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Geographic-Information-System-Based Risk Assessment of Flooding in Changchun Urban Rail Transit System

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Abstract: The frequent occurrence of urban flooding in recent years has resulted in significant damage to ground-level infrastructure and poses a substantial threat to the metro system. As the central city's core transportation network for public transit, this threat can have unpredictable consequences on travel convenience and public safety. Therefore, assessing the risk of urban flooding in the metro system is of utmost importance. This study is the first of its kind to employ comprehensive natural disaster risk assessment theory, establishing an assessment database with 22 indicators. We propose a GIS-based method combined with the analytical hierarchy process (AHP) and an improved entropy weight method to comprehensively evaluate the urban flood risk in Changchun City's metro systems in China. This study includes a total of nine metro lines, including those that are currently operational as well as those that are in the planning and construction phases, situated in six urban areas of Changchun City. In this study, we utilize the regional risk level within the 500 m buffer zone of the metro lines to represent the flood risk of the metro system. The proposed method assesses the flood risk of Changchun's rail transit system. The results reveal that over 30% of Changchun's metro lines are located in high-risk flood areas, mainly concentrated in the densely populated and economically prosperous western part of the central city. To validate the risk assessment, we vectorized the inundation points and overlaid them with the regional flood risk assessment results, achieving a model accuracy of over 90%. As no large-scale flood events have occurred in the Changchun rail transit system, we employed receiver operating characteristic (ROC) curves to verify the accuracy of the flood risk assessment model, resulting in an accuracy rate of 91%. These findings indicate that the present study is highly reliable and can provide decision makers with a scientific basis for mitigating future flood disasters.

Keywords: flood risk assessment; metro system; analytical hierarchy process (AHP); improved entropy weight method; Changchun; China

Citation: Liu, G.; Zhang, Y.; Zhang, J.; Lang, Q.; Chen, Y.; Wan, Z.; Liu, H. Geographic-Information-System-Based Risk Assessment of Flooding in Changchun Urban Rail Transit System. *Remote Sens.* **2023**, *15*, 3533. https://doi.org/10.3390/rs15143533

Academic Editors: Mirko Francioni, Stefano Morelli and Veronica Pazzi

Received: 24 May 2023
Revised: 6 July 2023
Accepted: 10 July 2023
Published: 13 July 2023

1. Introduction

With the continuous development of urbanization, subway transportation is becoming more and more popular as a fast and convenient transportation mode [1,2]. Nevertheless, abrupt natural disasters pose a threat to the subway system's safe operation [3]. Although large-scale flooding disasters in the subway are not common, their consequences are very serious once they occur [2,3]. Flooding is one of the more common urban natural disasters [4]. With increasing urbanization and population expansion, a large number of physical infrastructures and buildings inside the city block the infiltration of rainwater, resulting in an overflow of water that cannot be quickly removed, and can easily cause urban flooding [5]. Such flooding often overflows subway stations, causing a great threat to people's travel, property, and life [6].

Against the backdrop of frequent extreme weather, urban flooding is occurring globally and leading to the emergence of metro flooding, and the safety of the subway has been greatly challenged [7]. New York, a modern metropolis in the United States, was affected by Hurricane Sandy back in 2012, causing the entire metro system in New York to be crippled by flooding, with seven metro lines submerged. And in recent years, on 1 September 2021, cities were hit by Hurricane Ida, a 500-year rainstorm, resulting in flooding over the metro platforms and trains and causing traffic disruption. At the end of June of the same year, the Russian capital, Moscow, was flooded by heavy rains, and the stairs in the metro station turned into a waterfall. In terms of foreign countries' metro systems, their facilities are already very old, and many of them are tens or even hundreds of years old, which leads them to face a very high risk of metro flooding. In contrast, China's domestic subway system is not plagued by the "age-related" problems of foreign subways, but that does not mean it is safe in the face of extreme rainstorm events. Serious urban flooding triggered by an extreme rainstorm in Zhengzhou on 20 July 2021 caused severe waterlogging in Metro Line 5, resulting in 14 people being killed; this is historically known as the 7/20 incident [8]. Due to the unpredictable and uncontrollable nature of flooding [9], the safety assessment and risk control of subways are particularly important [10], but many issues and challenges remain in this area. In addition, urban floods can also have significant socio-economic and environmental impacts [8,11], so there is a need to better understand the potential risks and take effective measures to reduce losses and improve coping capabilities [11,12].

However, previous studies have mainly focused on regional flood risk assessments and are dominated by foreign studies. Foreign scholars have developed a series of urban rainfall models, such as SWMM, STORM, etc., to examine and predict the risk of regional flood events. For example, R.A. Sharifan (2010) used the SWMM model to simulate the rainfall runoff process for Shiraz, a historical city in Iran, to reduce the possibility of disaster occurrence [13]. Deepak Singh Bisht (2016) used the SWMM and MIKE URBAN models to design an efficient storm water drainage system to avoid the trouble of frequent flooding during rainy seasons [14]. Multi-criteria decision-making methods or machine learning can be used to assess the risk of flooding for the entire region. For example, Ekmekcioğlu et al. (2021) used the fuzzy AHP method for flood risk assessment in Istanbul, Turkey [15]. Eini et al. (2020) used two machine learning models, maximum entropy (MaxEnt) and genetic algorithm rule integration (GARP), to generate a flood hazard map for the city of Kermanshah [16]. Compared with foreign scholars in China, the research and development of storm water flooding models are late, and the developed models are not adaptable to the complex environment of large cities, so most scholars choose to use foreign models directly for risk assessment, such as the simulation performed by Fu et al. (2019) of a large-scale urban Yu flooding process in the Beijing Economic Development Zone in Yizhuang, the core area of China, to propose effective measures [17]. In addition to the use of storm water models, Chinese scholars have been slowly improving their research on regional flood risk in recent years, using various assessment methods or deep learning to study regional flood risk in detail; e.g., Wu et al. (2015) used flood risk assessment and risk level zoning to prevent flooding in watersheds and develop disaster mitigation plans [18]. Iran. Luu et al. (2019) used the multiple linear regression method TOPSIS to analyze the flood risk at the national level [19], and Chen et al. (2022) used random forest models to analyze the flood risk in the Yangtze River Delta region, China [20]. However, very few studies have focused on the flood risk assessment of metro tunnels, and the indicators of the evaluation system have not been set for metro systems. Although we consider the metro flood risk and regional flood risk as essentially the same, it is not scientific to extract the flood risk of the metro system directly through the regional flood risk assessment alone. The risk of flooding in the underground infrastructure was first proposed by Japan [3]. Herath and Dutta (2004) described the flooding of underground facilities in Japan and proposed a 3D modeling system designed to simulate urban flooding, including flooding in underground facilities [21]. Hashimoto and Park (2008) applied mathematical theory to analyze the flood event that occurred in Fukuoka City, Japan on 29 June 1999, which resulted in the flooding of metro stations and underground spaces [22].

In recent years, there has been an increasing number of studies on flood hazard assessments in metro systems, and the existing studies mainly use scenario simulation, analytical hierarchy process (AHP), GIS and remote sensing techniques, and multi-criteria decision-making (MCDM). For example, Aoki et al. (2016) proposed anti-flooding measures for underground stations in the Tokyo subway [23]. Lyuet al. (2018) used GIS-based modeling methods to study subway systems in the megacities of China [1]. Wang et al. (2021) used the fuzzy analytical hierarchy process (FAHP) method to analyze the risk of flooding in a large subway system in Beijing, China [2]. These studies have laid the groundwork for metro flood hazard and risk assessment, but there are still many problems in this area. For instance, the AHP method has too many subjective aspects because the study is determined by the subjective decisions of experts [24], whereas the scenario simulation method requires a large amount of data and needs to be accurate [25]. The random forest model, on the other hand, requires a large amount of data and a high level of operation for the researcher. And there are still gaps in our research on flood risk assessments in metro systems; the depth of research on them is currently insufficient and the number of studies is low. The methodologies used to assess risk are very simple and have not been further developed. The data samples are also not sufficient; most of the current studies use a small number of samples and lack sufficient real and timely data to support the authenticity and reliability of the research results, so new research methods are needed to improve the metro flood risk assessment.

To address the above-mentioned limitations, this study, for first time, uses the comprehensive hazard risk assessment theory of natural disasters proposed by Zhang and Liang et al. (2009) [26], combined with AHP hierarchical analysis and the improved entropy method, to analyze the risk of flooding in Changchun's rail transit system. The traditional comprehensive evaluation method decomposes the risk of flooding in metro stations into the following three elements: hazard, exposure, and vulnerability. And the comprehensive hazard risk assessment theory of natural disasters expands the risk formation principle from three to four elements, including hazard, exposure, vulnerability, and emergency response and recovery capability, through a multi-criteria decision-making method (MCDA). Using four elements is more reliable than using the traditional three elements. This integrated method helps to comprehensively and scientifically analyze the risk of metro flooding, while combining AHP and the improved entropy weight method for coupled analysis, from both subjective and objective aspects. Further, it solves both the influence brought on by the subjective factors of the AHP method, and the errors caused by the extremely small and unreasonable data in the survey. This coupled approach, which solves the metro flood risk assessment problem from different levels of analysis, is more reliable. Finally, the risk visualization using remote sensing (RS) and a geographic information system (GIS) is combined with 22 indicators appropriate for the Changchun rail system and the latest data to provide decision makers with a comprehensive, scientific, standardized, and convenient aid to consider the flood risk of the Changchun rail system in a comprehensive manner.

Changchun was the fifth city in China to open an extended subway system. The city rail transit system includes the subway and light rail. The light rail will not only have soaked vehicles and equipment when faced with flooding, but will also generate electrical hazards. Given this scenario, the present paper does not only consider the subway system when studying Changchun's rail transit system, but also adds indicators to consider the flood risks of the light rail and subway together. The city has been slow to develop, with incomplete lines and a small coverage area. There are many metro lines that are under construction and that have been planned by the Changchun government, which are also exposed to flood risk. The objectives of this paper are as follows: (1) to comprehensively consider flood risks in the planning and construction of metro lines and (2) to perform a comprehensive urban flood risk assessment of the completed rail transit systems in Changchun City. The findings of this study can provide scientific implications for future flood protection in the Changchun rail transit system particularly, and in other Chinese cities generally. This paper provides a reference index and an accurate assessment method for the Changchun rail transit system to facilitate the flood risk assessment of future lines.

