two to three hours, but there will be local water accumulation;

3. Because the river's water level rises, backing up into the drainage pipe network, the water cannot be discharged in time.
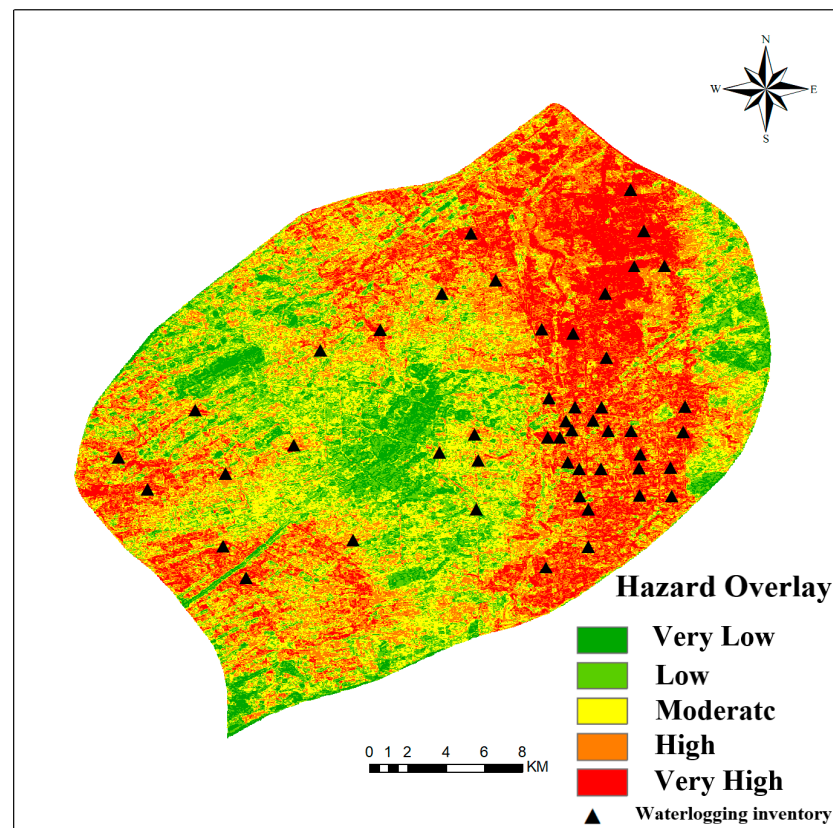
Figure 9. Waterlogging point verification map.

4.2. Comparison with Other Evaluation Methods

How to carry out risk assessment and analysis of urban waterlogging disasters and propose a set of corresponding technical frameworks is a hot issue in academic research. The current mainstream research methods mainly include: 1. Mathematical statistical method of historical disasters; 2. Index system method; 3. Rain and flood simulations; 4. Uncertainty analysis method; 5. Scenario simulation method. The method used in this study was to use the formation principle of natural disaster risk and the further development of various remote sensing and GIS data in the direction of the index system method. The main feature of the method used in this study is that, according to the characteristics of the disaster system, the researchers selected a certain index system based on their own experience or the experience of other scholars, and then processed the original index data through a series of mathematical methods, and finally obtained the process of regional risk. This method mainly focused on the selection of indicators and the optimization of the weight calculation of each indicator, which is suitable for risk assessment on large spatial scales.

The rainstorm simulation model simulation, scenario simulation method, historical disaster mathematical statistics' method, and index system method can all be used to evaluate urban-scale rainstorm and waterlogging disasters. However, the simulation of rain and the flood simulation model, and the method of scenario simulation have higher requirements for the accuracy of research data, and at the same time, they cannot reflect the causal relationship between various risk factors in the city, and they have a poor guiding effect on urban planning. Therefore, this paper selects the index system method as the construction method for the evaluation system, with the purpose of judging the functional relationship between the spatial elements at the urban scale and carrying out a comprehensive evaluation of waterlogging disaster risk.

4.3. The Guiding Significance of Risk Analysis

The results of the urban waterlogging disaster risk assessment have a lot of guiding significance. We can make corresponding emergency plans according to the evaluation results, so as to deal with urban waterlogging disasters in a timely, effective, and accurate way. According to the classification of the urban waterlogging risk grade in each region, the layout of the emergency relief materials' warehouse is optimized scientifically, so that the materials can be quickly delivered to the disaster area. According to the evaluation results, scientific site selection of the refuge is carried out, to avoid the selection of a refuge which is also a waterlogging point.

