Article

Spatiotemporal Urban Waterlogging Risk Assessment Incorporating Human and Vehicle Distribution

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Abstract: Due to the increase in frequency and severity, assessing and predicting urban waterlogging risk is critical. The risk assessment framework is based on three factors: hazard, exposure, and vulnerability. The assessment indicators, previously based solely on static indicators, account for the effects of varying temporal and spatial distributions of people and vehicles on the assessment results. Specifically, two dynamic indicators—the population density and the Traffic Performance Index (TPI)—are added to the mix to dynamically assess the risk of waterlogging in the central urban area of Suqian City of Jiangsu Province, China’s central urban area, over various periods. The findings indicate that four–six times more individuals are affected during peak hours than during other periods, and no important roads are within the scope of waterlogging during other periods, while nearly ten important roads will be affected during peak hours. Additionally, the characteristics of the temporal and spatial distribution of waterlogging risk can be more accurately represented by a combination of static and dynamic indicators. The highest risk areas are significantly more prominent during the weekday peak period than during other times; the morning peak is mainly affected by traffic performance indicators, the evening peak is mainly affected by population density, and the main factors affecting the other periods are the same as the other main factors affecting the peak period. The highest risk areas are mainly located in the eastern part of the central urban area of Suqian City, with the lowest risk in the north and south.

Keywords: waterlogging; risk assessment; dynamic assessment; GIS; spatial and temporal distribution

1. Introduction

Urban waterlogging refers to the city in the case of extreme rainfall or prolonged persistent rain due to the lack of municipal pipe network drainage capacity and leads to the city producing the phenomenon of water accumulation disaster [1]. With the acceleration of global warming and urbanization, urban waterlogging caused by extreme rainstorms has increased in frequency and intensity [2–4]. More than 170 people lost their lives in Krymsk, Russia in the June 2012 waterlogging disaster [5], and the city of Houston, USA suffered up to USD 2.7 billion in damages caused by the April 2016 waterlogging disaster [6]. Zhengzhou City in China caused 272 deaths due to waterlogging in July 2021, and the economic loss was CNY 120.6 billion [7]. Especially in cities with relatively concentrated populations and social resources [8], people’s lives and property safety are more vulnerable to the threat of waterlogging [9,10]. Therefore, it is essential to identify potentially affected areas and conduct scientific assessments to reduce waterlogging losses [11].

Currently, researchers have conducted extensive investigations on the assessment of urban waterlogging risks. These studies have used several methodologies, including historical catastrophe analysis using mathematical and statistical approaches, scenario simulation and modeling techniques, and index systems [12]. Hans de Moel [13] used...
historical, present, and future land use data of the Netherlands combined with maximum waterlogging inundation information to analyze urban flood risk under different models, and the study showed that the flood risk of the Netherlands will become more severe in the future and the flood losses will continue to increase exponentially. Boni [14] used a two-dimensional hydrodynamic model to simulate the flooding dynamics of Longyan city under different recurrence periods and various calendar times and assessed the flooding risk by calculating the spatial and temporal distribution of water and the disaster losses under multiple rainstorms. Sun [15] estimated the flooding risk index of 89 prefecture-level cities in eastern China by selecting six indicators, including the GDP. The study carried out a comprehensive analysis of the dangers of waterlogging risk and the exposure to flooding risk. Most current studies evaluate the risk according to hazard, exposure, and vulnerability [16]. However, the change in disaster-bearing bodies’ spatial and temporal distribution is seldom considered. With the acceleration of urbanization, the urban population’s rapid growth is accompanied by the development of transport demand. Transport infrastructure construction often needs to catch up with the speed of its order. Hence, the congestion problem during peak periods is particularly prominent, especially in the morning and evening peaks of weekdays and the peak periods of holidays [17]. In addition, as people and vehicles are more exposed during peak periods, the degree of exposure of disaster-bearing bodies is also a key influencing factor of waterlogging damage [18]. It has been demonstrated that, under the same intensity of rainfall conditions, the flow of people and vehicles outside during the morning and evening peak hours will be greater than at other times of the working day [19]. At the same time, relevant studies have shown that one of the keys to mitigating urban waterlogging disasters is effectively reducing the impact of waterlogging on road traffic [20,21]. Therefore, it is necessary to investigate the spatial and temporal distribution of people and vehicles during various periods.

In conclusion, this research uses an indicator system and model simulation to assess the waterlogging risk in the central urban area of Suqian City. The study also analyzes the temporal characteristics of the spatial distribution of people and vehicles, enabling a dynamic assessment of waterlogging risk. The aim is to improve the precision of waterlogging assessments, providing Suqian City with a basis for enhancing its ability to mitigate urban waterlogging and minimize associated damages.

