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Variable-Weight Suitability Evaluation of Underground Space Development Considering Socioeconomic Factors

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Abstract: The suitability evaluation of urban underground space (UUS) development can aid in making the planning, construction, and operation management of underground spaces more scientific, orderly and systematic. Taking the starting area of Changjiang New Town as an example, this study considered socioeconomic factors as a crucial cost indicator in the suitability evaluation index system of underground space development, and 15 evaluation factors affecting underground space utilization were selected in combination with geological environment conditions. The subjective weights of each evaluation factor were calculated using the analytic hierarchy process (AHP), and variable-weight theory was introduced to calculate the comprehensive variable weights. The comprehensive variable weights were modified, taking socioeconomic factors into consideration, so as to quantitatively evaluate the development suitability of underground space in the research area. A comparison between the evaluation results of the constant-weight and variable-weight methods showed that the latter can correct the efficaciously determined subjective weight using the AHP and make the evaluation result more scientific and reasonable. A comprehensive consideration of the impact of socioeconomic factors on development costs and benefits made the evaluation results more instructive. The evaluation results showed that the area with the best suitability for underground space development in the study area accounted for approximately 18.6%, and the second-best suitable area accounts for approximately 60.8%. Hence, the development prospect of the study area is good.

Keywords: underground space; suitability evaluation; variable-weight theory; socioeconomics

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1. Introduction

With the accelerating pace of urbanization in China, historic achievements have been made in urban construction. Rapid urbanization has led to various "urban diseases" [1,2], causing increasingly serious population, resource, traffic and environmental problems [3–5], and the demand for underground spaces in various regions has been high. However, underground space is a non-renewable resource [6,7], and unordered development will reduce the development capacity of urban underground space and lead to a series of environmental and safety problems. The suitability evaluation of underground space is a significant measure to ensure the coordinated planning [8–10], scientific construction, and green development of urban underground spaces [11,12]. Accordingly, it is of value to perform a thorough suitability evaluation of underground space.

Extensive studies are being conducted on the suitability evaluation of underground space development [13–15], and various evaluation methods have been proposed. For example, in the planning of the underground space in Minneapolis–St. Paul, Sterling et al. [16] comprehensively considered the influence of geotechnical layer distribution, hydrogeological conditions, and topography, and analyzed the distribution map of the various influencing factors by utilizing comprehensive superposition. Accordingly, the distribution of exploitable resources and the reasonable utilization of the underground space in Minneapolis were determined. Durmisevic and Sariyildiz [17] adopted a neural network algorithm to comprehensively analyze the factors affecting the construction of underground stations, and a model for the quality assessment of the underground space was established. Lu et al. [18] conducted a multilevel quantitative suitability evaluation of urban underground space engineering in geological environments, in which a multilayered suitability evaluation framework for urban underground space development was established. To determine the sustainable development of the underground space in the study area, Zhou et al. [19] combined the analytic hierarchy process and fuzzy comprehensive assessment method to construct a multilevel fuzzy comprehensive evaluation model. Liu et al. [20] considered the influence of the time dimension, integrated the classical entropy weight method with the weighting method of time dimension, and proposed the hybrid weight assignment model for urban underground space resources, i.e., entropy and time weighting model (E-TW). Zhang et al. [21] established a negative list of adverse factors affecting underground space development, including limiting factors, constraining factors and influencing factors, and examined the underground space resources of Xi'an city. For underground space development in mountainous plateau areas, Duan et al. [22] investigated the geological conditions using the index scale analytic hierarchy process and proposed an evaluation system suitable for Kunming, China. Dou et al. [23] developed a novel UUS geological suitability evaluation framework in 3D, and proposed a 3D geological suitability evaluation for UUS development based on combined weighting and improved technique for order preference by similarity to an ideal solution (TOPSIS).

As stated above, one or more methods, for instance, the AHP, negative list method, fuzzy synthesize judgment method, neural network algorithm, and comprehensive superposition method, have been used to construct an index system to evaluate the suitability of underground space development [24], as well as to calculate the weights of each factor that can reflect the relative importance in the overall evaluation system. Nevertheless, the calculated weights are typically constant, and the evaluation results are relatively subjective. Taking the most widely used method, analytic hierarchy process (AHP), for example, weights were calculated mainly based on the researcher's knowledge of the geology of the study area, then different influence factors were compared in pairs to score their relative importance [25]. In this way, a judgment matrix is obtained. Finally, a consistency test was performed on the matrix to improve the rationality of the judgment matrix. With this approach, subjectivity comes to the fore and is not neutralized by subsequent data processing.