2. Methodology and Data Sources

2.1. Methodology

In this study, the metro flood risk assessment is divided into four elements, including hazard, exposure, vulnerability, and emergency response and recovery capability, on the basis of the comprehensive risk assessment theory of natural disasters. Figures 1 and 2 show the technical steps adopted for this study. This study is divided into five steps for the risk assessment of Changchun's rail transit system. Step A performs data preprocessing and collection; this paper requires a lot of non-spatial data and multi-source spatial data support in order to generate indicator maps in GIS. And step B selects a total of 22 indicators separately, covering hydrological and geomorphological conditions, meteorological conditions, population facilities, and socio-economic conditions, to establish a complete indicator system. All risk indicators are processed in the GIS system and imported into the GIS system to form an indicator map so that each indicator can be visually represented. Step C uses AHP technique and improved entropy weighting method to calculate the subjective and objective weights of each indicator, respectively, and finally carries out comprehensive weighting calculation to obtain reasonable indicator weights. In step D, map superposition is performed in GIS using the previously calculated weights to obtain the regional hazard, exposure, vulnerability, and emergency response and recovery capability level maps. Based on the raster layers and weighting results in GIS, we generated the regional flood risk level of Changchun and obtained the regional integrated flood risk level map. Finally, we extracted the 500 m area along the metro as a buffer zone to obtain the risk level map of Changchun's rail transit system.

2.2. Data Sources

The elevation and slope were obtained from the geospatial data cloud with a resolution of 30 m. The average annual rainfall, the rainfall days (DR > 50 mm), and the maximum daily rainfall were processed as raster data in arcGIS10.8 using the kriging method, and the data used were obtained from the China Meteorological Administration. Both NDVI and LULC data were obtained from databox. Changchun river network and Changchun main road network are vector data, obtained from the geospatial data cloud, which can be accessed directly. Population density was obtained from UN world population density for the year 2020. The road network density and river network density can be obtained by searching the Changchun Statistical Yearbook. The type of exits and the number of exits were obtained from the Gaode Map and the author's fieldwork. Data on the percentage of vulnerable population and education status were obtained from Changchun Statistical Yearbook. Metro station density was obtained from arcGIS10.8 kernel density, with data from Gaode Map. GDP for 2022 was obtained from Databox, and Changchun metro lines are vector data, obtained from Gaode Map. Passenger flow was provided by the environmental assessment book of Jilin Zhengyuan Company, and the passenger flow of the line under construction was also predicted by the environmental assessment book of this company. The river network proximity was obtained in arcGIS10.8 using Euclidean distance, with data provided by Geospatial Data Cloud, and the metro line proximity was derived in acrGIS10.8 using Euclidean distance, as raster data, using data provided by Gaode Map. Metro line densities were obtained using line densities in arcGI10.8 with data from Gaode Map. Table 1 summarizes the selection of indicators and data sources for this study.

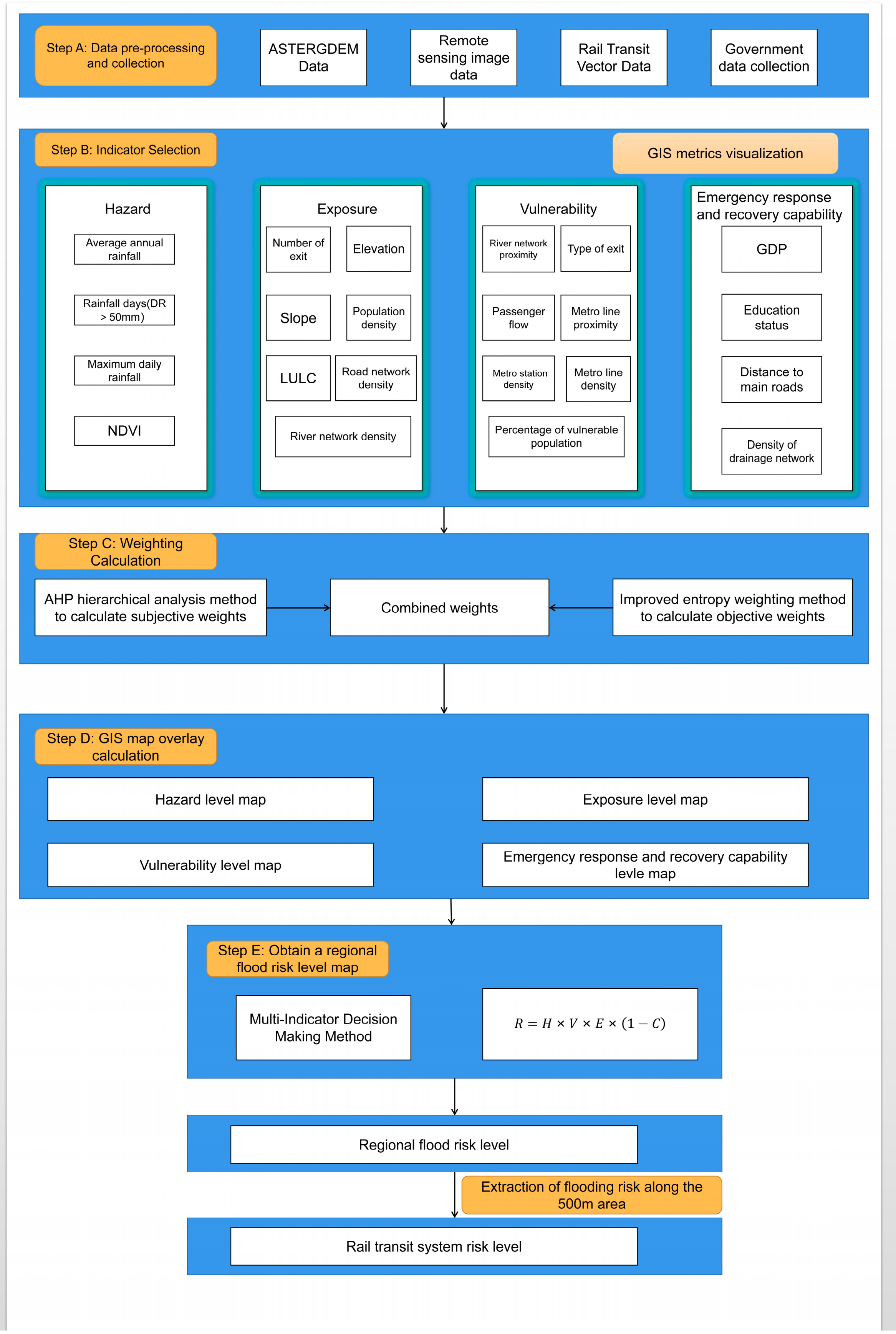

Figure 1. Flowchart of the flood risk assessment for the Changchun rail transit system.

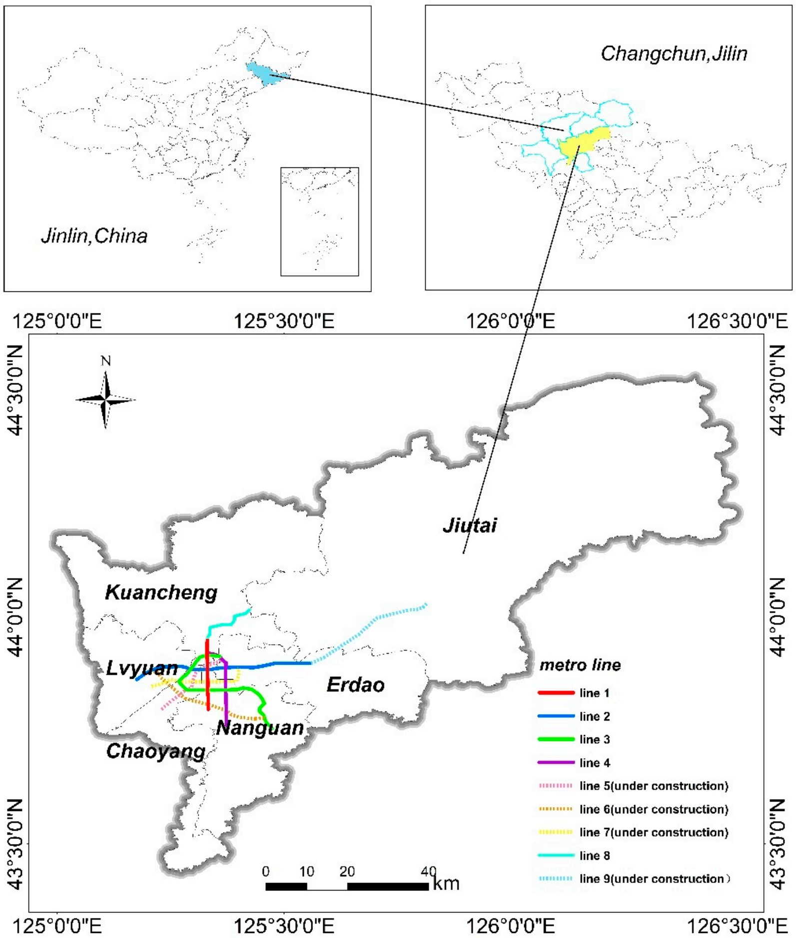

Figure 2. The geographical location of the study area and the Changchun rail transit system.

Table 1. Flood risk model indicators for rail transit systems and their data sources.

Parameters	Data Types	Source
Elevation	ASTER GDEM 30 m × 30 m	www.gscloud.cn (accessed on 1 September 2022)
Slope	ASTER GDEM 30 m × 30 m	www.gscloud.cn (accessed on 1 September 2022)
Average annual rainfall	Raster data	China Meteorological Administration
Rainfall days (DR > 50 mm)	Raster data	China Meteorological Administration
Maximum daily rainfall	Raster data	China Meteorological Administration
NDVI	Landsat 8 OLI/TIRS	https://www.databox.store (accessed on 3 October 2022)
LULC	Landsat 8 OLI/TIRS	https://www.databox.store (accessed on 13 October 2022)
Changchun river network	Vector data	www.gscloud.cn (accessed on 5 November 2022)
Main road network	Vector data	www.gscloud.cn (accessed on 8 November 2022)
Population density	Raster data 2020	UN world population density
Road network density	Raster data	Changchun Statistical Yearbook
River network density	Raster data	Changchun Statistical Yearbook
Type of exit	Vector data	Gaode Map
Number of exits	Vector data	Gaode Map
Percentage of vulnerable population	Attribute data 2022	Changchun Statistical Yearbook
Education status	Raster data 2023	Changchun Statistical Yearbook
Density of metro stations	Raster data 2023	Gaode Map
GDP	Raster data 2022	https://www.databox.store (accessed on 3 January 2023)
Metro line	Vector data	Gaode Map
Passenger flow	10,000 people	Jilin Province Zhengyuan Company environmental assessment book
River network proximity	Raster data	www.gscloud.cn (accessed on 14 March 2023)
Metro line proximity	Raster data	Gaode Map
Metro line density	Raster data	Gaode Map

3. Overview of the Study Area

3.1. Physical Geography Overview

Changchun (ancient name Xi Du) is the capital of Jilin Province, under the jurisdiction of seven districts, one county, and three county-level cities. The city is located at 43°05′~45°15′ north latitudes and 124°18′~127°05′ east longitudes, with a total area of 24,592 square kilometers. The city is located in the mid-latitude northern temperate zone, in the vicinity of the Songliao Plain in Northeast China, with relatively flat terrain. Generally, the study area has dry and windy weather in spring, and rainy and wet weather in summer, with large seasonal temperature differences and an annual rainfall of 600–700 mm. Within the city, the areas included in the rail line are extracted for the study. These include Chaoyang District, Kuancheng District, Erdao District, Nanguan District, Lvyuan District, and Jiutai District.