The paper is organized as follows. Section 2 describes the selection of assessment indicators and the quantification method of dynamic indicators, the construction of hydrological and hydrodynamic models, the calculation method of weights, and the calculation of the Urban Waterlogging Risk Index (UWRI). Section 3 analyzes the results of the model simulation, analyzes the spatial and temporal distribution characteristics of the crowd and vehicles in the central urban area of Suqian City, superimposes the waterlogging results with the distribution of the people and vehicles to analyze the waterlogging risk of the crowd and vehicles in different periods, and finally makes a comprehensive assessment of the overall waterlogging risk in the central urban area of Suqian City.

2. Materials and Methods
2.1. Study Area and Data

The central urban area of Suqian City is the case area of our research project, and we have a relatively complete set of the required research data. At the same time, Suqian City is also one of the representative typical cities in China today. Therefore, the central urban area of Suqian City is chosen as the study area for this paper. Suqian is situated in the northern region of Jiangsu Province between longitudes 117°56′ E to 119°10′ E and latitudes 33°8′ N to 34°25′ N, which is a transitional area from a subtropical zone to a warm temperate zone. With elevations ranging from 23 to 76 m, the northern part of Suqian’s central urban area tends to be high in the center and low in the perimeter. In contrast to the remainder of the land, which often has altitudes below 23 m, the section bordered by two canals (shown in yellow) is significantly higher, with elevations between 25 and 40 m (see Figure 1).
Suqian City has proliferated in recent years, with an increase in both the population and the number of vehicles, and the central urban area’s coverage has increased. The center metropolitan area now spans 359.32 square kilometers as of 2021. As a result, the disparity in the spatial and temporal distribution of the two categories of disaster-bearing body, crowd, and vehicle has become a non-negligible factor in assessing the risk of waterlogging. According to historical waterlogging spot data, many risk roads are within the range of familiar congested roads during peak hours, further increasing the risk of waterlogging.

The data involved in this study mainly include Digital Elevation Model (DEM) data, land use data, drainage network data, historical waterlogging spots data, road network water network vector data, nighttime remote sensing satellite data, etc. Detailed specifications of the data sets are provided in Table 1.

2.2. Methodology

The research methodology of this paper is as follows: Firstly, the assessment indicator framework considering the dynamic characteristics of the disaster-bearing body is constructed from three perspectives: hazard, exposure, and vulnerability. Secondly, the data of the hazard indicators under different rainfall scenarios are obtained through hydrological simulation. Lastly, the weights of the indicators are obtained through Spatial Principal Component Analysis (SPCA), and the Urban Waterlogging Risk Index (UWRI) is computed, which leads to the realization of the waterlogging risk mapping in the study area. Figure 2 summarizes the technical route and methods of this study.
**Table 1.** Summary of data sources employed in the study.

<table>
<thead>
<tr>
<th>Data</th>
<th>Sources</th>
<th>Time</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEM</td>
<td>Geospatial Data Cloud [<a href="http://www.gscloud.cn/">http://www.gscloud.cn/</a>, accessed on 1 January 2023]</td>
<td>2023</td>
<td>30 m</td>
</tr>
<tr>
<td>Land use</td>
<td>Sourced from Esri, interpreted from Sentinel-2 satellite remote sensing images</td>
<td>2020</td>
<td>10 m</td>
</tr>
<tr>
<td>Road network</td>
<td>Sourced from the “Six Lines Control Special Plan for the Central Urban Area of Suqian City (2016–2030)”</td>
<td>2016</td>
<td>–</td>
</tr>
<tr>
<td>Population data</td>
<td>Baidu’s heat map</td>
<td>2023</td>
<td>200 m</td>
</tr>
<tr>
<td>Transportation data</td>
<td>Amap of Road Condition</td>
<td>2023</td>
<td>1000 m</td>
</tr>
<tr>
<td>Vegetation cover</td>
<td>Resource and Environment Science and Data Center [<a href="https://www.resdc.cn">https://www.resdc.cn</a>] (accessed on June 2020)</td>
<td>2020</td>
<td>100 m</td>
</tr>
<tr>
<td>landsat8 remote sensing</td>
<td>Geospatial Data Cloud [<a href="http://www.gscloud.cn/">http://www.gscloud.cn/</a>] (accessed on 4 July 2020)</td>
<td>2020</td>
<td>30 m</td>
</tr>
<tr>
<td>Water System</td>
<td>Provided by the Suqian municipal government, based on current land use data</td>
<td>2020</td>
<td>–</td>
</tr>
<tr>
<td>Drainage Network</td>
<td>Provided by the Suqian municipal government</td>
<td>2020</td>
<td>–</td>
</tr>
<tr>
<td>historical waterlogging spots</td>
<td>Derived from the “Drainage Special Plan for the Central Urban Area of Suqian City (2021–2035)” (Draft for comments)</td>
<td>2016–2018</td>
<td>–</td>
</tr>
</tbody>
</table>
2.2.1. Construction of The Assessment Indicator System