Our aims were to study the relationship between the indicators on an urban scale and to plan urban construction to reduce urban waterlogging. In addition, the outcome of the research should promote the sustainable development of cities and improve the ability of cities to cope with urban waterlogging risk. Urban planning should reduce the proportion of impervious surface cover and increase the area of vegetation for storm runoff mitigation. Land cover and vegetation coverage will affect the behavior of surface water, and a reasonable municipal layout can reduce environmental injustice. According to the processing results of the vulnerability indicators, we should strengthen the protection of those areas with high vulnerability indicators, such as vulnerable population groups and buildings that are more vulnerable to disasters. The vulnerable groups are mainly the old, the weak, the sick, and the disabled. The protection of the road infrastructure should also be strengthened in waterlogging risk areas. The road network is particularly vulnerable to waterlogging and the interruption of the traffic will bring a series of adverse consequences.

5. Conclusions

In this study, we sorted out 18 kinds of urban waterlogging risk-adjusting factors, according to the principle of natural disaster risk formation, and used GIS to fuse multi-source data to establish a geospatial database. Finally, the MCDA (AHP) method was used to develop the urban waterlogging risk assessment map. The advantage of this method is that it incorporates the impact of human factors on the risk of urban flooding and does not require refined time-series data or data such as river flow, which are not available in many areas. In this study, we developed the urban waterlogging disaster risk assessment map for Changchun City, which integrates the urban waterlogging disaster hazard, exposure, vulnerability, and emergency responses and recovery capability maps, which can provide useful information for relevant departments and decision-makers. In order to improve and implement waterlogging response measures in the region, and provide a basis for urban planning, the generated waterlogging risk map is helpful for timely communication with local people, who may be affected in the event of waterlogging. In addition, the urban waterlogging risk assessment framework developed based on the MCDA method can be applied to other regions of China and other cities to create urban waterlogging risk assessment maps. When applying this method to other cities, the local natural environment and the human environment need to be considered. The accuracy of the results of the urban waterlogging risk map generated in this study depends on the quality of data and the researchers' selection of indicators and weight calculation. Therefore, the subjectivity of research can be overcome in future research. In addition, neural networks and deep learning models are increasingly used in risk analysis of indicator methods.