3.2. Socio-Economic Profile

Changchun is an important economic zone in the northeastern part of China, with annual gross domestic product (GDP) of CNY 710.312 billion. The primary industrial sector added a value of CNY 52.374 billion, the secondary industrial sector added a value of CNY 296.047 billion, and the tertiary industrial sector added a value of CNY 361.890 billion. The three industrial structures contribute to the city's GDP at the ratio of 7.4:41.7:50. Changchun City has a strong provincial capital strategy under the vested interests of the growing economy, becoming the second largest economic city in Northeastern China. In terms of population, the total resident population of the city at the end of the 2022 was 9,087,200. Among them, the population of the urban area was 5,837,600, and the population of the four counties was 3,249,600.

On 30 June 2017, the Changchun rail transit opened line 1 for a trial operation, which is the first subway line in Changchun. By 2022, Changchun City had a total of 10 subway lines and 173 stations (including those that are under planning). Although the Changchun subway started a bit late, a large part of the transit is completed, making full use of the unbuilt land, reducing land costs, and feeding the city. Since subway disasters have been numerous, preventing flood in Changchun's rail transit, providing guidelines for flood prevention for lines under planning and construction, and reducing people's economic losses are the main purposes of this paper.

4. Analysis of Indicators and Calculation of Weights

4.1. Analysis of Indicators

4.1.1. Hazard Indicators

Hazard is the probability of flooding in the metro system and the degree of risks it may cause.

(1) Maximum daily rainfall: The maximum daily rainfall in Changchun is concentrated in the easternmost part of the city (Figure 3a). The maximum daily rainfall is closely related to the occurrence of flood events and the degree of impact on the metro system and can be directly correlated with the metro system. The design and construction process of the metro system needs to determine the maximum daily rainfall according to the local climatic conditions, which has a significant impact on the drainage system of the metro system. When flooding threatens the metro system, it needs to be quickly discharged through the drainage system [27]. If the maximum daily rainfall is too high, the drainage system of the subway system may not be able to bear the impact due to the affected capacity of the drainage system.

(2) NDVI (normalized difference vegetation index): Changchun City has less vegetation cover in the urban area and a higher vegetation cover in the east (Figure 3b). A high vegetation cover reduces the runoff rate, slows down the water flow through vegetation absorption, and reduces the impact of flooding on the subway system. The root system of vegetation also stabilizes the soil, reduces soil erosion and sediment

accumulation, and helps to keep the drainage system around the subway system open, which is the reason why we selected NDVI as the hazard index [28].

(3) Average annual rainfall: Changchun City's precipitation decreases from east to west [10]. Rainfall is one of the main causes of flooding in the subway (Figure 3c). The annual rainfall is a comprehensive consideration that reflects the overall rainfall in the Changchun area and is directly correlated with the flood risk.

(4) Rainfall days (DR > 50 mm): Changchun has more rainfall days in the eastern part of the city (Figure 3d). The selection of this threshold is based on the understanding of the rainfall characteristics and drainage system capacity in the Changchun area, which can accurately determine the flood risk and provide the basis for early warning and decision making. This indicator is practical and operable. If there are too many days in which the rainfall is greater than 50 mm, it may lead to the overloading of the drainage system, making it unable to drain the rainwater from the metro system in time, thus leading to waterlogging [12].

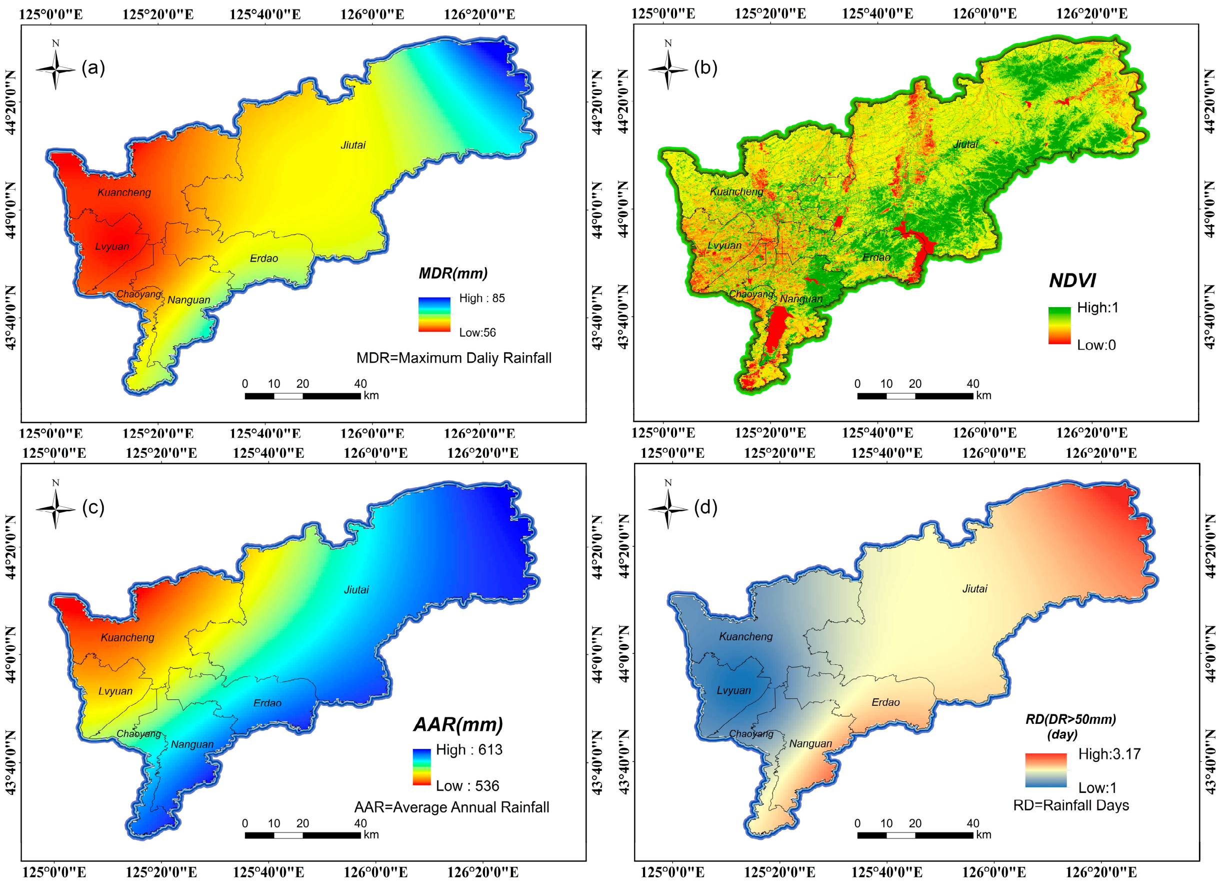

Figure 3. Hazard index: (**a**) maximum daily rainfall; (**b**) NDVI; (**c**) average annual rainfall; (**d**) rainfall days (DR > 50 mm).

4.1.2. Exposure Indicators

In the case of metro flooding, exposure refers to the extent to which the area and population where the metro is located, buildings, facilities, infrastructure, etc., are exposed to the threat of flooding. In this paper, the following indicators are selected to assess the exposure of the metro system to urban flooding:

(1) Population density: The population of Changchun is mainly concentrated in the western part of the main urban area and is sparser elsewhere (Figure 4a). Population density is one of the very important exposure indicators in metro flooding hazards, as it is directly related to the number of potentially affected people and areas. A high

population density means that more people and buildings are distributed in the same area [29] and more people and buildings are likely to be affected in case of metro flooding. Population density, as an expositional indicator, can guide the planning and preventive measures of the Changchun metro system, especially in high population density areas; priority can be given to strengthening drainage systems and flood control facilities.

(2) Elevation: The elevation of Changchun City is mainly concentrated in the east and south, and the rail transit system is built in the western part of the urban area, where the elevation is lower (Figure 4b). Elevation is an important factor in assessing the vulnerability of the metro system to flooding. The lower the elevation, the more vulnerable the metro system is to flooding, and vice versa [30]. By knowing the elevation information in the area where the Changchun rail transit system is located, potential inundation areas can be identified, and a basis can be provided for developing early warning systems and emergency response plans. Elevation information can also guide planning and improvement measures, especially in areas of high flood risk, where enhanced flood protection measures and improved drainage systems can be considered.

(3) Slope: The slope is extracted from the elevation in the GIS, and the slope can affect the drainage performance of the subway platform or inter-station road (Figure 4c). If the slope of a subway platform or inter-station road is too small or lacks drainage facilities, it may lead to ponding and flooding when rainfall is high, thus affecting the operation of the subway system [31]. Slope, as an indicator of exposure, can also be used to assess the flood protection that the facility needs and to guide planning and improvement measures.

(4) LULC (land use and land cover): Different land use types result in different runoff conditions due to ground cover, which affects the flood risk of the metro system (Figure 4d). If the land use type near the metro station is urban construction land and the surface cover is mainly made of cement, asphalt, and other concrete materials, it will lead to a large amount of runoff not being able to infiltrate into the soil after rainfall and form ponding water, increasing the risk of flooding. The surface cover conditions of different land use types can affect the ability of vertical infiltration [32]. In this paper, we classify artificial ground as very high exposure, water bodies as medium exposure, and forest land as very low exposure.

