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Suitability Assessment of Multilayer Urban Underground Space Based on Entropy and CRITIC Combined Weighting Method: A Case Study in Xiong'an New Area, China

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Abstract: Suitability assessment is an essential initial step in the scientific utilization of underground space. It plays a significant role in providing valuable insights for optimizing planning and utilization strategies. Utilizing urban underground space has the potential to enhance the capacity of urban infrastructure and public service facilities, as well as mitigate issues such as traffic congestion and land scarcity. To effectively plan and utilize urban underground space, it is crucial to conduct a suitability assessment. This assessment helps identify the factors that influence the utilization of underground space and their impacts, offering guidance on avoiding unfavorable conditions and ensuring the safety of planned underground facilities. To achieve objective and reasonable evaluation results, this paper proposed an assessment method that combines entropy and CRITIC (CRiteria Importance Through Intercriteria Correlation) weighting. Taking Xiong'an New Area as a study area, a suitability assessment indicator system for underground space was established. The system included criteria indicators and sub-criteria indicators. By analyzing the weights, the study identified the difference of suitability and critical affecting factors for shallow, sub-shallow, sub-deep, and deep underground space. The results showed that deep layers had better suitability than shallow layers in the study area. The regions with inferior and worse suitability were mostly located around Baiyangdian Lake, with proportions of acreage at 54.69% for shallow layer, 42.06% for sub-shallow layer, 41.69% for sub-deep layer, and 42.03% for deep layer. Additionally, the dominant affecting factors of suitability varied in different layers of underground space. These findings provide valuable evidence for the scientific planning and disaster prevention of underground space in Xiong'an New Area, and also serve as references for studying suitability in other areas.

Keywords: multilayer underground space; suitability assessment; entropy; CRITIC; Xiong'an New Area

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1. Introduction

Due to rapid urbanization, many cities are facing saturation in the utilization of aboveground land, leading to problems such as traffic congestion and land resource shortage [1,2]. To accommodate urban sustainable development, the utilization of underground space has emerged as an efficient means to expand urban space [3–5]. Therefore, integrated planning that includes both aboveground and underground space is considered an optimal approach [6,7]. Unlike aboveground space, underground space is a non-renewable resource that is difficult to transform once built into some kind of infrastructure. As a result, conducting suitability assessment of underground space before urban planning becomes particularly significant.

Existing research shows that, as the carrier of underground space, the geological environment plays a crucial role in the utilization of underground space [8]. Understanding how the geological environment constrains the use of underground space and identifying the geological factors that affect it can help in avoiding or transforming unfavorable geological conditions. In particular, in newly building cities, the utilization of underground space is primarily influenced by geological factors rather than existing surface buildings and underground infrastructure, unlike in already built-up cities [9]. Assessing suitability can provide valuable insights for optimizing planning and utilization strategies of underground space. Therefore, studying the geological suitability of underground space holds significant theoretical and practical importance.

Existing studies on the suitability of underground space primarily rely on geological analysis, which is an essential and valid method [10,11]. The assessment system for the suitability of urban underground space (UUS) incorporates various geological factors, which differ depending on the region's geological characteristics [12–14]. These factors typically include active faults, land subsidence, groundwater level, bearing capacity of soils, compression of soils, ground elevation, sands liquefaction, soft soils [15–18]. However, while researchers generally agree on the geological factors that affect the suitability of underground space in the same study area, they may differ in the weights assigned to these factors. Therefore, the critical issue lies in selecting an assessment method that incorporates reasonable indicator weights. Various methods have been developed to analyze the suitability of underground space, including AHP (analytic hierarchy process) [19–21], entropy [22–24], neural network [25,26], fuzzy mathematics [27–29], TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [16,30], etc. The combined application of different methods has been shown to be more reasonable [31–33], considering that each method has its own advantages and disadvantages [34,35]. The critical issues in the selection of an assessment method are the objectivity of weights, correlation, discreteness, and comparative intensity of affecting factors. In this paper, an entropy and CRITIC (Criteria Importance Through Intercriteria Correlation) combined weighting method was applied to obtain reasonable weights. The entropy method, derived from information theory [36], was used to derive objective weights but focused on discreteness while ignoring correlation and comparative intensity of data [11,37]. However, the CRITIC method can effectively compensate for this deficiency [38–40]. Therefore, the combination of these two methods ensures the rationality of the objective weight of the selected indicators.

Consequently, taking Xiong'an New Area, a newly planned city, as a case study, this research established a multilayer assessment indicator system for the underground space. The study also identified the suitability and critical affecting factors of underground space. It is important to note that this paper specifically focused on the geological characteristics that affect the utilization of urban underground space (UUS), while other socioeconomic factors were not considered.

2. Study Area

The Xiong'an New Area, established as a national new district in 2017, is located in the eastern alluvial plain of the Taihang Mountains, at the central part of the North China Plain. It covers an area of 1770 km^2 and mainly consists of Rongcheng County, Anxin County, and Xiongxian County (Figure 1) [41]. Geographically, these counties are located within Hebei Province. The ground elevation in the area is less than 26 m, and the terrain is relatively flat. The study area is characterized by Quaternary deposits with a depth of over 100 m [42]. It is situated in the Jizhong platform depression, where buried faults are relatively well-developed, but modern activities are very weak [43]. The climate of the study area falls under the warm temperate continental monsoon zone, with an average annual temperature of 12.1 °C, average precipitation of 478 mm, and a maximum evaporation of 1762 mm [44,45]. Additionally, the area is home to Baiyangdian Lake, the largest freshwater wetland in the North China Plain [46].

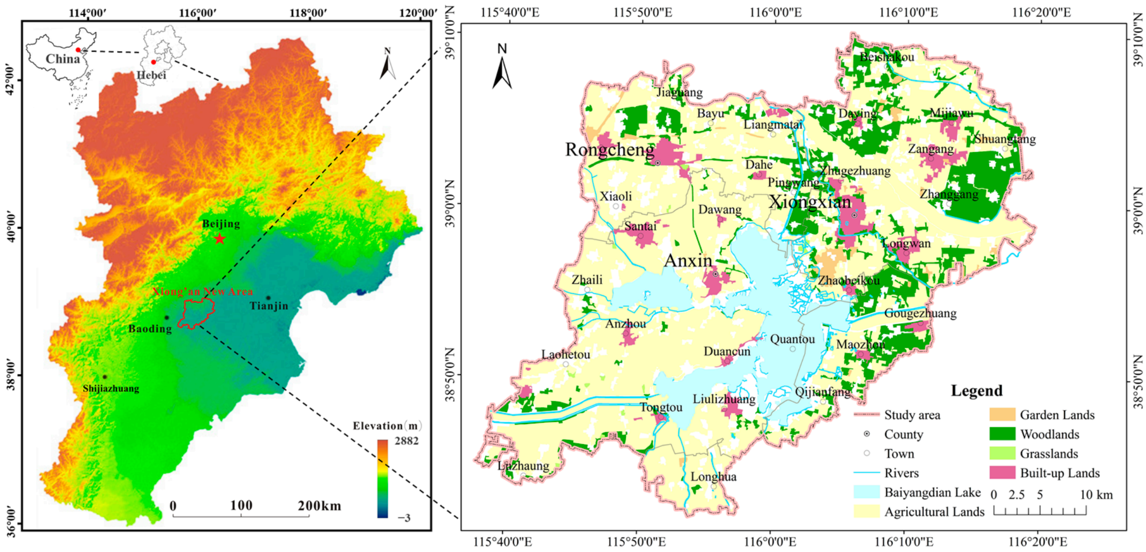


Figure 1. Location of the study area.

Furthermore, in accordance with the Planning Outline of Xiong'an New Area, the urban underground space will be utilized in an orderly manner based on different depth levels. These depth levels include the shallow layer (L_1: 0~−15 m), sub-shallow layer (L_2: −15~−30 m), sub-deep layer (L_3: −30~−50 m), and deep layer (L_4: −50~−100 m). The shallow and sub-shallow layers will be actively exploited, while the sub-deep and deep layers will be appropriately utilized.

3. Materials and Methods

3.1. Establishment of Suitability Assessment Frame

During the initial phase of assessing the suitability of urban underground spaces, a system of assessment indicators was developed by analyzing geological factors. Figure 2 illustrates four types of criteria indicators: topography, geotechnical characteristics, hydrogeological conditions, and adverse geological phenomena. These criteria indicators include various sub-criteria indicators and were considered in the suitability assessment. Some of these indicators are positive, such as geotechnical characteristics, where a larger value indicates better suitability of urban underground spaces. On the other hand, some indicators are negative, such as adverse geological phenomena, which indicate the opposite. To obtain comprehensive evaluation results, data on sub-criteria indicators from multiple layers should be obtained beforehand. Topography indicators, including ground elevation, were obtained from DEM (Digital Elevation Model) measurements. Geotechnical characteristics, such as bearing capacity and compression modulus of soils, were determined through standard penetration tests, shear tests, and geotechnical tests conducted in engineering geological boreholes. Hydrogeological conditions, such as groundwater buried depth, were measured in the field through groundwater level measurements, while aquifer thickness was inferred from lithology data obtained from geological boreholes. Adverse geological phenomena, such as land subsidence rate, were measured using InSAR (Interferometric Synthetic Aperture Radar) remote sensing. Sands liquefaction index was determined through standard penetration tests conducted in the engineering geological boreholes, and chemical corrosion of groundwater and soils was assessed through chemical experiments. All the aforementioned work was carried out by the China Geological Survey project.