Waterlogging risk assessment is a comprehensive assessment of the natural and social attributes of waterlogging [22,23]. The waterlogging risk assessment framework usually contains three aspects: “Hazard”, “Exposure”, and “Vulnerability” [24–26]. Selecting appropriate indicators is the first step of waterlogging risk assessment. Based on the available literature and research data, ten indicators are chosen for this study to evaluate the urban waterlogging risk [27,28]. Among them, the depth and time of water accumulation are the results of a calculation based on the model’s comprehensive drainage pipe network capacity. They are the intuitive embodiment of urban waterlogging risk. The adverse effects of urban waterlogging on people and vehicles can be assessed by considering the depth and duration and the water flow velocity resulting from waterlogging [29]. Therefore, this study selects three indicators to reflect the hazard of waterlogging: waterlogging depth, duration, and water flow velocity. Exposure analysis is conducted using six indicators: distance from water bodies, vegetation cover, road network density, building density, population density, and Traffic Performance Index (TPI), and vulnerability analysis is conducted using one indicator, GDP. Population density and the traffic performance index are dynamic indicators; the remaining eight are static. Some of the indicators are described as shown in Figure 3.

Distance from Water Bodies

When the intensity of rainfall increases or the duration of rainfall is long, the rainfall exceeds the storage capacity of the water system, and the river becomes a new source of disaster. A significant positive correlation exists between the distance from water bodies and the degree of waterlogging [30,31]. The distance from water bodies is calculated by measuring the Euclidean distance from the center of each grid to the initial point. The risk is reduced in the southern portion of Suqian City’s center urban area since it is distant from the water system.
Figure 3. Distance from water bodies (a), NDVI (b), road network density (c), NDBI (d), nighttime light intensity (e).

Vegetation Cover (Normalized Difference Vegetation Index (NDVI))

Vegetation cover is the percentage of the vertical projected area of vegetation in the unit area. Vegetation can effectively trap rainfall and reduce stormwater runoff, reducing the
risk of waterlogging. The study uses NDVI to indicate the degree of vegetation cover [32]. The northern part of the central urban area of Suqian City has a higher vegetative cover, therefore it is less exposed.

Road Network Density

When urban waterlogging occurs, heavy rainfall causes large areas of road surface to be submerged, paralyzing traffic, and the more complex the road network, the higher the risk of waterlogging. Road network density is expressed as the total length of the road network per unit area.

Building Density (Normalized Difference Built-Up Index (NDBI))

Residential buildings are the main disaster-bearing body of storm waterlogging, and the greater the building density, the greater the exposure, and the greater the economic losses caused. The study used NDBI to represent building density [33].

GDP (Nighttime Light Intensity)

The higher the GDP of the region, the more serious the economic loss caused by waterlogging. Since refined GDP data are challenging to obtain, this study uses nighttime light intensity for representation, and the higher the intensity of nighttime light, the higher the level of GDP in the region [34,35]. The nighttime light intensity in the central urban area of Suqian City is higher, which means the vulnerability is higher.

The results indicate that there is generally a higher concentration of individuals and vehicles during weekdays than on weekends or days off. Specifically, between 20:00 and 7:00, residential areas tend to attract many people. Conversely, between 9:00 and 17:00, various workplaces serve as the primary gathering locations for people [36]. In addition, the morning and evening peak hours will have a higher crowd, vehicle aggregation, and exposure than these two periods. As previously stated, there is an increased likelihood of increased exposure to people and vehicles in the event of waterlogging during peak hours. Therefore, it would be more meaningful to study the spatial and temporal distribution characteristics of crowd and vehicle peak hours and use the results for waterlogging risk assessment. In this study, based on the use of static indicators, two dynamic indicators, namely population density (crowd) and traffic index (vehicle), are selected to capture the heat map and road condition maps of downtown Suqian for the three periods of evening peak 17:00–19:00 on 13 March 2023, morning peak 7:00–9:00, and 12:00–13:00 at noon (control group) on 19 April 2023, to provide a case study of the heat map and road condition maps of the crowd and vehicle. A case study is conducted to incorporate people’s and vehicles’ spatial and temporal distribution characteristics in the waterlogging risk assessment. The quantification methods of the two dynamic indicators are as follows.

Population Density

The severity of urban waterlogging is closely related to population density. The greater the population density, the greater the number of people affected by waterlogging directly from the disaster [37]. Heat maps use the acquired mobile phone base station to locate the number of users in the area and render the map color by the number of users. The color of the heat map is determined by the number of people, indicating the level of population density in a certain area. Census data are utilized to record and analyze projections regarding the growth and distribution of the current population across different locations. To establish a quantitative relationship between the two, this paper uses population density in different periods to reflect the dynamic characteristics of the waterlogging indicator based on the real-time heat map of population aggregation. It uses China’s Seventh Population Census 2020 data to expand the vectorized grid population to quantify population density. The specific process is as follows [38,39]:
(1) In GIS, the heat map layer is reclassified according to the corresponding relationship between heat map color and population density, and the thermal value of each level is extracted.