Most importantly, these methods do not take into account the influence of internal variability in the indicators on the suitability of development. In fact, in the process of conducting a suitability assessment, even if other factors perform well, as long as a certain index is poor to a certain extent, the overall suitability will worsen, making the evaluation results deviate from the actual situation. That is, the internal differences of indicators have a great influence on development suitability. Therefore, the poor indicator weights should be incentivized to avoid being "neutralized" by the better indicators. This problem can be effectively solved using the variable-weight integrated model. The corresponding variable-weight model, on the basis of determining constant weights through the AHP, is selected to redistribute the constant weight: motivate the weight of poor index and the weight of excellent index, which effectively balances the influence of the internal differences of indicators on the evaluation results. It can also weaken the subjective proportion of other evaluation methods and bring the evaluation partition more in line with the actual situation.

In the suitability evaluation process of underground spaces, whether the selection of evaluation indicators is comprehensive or not is a key factor. In addition to geological environment factors, socioeconomic conditions, such as the demand and cost subjects of an urban underground space, play a crucial role in the decisions made in terms of development of urban underground spaces [26–28] and have attracted increasing attention [29]. Taking the various districts and counties in Shanghai for instance, He et al. [30] studied the correlation between the intensity of underground space development and three urbanization indicators, namely the per capita GDP, population density, and housing prices. The results suggested that both the population density and GDP per capita are strong predictors of the development intensity of underground space. Liu et al. [31] came to the conclusion that per capita GDP is an essential indicator determining the stage of underground space development. Qiao et al. [32] investigated the potential socio-environmental losses caused by underground space use, and set up a framework for the monetary valuation of these losses. In Stockholm, Tokyo, and Paris, Bobylev [33] investigated the connection between population density and the capacity of urban underground infrastructure. Urban underground space development was found to be fueled by a high population density. It can be seen that the population density and per capita GDP have a particularly decisive influence on the spatial differentiation of the intensity of underground space development. Furthermore, locations with good economies and dense populations are more likely to develop underground spaces. The relationship between urban underground space development and socioeconomic factors, such as the population density, per capita GDP, and housing prices, has been extensively studied [34–36]. When the geological environment is similar, social and economic conditions determine the high demand and cost of underground space development. In other words, there is lower demand and scale for underground space development in areas with weaker social and economic conditions. Therefore, the development costs are also lower, and vice versa.

In summary, scholars have extensively evaluated the advantages and disadvantages of geological environment circumstances in determining whether underground space development is appropriate, but the influence of socioeconomic conditions on underground space development is often ignored. Even if socioeconomic conditions are taken into account, relevant studies have mostly been carried out to prove the correlation between socioeconomic factors such as population density, per capita GDP and the status of surface construction and urban underground space development, and from the perspective that population density and per capita GDP determine the high demand of underground space development, or socioeconomic conditions are taken as benefit indicators into the suitability evaluation system of urban underground space development. The research angle is relatively simple.

Geological conditions are the foundation of underground space development, and socio-economic conditions are the necessary conditions. Socioeconomic conditions determine the demand, cost and economic benefit of underground space development. In areas with weak socioeconomic conditions, the development demand and scale of underground space are relatively low, and the development cost and economic benefits brought by the development are also relatively low. Taking the starting area of Changjiang New Town as an example, this study takes socioeconomic factors as an important cost indicator in the suitability evaluation system of underground space, and 15 evaluation factors affecting the underground space utilization were selected in combination with geological environment conditions. The subjective weights of each evaluation factor were worked out using a program [37] that was based on the meaning of the analytic hierarchy process (AHP), and the variable-weight theory was introduced to calculate the comprehensive variable weights. Moreover, the evaluation results are modified from the perspective of socioeconomic conditions bringing development benefits, so as to quantitatively evaluate the development suitability of underground space in the research area. In this way, the positive and negative effects of social and economic conditions on underground space development are comprehensively considered, so the research angle is comprehensive and scientific.