(5) Main road density: The areas with a high road network density in Changchun are concentrated in the western part of the main urban area, and the distribution of underground transportation facilities such as the subway system is also relatively dense (Figure 4e). This means that the population density and building density may also be high [33], which may lead to areas around the metro system being prone to flooding, increasing the risk of flooding in the metro system. The main road density reflects the distribution and connectivity of urban roads, which not only provides information on the main paths of the flood flows, but is also closely related to the drainage system of the city.

(6) River network density: Areas with a higher river network density have a higher likelihood of flooding (Figure 4f). When the area receives high rainfall or there is prolonged rainfall, the rivers around the metro system may rise, increasing the exposure of the metro system to flood risk. By analyzing the density of the river network, potential flood accumulation areas and flow paths can be identified to help assess the exposure of the Changchun metro system to flood events. Rivers in areas with a high river network density may interact with each other to form river systems. During high rainfall, the water flow in the river system may increase and be more difficult to control, posing a flood risk to the metro system [30].

(7) Exit number: Metro stations with a large number of entrances and exits are usually located in areas with heavy traffic, dense surrounding buildings, and complex layers of underground pipes (Figure 4g). During rainfall, the drainage system is prone to

failure and serious water accumulation on the ground, which directly affects the entrance and exit channels of the subway station and increases the subway stations' exposure to flood risk. The exit number, selected as an indicator of exposure, can provide key information to help assess the flood risk of the Changchun rail transit system. The number of exits reflects the degree of exposure of the rail transit system to flood intrusion, potential inundation risk, evacuation difficulties, and the degree of association with the urban drainage system, which can help identify potential risk areas and improve emergency response capabilities.

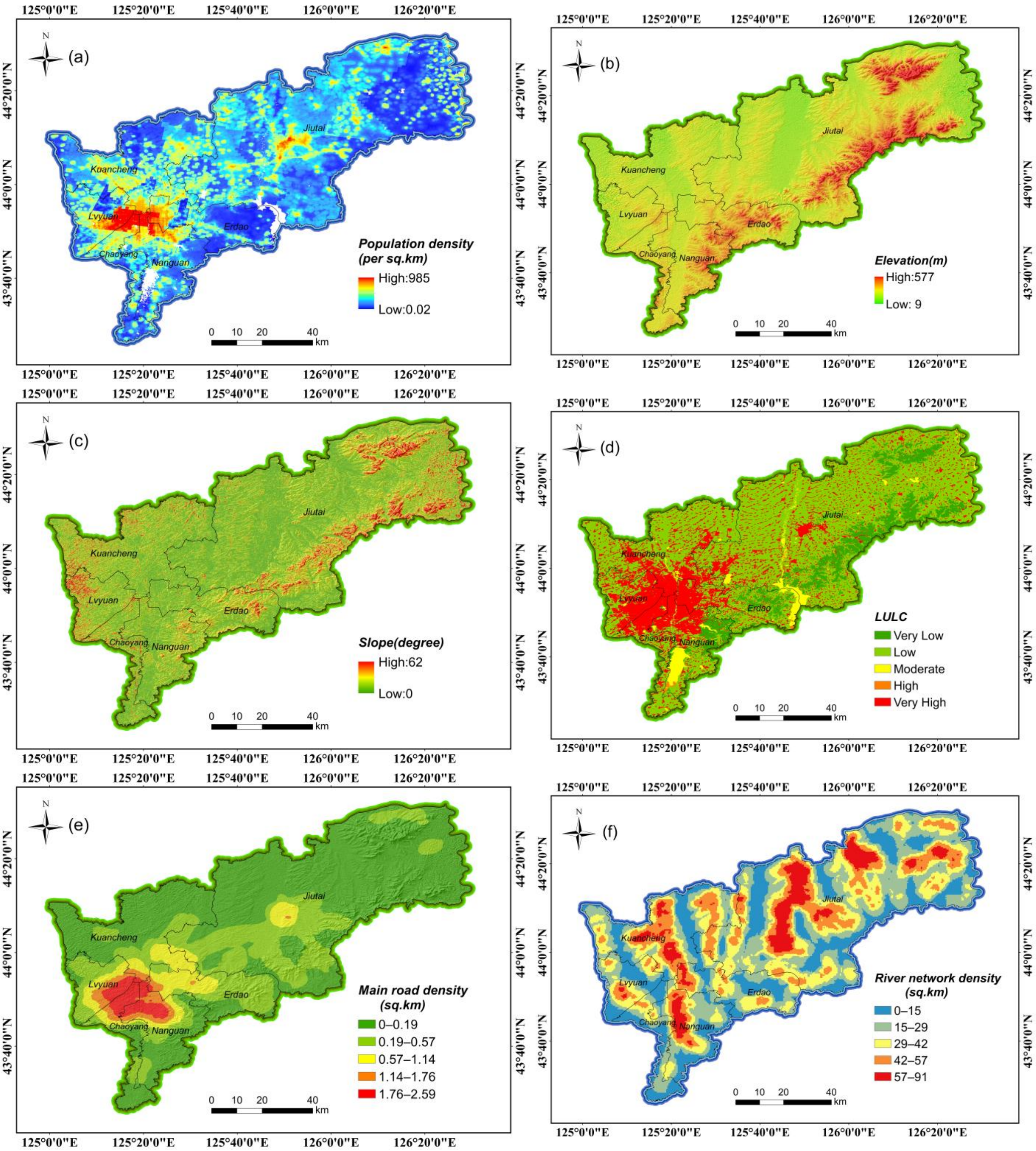

Figure 4. *Cont.*

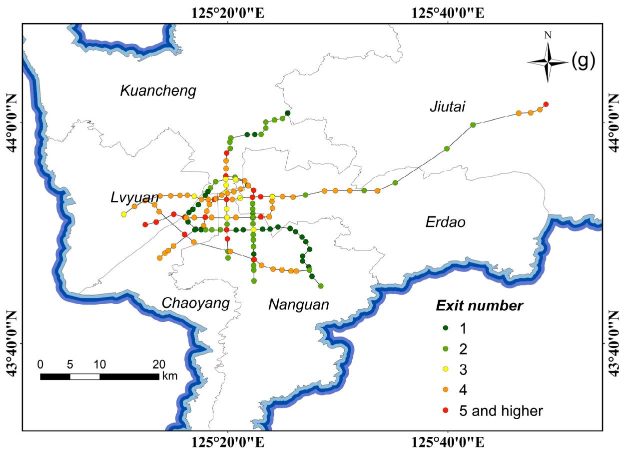

Figure 4. Exposure index: (**a**) population density; (**b**) elevation; (**c**) slope; (**d**) LULC; (**e**) main road density; (**f**) river network density; (**g**) exit number.

4.1.3. Vulnerability Indicators

In metro flooding, vulnerability refers to the degree of damage to intrinsic individuals and facilities. In this paper, the following indicators are selected to reflect the vulnerability of metro flooding:

(1) Type of metro stations: After the field survey, the Changchun metro stations were divided into four categories, i.e., above ground, underground, semi-underground, and elevated stations (Figure 5a). Elevated stations are fully exposed and have the highest risk level, above-ground stations are second to elevated stations, and underground stations linked to underground shopping malls, train stations, and other structures have the lowest risk level.

(2) River network proximity: We set the proximity of the river network as 200 m, 400 m, 600 m, 800 m, and 1000 m from the nearest river (Figure 5b). Generally, the closer the river, the higher the flood risk and vulnerability of the metro system, and vice versa. The river network proximity reflects the degree of flood threat to the metro station, as well as the potential inundation risk, differences in the geological conditions, and emergency evacuation.

(3) Metro station density: The metro station density refers to the number of stations per unit area in the metro system, which is also an important factor in the metro flood risk assessment and has a certain influence on the outcomes of the vulnerability assessment (Figure 5c). Changchun metro stations are densely concentrated in the central city, and a higher metro station density means there are shorter distances between stations in the metro system, which means passengers can quickly reach any station in a short time. However, at the same time, a higher metro station density also means that in the case of flood events, the affected area is larger, the area of metro stations and the number of internal platforms inside stations are relatively high, and the cost of flood protection measures is also higher. This can increase the vulnerability of the metro system and lead to greater damage to the metro system [34]. We selected metro station density as a vulnerability indicator to reflect the connectivity, evacuation efficiency, flood resilience, and operational effectiveness of the metro system during flood events.

(4) Passenger flow: Changchun rail transit lines 1, 2, and 5 are the backbone lines, while the other lines are secondary lines (Figure 5d). A higher passenger flow means a higher load on the metro system. In heavy rain, water and dirt will cause the metro system to fail or paralyze more easily, making the metro system more susceptible to flood risks and increasing the difficulty of coping with flooding. Moreover, changes in the passenger flow will also affect the implementation of the emergency plan for metro flooding, especially in the evacuation process, i.e., how to ensure the safe

evacuation of the passengers. Under flooding circumstances, quick evacuation could become a difficult part of the emergency plan, and the increase in passenger flow will increase this difficulty [35]. By considering the passenger flow, the staffing pressure and response capacity of vulnerable stations in the Changchun subway system can be assessed, providing an important reference for the development of corresponding emergency plans and improvement measures.

(5) Percentage of vulnerable population: The proportion of vulnerable population is larger in Green Park and Jiutai District (Figure 5e). The vulnerable population faces higher risks in the case of metro flooding, and it is likely to be difficult to secure help in time. Vulnerable populations have lower incomes and lack sufficient financial support to take safety precautions and receive timely emergency assistance. The economic losses and impacts during floods are greater, and the financial difficulties of recovery and reconstruction are more severe. Vulnerable people usually have fewer health and medical resources, and their ability to help themselves and help each other is weaker [36]. The percentage of vulnerable population was chosen as a vulnerability indicator to consider the distribution and vulnerability of special groups in the metro system.

(6) Metro line proximity: Areas that are closer to metro lines are generally considered to have a higher vulnerability in metro flood risk assessments because they will be more directly and severely affected by flooding, and the metro lines will be more easily damaged (Figure 5f). In addition, if the areas closer to the metro lines are densely built, it may cause the accumulation of flood water in these buildings, increasing the risk of disaster and exacerbating vulnerability. Areas at a greater distance from the subway lines may also be affected by flood events, but their risk level is generally considered relatively low in the assessment due to their distance from the subway lines. The choice of metro line proximity as a vulnerability indicator helps to assess the vulnerability of the metro system and its surrounding areas to flood events.