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References

1. Yin, Z.; Yin, J.; Xu, S.; Wen, J. Community-based scenario modelling and disaster risk assessment of urban rainstorm waterlogging. *J. Geogr. Sci.* **2011**, *21*, 274–284. [CrossRef]
2. Sofia, G.; Ragazzi, F.; Giandon, P.; Dalla Fontana, G.; Tarolli, P. On the linkage between runoff generation, land drainage, soil properties, and temporal patterns of precipitation in agricultural floodplains. *Water Resour.* **2019**, *124*, 120–138. [CrossRef]
3. Sofia, G.; Roder, G.; Fontana, G.D.; Tarolli, P. Flood dynamics in urbanised landscapes: 100 years of climate and humans' interaction. *Sci. Rep.* **2017**, *7*, 40527. [CrossRef] [PubMed]
4. Sofia, G.; Prosdocimi, M.; Fontana, G.D.; Tarolli, P. Modification of artificial drainage networks during the past half-century: Evidence and effects in a reclamation area in the Veneto floodplain (Italy). *Anthropocene* **2014**, *6*, 48–62. [CrossRef]
5. Su, M.; Ying, Z.; Yan, H.; Chen, Q.; Chen, S.; Chen, Z.; Hong, X. The influence of landscape pattern on the risk of urban water-logging and flood disaster. *Ecol. Indic.* **2017**, *92*, 133–140. [CrossRef]
6. Hallegatte, S.; Green, C.; Nicholls, R.J.; Corfee-Morlot, J. Future flood losses in major coastal cities. *Nat. Clim. Chang.* **2013**, *3*, 802. [CrossRef]
7. Woodruff, J.D.; Irish, J.L.; Camargo, S.J. Coastal flooding by tropical cyclones and sea-level rise. *Nature* **2013**, *504*, 44–52. [CrossRef]
8. Fahy, B.; Brenneman, E.; Chang, H.; Shandas, V. Spatial analysis of urban flooding and extreme heat hazard potential in Portland, OR. *Int. J. Disaster Risk Reduct.* **2019**, *39*, 101117. [CrossRef]
9. Li, C.; Cheng, X.; Li, N.; Du, X.; Yu, Q.; Kan, G. A Framework for Flood Risk Analysis and Benefit Assessment of Flood Control Measures in Urban Areas. *Int. J. Environ. Res. Public Health* **2016**, *13*, 787. [CrossRef]
10. Huang, H.; Xi, C.; Zhu, Z.; Xie, Y.; Kai, L. The changing pattern of urban flooding in Guangzhou, China. *Sci. Total Environ.* **2017**, *622*, 394–401. [CrossRef]
11. Tehrany, M.S.; Jones, S.; Shabani, F. Identifying the essential flood conditioning factors for flood prone area mapping using machine learning techniques. *Catena* **2019**, *175*, 174–192. [CrossRef]
12. Wang, C.; Du, S.; Wen, J.; Zhang, M.; Gu, H.; Shi, Y.; Xu, H. Analyzing explanatory factors of urban pluvial floods in Shanghai using geographically weighted regression. *Stoch. Environ. Res. Risk Assess.* **2017**, *31*, 1777–1790. [CrossRef]
13. Zhang, Y.; Xia, J.; Yu, J.; Randall, M.; Zhang, Y.; Zhao, T.; Pan, X.; Zhai, X.; Shao, Q. Simulation and assessment of urbanization impacts on runoff metrics: Insights from landuse changes. *J. Hydrol.* **2018**, *560*, 247–258. [CrossRef]
14. Shuster, W.D.; Bonta, J.; Thurston, H.; Warnemuende, E.; Smith, D.R. Impacts of impervious surface on watershed hydrology: A review. *Urban Water J.* **2005**, *2*, 263–275. [CrossRef]
15. Jiansheng, W.U.; Zhang, P. The effect of urban landscape pattern on urban waterlogging. *Acta Geogr. Sin.* **2017**, *72*, 444–456. [CrossRef]
16. Ahammed, F. A review of water-sensitive urban design technologies and practices for sustainable stormwater management. *Sustain. Water Resour. Manag.* **2017**, *3*, 269–282. [CrossRef]
17. Miao, Z.T.; Han, M.; Hashemi, S. The effect of successive low-impact development rainwater systems on peak flow reduction in residential areas of Shizhuang, China. *Environ. Earth Sci.* **2019**, *78*, 51. [CrossRef]
18. Shao, W.; Zhang, H.; Liu, J.; Yang, G.; Chen, X. Data Integration and its Application in the Sponge City Construction of CHINA. *Procedia Eng.* **2016**, *154*, 779–786. [CrossRef]
19. Wu, J.; Yang, R.; Song, J. Effectiveness of low-impact development for urban inundation risk mitigation under different scenarios: A case study in Shenzhen, China. *Nat. Hazards Earth Syst. Sci.* **2018**, *18*, 2525–2536. [CrossRef]
20. Zimmer, C.A.; Heathcote, I.W.; Whiteley, H.R.; Schroter, H. Low-Impact-Development Practices for Stormwater: Implications for Urban Hydrology. *Can. Water Resour. J.* **2007**, *32*, 193–212. [CrossRef]
21. Zhao, G.; Pang, B.; Xu, Z.; Yue, J.; Tu, T. Mapping flood susceptibility in mountainous areas on a national scale in China. *Sci. Total Environ.* **2018**, *615*, 1133–1142. [CrossRef] [PubMed]
22. Wang, Z.; Lai, C.; Chen, X.; Yang, B.; Zhao, S.; Bai, X. Flood hazard risk assessment model based on random forest. *J. Hydrol.* **2015**, *527*, 1130–1141. [CrossRef]
23. Roy, S.; Bose, A.; Singha, N.; Basak, D.; Chowdhury, I.R. Urban waterlogging risk as an undervalued environmental challenge: An Integrated MCDA-GIS based modeling approach. *Environ. Chall.* **2021**, *4*, 100194. [CrossRef]
24. Dong, Y.; Ren, Z.; Fu, Y.; Miao, Z.; He, X. Recording Urban Land Dynamic and Its Effects during 2000–2019 at 15-m Resolution by Cloud Computing with Landsat Series. *Remote Sens.* **2020**, *12*, 2451. [CrossRef]
25. Lb, A.; Kw, A.; Idmt, B.; Omr, C.; Apvb, C.; Mgmc, D. Urban flood resilience–A multi-criteria index to integrate flood resilience into urban planning. *J. Hydrol.* **2019**, *573*, 970–982. [CrossRef]
26. Moghadas, M.; Asadzadeh, A.; Vafeidis, A.; Fekete, A.; Kötter, T. A multi-criteria approach for assessing urban flood resilience in Tehran, Iran. *Int. J. Disaster Risk Reduct.* **2019**, *35*, 101069. [CrossRef]
27. Saaty, T.L. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*; McGraw-Hill: Basel, Switzerland, 1980.