In this study, the comparison between the evaluation results of the constant-weight and variable-weight methods showed that the latter can correct the efficaciously determined subjective weight using the AHP and make the evaluation result more scientific and reasonable. A comprehensive consideration of the impact of socioeconomic factors on development costs and benefits made the evaluation results more instructive. The evaluation results shows that the area with the best suitability for underground space development in the study area accounts for approximately 18.6%, and the second-best suitable area accounts for approximately 60.8%. Hence, the development prospect of the study area is good.

2. Overview of the Research Area

Wuhan is located in the eastern part of Jianghan Plain, with low hills in the city and low-lying north and a high south, gradually tilted from north to south. Changjiang New Town, which is in the northeast of Wuhan, includes two areas: Shenjiaji and Wuhu. The construction is divided into three phases: the short-term starting area, the medium-term development area, and the long-term control area. The starting area is in the southwest corner of the town; Figure 1 shows the planning scope, with an area of approximately 58.8 km^2. In terms of the morphogenesis, the starting area can be broadly divided into three geomorphic units: alluvial lacustrine plain, alluvial plain, and denuded and accumulated lowland. In the starting area, the strata are mainly composed of the upper Quaternary overburden, the underlying Mesozoic–Cainozoic continental deposit, and a small amount of Paleozoic marine sedimentary deposit; the surface strata of the area belong to quaternary loose deposits without bedrock outcropping. In terms of the regional geology setting, the starting area has undergone multiple phases of tectonic reworking, mainly by folding, and the fractures are well developed: the prominent NW trending faults are known as Xiangguang and Xinhuang faults, while the NE trending fault is the Yangtze Fault (as shown in Figure 2). The starting area has abundant groundwater deposits, and the main type is pore-confined water; these deposits have a small amount of water, a large, buried roof, weak corrosion, and little influence on the underground space development.

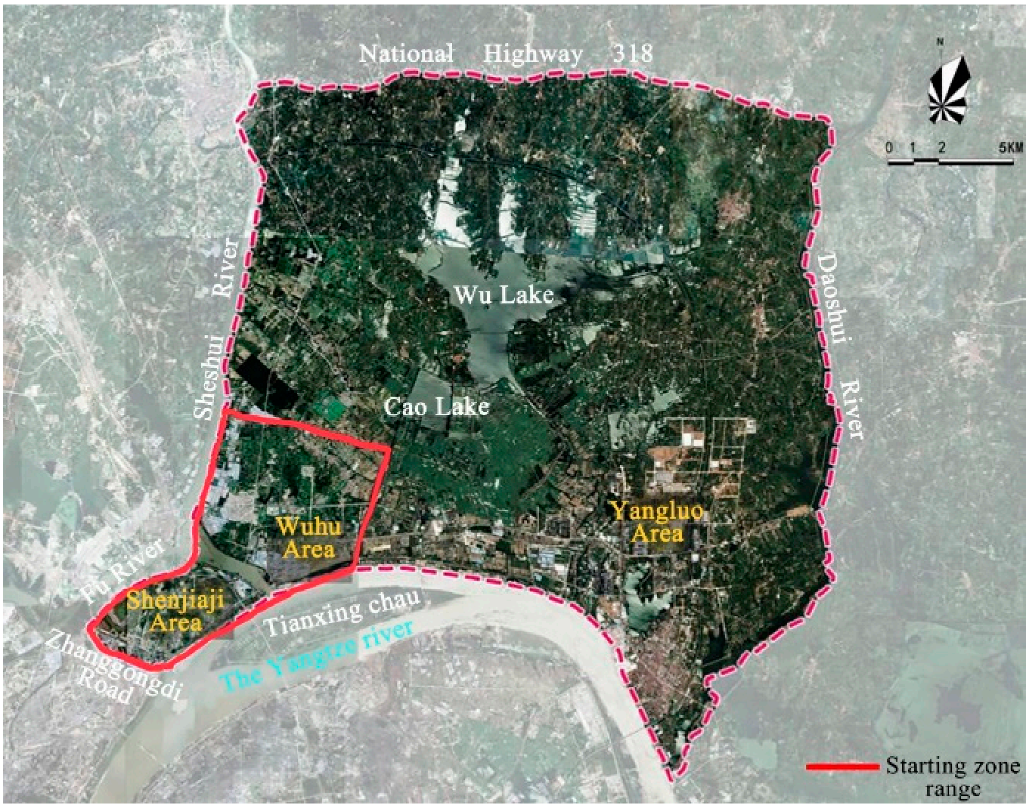


Figure 1. Schematic of the planning study area of Changjiang New Town.