(7) Metro line density: We generated the Changchun rail transit line density by using the subway line density in GIS with a search radius of 1 km (Figure 5g). The densest concentration of rail transit in Changchun is in the central city. Areas with a higher metro line density are generally considered to have a higher vulnerability in the metro flood risk assessment because when flood events occur, more metro tunnels and stations may be inundated and damaged, and metro services may be interrupted for longer periods of time, resulting in more significant impacts on the city and passengers. On the other hand, cities or regions with lower metro line densities may not be susceptible to flood risk in the metro flood risk assessment, as their vulnerability ratings are relatively low due to the smaller size of the metro.

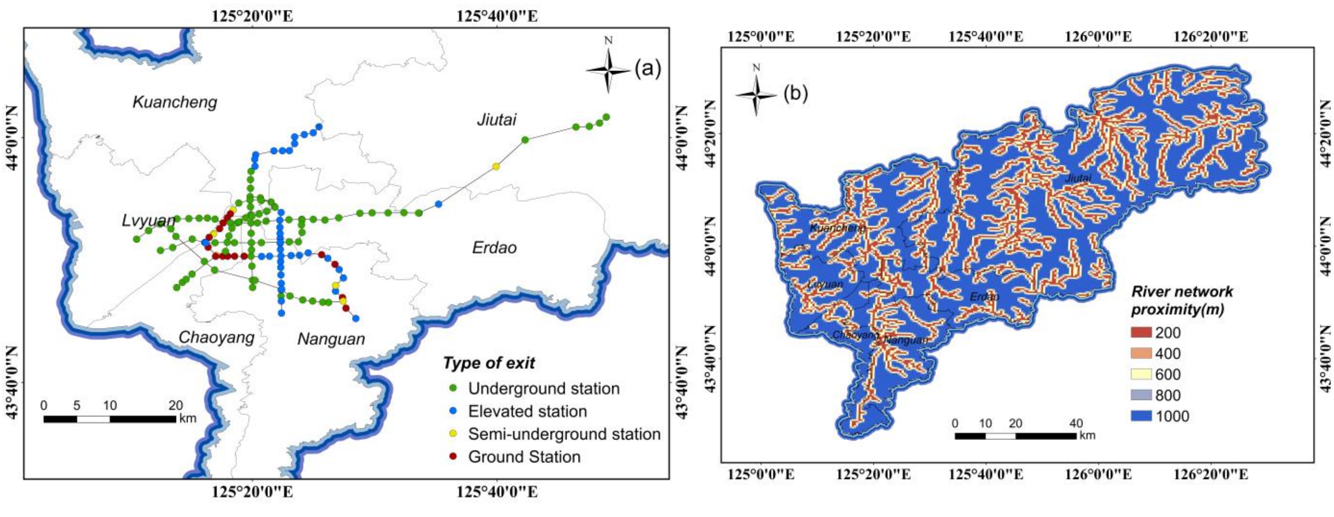

Figure 5. *Cont.*

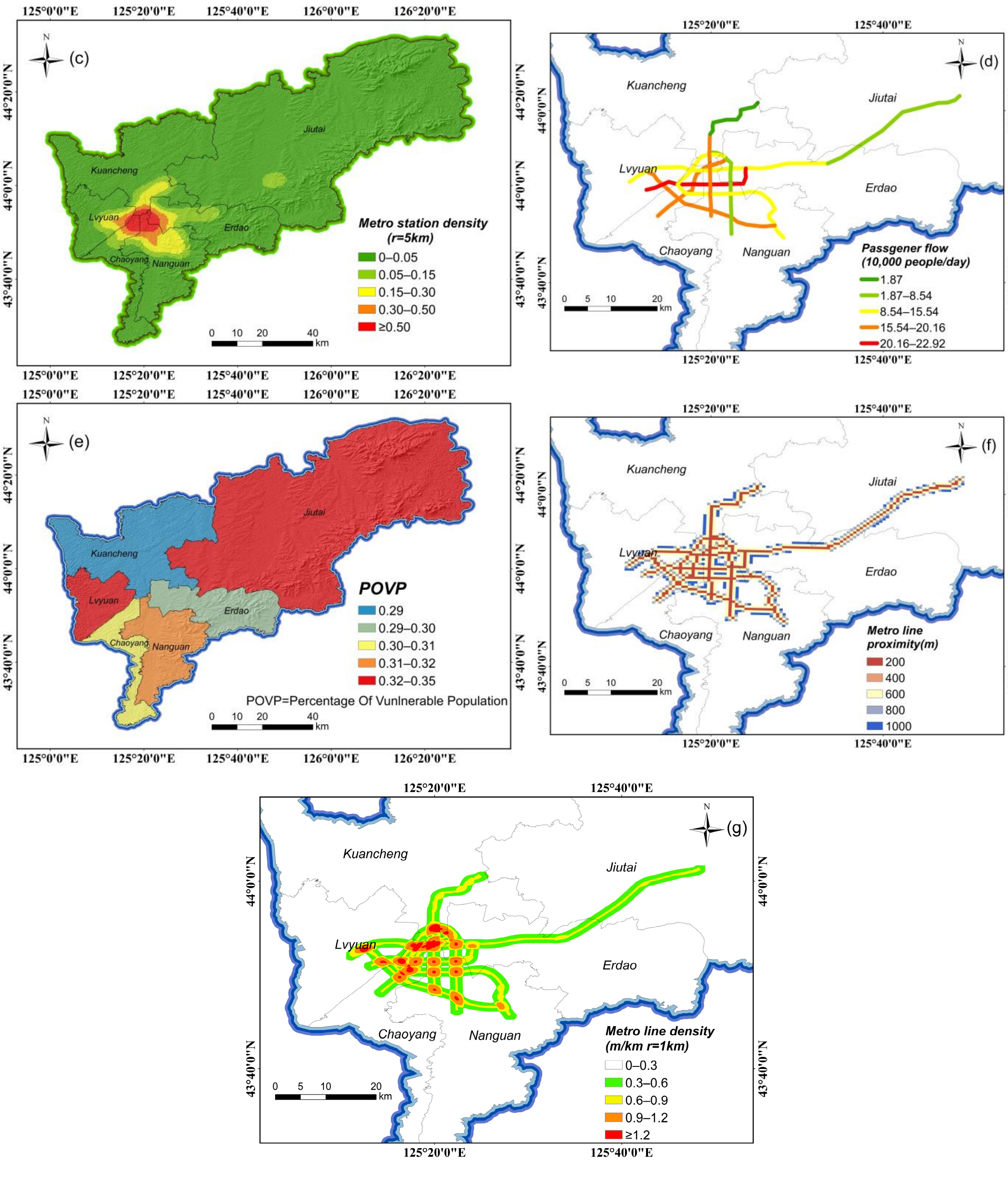

Figure 5. Vulnerability index: (**a**) type of exit; (**b**) river network proximity; (**c**) metro station density; (**d**) passenger flow; (**e**) percentage of vulnerable population; (**f**) metro line proximity; (**g**) metro line density.

4.1.4. Emergency Response and Recovery Capability Indicators

Emergency response and recovery capability in the context of metro flooding is defined as the ability of the government and individuals to effectively predict and identify potential risks, take appropriate preventive measures, mitigate disaster hazards, and reduce disaster losses in the face of metro flooding. In this paper, the following indicators are selected to assess the emergency response and recovery capabilities of the metro system in Changchun City.

(1) GDP: The GDP, as an important economic indicator, is good for enhancing the disaster prevention and mitigation capacity of metro flooding [37], strengthening the construction of public facilities and urban planning, and providing a good post-disaster reconstruction capacity afterward (Figure 6a). The choice of using the GDP as an emergency response and recovery capability indicator helps us to assess the economic resource input, post-disaster recovery capacity, and social welfare protection level of the area where the Changchun rail transit system is located.

(2) Distance to main road: The distance to main roads refers to the distance from a location to the nearest major road. In the metro flood risk assessment, the distance to the main road has a certain influence on the disaster prevention and mitigation capacity (Figure 6b). In the event of flooding, the main road may be submerged, or traffic disruption may occur, thus affecting rescue and evacuation. When the distance from the main road is far, it may take longer and cost more for people to reach safety, which may affect the efficiency and timeliness of emergency evacuation. On the contrary, locations closer to the main roads may be more convenient and efficient for rescue and evacuation, allowing for a faster escape from flooded areas and reducing casualties. The choice of using the distance to main roads as an emergency response and recovery capability indicator helps us to assess the evacuation and rescue capability, material transportation, emergency services and support, and communication and liaison capability of the area where the Changchun metro system is located.

(3) Education status: Education status refers to the proportion of a given population with different levels of education (Figure 6c). In the metro flood risk assessment, the level of education has a certain influence on the disaster prevention and mitigation ability. Personnel with higher education or professional training may be more advantageous in terms of disaster preparedness and response capabilities. Highly educated people may have higher scientific literacy and skills, be more knowledgeable about disaster warning information and response measures, and be able to take the right and effective measures to protect themselves and others. They are also likely to be more aware of disaster risks and be prepared to respond and mitigate possible consequences. In contrast, people with low levels of education may lack a proper understanding and assessment of disaster risks and lack the relevant knowledge and skills to respond to disasters. These people may perform wrong or unsafe actions or fail to understand or perceive risks when disasters occur, leading to increased losses [38]. In summary, the selection of education level as an emergency response and recovery capability indicator helps to assess the preparedness and action capacity of residents in the area where the Changchun rail transit system is located.

(4) Density of drainage network: We define the drainage pipe network density as the length of regional pipes compared to the area of the upper region. The drainage pipe network density has an important impact on the metro flood risk assessment (Figure 6d). The higher the drainage network density, the better the metro system is able to handle and discharge the water flow in the face of flooding, and therefore, the flood risk assessment results will be more optimistic. In summary, using the drainage network density as an emergency response and recovery capability indicator can help us to assess the drainage capacity of the area where the metro system is located and its ability to cope with flood risks, and provide an important basis for flood resistance measures and emergency planning of the metro system to ensure the safe operation of the metro system and the safety of the passengers.