(2) The heat map grid image is vectorized into point elements and the population data are extrapolated by using the RGB values of the heat map color and the population density legend provided by Baidu (Figure 4).

(3) The xy coordinates of each pixel point are extracted and the study area is divided into a grid of 200 m × 200 m, the pixel point population data are counted into the grid, and the vectorized grid population sample is expanded using the data of the seventh census.

(4) Based on the Population Density \((P_d)\) formula (unit: person/hm\(^2\)), the final population density data is calculated.

\[
P_d = \frac{POP}{S}
\]

In the formula, \(POP\) is the total population in the region (person); \(S\) is the region’s total area (hm\(^2\)).

Figure 4. Relationship between color map and population density.

Traffic Performance Index (TPI)

Compared with other periods, the peak period shows a greater volume of traffic exposure, resulting in a proportionally higher concentration of crowded road sections and a correspondingly increased congestion level. Therefore, when a rainfall event occurs, if waterlogging occurs in the packed road section, it may cause more severe impacts and losses [40]. The Traffic Performance Index (TPI) is introduced to assess the road network’s risk level. TPI is an indicator that comprehensively reflects the clear or congested road network. By superimposing historical waterlogging spots, the crowded sections with the risk of waterlogging can be found, and these roads are designated as “important roads”. The range of TPI values and the corresponding congestion degree are shown in Table 2.
In this study, we reclassify the road condition map layers by capturing the real-time traffic condition maps of three periods and reclassifying the traffic condition map layers based on the correspondence between the map color and the congestion in GIS. Amap (13.01.1.2043) is a Chinese software that provides digital maps, navigation, and location services with real-time traffic and road conditions. According to the classification of the color and congestion given by the Amap, green indicates smooth traffic, yellow indicates slow traffic, red indicates congestion, and deep red indicates severe congestion. According to the definition of the TPI and the location of the historical waterlogging spots, the exposure size is assigned 0 to 10. This paper gives the values of smooth traffic, slow, congested, and severe congestion as 0, 2, 4, and 6, respectively. For the severely congested roads on the historical waterlogging spots, the value is set at 8. For other routes on the historical waterlogging point, the TPI is increased by one level from the original (see Figure 5). The higher its value, the higher the exposure. Finally, based on the results of the waterlogging simulation, constructed buffer centers are delineated for the congested road.

![Waterlogging spots](image)

**Figure 5.** Correspondence between TPI and congestion level.

### Table 2. TPI value and congestion degree corresponding table.

<table>
<thead>
<tr>
<th>Value Range</th>
<th>0–2</th>
<th>2–4</th>
<th>4–6</th>
<th>6–8</th>
<th>8–10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congestion degree</td>
<td>clear</td>
<td>unblocked</td>
<td>minor congestion</td>
<td>moderate congestion</td>
<td>severe congestion</td>
</tr>
</tbody>
</table>

2.2.2. Waterlogging Scenario Simulation

MIKE 21 is the most versatile simulation tool for physical, chemical, or biological processes in two-dimensional waters [41]. It is often used to simulate the diffuse flow process of rainwater in different topographic conditions, such as roads, neighborhoods, green areas, and rivers under specific rainfall scenarios, to provide a basis for the assessment of waterlogging risk, since the results of its simulation are the actual inundation situation in the study area [42]. In this study, MIKE 21 is used to construct a two-dimensional ground model to dynamically simulate rainfall scenarios in the central urban area of Suqian City to simulate rainfall runoff and waterlogging conditions. The three indicators of waterlogging depth, waterlogging duration, and water flow velocity obtained are used to analyze the causative factors in the waterlogging disaster and to assess the risk of waterlogging.
This simulation is based on the original elevation data. The building is raised by 10 m, the road is reduced by 0.15 m, and the river is reduced by 2 m to make the basic terrain more realistic [43]. The initial water depth is determined as the lowest elevation of the landscape according to the actual terrain situation, and the ground roughness is comprehensively determined according to the model recommendations and the ground confluence roughness parameters.

(1) Rainstorm intensity formula

Using the storm intensity formulas provided in the “Study on Design Storm Patterns for Suqian Central City” and the “Report on Preparation of Storm Intensity Formulas for Suqian City”, different rainfall return periods are set to calculate the storm intensity under a short calendar time. The formula for the rainstorm intensity in the central urban area of Suqian City for a short duration is \( p = 2–50 \text{ a}, \ t = 5–180 \text{ min} \):

\[
i = \frac{61.2(1 + 1.05\lg T)}{(t + 39.4)^{0.996}}
\]

where \( i \) is the rainfall intensity (mm/min), \( t \) is the rainfall duration (min), and \( P \) is the rainfall return period (a). Based on Equation (1), the rainfall intensity in the central urban area of Suqian City is calculated under different rainfall recurrence periods.