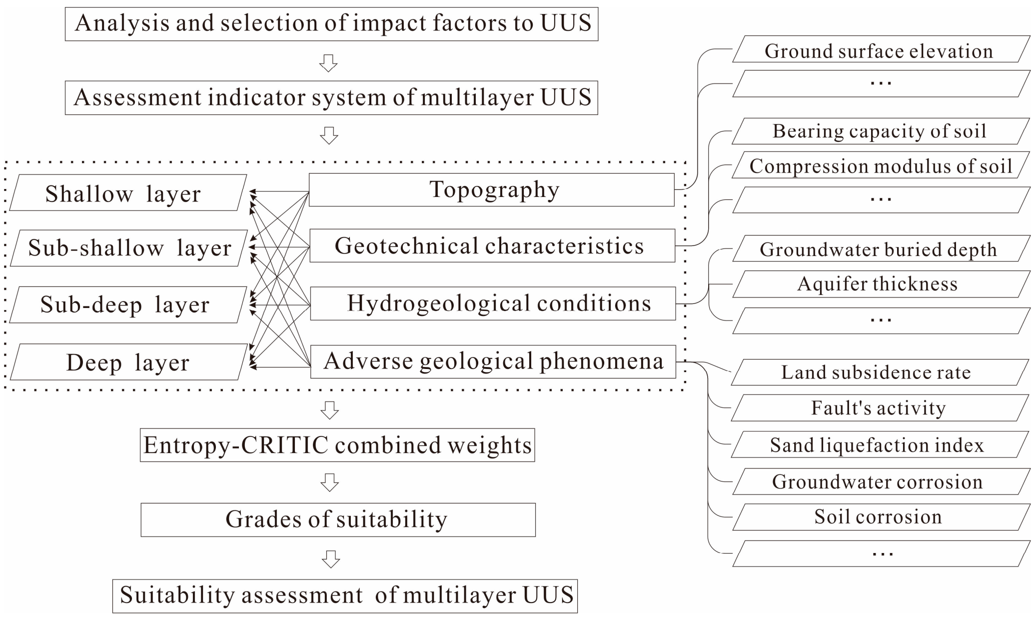


Figure 2. Frame flow chart of suitability assessment to UUS.

The relationships among various indicators were analyzed using entropy and CRITIC methods to determine the combined weights that represent the significance of different indicators. These indicator weights were then input into the evaluation model, which was the weighted average comprehensive index model, to calculate the comprehensive indexes of geological suitability. The final maps of grading evaluation for the multilayer UUS were generated using ArcGIS 10.8 software.

3.2. Establishment of Assessment Model

The suitability of underground space in Xiong'an New Area is evaluated using the weighted average comprehensive index model. The comprehensive index, *CI*, is obtained through the assignment of scores to indicators and calculation of indicator weights. The assessment model is as follows:

$$CI = \sum_{j=1}^{n} k_j \cdot w_j, j = 1, 2, \cdots, n$$

where *CI* is the comprehensive index, w_j is the indicator weight, k_j is the score assignment of the indicator, and n is the number of indicators.

3.3. Calculation of the Entropy-CRITIC Combined Weights

3.3.1. Entropy Weighting

(1) Establish an initial assessment indicators matrix, X.

$$X = (X_{ij})_{m\times n} \tag{1}$$

where m is the number of evaluating objects, n is the number of indicators, i is the i-th object, and j is the j-th indicator.

(2) Construct a normalization matrix, Y.

$$Y = (Y_{ij})_{m\times n} \tag{2}$$

where Y_{ij} satisfies the following Equations (3) or (4):

$$Y_{ij} = \frac{X_{ij} - minX_j}{maxX_j - minX_j}. \quad (3)$$

Here, j is a positive indicator.

$$Y_{ij} = \frac{maxX_j - X_{ij}}{maxX_j - minX_j}. \quad (4)$$

Here, j is a negative indicator.

(3) Calculate the contribution of the i-th object to the j-th indicator, P_{ij}.

$$P_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{m} Y_{ij}} \quad (5)$$

(4) Calculate the entropy value of the j-th indicator, E_j.

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

where $k = 1/\ln m$.

(5) Calculate the otherness coefficient of the j-th indicator, G_j.

$$G_j = 1 - E_j \quad (7)$$

(6) Calculate the entropy weight coefficient of the j-th indicator, v_j.

$$v_j = \frac{G_j}{\sum_{j=1}^{n} G_j} \quad (8)$$

3.3.2. CRITIC Weighting

(1) Based on Equation (2), the standard deviation of the j-th indicator, S_j, is calculated.

$$S_j = \sqrt{\frac{\sum_{i=1}^{m} \left(Y_{ij} - \overline{Y}_j\right)^2}{n-1}} \quad (9)$$

(2) Based on Equation (2), the correlation coefficient between the b-th and j-th indicators, r_{bj}, is calculated.

$$r_{bj} = \frac{\sum_{b,j=1}^{n} \left(Y_{ib} - \overline{Y}_b\right)\left(Y_{ij} - \overline{Y}_j\right)}{\sqrt{\sum_{b=1}^{n} \left(Y_{ib} - \overline{Y}_b\right)^2 \sum_{j=1}^{n} \left(Y_{ij} - \overline{Y}_j\right)^2}} \quad (10)$$

(3) Calculate the conflicting characteristic between the b-th and j-th indicators, A_j.

$$A_j = \sum_{b=1}^{n} \left(1 - r_{bj}\right) \quad (11)$$

(4) Calculate the quantity of information contained in j-th indicator, C_j.

$$C_j = S_j\, A_j \quad (12)$$

(5) Calculate the weight coefficient of the j-th indicator, u_j.

$$u_j = \frac{C_j}{\sum_{j=1}^{n} C_j} \quad (13)$$

3.3.3. Combined Weighting

Based on v_j and u_j, the combination weight of j-th indicator, w_j, is calculated.

$$w_j = \frac{v_j u_j}{\sum_{j=1}^{n} v_j u_j} \tag{14}$$

4. Results

4.1. Assessment Indicator System

Based on the actual geological conditions of the study area, an assessment indicator system was established, comprising four kinds of criteria indicators: topography, geotechnical characteristics, hydrogeological conditions, and adverse geological phenomena (Table 1). Additionally, the assessment of four application layers of UUS (L_1: 0~−15 m, L_2: −15~−30 m, L_3: −30~−50 m, L_4: −50~−100 m) involved the evaluation of different combinations of sub-criteria indicators. These sub-criteria indicators included ground elevation, bearing capacity of soils, compression modulus of soils, groundwater buried depth, aquifer thickness, land subsidence rate, sands liquefaction index, chemical corrosion of groundwater, and chemical corrosion of soils (Table 1).

Table 1. Assessment indicators of suitability to multilayer UUS in the study area.

Criteria Indicators	Sub-Criteria Indicators (Unit)	Grading Criteria of Suitability				Application Layer
		Grade I	Grade II	Grade III	Grade IV	
Topography	Ground elevation (m)	<8	8~8.5	8.5~9	>9	L_1~L_4
Geotechnical characteristics	Bearing capacity of soils (0~−5 m) (kPa)	<80	80~100	100~130	>130	L_1
	Bearing capacity of soils (−5~−10 m) (kPa)	<100	100~130	130~160	>160	L_1
	Bearing capacity of soils (−10~−15 m) (kPa)	<110	110~130	130~170	>170	L_1
	Bearing capacity of soils (−15~−30 m) (kPa)	<130	130~160	160~200	>200	L_2
	Bearing capacity of soils (−30~−50 m) (kPa)	<130	130~160	160~200	>200	L_3
	Bearing capacity of soils (−50~−100 m) (kPa)	<130	130~160	160~200	>200	L_4
	Compression modulus of soils (0~−5 m) (MPa)	<4	4~11	11~15	>15	L_1
	Compression modulus of soils (−5~−10 m) (MPa)	<4	4~11	11~15	>15	L_1
	Compression modulus of soils (−10~−15 m) (MPa)	<4	4~11	11~15	>15	L_1
	Compression modulus of soils (−15~−30 m) (MPa)	<4	4~11	11~15	>15	L_2
	Compression modulus of soils (−30~−50 m) (MPa)	<4	4~11	11~15	>15	L_3
	Compression modulus of soils (−50~−100 m) (MPa)	<4	4~11	11~15	>15	L_4

Table 1. *Cont.*

Criteria Indicators	Sub-Criteria Indicators (Unit)	Grading Criteria of Suitability				Application Layer
		Grade I	Grade II	Grade III	Grade IV	
Hydrogeological conditions	Groundwater buried depth (m)	<5	5~10	10~15	>15	L_1~L_4
	Aquifer thickness (0~−15 m) (m)	>7.5	5~7.5	2.5~5	<2.5	L_1
	Aquifer thickness (−15~−30 m) (m)	>7.5	5~7.5	2.5~5	<2.5	L_2
	Aquifer thickness (−30~−50 m) (m)	>7.5	5~7.5	2.5~5	<2.5	L_3
	Aquifer thickness (−50~−65 m) (m)	>7.5	5~7.5	2.5~5	<2.5	L_4
	Aquifer thickness (−65~−80 m) (m)	>7.5	5~7.5	2.5~5	<2.5	L_4
	Aquifer thickness (−80~−100 m) (m)	>7.5	5~7.5	2.5~5	<2.5	L_4
Adverse geological phenomena	Land subsidence rate (mm/a)	>50	30~50	10~30	<10	L_1~L_4
	Sands liquefaction index	>18	6~18	<6	0	L_1
	Chemical corrosion of groundwater	Strong	Medium	Weak	Micro	L_1~L_4
	Chemical corrosion of soils	Strong	Medium	Weak	Micro	L_1~L_4

The suitability of underground space in the study area was categorized into four grades: grade I (Worse suitability), grade II (Inferior suitability), grade III (Moderate suitability), and grade IV (Good suitability) [15,18]. The classification of ground elevation, chemical corrosion of groundwater, and chemical corrosion of soils was based on the grading criteria outlined in the 'Code for geo-engineering site investigation and evaluation of urban and rural planning (CJJ57-2012)'. The classification of bearing capacity of soils and compression modulus of soils was referenced from Gao's grading criteria [47]. The land subsidence rate was classified according to the grading criteria specified in the 'Specifications for risk assessment of geological hazard (GB/T 40112-2021)', while the sands liquefaction index was classified based on the grading criteria provided in the 'Code for seismic design of buildings (GB 50011-2010)'. The classification of groundwater buried depth and aquifer thickness was determined in accordance with the recommendations of local geological experts.