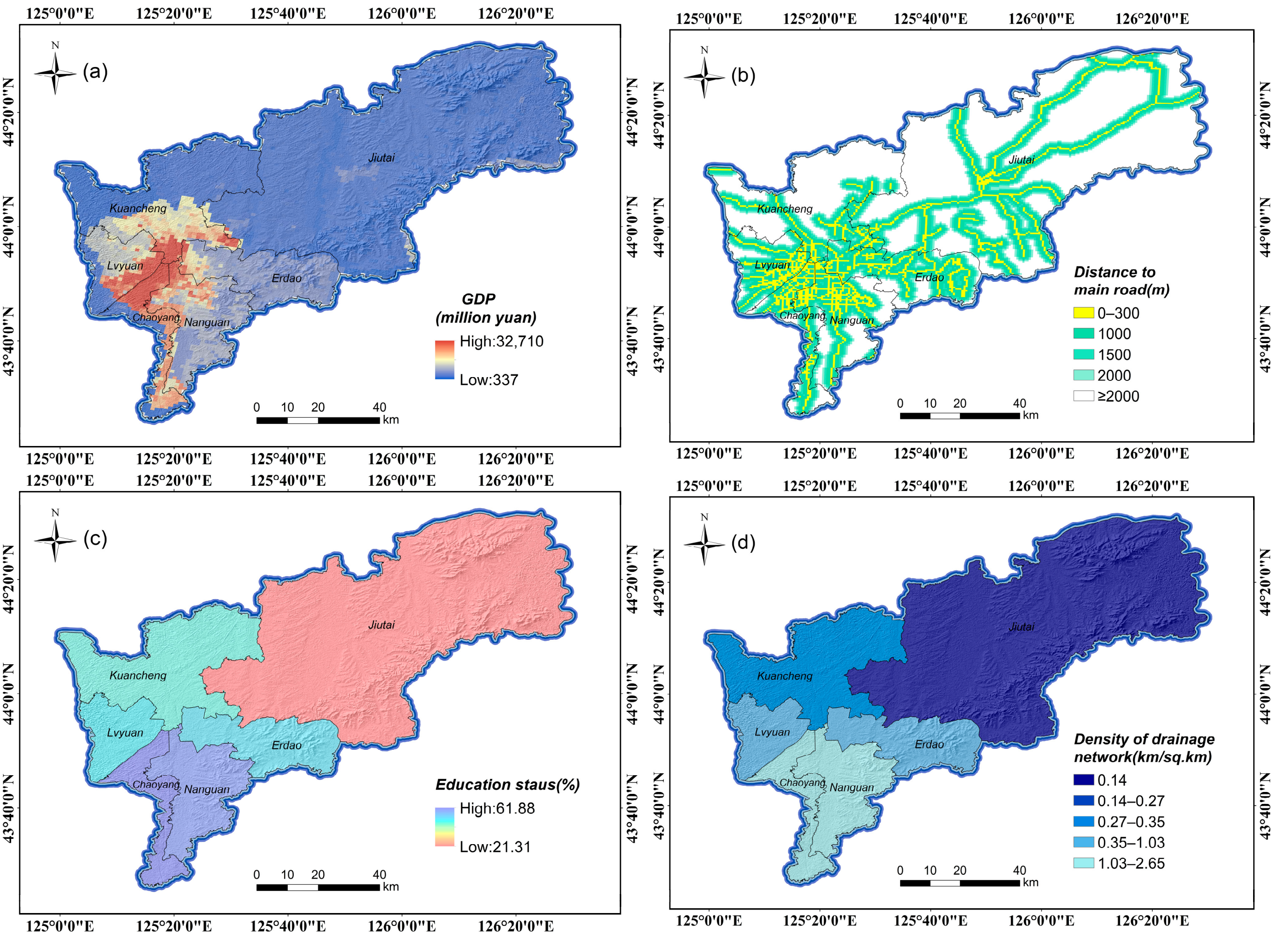

Figure 6. Emergency response and recovery capability index: (**a**) GDP; (**b**) distance to main road; (**c**) education status; (**d**) density of drainage network.

4.2. Calculation of Weights

4.2.1. Using the AHP Hierarchical Analysis Method to Calculate the Subjective Weights

The AHP method was first proposed by Professor T.L. Saayt at the University of Pittsburgh in the 1970s. It is a systematic multi-objective decision-making method that combines quantitative and qualitative analyses.

AHP is a quantitative method used for decision making and problem solving. The following are the steps of the AHP method [39,40].

(1) Establish the hierarchy: Hierarchize the decision problem and construct a hierarchy consisting of decision level, criterion level, indicator level, and sub-indicator level.
(2) Quantify the hierarchy: In this paper, each element in the indicator layer is ranked according to the input provided by five experts from the disaster research team of Northeast Normal University, and their relative importance is compared using numbers from 1 to 9, where 1 represents equal importance and 9 represents extreme importance.
(3) Calculation of weights: The weights are calculated using the mathematical model of the hierarchical analysis method. The calculation process involves calculating the feature vector of each level and the weight of each element.
(4) Consistency test: The maximum eigenvalue λmax of the matrix is obtained, while the corresponding eigenvectors are obtained, and the consistency of the judgment matrix is verified according to Equations (1) and (2), in Table 2.

Table 2. Random consistency index test (RI) table.

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

$$CR = \frac{CI}{RI} \quad (2)$$

(5) Comprehensive analysis: The obtained weights are used for the comprehensive analysis to find the optimal solution or decision.

4.2.2. Improvement of Entropy Weight Method to Calculate Objective Weights

(1) Construct the original index data matrix. Assuming that there are m samples to be evaluated and n evaluation indicators, the original indicator data matrix is formed as follows [41]:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \quad (3)$$

where x_{ij} denotes the value of the i-th sample and the j-th evaluation index.

(2) Data processing: In order to eliminate the influence of different levels on the evaluation results, the indicators are normalized, and the single standardized data are calculated using the following formula:

$$4x'_{ij} = \frac{x_{ij} \ - minx_{ij}}{maxx_{ij} - minx_{ij}} \quad (4)$$

(3) Calculate the share of the ith sample in the total value of the indicator for the jth indicator as follows:

$$p_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{m} x'_{ij}} \quad (5)$$

(4) Calculate the entropy value of the jth indicator as follows:

$$E_j = -k \sum_{i=1}^{m} p_{ij} ln p_{ij} \quad (6)$$

where constants $k = \frac{1}{lnm}$, $k > 0$.

(5) Calculate the improved entropy value as follows:

$$E'_J = \frac{1}{1 + e^{-E_j}} \quad (7)$$

(6) Calculate the coefficient of variation of the jth indicator d_j. The entropy method assigns weights to each indicator based on the degree of difference in the sign value of each indicator so as to derive the corresponding weight of each indicator, d_j. The larger it is, the greater the importance of the indicator, as calculated using the following formula:

$$d_j = 1 - E'_J \quad (8)$$

(7) Calculate the objective weights as follows:

$$s_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \quad (9)$$

4.2.3. Calculating the Combined Weights

Using the multiplicative integration method, the subjective weights are combined with the objective weights to obtain the combined weights.

$$W_j^* = \frac{w_{jd_j}}{\sum_{j=1}^{n} w_{jd_j}} \tag{10}$$

The results of the calculations are shown in the following Table 3.

Table 3. Weight of indicators.

Criterion Layer	Criterion Layer Weights	Indicator Layer	Indicator Layer Weights
Hazard	0.4668	Average annual rainfall	0.1025
		Maximum daily rainfall	0.2597
		Rain days (DR > 50 mm)	0.2854
		NDVI	0.3523
Exposure	0.1603	Number of exits	0.2174
		Elevation	0.1829
		Slope	0.1683
		River network density	0.0546
		Population density	0.2
		Road network density	0.0937
		LULC	0.0831
Vulnerability	0.2776	Percentage of vulnerable population	0.0871
		River network proximity	0.0763
		Type of exit	0.2541
		Metro station density	0.1431
		Passenger flow	0.1875
		Metro line density	0.1241
		Metro line proximity	0.1277
Emergency responseand recovery capability	0.0953	GDP	0.2043
		Drainage pipe network density	0.2687
		Education status	0.3887
		Distance to main road	0.1383

5. Modeling of Flood Risk along Rail Transit Systems

5.1. Guideline Layer Modeling of Flood Risk along Rail Transit Systems

In this paper, the "H-E-V-C" assessment framework is used to construct the metro flood risk index (R).

Further, we used a logistic regression model to calculate the flooding hazard (H) along the subway line; the larger the value ($0 \le H \le 1$), the higher the risk of flooding, and the formula uses the values calculated in Formula (3) as follows:

$$H = \frac{exp(b_0 + b_1x_1 + b_2x_2 \cdots + b_kx_k)}{1 + exp(b_0 + b_1x_1 + b_2x_2 \cdots + b_kx_k)} \tag{11}$$

where H is the probability of occurrence of flooding hazards along the subway line, x_k is each criterion, and b_k is the calculated regression probability. The equations for each criterion layer of exposure, vulnerability, and disaster prevention and mitigation capacity are as follows:

$$E = \sum_{i=1}^{n} = W_{ei}X_{ei} \tag{12}$$

$$V = \sum_{i=1}^{n} = W_{pi}X_{pi} \tag{13}$$

$$C = \sum_{i=1}^{n} = W_{ri}W_{ri} \tag{14}$$

where E, V, and C represent the values of exposure, vulnerability, and disaster prevention and mitigation capacity, respectively; n is the total number of indicators; i is the ith indicator; W_{ei}, W_{pi}, and W_{ri} are the weights of the factors obtained; and X_{ei}, X_{pi}, and X_{ri} are the quantitative values of the indicators corresponding to exposure, vulnerability, and emergency response and recovery capability, respectively.

5.2. Modeling of Flood Risk Index along the Metro System

In this study, the urban flood risk index (R) and hazard (H) exposure (E) vulnerability (V) are positively correlated and negatively correlated with the emergency response and recovery capability (C).

$$R = H \times E \times V \times (1 - C) \tag{15}$$

6. Results and Analysis

6.1. Hazard, Exposure, Vulnerability, and Emergency Response and Recovery Capability Level Maps

Based on the weights of each indicator, the calculation was made using the raster calculator in GIS, and the results are shown in Figure 7. In this paper, four indicators are selected to assess the hazard of five urban areas in Changchun, mainly guided by rainfall conditions and vegetation cover. As shown in Figure 7a, the rainfall in Changchun increases from east to west in order, and the vegetation cover is concentrated in the south of Jiutai District; the hazard decreases from east to west in this way, but due to the excessive impervious area in the central city, although there is little rainfall, part of the hazard is also in a medium state.