(2) Suqian City storm rainfall pattern

According to the “Study on Design Rainstorm Pattern of Suqian Central City” issued by the Suqian Municipal Water Conservancy Bureau, the short-duration rain pattern is determined by the Chicago method (K&C). The K&C rain pattern is based on the rainstorm intensity formula to design a typical rainfall. The rainfall process is divided into two parts, pre-peak and post-peak, and the peak position coefficients of the statistical rainfall samples are substituted. The K&C rainfall pattern corresponding to a specific return period and rainfall duration is finally determined. The design recurrence period of the urban drainage network in the Suqian city center is less than once in 20 years. Therefore, the simulation selected a short duration of 180 min once in 20 years beyond the pipeline design recurrence period for scenario simulation.

(3) Simulation time

The step length is 5 min, and the number of steps is 36. For other parameters, please refer to the Mike21 user manual [44].

2.2.3. Modeling of Urban Waterlogging Risk Assessment

(1) The weight of indicators

The indicators’ weights correspond to the relative importance of each indicator within the system, and any possible relationships among the chosen indicators will result in redundant data and make analysis more challenging [9]. Principal Component Analysis (PCA) can prevent the overlapping and coverage of information caused by the correlation between indicators, reduce the calculation time, and improve the calculation efficiency. At the same time, it ensures the relative integrity of data information and improves the accuracy of evaluation [45]. Among them, Spatial Principal Component Analysis (SPCA) is a weight calculation tool that compresses the report from multiple raster maps into several representative composite variables, inputs the standardized raster data of each index into the “principal component analysis” module to calculate the eigenvalues, and, finally, calculates the weight of each index [46]. The step length is 5 min, and the number of steps is 36. For other parameters, please refer to the Mike21 user manual [44].

(2) Urban Waterlogging Risk Index (UWRI)
The UWRI is positively correlated with “Hazard”, “Exposure”, and “Vulnerability”. The formula for calculating the UWRI is as follows [35]:

\[ UWRI = H + E + V \] (3)

In the formula, \( H / E / V = \sum_{i=1}^{n} x_{i} \frac{w_{hi}}{w_{ei} / v_{wi}} \). \( H, E, \) and \( V \) correspond to hazard, exposure, and vulnerability. \( n \) is the total number of indicators, and \( i \) is the \( i \)th indicator, where \( W_{hi}, W_{ei}, \) and \( W_{vi} \) are the weights of the factors obtained from the spatial principal component analysis, and \( X_{hi}, X_{ei} \) and \( X_{vi} \) are the values of the indicators corresponding to \( H, E, \) and \( V, \) respectively.

3. Results
3.1. Hydrologic Simulation Results and Analysis

The model outputs (Figure 6) show the study area’s 20 year return periods and 3 h durations (20 at 3 h) waterlogging depth and duration. Table 3 gives the extent of inundation for different water depth classes. According to the “Outdoor Drainage Design Code” [47], “Technical Code for Prevention and Control of Urban Waterlogging” (GB51222-2017), and other relevant design specifications from the literature studies, depths of less than 15 cm are generally regarded as waterlogging depths that do not cause traffic or other impacts. The waterlogging depths (h) obtained under the design storm conditions are graded and are shown in Table 4. In the pre-peak period, the waterlogging depths all show an increasing trend; after the peak, the waterlogging depths in areas with solid drainage capacity of the pipeline network show a slow decreasing trend; and in areas without pipeline network and in low-lying areas, the waterlogging depths still increase with the increase in the rainfall duration.

### Table 3. The area is inundated by rainfall.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Inundated Area (km(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~0.14</td>
<td>268.39</td>
</tr>
<tr>
<td>0.15~0.3</td>
<td>22.41</td>
</tr>
<tr>
<td>0.31~0.44</td>
<td>11.32</td>
</tr>
<tr>
<td>0.45~0.6</td>
<td>5.23</td>
</tr>
<tr>
<td>&gt;0.6</td>
<td>5.75</td>
</tr>
<tr>
<td>Total</td>
<td>313.10</td>
</tr>
</tbody>
</table>

### Table 4. Criteria for waterlogging risk classification.

<table>
<thead>
<tr>
<th>Grade of Waterlogging</th>
<th>Classification Criteria (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-waterlogging</td>
<td>( h &lt; 0.15 )</td>
</tr>
<tr>
<td>Mild waterlogging</td>
<td>( 0.15 \leq h \leq 0.3 )</td>
</tr>
<tr>
<td>Moderate waterlogging</td>
<td>( 0.3 &lt; h &lt; 0.45 )</td>
</tr>
<tr>
<td>Severe waterlogging</td>
<td>( 0.45 \leq h \leq 0.6 )</td>
</tr>
<tr>
<td>Worst Waterlogging</td>
<td>( 0.6 &lt; h )</td>
</tr>
</tbody>
</table>