The adverse geological phenomena in the area include karst and soft soil settlements. Karst is strongly developed in areas south of Zhujia River and Shenjiaji area located in the soluble rock strip. In addition, the areas prone to soft soil settlement are continuously distributed on both sides of Zhujia River and in the area near the Yangtze River, scattering along the Hankou north road and its northward area, and the soft soil is buried deep. The wide and deep covering area of solvable rock and soft soil greatly increases the risk of geological disasters and plays a key role in underground space development [38,39].

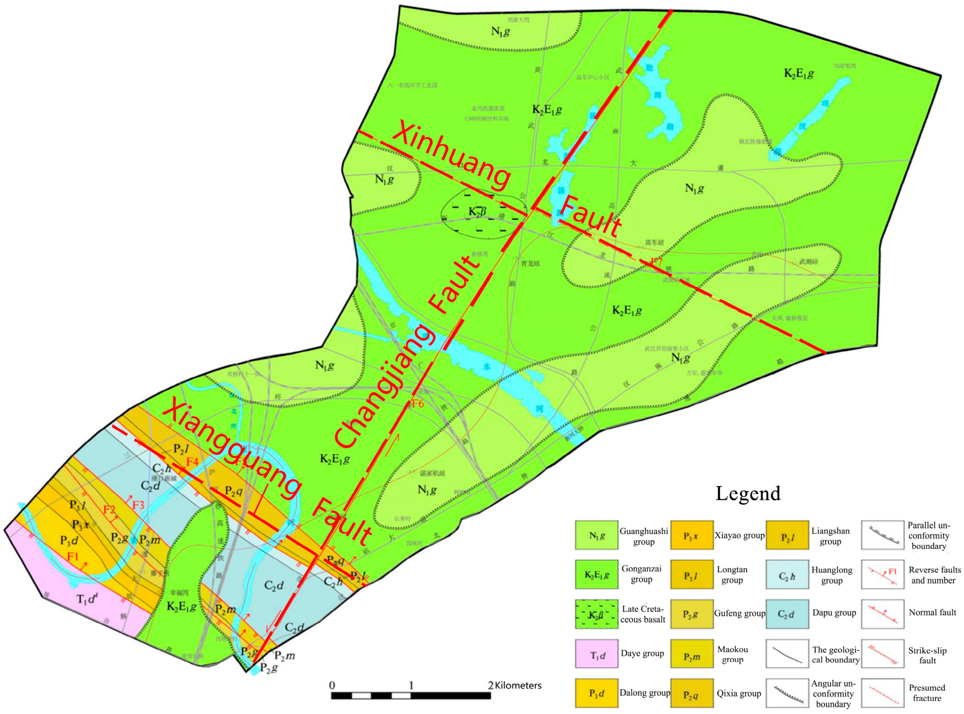


Figure 2. Schematic of the bedrock geology and fractures in the starting area of Changjiang New Town.

In recent years, Wuhan has maintained a stable and healthy level of socioeconomic development. Taking the social and economic statistics from 2021 as an example, the permanent resident population was 13,648,900, with an increase of 9.7% over the previous year; the annual regional GDP reached 17.71676 billion CNY, a year-on-year growth of 12.2%; the per capita disposable income of urban residents in the city was 55,297 CNY, increasing by 1.9% over the previous year. The existing buildings in the starting area are schools, large residential communities, and factories such as logistics parks and industrial parks. The distribution is sparse, and the development degree is not high. Therefore, the population density and housing prices are lower compared with those in the urban area, and the level of economic development is relatively poor.

3. Research Methods

3.1. Integrated Variable-Weight Evaluation Model

Li et al. [40] proposed a comprehensive variable-weight decision model and provided three axiomatic definitions for the variable weights: punitive variable weight, incentive variable weight, and hybrid variable weight.