4.2. Characteristics of Geological Indicators

4.2.1. Topography

The study area exhibited distinct sedimentary facies characteristics, with an alluvial-proluvial facies observed in the northwestern region and an alluvial-lacustrine facies observed in the southeastern region. This differentiation in sedimentary facies was roughly delineated by the connection line between Rongcheng urban districts and northern Anxin [48].

Based on the DEM elevation measuring data in 2021 (Figures 3 and 4), the study area exhibited a relatively flat topography with a gradual decrease in elevation from northwest to southeast, characterized by a gradient of less than 2‰. The ground elevation mostly ranged between 6 m and 10 m, with the highest point reaching 26 m in Jiaguang town, Rongcheng County. However, around Baiyangdian Lake, the ground elevation was less than 5 m. It is important to note that when the ground elevation drops below 9 m, there is a potential risk of inundation for underground space, as indicated by the warning water level of Baiyangdian Lake.

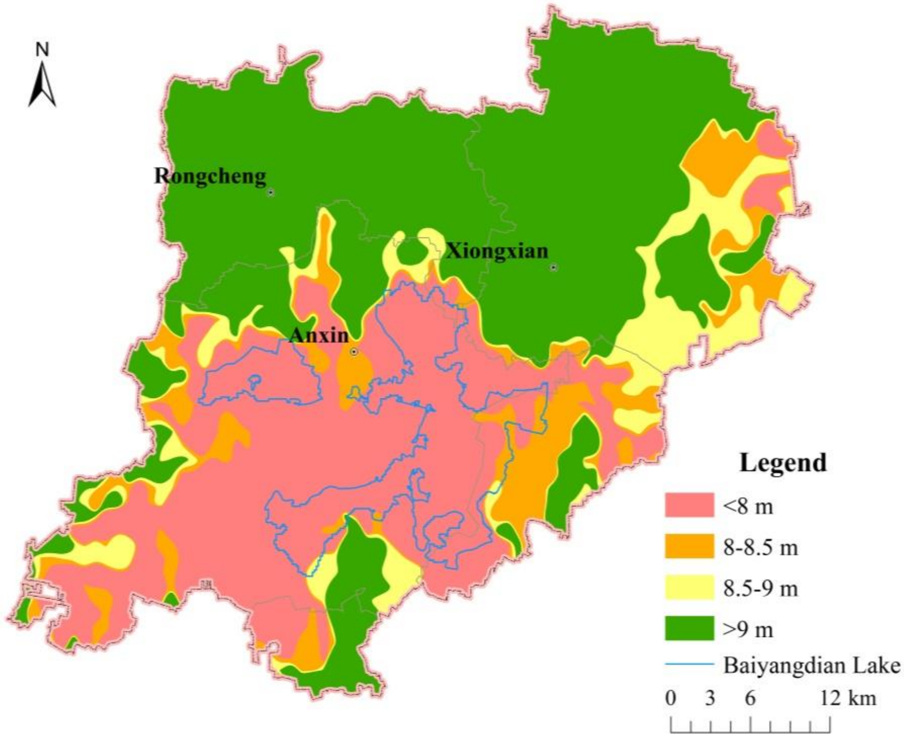


Figure 3. Zoning map of ground elevation.

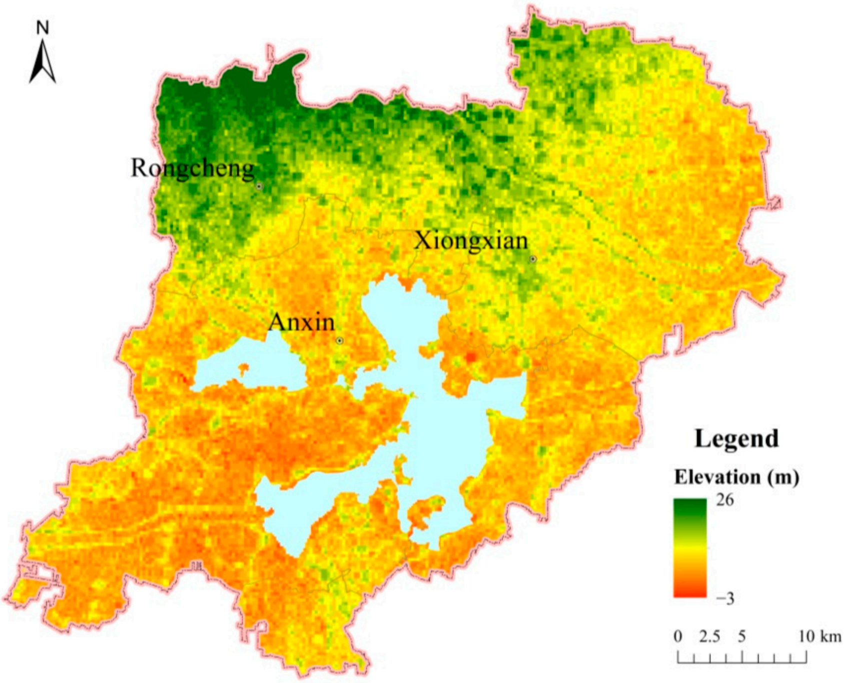
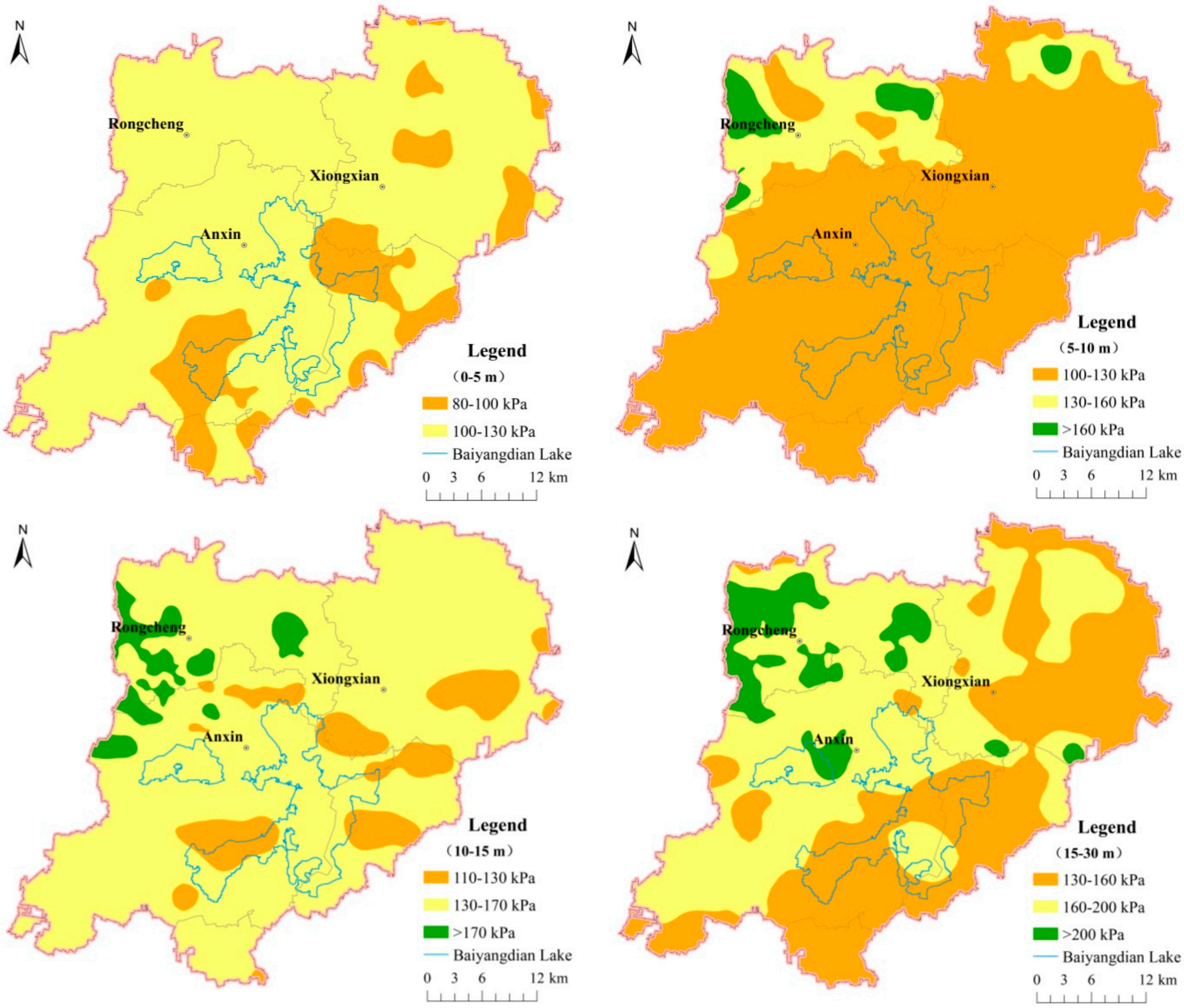


Figure 4. DEM map of ground elevation.

4.2.2. Geotechnical Characteristics

The planning areas of underground space were found to be deposited with Quaternary soils, which consisted of sands, clays, and silts. Additionally, the main soil layers were evenly distributed to a certain extent, and their sedimentary rhythm was relatively stable. The geotechnical test data, including natural void ratio, liquidity index, and organic matter content, did not indicate the presence of soft soils.