The simulation results show that the waterlogging depth is below 0.15 m in most areas, 0.15~0.45 m in a few areas, and above 0.45 m in fewer areas. The areas with mild waterlogging are in the lower terrain, such as rivers and urban roads. In contrast, the areas with moderate and higher waterlogging are mainly concentrated in the eastern and southern regions of the study area, which are low-lying and have insufficient drainage facilities. The waterlogging duration is less than 30 min in most areas and more than 90 min in a few areas, mainly due to the inadequate capacity of the drainage pipe network and the insufficient drainage facilities in the fringe areas of the central city; fewer areas are concentrated between 30 and 90 min.
3.2. Characteristics of Spatial and Temporal Distribution of People and Vehicles

3.2.1. People

In this study, the population density data obtained through GIS processing are categorized into five classes according to the size of the image element value using Jenks. The color warm and cold reflects the crowd gathering high and low [36] to obtain the central urban area of Suqian City’s morning and evening peak and noon period of the spatial distribution characteristics of the crowd, as shown in Figure 7.
During the morning peak hour, the total area of the area with a population density of more than 1000 person/hm² is 28.26 hm², and the maximum population density is 1426 person/hm²; during the noon hour, the total area of the area with a population density of more than 1000 person/hm² is 4.32 hm², and the maximum population density is 1072 person/hm². During the evening peak hour, the area with a population density of more than 1000 persons/hm² has a total area of 3115.89 hm², with a maximum population density of 3805 persons/hm².

A comparison of the spatial distribution map of the population during the morning and evening peaks and the noon hours shows that the high aggregation areas occur in schools, stations, and recreational areas. Among them, the high aggregation area in the evening peak accounts for 8.67% of the total area of the study area. In comparison, the high aggregation area in the morning peak and noon hours accounts for less than 0.1% of the total area of the study area.

3.2.2. Vehicles

This study uses the traffic road condition map to reflect vehicles’ spatial and temporal distribution characteristics. The captured Amap of road condition data of three weekday periods are processed by GIS and then superimposed on the historical waterlogging spots.
The TPI results are shown in Figure 8. Only localized areas are shown in the figure, and the TPI of the non-displayed sites are all zero.

Figure 8. Cont.
3.3. Waterlogging Risk Assessment

3.3.1. Impact of Waterlogging on People and Vehicles at Different Times of Day

The 3 h waterlogging simulation is superimposed on the results of the spatial and temporal distribution of people and vehicles to explore the impact of waterlogging on people and vehicles at different times, as shown in Table 5. The results show that waterlogging occurs at other times of the day, and the number of people and roads affected will vary. The number of people affected by waterlogging in the morning and evening peaks is 5.6 and 4.6 times higher than in the noon hours. Within the risk of waterlogging, no important roads are affected during the noon hours, while nearly ten important roads are affected during the peak hours. If waterlogging occurs during peak hours, the risk to crowds and vehicles will be much greater than during noon hours. Therefore, studying the spatial and temporal distribution of waterlogging risk is essential as it can vary significantly from one time of day to another. Particular attention needs to be paid to assessing waterlogging risk during peak hours when the number of people and vehicles exposed is more significant and the risk is higher than at other times.

3.3.2. Distribution of Waterlogging Risk

The waterlogging depth, waterlogging duration, waterflow velocity, population density, and TPI in the indicator system are numerically calculated, and the spatial distribution of the five indicators is shown in Figure 9. It is presented as a raster map in the GIS with a 30 m × 30 m scale.

As can be seen from the figure, severe congestion during peak hours mainly occurs in Yingbin Avenue, Xihu Road, Development Avenue, Yellow River Road (the four roads through the superposition of the historical waterlogging spots), Development Avenue, and Xihu Road intersection in the waterlogging spots, and in the range of severe congestion. Hence, the risk of this place is higher, and we need to pay attention to it. Comparing the peak period to noon, the congested road section at noon is 0, and there is only one slow road. In contrast, the packed road section in the morning and evening peaks has 21 and 32, respectively; the risk of exposure is more significant and more attention needs to be paid to it. Based on the range of roads covered by waterlogging, as shown in the literature collection and simulation results, the road buffer zone is set to 300 m [48,49].

Figure 8. Road congestion: morning peak (a), noon (b), evening peak (c).
Table 5. Impact of waterlogging on people and vehicles at different times of day.