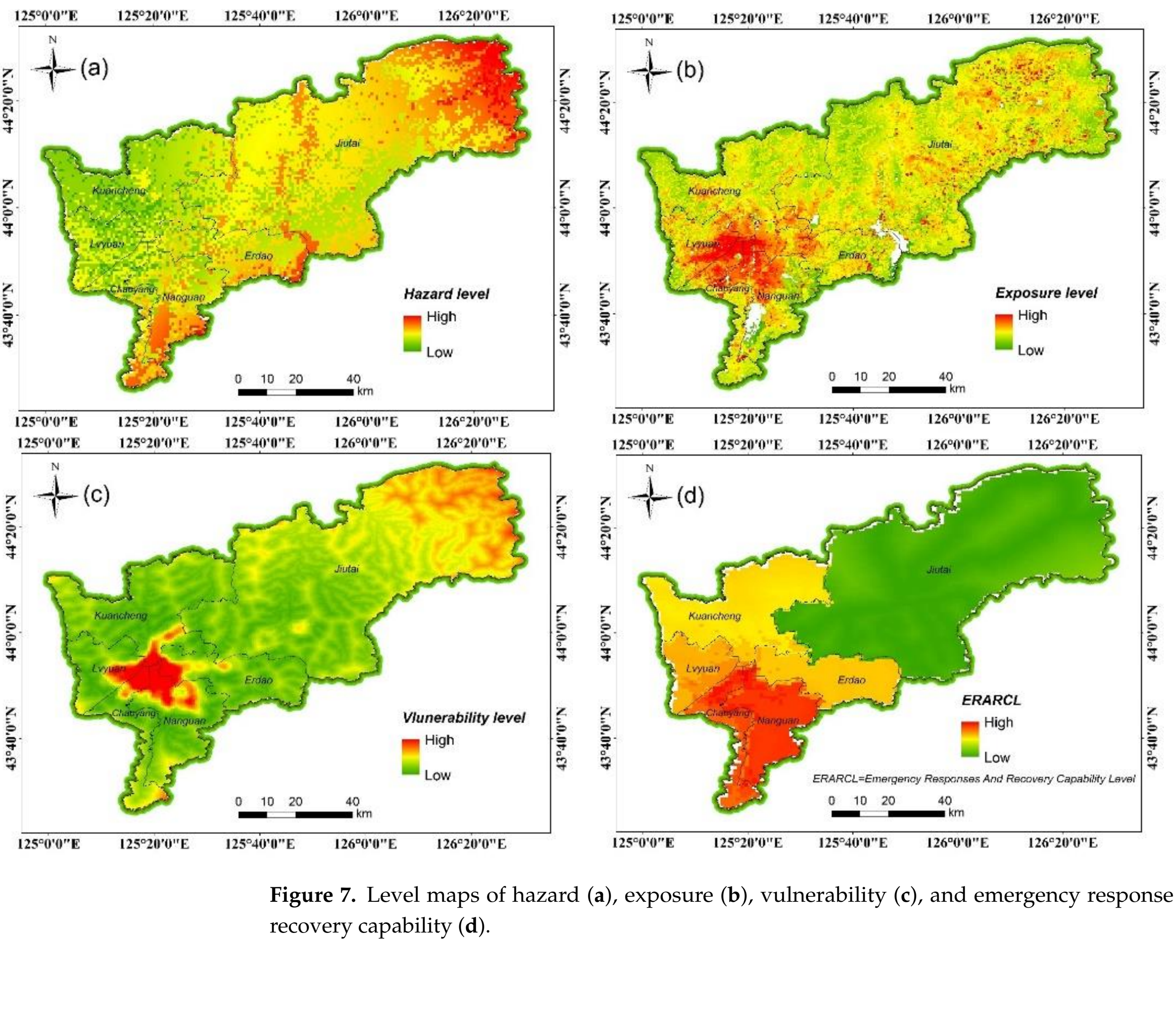

Figure 7. Level maps of hazard (**a**), exposure (**b**), vulnerability (**c**), and emergency response and recovery capability (**d**).

The exposure is measured by seven indicators, such as the population density, elevation, slope, and number of entrances and exits. As shown in Figure 7b, a high exposure is mainly concentrated in the central city of Changchun, where the terrain is low, the population and buildings are very dense, and all of the areas consist of man-made surfaces. Other high-exposure spaces are concentrated around the road and river networks.

The vulnerability is then evaluated by indicators, such as the river network proximity, passenger flow, subway line density, etc. As shown in Figure 7c, the high vulnerability areas are attributed to a higher passenger flow and a high station and line density concentrated along the subway line. The other vulnerable areas are distributed in the Jiutai district, where the vulnerable population is high.

The emergency response and recovery capability factor is evaluated using four indicators, namely, the GDP per capita, education level, distance to main roads, and drainage network density. Figure 7d shows that the places with a high disaster prevention and mitigation capacity are concentrated in the central city with a higher economic level, high education level, and high density of drainage network, and the central city is close to the main roads, which is better for rescue and evacuation.

6.2. Regional Flood Risk and Its Validation

6.2.1. Regional Flood Risk

The regional flood risk is calculated according to Equation (15) and divided into five levels using the natural interruption point method, as shown in Figure 8a. The high-risk areas account for a relatively low percentage, but it is mainly concentrated in the central urban areas in the west, where the economy is prosperous and the population is relatively dense, which still cannot be ignored. Slow-risk areas are mainly concentrated in the east, where the vegetation is dense, the elevation is high, and the population is sparse.

6.2.2. Validation

Changchun is rainy in the summer, which often leads to the flooding of roads and even the formation of more than half a meter of water at lower terrains. In addition, due to the relatively old drainage system, the drainage pipes in many places will be flooded in the case of excessive rainfall and be unable to drain properly, making urban flooding more serious, and forming flooding points. In this paper, we verify the accuracy of the regional flood risk assessment based on the data of more than fifty flooding points published by the Changchun traffic police in 2022. As shown in Figure 8b, the flooding points in Changchun are densely concentrated in the central city, and we vectorized the point data and superimposed them with the regional assessment results to find that 90% of the flooding points are in high-risk areas, which indicates that the results are reliable and can be trusted.

6.3. Flood Risk of Rail Transit Systems and Its Validation

6.3.1. Flood Risk of Rail Transit System

For the metro system, the area it is located in is part of the regional flood risk research object, and the flood risk level along the metro system can be extracted by the regional flood risk. We selected the area of 500 m around the line as a buffer zone for the flood risk assessment of the Changchun City rail transit system, as shown in Figure 9. We used the natural interruption point method to divide it into five levels, so that its risk level can be clearly distinguished.

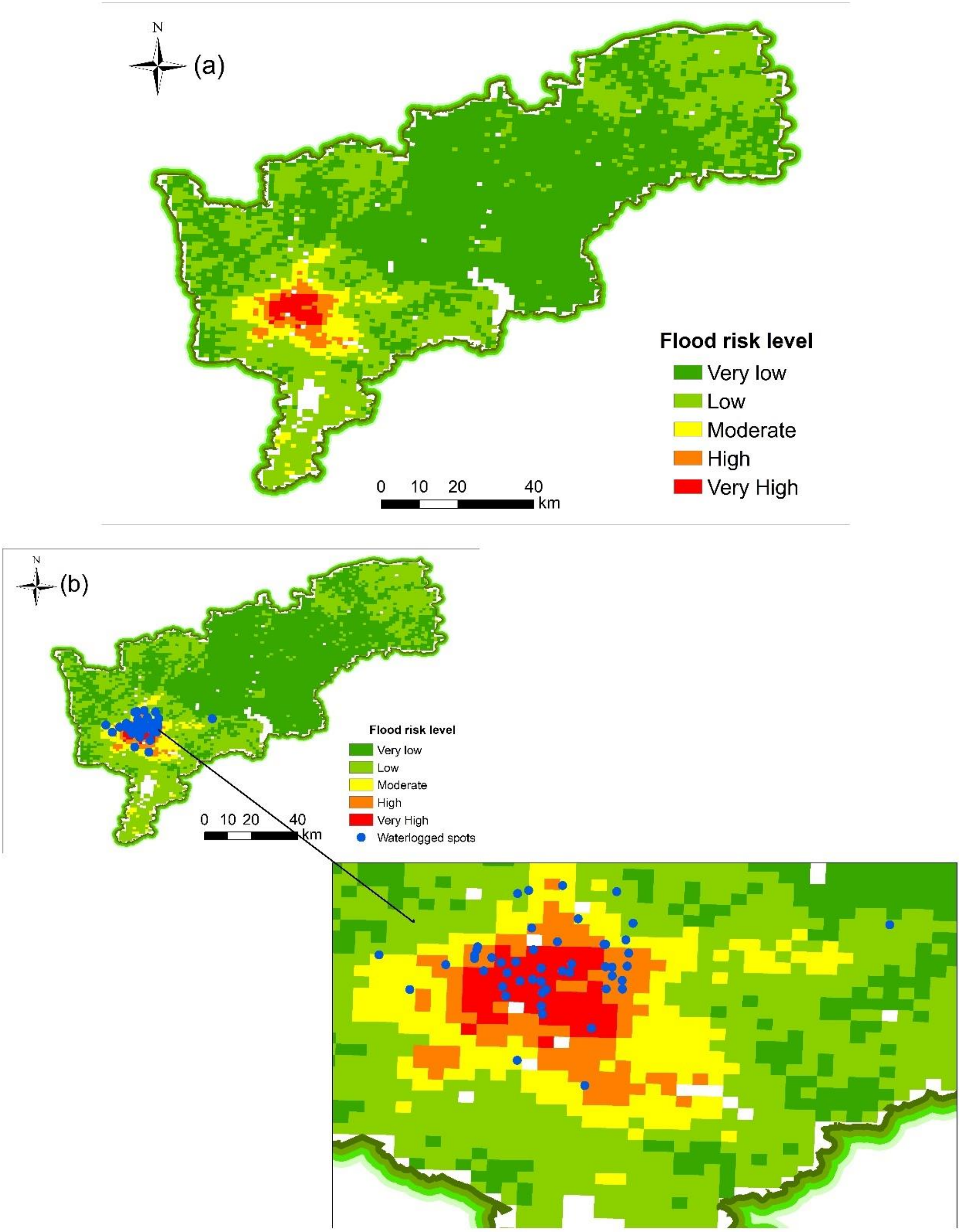

Figure 8. (**a**) Regional flood risk level map; (**b**) regional flood risk level verification map.