The bearing capacity and compression modulus of the soils varied with depth. Based on data from standard penetration tests, shear tests, and geotechnical tests conducted in engineering geological boreholes, the bearing capacity of each individual soil layer was determined. The bearing capacity of the foundation soils at different depths was then calculated by integrating the data of the individual soil layers using the weighted average method. The bearing capacity ranges for depths of 0~−5 m, −5~−10 m, −10~−15 m, −15~−30 m, −30~50 m, and −50~−100 m were found to be 95~130 kPa, 100~180 kPa, 110~250 kPa, 145~240 kPa, 180~280 kPa, and 180~280 kPa, respectively (Figure 5). Additionally, the compression modulus of the soils at different depths was determined based on lateral confined test data. The majority of the compression modulus values for depths of 0~−5 m, −5~−10 m, −10~−15 m, −15~−30 m, −30~−50 m, and −50~−100 m ranged from 4 MPa to 15 MPa (Figure 6).



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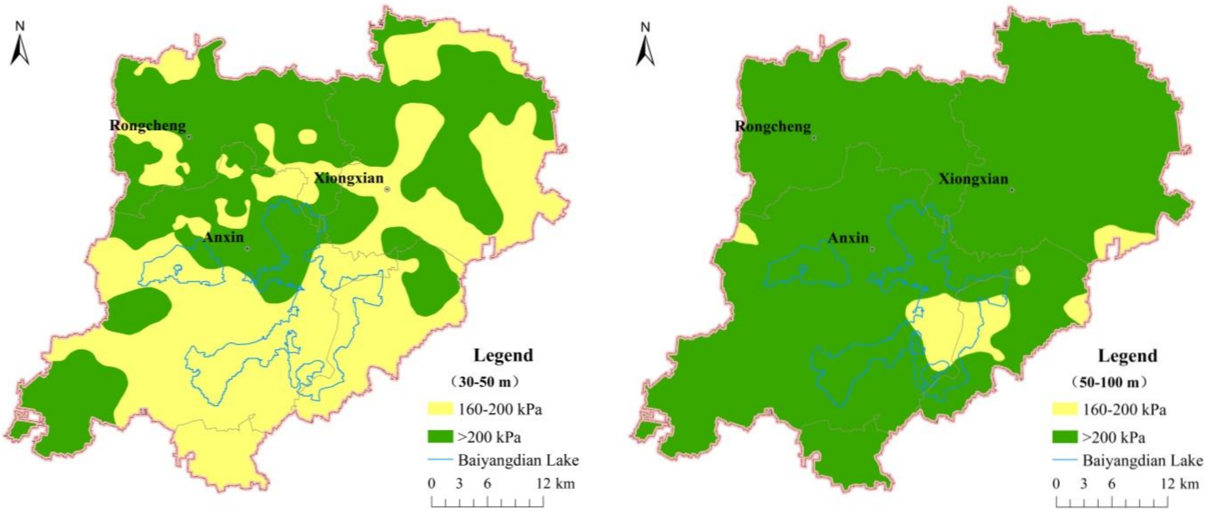
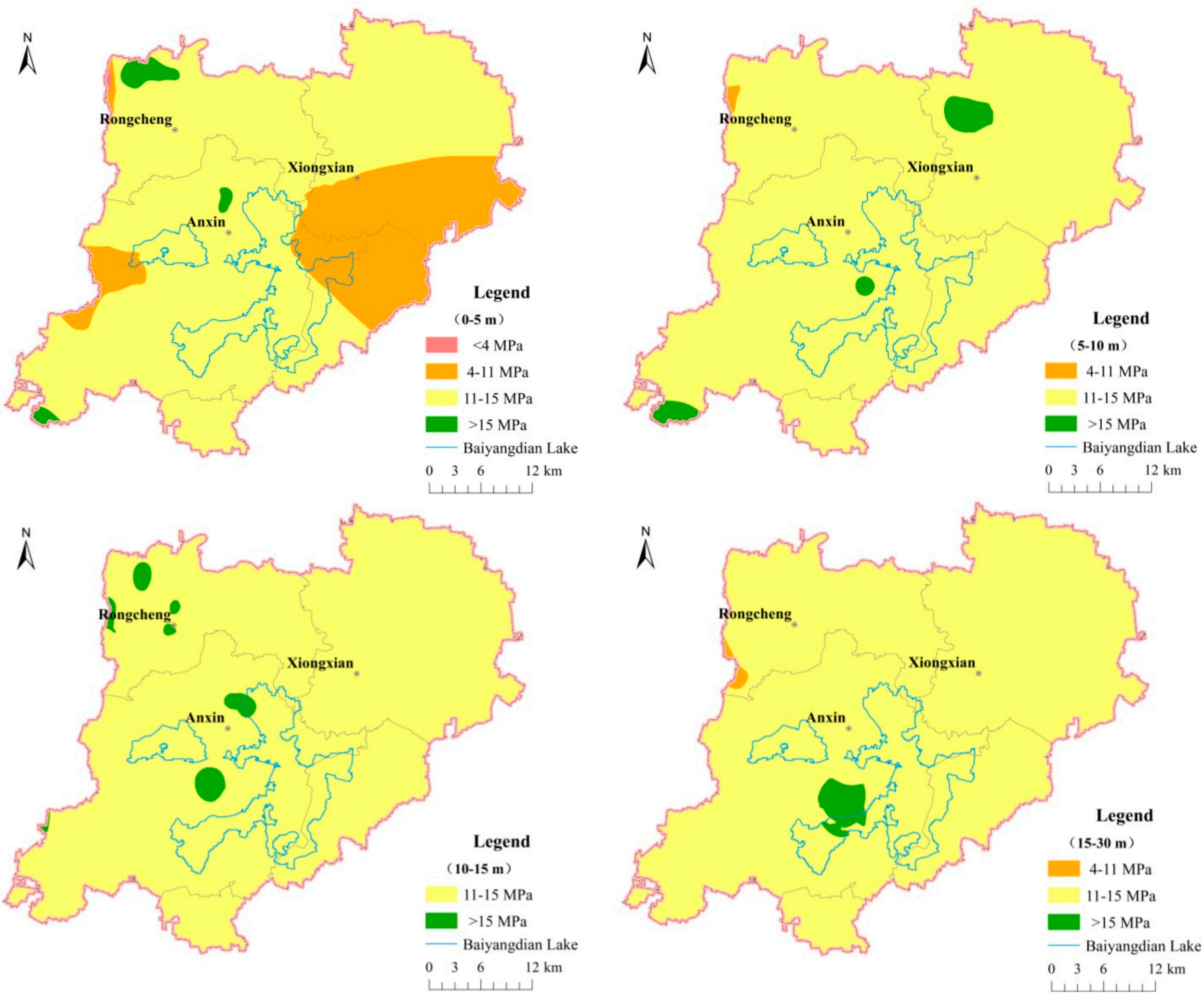


Figure 5. Bearing capacity zoning map of soils within different buried depths.



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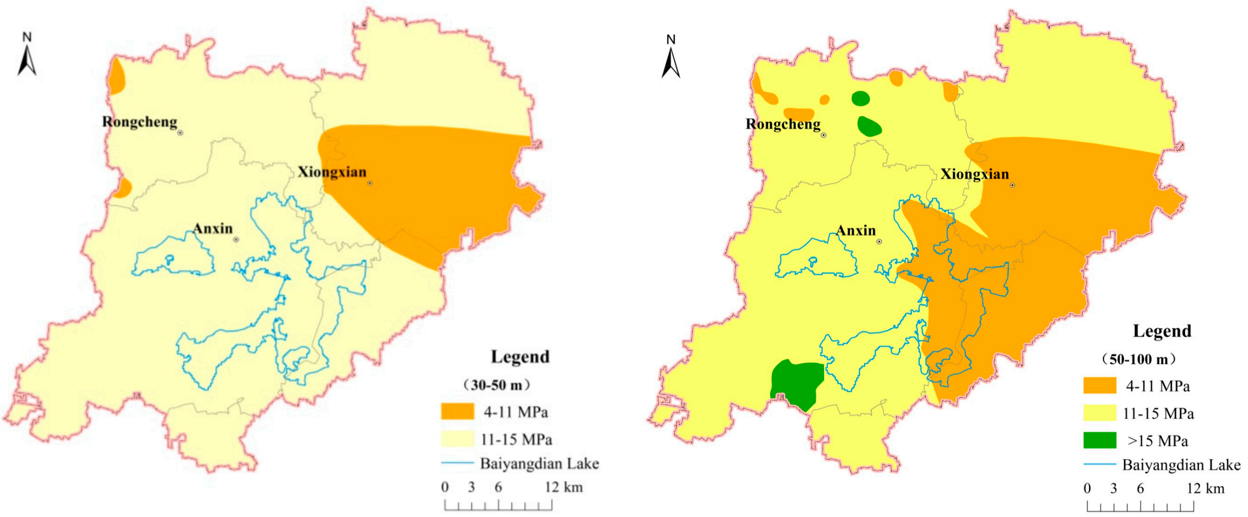
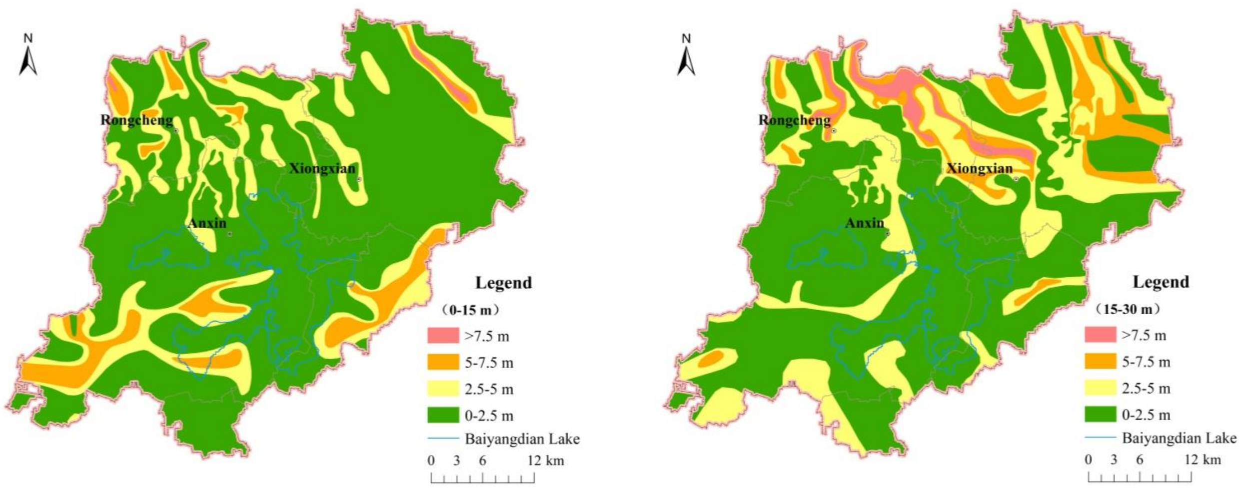


Figure 6. Compression modulus zoning map of soils within different buried depths.