<table>
<thead>
<tr>
<th>Period</th>
<th>Number of People Affected (in 10,000)</th>
<th>Number of Roads Affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning peak</td>
<td>22.27</td>
<td>9</td>
</tr>
<tr>
<td>Noon</td>
<td>3.95</td>
<td>0</td>
</tr>
<tr>
<td>Evening peak</td>
<td>18.06</td>
<td>8</td>
</tr>
</tbody>
</table>

3.3.2. Distribution of Waterlogging Risk

The waterlogging depth, waterlogging duration, water flow velocity, population density, and TPI in the indicator system are numerically calculated, and the spatial distribution of the five indicators is shown in Figure 9. It is presented as a raster map in the GIS with a 30 m × 30 m scale.

SPCA is used to calculate the weights of the ten indicators, and the results are shown in Table 6. The weighting results from all three periods show that waterlogging duration, distance from the water system, vegetation cover, and building density have a relatively significant impact on waterlogging and cannot be ignored. Since the evening peak has the most important flow of people, the population density substantially affects the evening peak. In contrast, the traffic index of the morning peak has a more significant impact on it. In addition, waterlogging depth and flow velocity in the hazard indicators have a lesser effect on waterlogging.

Table 6. Weight of indicators.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Morning Peak</th>
<th>Noon</th>
<th>Evening Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterlogging depth</td>
<td>0.0420</td>
<td>0.0462</td>
<td>0.0389</td>
</tr>
<tr>
<td>Waterlogging duration</td>
<td>0.1721</td>
<td>0.1853</td>
<td>0.1648</td>
</tr>
<tr>
<td>Water flow velocity</td>
<td>0.0095</td>
<td>0.0106</td>
<td>0.0091</td>
</tr>
<tr>
<td>Distance from water bodies</td>
<td>0.1228</td>
<td>0.1332</td>
<td>0.1170</td>
</tr>
<tr>
<td>Vegetation cover (NDVI)</td>
<td>0.1858</td>
<td>0.2260</td>
<td>0.1788</td>
</tr>
<tr>
<td>Road network density</td>
<td>0.0467</td>
<td>0.0840</td>
<td>0.0798</td>
</tr>
<tr>
<td>Building density (NDBI)</td>
<td>0.1751</td>
<td>0.2158</td>
<td>0.1715</td>
</tr>
<tr>
<td>Population density</td>
<td>0.0559</td>
<td>0.0287</td>
<td>0.1698</td>
</tr>
<tr>
<td>TPI</td>
<td>0.1471</td>
<td>0.0330</td>
<td>0.0471</td>
</tr>
<tr>
<td>GDP (nighttime light intensity)</td>
<td>0.0430</td>
<td>0.0372</td>
<td>0.0232</td>
</tr>
</tbody>
</table>

According to the results of the model calculations, the risk level of the morning peak waterlogging risk map is divided using Jenks [35], and the risk of waterlogging in the remaining two periods is divided by the same level to form the central urban area of the Suqian City waterlogging risk map, as shown in Figure 10. The peak-hour risk map shows that the highest risk areas are all in the central east region of the major city; the south and north are the lowest risk areas. Combining Figure 9 with the risk map of peak hours, it is clear that the morning peak’s highest danger area is more impacted by traffic congestion. In contrast, the evening peak’s highest risk area is more affected by the distribution of crowds. The location of different peak areas in each period is shown in Table 7. The morning, noon, and evening peak highest risk areas account for 9.59%, 6.25%, and 12.48% of the total area, respectively.
Figure 9. Cont.
Figure 9. Waterlogging depth (a), waterlogging duration (b), water flow velocity (c), population density (d–f), TPI (g–i). Morning peak (d,g), noon (e,h), evening peak (f,i).

Table 7. The distribution area of different waterlogging risk levels in different periods.

<table>
<thead>
<tr>
<th>Grade of Risk</th>
<th>Morning Peak (km²)</th>
<th>Noon (km²)</th>
<th>Evening Peak (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The lowest risk</td>
<td>40.94</td>
<td>37.16</td>
<td>38.20</td>
</tr>
<tr>
<td>The lower risk</td>
<td>84.64</td>
<td>81.48</td>
<td>82.84</td>
</tr>
<tr>
<td>The medium risk</td>
<td>132.22</td>
<td>143.84</td>
<td>127.70</td>
</tr>
<tr>
<td>The higher risk</td>
<td>67.06</td>
<td>74.38</td>
<td>65.72</td>
</tr>
<tr>
<td>The highest risk</td>
<td>34.46</td>
<td>22.46</td>
<td>44.86</td>
</tr>
</tbody>
</table>
According to the results of the model calculations, the risk level of the morning peak waterlogging risk map is divided using Jenks [35], and the risk of waterlogging in the remaining two periods is divided by the same level to form the central urban area of Suqian City waterlogging risk map, as shown in Figure 10. The peak-hour risk map shows that the highest risk areas are all in the central east region of the major city; the south and north are the lowest risk areas. Combining Figure 9 with the risk map of peak hours, it is clear that the morning peak's highest danger area is more impacted by traffic congestion. In contrast, the evening peak's highest risk area is more affected by the distribution of crowds. The location of different risk areas in each period is shown in Table 7. The morning, noon, and evening peak highest risk areas account for 9.59%, 6.25%, and 12.48% of the total area, respectively.