28. Qza, B.; Zwb, C.; Hui, Z.D.; Gdf, A.; Pt, A. Identifying dominant factors of waterlogging events in metropolitan coastal cities: The case study of Guangzhou, China. *J. Environ. Manag.* **2020**, *271*, 110951. [CrossRef]

29. Mahmoud, S.H.; Gan, T.Y. Urbanization and climate change implications in flood risk management: Developing an efficient decision support system for flood susceptibility mapping. *Sci. Total Environ.* **2018**, *636*, 152–167. [CrossRef]

30. Hoque, M.; Tasfia, S.; Ahmed, N.; Pradhan, B. Assessing Spatial Flood Vulnerability at Kalapara Upazila in Bangladesh Using an Analytic Hierarchy Process. *Sensors* **2019**, *19*, 1302. [CrossRef]

31. Tayyab, M.; Zhang, J.; Hussain, M.; Ullah, S.; Liu, X.; Khan, S.N.; Baig, M.A.; Hassan, W.; AlShaibah, B. GIS-Based Urban Flood Resilience Assessment Using Urban Flood Resilience Model: A Case Study of Peshawar City, Khyber Pakhtunkhwa, Pakistan. *Remote Sens.* **2021**, *13*, 1864. [CrossRef]

32. Sankar, S.A. A Study on Moyna Basin Water-Logged Areas (India) Using Remote Sensing and GIS Methods and Their Contemporary Economic Significance. *Geogr. J.* **2014**, *2014*, 401324. [CrossRef]

33. Hamidi, A.R.; Wang, J.; Guo, S.; Zeng, Z. Flood vulnerability assessment using MOVE framework: A case study of the northern part of district Peshawar, Pakistan. *Nat. Hazards J. Int. Soc. Prev. Mitig. Nat. Hazards* **2020**, *101*, 385–408. [CrossRef]

34. Peng, C.; Zhang, J.; Zhang, L.; Sun, Y. Evaluation of Resident Evacuations in Urban Rainstorm Waterlogging Disasters Based on Scenario Simulation: Daoli District (Harbin, China) as an Example. *Int. J. Environ. Res. Public Health* **2014**, *11*, 9964–9980. [CrossRef]

35. Roy, S.; Bose, A.; Chowdhury, I.R. Flood risk assessment using geospatial data and multi-criteria decision approach: A study from historically active flood-prone region of Himalayan foothill, India. *Arab. J. Geosci.* **2021**, *14*, 999. [CrossRef]

36. Omran; El-Sayed, E. Evolving waterlogged identification system to assess spatiotemporal impact of the new Suez Canal corridor, Egypt. *J. Coast. Conserv.* **2017**, *21*, 849–865. [CrossRef]

37. Sar, N.; Chatterjee, S.; Adhikari, M.D. Integrated remote sensing and GIS based spatial modelling through analytical hierarchy process (AHP) for water logging hazard, vulnerability and risk assessment in Keleghai river basin, India. *Modeling Earth Syst. Environ.* **2015**, *1*, 31. [CrossRef]

38. Saha, A.K.; Agrawal, S. Mapping and assessment of flood risk in Prayagraj district, India: A GIS and remote sensing study. *Nanotechnol. Environ. Eng.* **2020**, *5*, 11. [CrossRef]

39. Alam, R.; Quayyum, Z.; Moulds, S.; Radia, M.A.; Butler, A. Dhaka City Water logging Hazards: Area Identification and Vulnerability Assessment through GIS-Remote Sensing Techniques. *Res. Sq.* **2021**, *1*, 27. [CrossRef]

40. Tran, D.; Xu, D.; Dang, V.; Alwah, A. Predicting Urban Waterlogging Risks by Regression Models and Internet Open-Data Sources. *Water* **2020**, *12*, 879. [CrossRef]

41. Shah, A.A.; Ye, J.; Abid, M.; Khan, J.; Amir, S.M. Flood hazards: Household vulnerability and resilience in disaster-prone districts of Khyber Pakhtunkhwa province, Pakistan. *Nat. Hazards* **2018**, *93*, 147–165. [CrossRef]