4.2.3. Hydrogeological Conditions

The regional aquifer structure was determined by generalizing the lithology data obtained from geological boreholes in the Quaternary strata. Within a depth of 100 m, there were six relatively continuous aquifers located at different intervals: 0~−15 m, −15~−30 m, −30~−50 m, −50~−65 m, −65~−80 m, and −80~−100 m. Although the thickness of each aquifer varied regionally, the average thickness in most areas was less than 2.5 m (Figure 7).

Based on the measurement data of groundwater level in 2021, it was observed that the predominant buried depth of mixed groundwater in six aquifers was between 5 m and 20 m (Figure 8). However, the surrounding zone of Baiyangdian Lake exhibited a lesser depth of less than 5 m. In general, the groundwater flow direction under current conditions was observed to be from northwest to southeast [49].



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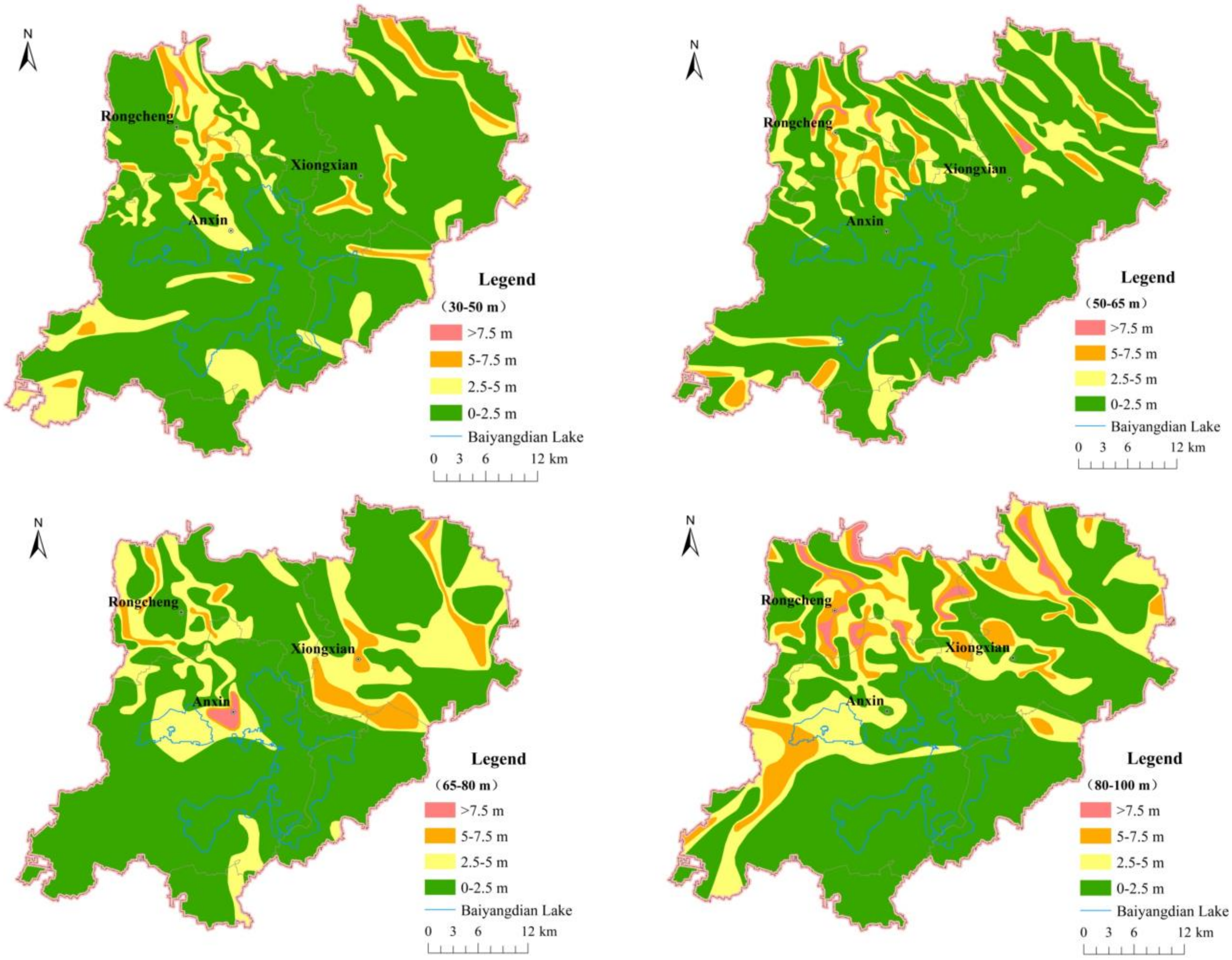

Figure 7. Aquifer thickness zoning map of soils within different buried depths.

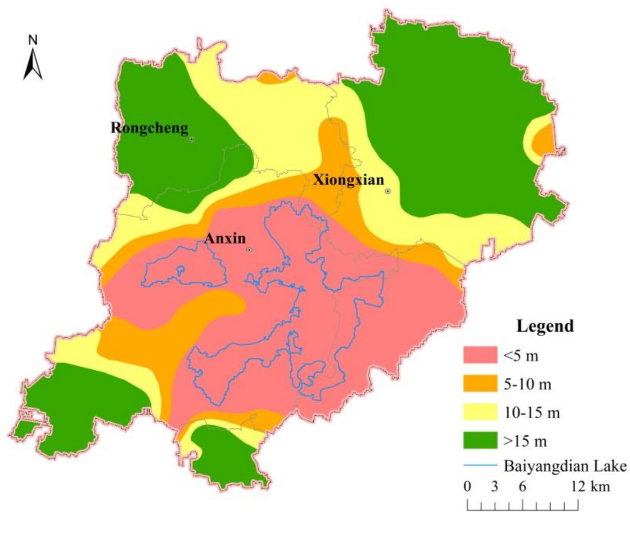

Figure 8. Zoning map of groundwater buried depth.

4.2.4. Adverse Geological Phenomena

Based on the comprehensive geophysical prospecting and borehole stratigraphic dislocation records, multiple faults were detected in Xiong'an New Area, such as the Niudong fault, Rongdong fault [50]. However, these faults have shown inactive features since the

Late Pleistocene, suggesting a relatively stable geological structure [43,51]. Nonetheless, there have been some adverse geological phenomena observed [52], including land subsidence, liquefaction of sands, chemical corrosion of groundwater, and chemical corrosion of soils.

According to the PS-InSAR (Persistent Scatterer Interferometric Synthetic Aperture Radar) remote sensing data during 2021, the land subsidence rate exhibited spatial variation (Figure 9). Most regions showed a rate lower than 10 mm/a, while several northern sites displayed higher rates of more than 30 mm/a. The sands liquefaction index was calculated based on the data of standard penetration tests conducted in the engineering geological boreholes. According to the index, potential sands liquefaction would primarily occur in the central and southern parts of the study area (Figure 10), considering the current groundwater buried depth. The corrosion intensity of both groundwater and soils, as observed from the data of groundwater chemical and soil chemical experiments, showed distribution characteristics of being higher in the southeast and lower in the northwest (Figures 11 and 12).

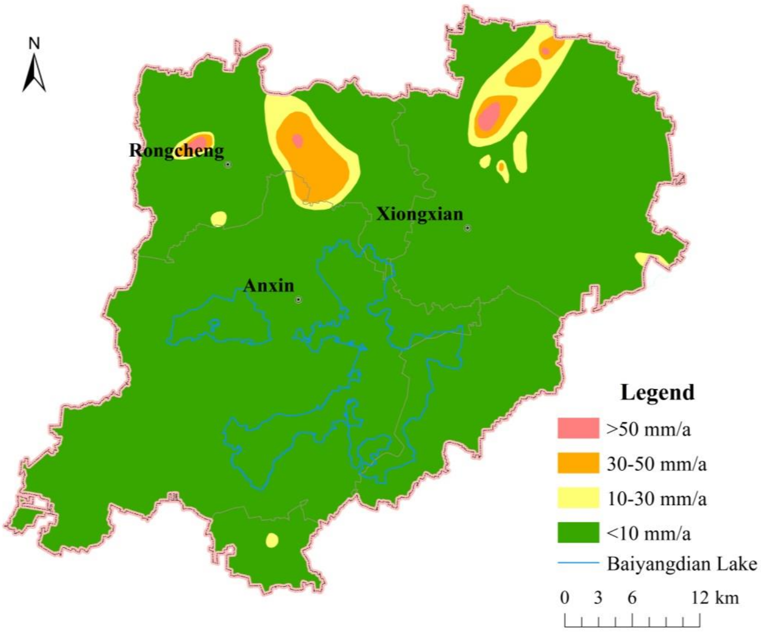

Figure 9. Zoning map of land subsidence rate.