4. Discussion

Since the historical waterlogging sites used in the study did not specify the rainfall conditions and severity of each waterlogging event, the rainfall intensity and duration corresponding to the circumstances could not be determined, which may introduce some uncertainty in the conclusions. In subsequent studies, comprehensive data on historical waterlogging events will be obtained as soon as possible for a more accurate urban waterlogging assessment. In addition, waterlogging depth and water flow velocity have little impact on the risk of waterlogging, as the central urban area of Suqian City has little...
elevation change; the duration of waterlogging is the factor to be concerned about. Whether this conclusion applies to all cities with little elevation change needs to be explored further.

The TPI, a dynamic indicator chosen in this study, has not been used in previous studies related to waterlogging risk assessment. Population density are static data used in other risk assessments. In contrast, this study uses population density at different times of the day, which is variable [50–54]. In addition, dynamic indicators can effectively assess the risk of waterlogging in different periods. The combination of static and dynamic indicators can better reflect the spatial and temporal distribution characteristics of waterlogging risk and improve the reliability of the assessment results. The results of the spatial and temporal distribution of crowd vehicles show that the evening peak is the time of day with the highest concentration of population and the most congested period sections. This may be related to the fact that it is the peak time to leave work, or it may be associated with the recreational activities that the crowd is engaged in. At the same time, this characteristic also applies to most cities in China, where the degree of crowd and vehicle outdoor gathering during weekday peak hours is much higher than at other times.

In this study, combining the waterlogging results from hydrological modeling with the dynamic distribution of people and vehicles when storms occur, if the emergency department can find the risk points quickly and pedestrians and drivers can avoid the risky roads, this can significantly reduce the damage caused by waterlogging. In the follow-up study, the verification of the waterlogging results simulated by the model and the spatiotemporal distribution results of the population and vehicles will be increased to improve the reliability of the evaluation results. At the same time, it will also conduct corresponding research and suggestions on disaster prevention and mitigation facilities near risk points.

The results of the risk map show that the northern and southern parts of the central urban area of Suqian City are at the lowest risk. The main reason for the low risk is fewer people, vehicles, and buildings nearby. The northern part of the area is densely vegetated, while the southern part is farther away from the water system. Natural conditions and social factors mainly determine the risk of waterlogging in the central urban area of Suqian City. There are significant differences in the risk maps at different times of the day, so it is recommended that the factor of other times of the day be taken into account during the production of waterlogging risk maps by cities in the future.

5. Conclusions

This study addresses the shortcomings of previous studies that only used static data. Taking the central urban area of Suqian as an example, a risk assessment method considering dynamic indicators is proposed. The research results indicate that:

1. Of the three hazard indicators included in the study, the waterlogging duration significantly impacts the waterlogging risk in the center of Suqian City.
2. The degree of congregation of crowds and vehicles varies by time of day. For the central urban area of Suqian City, the evening peak crowd gathering area is much larger than the morning peak and midday; at the same time, compared with the peak and other periods, the difference in traffic congestion is more prominent, there is no congestion at other periods, while there are more congested sections in the peak hour.
3. The impact of waterlogging on people and vehicles varies significantly by time of day, with waterlogging occurring during peak hours having a much more significant impact on people and vehicles than during other periods. Therefore, studying the spatial and temporal distribution of waterlogging risk is essential, especially during peak hours.
4. From the risk assessment results of the three periods, the four indicators of waterlogging duration, distance from water bodies, vegetation cover, and building density all have relatively significant impacts on waterlogging, which should not be ignored. In addition, the risk at other times of the day shows different distribution characteristics; the distribution of the highest risk areas in the morning peak is mainly related to the
TPI, and the distribution of the highest risk areas in the evening peak is primarily associated with the population density. There are fewer highest risk areas in the other periods. Therefore, the morning peak needs to focus on vehicle congestion, and the evening peak needs to focus on the spatial distribution of the crowd. The highest risk areas are all in the east of the center of the central city, while the north and south regions have the lowest risk. The peak period other than the time slots’ highest risk area is much larger; therefore, attention should be paid to the assessment of the risk of waterlogging at different times, especially during the peak period, and attention should be paid to the study of the spatial and temporal distribution of the disaster-bearing body, which can help to determine the approximate location of the most waterlogged areas through the time of occurrence of the waterlogging and the targeted rescue efforts. Finally, it is recommended to emphasize the dynamic influencing factors in the risk assessment in the future, supposing that the public can avoid risky roads in advance when waterlogging occurs, and the government and relevant emergency departments can sort out the congested roads with waterlogging spots. In that case, it will help the rescue operation and reduce the waterlogging loss.

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