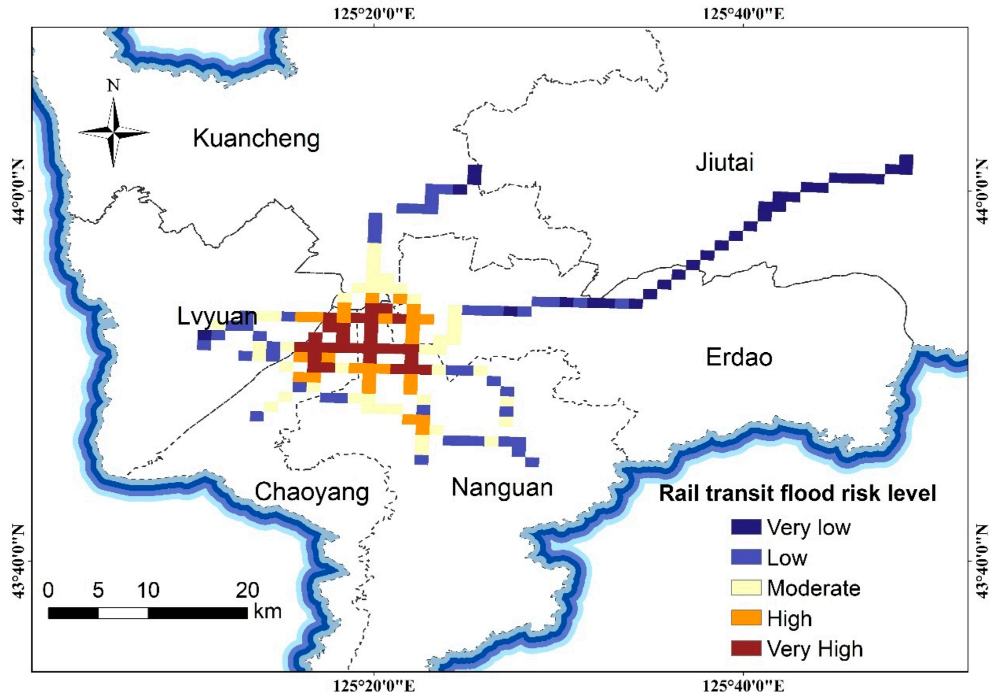

Figure 9. Rail transit flood risk level map.

6.3.2. Validation

Since there is no larger-scale flooding in the Changchun metro system, this paper used the receiver operating characteristic (ROC) curve to verify it, as shown in Figures 9 and 10. The receiver operating characteristic (ROC) curve is widely used for the accuracy validation of binary classification models. The method plots the corresponding curves using the true positive rate as the vertical coordinate and the false positive rate as the horizontal coordinate, and the area under the ROC curve (AUC) value is used to evaluate the accuracy of the flood risk assessment of the Changchun City rail transit system, as shown in Table 4. The ROC curve shows a 91% accuracy rate.

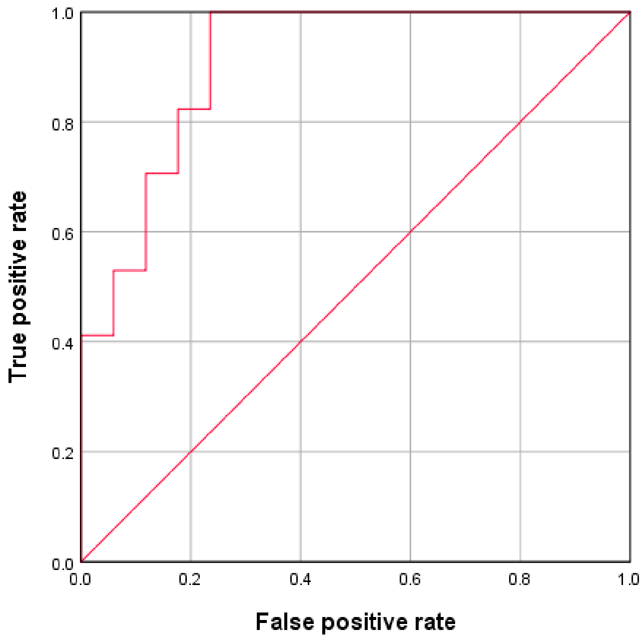

Figure 10. Receiver operating characteristic (ROC) curve.

Table 4. AUC values and their corresponding accuracy.

AUC Value	**0.5–0.6**	**0.6–0.7**	**0.7–0.8**	**0.8–0.9**	**0.9–1.0**
Accuracy	Failed	Different	Normal	Good	Excellent

7. Discussion

The rail transport network in Changchun is undergoing a phase of fast expansion, with several lines under planning to be constructed. There has not been a large-scale subway flood event, and the experience is insufficient, but with the change in climate, extreme weather events will become more frequent and intense, and the possibility of larger flood disasters will increase. In such cases, this study becomes important for the assessment of the flood risk of the rail transit system. This study mainly integrated the AHP and improved entropy weighting methods to evaluate the rail transit system in Changchun City, China. We selected several indicators regarding the metro system, including the passenger flow, metro line density, metro station density, station type, and other indicators, to evaluate the flood risk of the rail transit system. The findings of this study will provide scientific help and guidance for subsequent metro construction planning and enable decision makers to provide protective measures for stations with a higher risk and reduce the impact of flooding. It is worth mentioning that previous studies have not considered the impact of drainage systems on the metro system, and they did not choose drainage networks as an indicator for data reasons. In this study, the drainage network density is chosen as an indicator of the emergency response and recovery capability component, which will play a crucial role in the flood and inundation risk assessment.

The significance of our assessment of the flood risk in Changchun's rail transit system is to identify possible flood risks in advance and take appropriate preventive and mitigation measures to ensure the stable operation of the rail transit system and passenger safety. This can effectively reduce the damage to the city and people's lives and property caused by flood disasters, and can improve the level of emergency management and public services of the city. At the same time, assessing flood risks can also help to promote sustainable urban planning and construction, improve the resilience and adaptability of the city, and protect the line construction afterward. After a thorough review of the literature, we found that the existing research methods mainly focus on the regional flood risk, and the methods of the regional flood risk assessment include (1) the scenario analysis method, (2) the hydrological analysis method, (3) the terrain analysis method, (4) the statistical analysis method, (5) the index system method, (6) the neural network and deep learning method, etc. However, in this paper, we analyzed the metro flooding disaster from several angles and aspects based on the formation theory of disaster. Here, we selected and combined 22 indicators for risk evaluation. The indicator weights were calculated using a combination of the AHP and improved entropy weight methods, and the scientific nature of the weights was heavily optimized to make the evaluation more reasonable and scientific.

Regarding the research methods employed, the scenario analysis method, hydrological analysis method, and statistical analysis method require a substantial amount of accurate data for assessment, and they do not comprehensively consider the influence of human factors on metro system flooding. On the other hand, neural network and deep learning models necessitate significant expertise and technical skills, as well as ensuring the quality, quantity, and accuracy of the relevant data. Considering these limitations, we opted for the index system method to comprehensively assess the metro flood risk, taking into account various factors such as human factors, socio-economic conditions, and infrastructure issues. Additionally, we considered the impact of the metro system and drainage infrastructure to comprehensively address the problems caused by disasters.

In recent years, increased attention has been paid to the metro flood risk. Lyu et al. (2018) employed the I-AHP modeling approach to study the flood hazard in Guangzhou's metro system [1], while Wang et al. (2021) used the FAHP approach to analyze the flood hazard risk in a large metro system in Beijing. Both studies utilized improved AHP methods for the flood risk assessment in metro systems [2]. However, although the I-AHP and FAHP approaches, to some extent, mitigate the influence of subjective factors, their effectiveness in this regard is limited, insufficient, and one-sided. In this paper, we utilize the AHP method and an improved entropy weight method to not only analyze the problem subjectively, but also to combine subjective and objective perspectives to analyze and address the issue from a different level. As a result, we provide practical recommendations for the rail transit system in Changchun, offering suggestions for disaster prevention in the already established lines as well as for lines 5, 6, 7, and 9, which are currently under construction.

When evaluating the flood risk of the entire metro system, it is crucial to consider the influence of the subsidence environment on the flood risk. However, as Changchun is not a resource-based city and does not heavily rely on groundwater extraction, it has not experienced significant subsidence in recent years. Therefore, this paper does not take into account the flood risk of the Changchun rail transit system in the subsidence environment. It should be noted that this assessment is not absolute for the future, and future studies should consider the flood risk of the Changchun rail transit system environment.

8. Conclusions

As a city where the rail transit system will develop rapidly in the future, this study proposes a method based on the GIS combined with the AHP and improved entropy weight methods to assess the flood risk of Changchun's future rail transit system under frequent and intense extreme weather events in current and future scenarios. The main conclusions of this study are as follows:

(1) The flood risk of Changchun's rail transit system is decreasing from the central urban area to the surrounding areas, reflecting a dispersion from the center to the outside. The rail transit located in the central urban area has a higher risk level, and the lines that are under construction need to be prepared in advance for prevention, while those that are already built need more human and material resources for protection.

(2) The very-high-risk and high-risk areas of the Changchun rail transit system account for 15% and 16.2%, respectively. Both of these two risk categories account for a total of 31.2% of the total area, most of which is located in the central urban area. A large area of rail transit is at a higher risk of flooding and needs to be paid attention to in order to prevent flooding in the future.

(3) In this paper, we proposed an MCDA method based on GIS combined with the AHP and improved entropy weight methods using the following four factors of disaster for the first time: hazard, exposure, vulnerability, and emergency response and recovery capability. Based on this integrated approach, we established a risk assessment system containing 22 indicators from disaster formation theory. Because the indicator system established by this method is complete and integrates several aspects, it can be quickly applied to different cities and facilitated for other urban researchers.

Although the assessment of the subway flood risk is essentially an assessment of the regional flood risk, the 500 m buffer zone that we extracted does not directly reflect the flood risk of the overall Changchun rail transit system. This method has some limitations and uncertainty, which should be optimized in future research to select a suitable model for its direct assessment.

Author Contributions: Conceptualization, G.L.; Methodology, G.L. and Q.L.; Formal analysis, G.L. and J.Z.; Data curation, G.L. and Z.W.; Writing—original draft, G.L.; Writing—review & editing, J.Z. and Y.C.; Funding acquisition, Y.Z. and H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key Scientific and Technology Research and Development Program of Jilin Province (20200403074SF); the Key Scientific and Technology Research and Development Program of Jilin Province (20180201033SF); and the Key Scientific and Technology Research and Development Program of Jilin Province (20180201035SF).

Data Availability Statement: The codes and data for this article are freely available at https://www.gscloud.cn (accessed on 5 December 2022), http://data.cma.cn/ (accessed on 25 February 2023), https://www.databox.store (accessed on 21 January 2023), and http://www.guihuayun.com/ (accessed on 6 October 2022).

Conflicts of Interest: The authors declare no conflict of interest.

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