4.3. Weights of Indicators

In this study, the study area was divided into multiple cells using a grid of 500 m by 500 m. These cells were selected as assessment samples for four layers of UUS, namely, L_1, L_2, L_3, and L_4. An initial assessment indicator matrix was created using Equation (1). Entropy and CRITIC weights were then calculated based on Equations (2)–(13). Using Equation (14), combined weights were calculated based on entropy and CRITIC weighting methods (Figure 13). The L_1 layer of UUS was taken as an example to illustrate the calculating processes and outcomes; the information is presented in Tables 2 and 3.

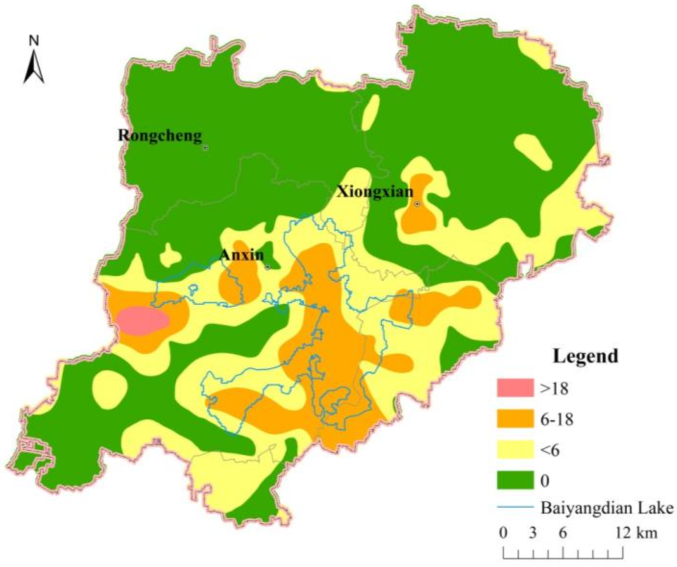

Figure 10. Zoning map of sands liquefaction index.

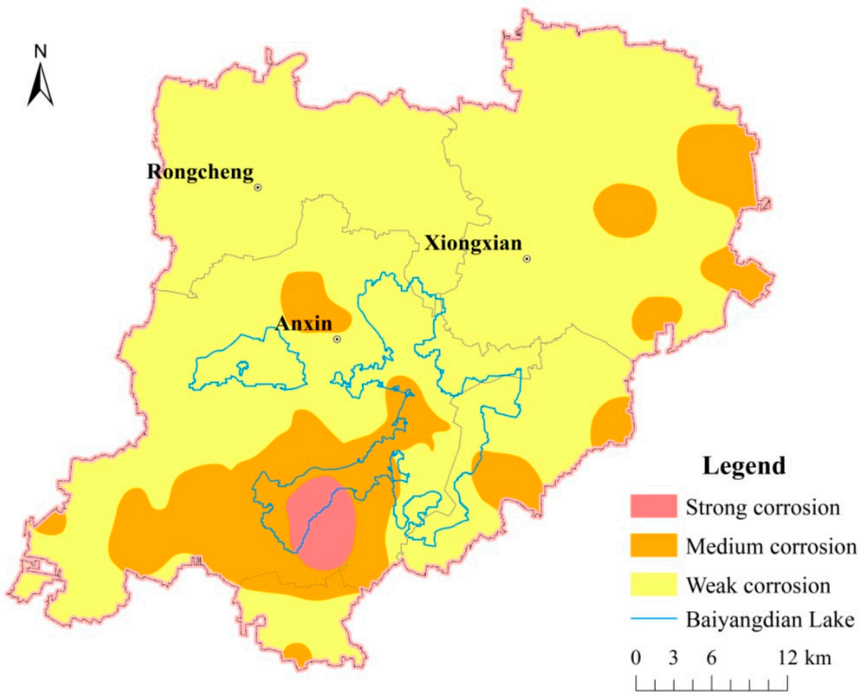

Figure 11. Zoning map of groundwater chemical corrosion intensity.

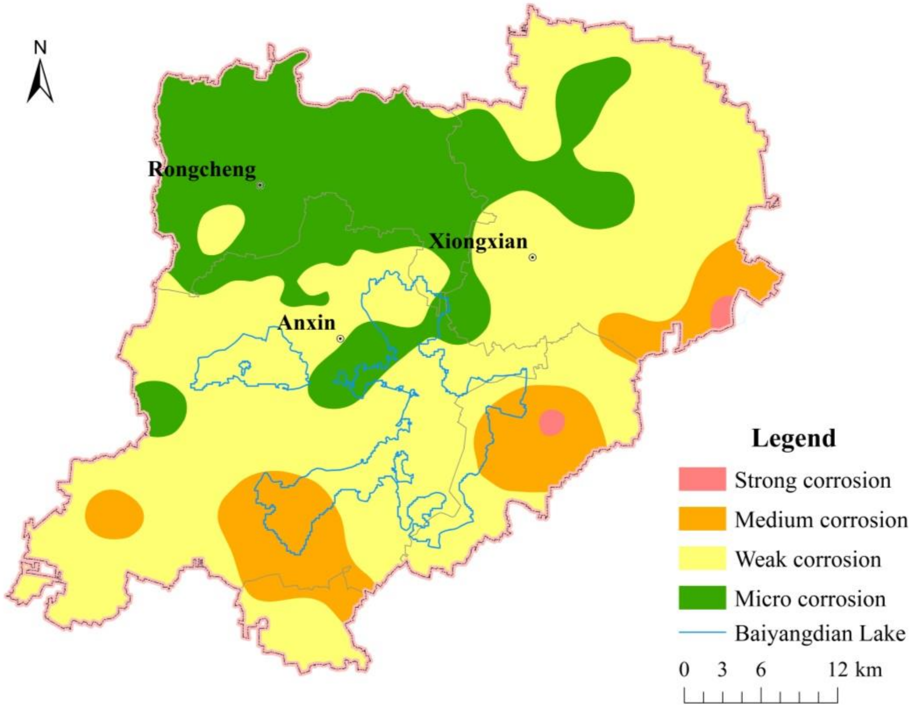

Figure 12. Zoning map of soil chemical corrosion intensity.

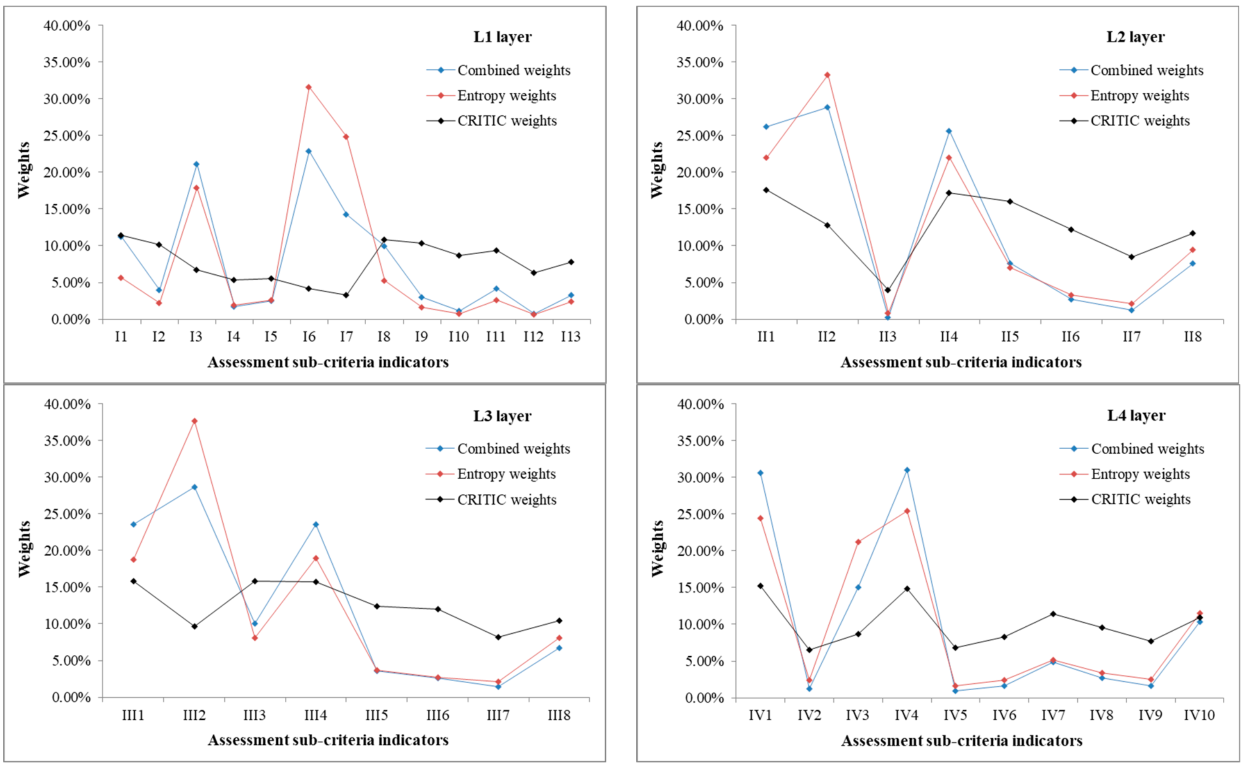

Figure 13. Weights curve of sub-criteria indicators for L_1~L_4 layers.

Table 2. Processes and outcomes information with entropy weighting method for L_1 layer.

Criteria Indicators	Sub-Criteria Indicators	Entropy Values, E	Otherness Coefficients, G	Entropy Weights, v
Topography	Ground elevation, I_1	0.9281	0.0719	5.61%
Geotechnical characteristics	Bearing capacity of soils (0~−5 m), I_2	0.9710	0.0290	2.26%
	Bearing capacity of soils (−5~−10 m), I_3	0.7707	0.2293	17.90%
	Bearing capacity of soils (−10~−15 m), I_4	0.9759	0.0241	1.88%
	Compression modulus of soils (0~−5 m), I_5	0.9660	0.0340	2.65%
	Compression modulus of soils (−5~−10 m), I_6	0.5948	0.4052	31.62%
	Compression modulus of soils (−10~−15 m), I_7	0.6823	0.3177	24.80%
Hydrogeological conditions	Groundwater buried depth, I_8	0.9330	0.0670	5.23%
	Aquifer thickness (0~−15 m), I_9	0.9788	0.0212	1.65%
Adverse geological phenomena	Land subsidence rate, I_{10}	0.9903	0.0097	0.76%
	Sands liquefaction index, I_{11}	0.9671	0.0329	2.57%
	Chemical corrosion of groundwater, I_{12}	0.9913	0.0087	0.68%
	Chemical corrosion of soils, I_{13}	0.9694	0.0306	2.39%

Table 3. Processes and outcomes information with CRITIC weighting method for L_1 layer.

Criteria Indicators	Sub-Criteria Indicators	Deviation Values, S	Conflicting Values, A	Quantity of Information, C	CRITIC Weights, u
Topography	Ground elevation, I_1	0.439	9.508	4.173	11.45%
Geotechnical characteristics	Bearing capacity of soils (0~−5 m), I_2	0.345	10.747	3.711	10.18%
	Bearing capacity of soils (−5~−10 m), I_3	0.255	9.640	2.459	6.75%
	Bearing capacity of soils (−10~−15 m), I_4	0.191	10.258	1.963	5.39%
	Compression modulus of soils (0~−5 m), I_5	0.192	10.464	2.013	5.52%
	Compression modulus of soils (−5~−10 m), I_6	0.129	11.674	1.507	4.14%
	Compression modulus of soils (−10~−15 m), I_7	0.092	13.087	1.200	3.29%
Hydrogeological conditions	Groundwater buried depth, I_8	0.415	9.535	3.957	10.86%
	Aquifer thickness (0~−15 m), I_9	0.304	12.356	3.761	10.32%
Adverse geological phenomena	Land subsidence rate, I_{10}	0.228	13.771	3.145	8.63%
	Sands liquefaction index, I_{11}	0.350	9.728	3.403	9.34%
	Chemical corrosion of groundwater, I_{12}	0.225	10.259	2.305	6.32%
	Chemical corrosion of soils, I_{13}	0.298	9.557	2.846	7.81%

4.4. Assessment Results

The suitability of urban underground space at different depths was evaluated based on the distribution of geological indicators in the study area, as shown in Figures 14–17.

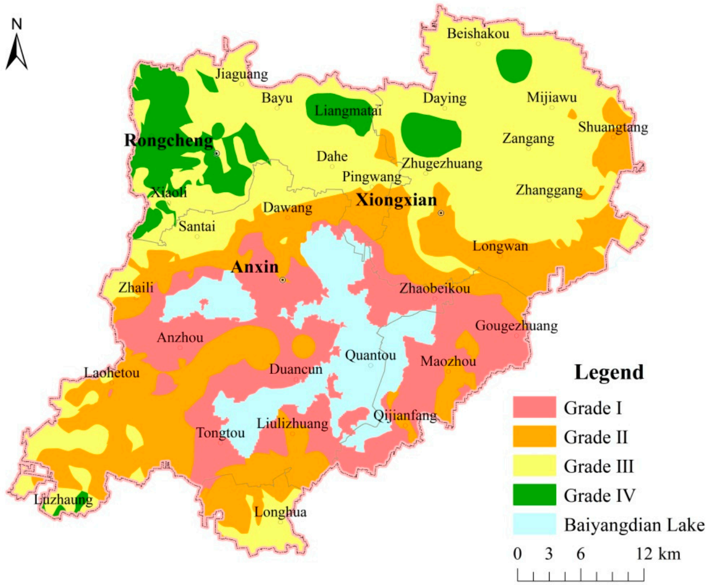

Figure 14. Suitability zoning map of L_1 layer.

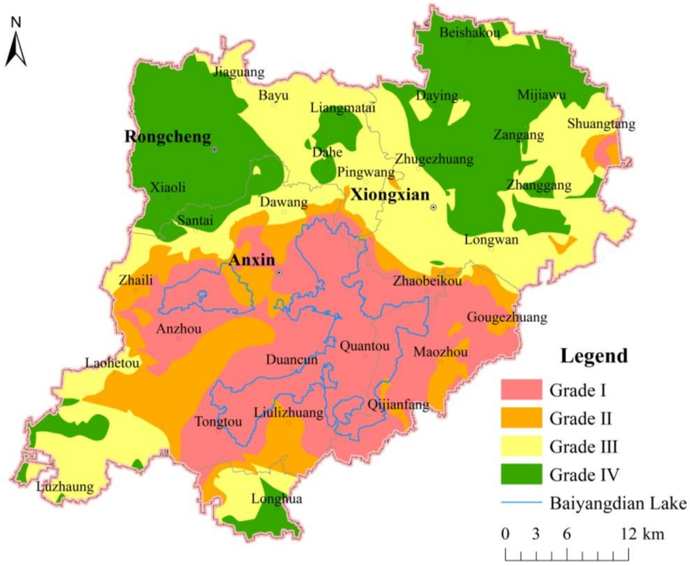

Figure 15. Suitability zoning map of L_2 layer.

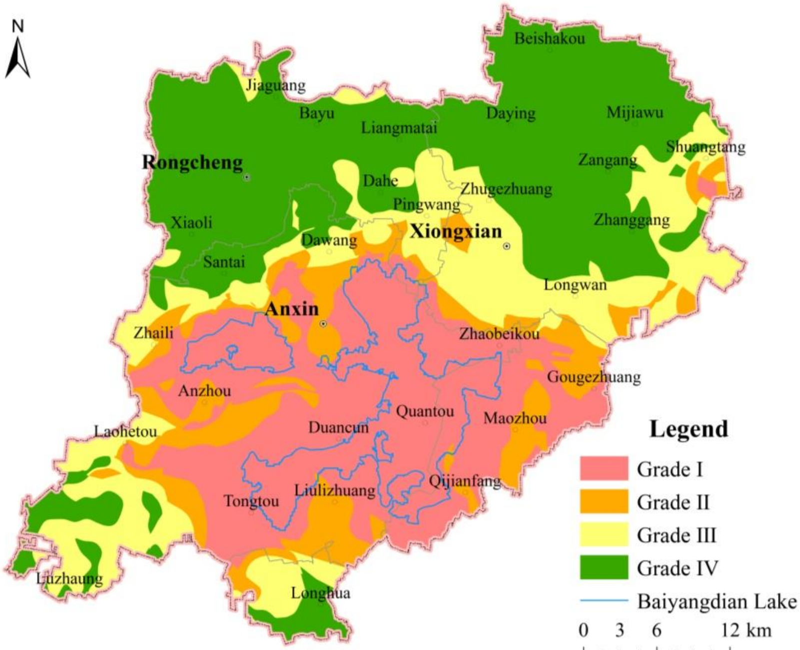

Figure 16. Suitability zoning map of L_3 layer.

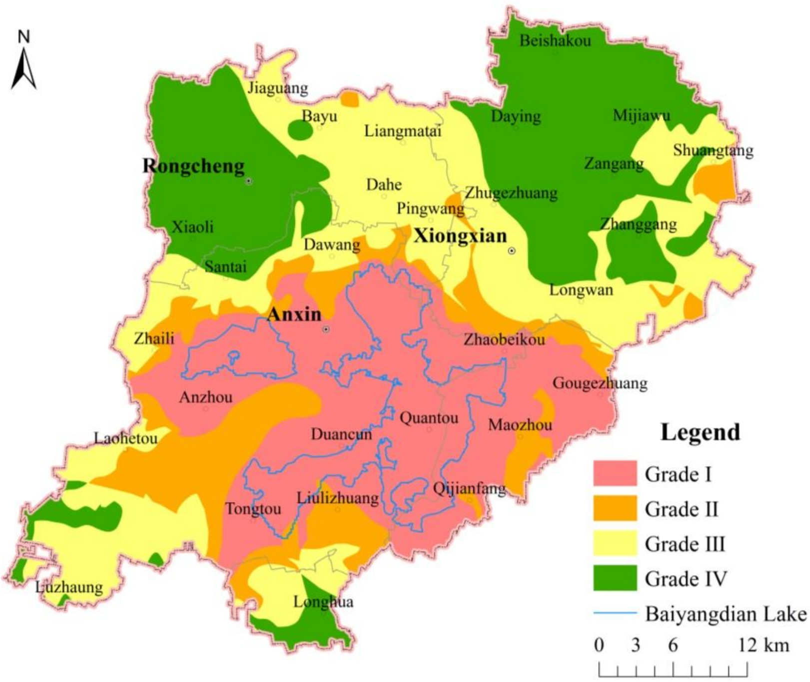

Figure 17. Suitability zoning map of L_4 layer.

For the shallow layer (L_1) within a depth of 0~−15 m, grade I, grade II, grade III, and grade IV accounted for 28.87%, 25.82%, 37.59%, and 7.72% of the study area, respectively (Figure 14). It was important to note that the Baiyangdian Lake region occupied 34.72% of the space classified as grade I and 0.81% of the space classified as grade II. Some scholars have suggested that larger lakes could have an impact on the use of shallow underground space [17]. In order to account for this, Baiyangdian Lake, including its wetland area, was used as a sensitive indicator to adjust the assessment result. Accordingly, all regions of Baiyangdian Lake were adjusted to grade I. The revised acreages with grade I, grade II, grade III, and grade IV accounted for 29.08%, 25.61%, 37.59%, and 7.72%, respectively. Based on the evaluation result, it was found that most of Rongcheng and Xiongxian, particularly the Rongcheng regions, were considered good or moderately suitable for underground space utilization. On the other hand, the regions around the central-eastern areas of Anxin were found to be less suitable due to issues with the bearing capacity and compression modulus of soils. As a result, the compression modulus of soils (−5~−10 m), bearing capacity of soils (−5~−10 m), and compression modulus of soils (−10~−15 m) were given higher weights in assessing underground space suitability compared to other sub-indicators.

For the deep layer (L_2) within a depth of −15~−30 m, grade I accounted for about 28.27% of the total acreage, grade II accounted for 13.79%, grade III accounted for 29.91%, and grade IV accounted for 28.03% (Figure 15). The analysis showed that the most suitable regions were mainly located near the west of Rongcheng and the central-north of Xiongxian. On the other hand, the regions around Baiyangdian Lake were found to be less suitable due to factors such as soil bearing capacity, ground elevation, and groundwater buried depth. Among these factors, the weights assigned to bearing capacity of soils (−15~−30 m), ground elevation, and groundwater buried depth were relatively high, indicating their significant influence on the suitability of underground space, accounting for 28.89%, 26.22%, and 25.60%, respectively, compared to other sub-indicators.

For the sub-deep layer (L_3), which was within a depth of −30~−50 m, the area occupied by grade I, grade II, grade III, and grade IV was 29.32%, 12.37%, 20.64%, and 37.67%, respectively. This indicated that the majority of the central-eastern regions of Rongcheng and Xiongxian were highly suitable for underground space utilization due to factors such as soil bearing capacity, groundwater buried depth, and ground elevation (Figure 16). Among these factors, the weights assigned to soil bearing capacity (−30~−50 m), groundwater buried depth, and ground elevation were relatively higher at 28.62%, 23.57%, and 23.55%, respectively, compared to other sub-indicators.

For the deep layer (L_4) within a depth of −50~−100 m, approximately 28.46% of the total area was classified as grade I, 13.57% as grade II, 29.52% as grade III, and 28.45% as grade IV (Figure 17). The assessment result revealed that the regions with good suitability were primarily located near the west of Rongcheng and the central-north of Xiongxian. On the other hand, the regions with poorer suitability were found around the central-east of Anxin, mainly due to factors such as groundwater buried depth, ground elevation, and compression modulus of soils. These factors, groundwater buried depth, ground elevation, and compression modulus of soils (−50~−100 m), were assigned higher weights, indicating their significance in determining underground space suitability, accounting for 31.02%, 30.66%, and 15.09%, respectively, compared to other sub-indicators.

5. Discussion

Firstly, in the suitability assessment of UUS, faults are typically an important geological factor to consider [53]. However, in this case study, faults were not included in the assessment indicator system due to their weak activity and minimal impact on the planning and construction of Xiong'an New Area [43,51]. The study area did not show other adverse geological phenomena, such as collapsible loess and gravel. However, it is important to note that the river flow in the study area is generally small and seasonal. Since these rivers have limited impact, they have not been included in the assessment indicator system. Additionally, based on the evaluation results of the four layers, the areas that were deemed good and moderate in suitability were mainly located in the north, south, and southwest of the study area. On the other hand, the inferior and worse suitable regions were mostly found around Baiyangdian Lake (Figure 18). This finding aligns well with the characteristics of stratigraphic sedimentary facies.

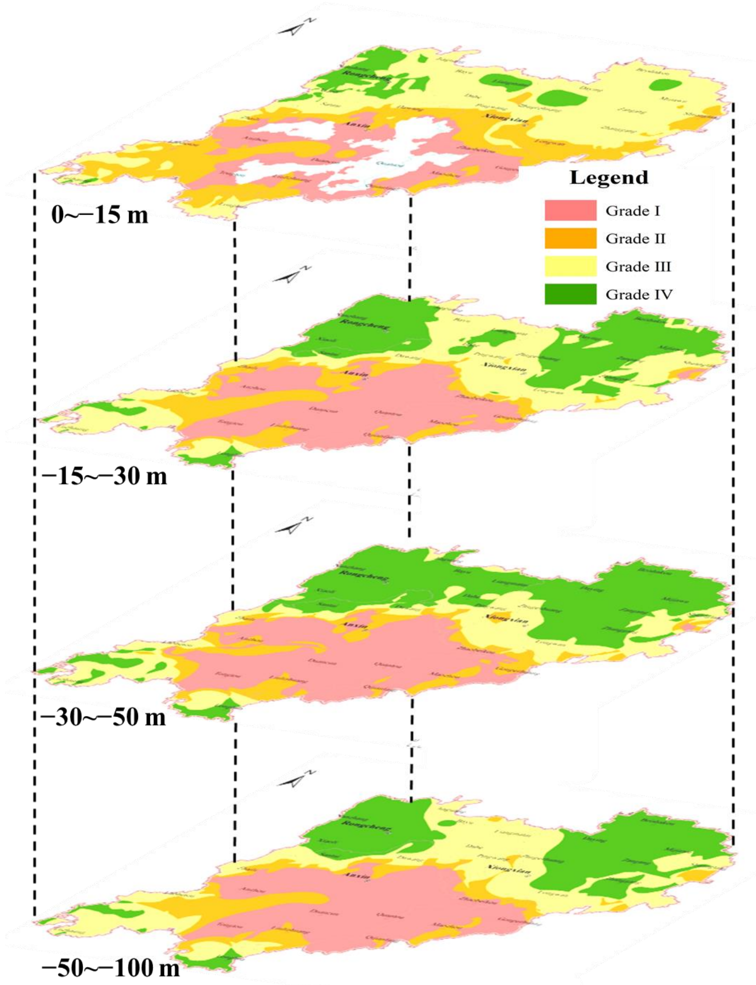

Figure 18. The integrated suitability assessment results of multilayer urban underground space.

Secondly, when the study area is divided into smaller evaluation units, such as smaller grids and more cells, the calculated weights are theoretically more accurate. However, in this paper, the grid size of 500 m by 500 m was temporarily set without further subdivision, in order to focus on the research method and reduce the amount of calculation. Subsequent researchers can refine the segmentation based on the acreage of the selected study area.

Thirdly, the planning and construction period of a city, especially for newly building cities such as Xiong'an New Area with a 'millennium plan' [54], is generally long. The utilization of urban underground space is a gradual process that may be also influenced by various socioeconomic conditions. In this study, we focused on examining the geological factors that affect the suitability of multilayer underground urban spaces (UUS), without considering socioeconomic factors and excavation types of underground facilities. However, it is important to note that future research should also investigate these aspects. This is also the limitation in this paper. If data on socioeconomic factors and excavation types could be obtained, they would provide more valuable insights for planning managers in optimizing planning and utilization strategies of underground space.

Finally, up to now, there have been limited studies on the suitability of underground space in Xiong'an New Area, as revealed by the literature review. Only Gao [47] has conducted a study on this topic. In contrast to this paper, Gao classified the underground space of Xiong'an New Area into three layers: shallow layer (0~−30 m), sub-deep layer (−30~−50 m), and deep layer (−50~−70 m). The evaluation indicators used in Gao's study included compression modulus of soils, groundwater depth, land subsidence rate, and aquifer thickness. However, the bearing capacity of soils was not considered. The evaluation method employed was the entropy-cloud model. The evaluation results differed from those of this paper. The areas with the worst grades were primarily located in the northern part of Xiongxian County. Similar to the findings of this paper, the Baiyangdian area generally exhibited a lower grade compared to its surrounding areas. After consulting the opinions of local geological experts, it is believed that the weights of indicators determined in this paper are more reasonable. This is because the evaluation takes into account the correlation, discreteness, and comparative intensity of the affecting indicators, making the results more valuable for reference.

6. Conclusions

(1) A process was proposed to assess the suitability of multilayer UUS based on the impacts of geological environments. The case study of Xiong'an New Area was used to establish an assessment indicator system, including four types of criteria indicators: topography, geotechnical characteristics, hydrogeological conditions, and adverse geological phenomena. The suitability of four vertical layers within a depth of 100 m was identified, providing guidance for urban planners and constructors. To ensure an objective and rational assessment, the entropy and CRITIC combined method was employed to determine the weights of sub-criteria indicators, considering the discreteness, correlation, and comparative intensity of data. Compared with previously used combination by other researcher, this paper demonstrated a better method. This combined weighting method can be applied to similar regions for the suitability assessment of UUS.

(2) The evaluation results indicated that the suitability of UUS in Xiong'an New Area varied depending on the depth of strata. Deeper layers showed better suitability, while shallower layers showed relatively worse suitability. The proportions of acreage with good and moderate suitability were as follows: 45.31% for shallow layer, 57.94% for sub-shallow layer, 58.31% for sub-deep layer, and 57.97% for deep layer. When considering the plane distribution state, the good and moderate suitable zones were predominantly located in the north, south, and southwest of the study area. Conversely, the inferior and worse suitable zones were mainly found around Baiyangdian Lake. Although the factors influencing the suitability of the four layers differed, the main indicators were the bearing capacity of soils, compression modulus of soils, groundwater buried depth, and ground elevation, which carried higher weights. Groundwater buried depth was significantly affected by artificial exploitation of groundwater, while the other three indicators are primarily influenced by the sedimentary process of strata.

(3) The paper focused on the geological indicators affecting the utilization of UUS in Xiong'an New Area. However, it did not include socioeconomic factors and excavation types of underground facilities. Although the UUS utilization in Xiong'an New Area is still in the initial stage, future studies should consider socioeconomic progress, existing underground infrastructures, and the difficulty of excavation based on the evaluation results.

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