The comprehensive variable-weight evaluation model can be expressed as $\sum_{i=1}^{m} N_i(x_1, \ldots, x_m) \cdot X_i$, where $N_i(x_1, \ldots, x_m)$ is the variable weight determined by the factor state value, and based on its variation, the variable weight can be categorized into three types: incentive, penalty, and hybrid type. With the concept of state variance vector introduced, suppose we define that $X_i = (x_1, \ldots, x_m)$ is the state vector of factor i, $S_i = (S_1, \ldots, S_m)$ is the state variable-weight vector, and $W_i = (W_1, \ldots, W_m)$ is the constant-weight vector, the constant-weight vector and the state variable-weight vector are normalized and multiplied to work out the variable-weight vector, as shown in the following ($N_i(x_1, \ldots, x_m)$, $S_i = (S_1, \ldots, S_m)$,$W_i = (W_1, \ldots, W_m)$ are abbreviated as N_i,S_i,W_i in the formula):

$$\mathbf{N_i} = \frac{\mathbf{W_i} \cdot \mathbf{S_i}}{\sum\limits_{i=1}^{m} (W_i \cdot S_i)}, i = (1, 2, \cdots, m) \tag{1}$$

where N_i is the variable-weight vector; W_i is the constant-weight vector; S_i is the state variable-weight vector of indicator i.

The variable-weight vector $N_i(x_1, \ldots, x_m)$ has two main properties: (a) normalizability: $\sum\limits_{i=1}^{m} N_i(x_1, \ldots, x_m) = 1$; (b) continuity: $N_i(x_1, \ldots, x_m), i = (1, 2, \cdots, m)$ is continuous for any variable x_j. When $N_i(x_1, \ldots, x_m)$ satisfies properties a, b, and $N_i(x_1, \ldots, x_m)$ decreases monotonically with respect to x_j, then W(X) is referred to as a variable-weight vector that is punishing. If $N_i(x_1, \ldots, x_m)$ satisfies properties a, b, and $N_i(x_1, \ldots, x_m)$ rises monotonically with respect to x_j, then $N_i(x_1, \ldots, x_m)$ is a variable-weight vector that is motivating. If $N_i(x_1, \ldots, x_m)$ satisfies properties a and b, and $N_i(x_1, \ldots, x_m)$ reduces monotonically with respect to x_j and grows monotonically with respect to x_j, then $N_i(x_1, \ldots, x_m)$ is referred to as a hybrid variable vector.

The constant-weight vector $W_i = (W_1, \ldots, W_m)$ and the state variable-weight vector $S_i = (S_1, \ldots, S_m)$ are normalized and multiplied to work out the variable-weight vector $N_i(x_1, \ldots, x_m)$; consequently, the selection of the state variable-weight vector $S_i = (S_1, \ldots, S_m)$ is of great concern, and the state variable-weight vector hinges on the variable-weight function. The purpose of introducing the variable-weight model into the evaluation of urban underground space development suitability is to highlight the negative impact of the "poor" value of the index, motivate the "good" value of the index, and neither punish nor motivate the "general" value of the indicator. Therefore, the penalty-incentive variable-weight function of the state is selected as Equation (2):

$$S_i = \begin{cases} \frac{a-b}{\alpha-\lambda}\lambda \ln \frac{\lambda}{x_j} + a & x_i \in (0, \lambda] \\ \frac{b-a}{\alpha-\lambda}x_j + \frac{a\alpha-b\lambda}{\alpha-\lambda} & x_i \in (\lambda, \alpha] \\ \frac{a-b}{2(\alpha-\lambda)(\beta-\alpha)}\left(\beta - x_j\right)^2 + c & x_i \in (\alpha, \beta] \\ c & x_i \in (\beta, \mu] \\ k(1-\mu)\ln \frac{1-\mu}{1-x_j} + c & x_i \in (\mu, 1) \end{cases} \tag{2}$$

where a, b and c are the evaluation strategy; k is the adjustment coefficient; (0, λ] is the rejection interval; (λ, α] is the strong penalty interval; (α, β] is the initial penalty interval; (β, μ] is the qualified interval; and (μ, 1] is the incentive interval.

As far as the evaluation system of the underground space development suitability is concerned, if there are one or two hazard indicators with quite low scores, regardless of the selection of the comprehensive constant-weight assessment method, it may be neutralized by the favorable values of the other indicators, making the final evaluation results to deviate from the actual engineering geological environment. As stated above, the variable-weight suitability evaluation of the underground space development should ensure that the final evaluation value is significantly reduced if there is a poor index value, even if the constant-weight value of the indicator is relatively small. However, it does not necessarily increase the final evaluation value if only one index value is outstanding, that is, the penalty intensity should be stronger than the incentive in the comprehensive variable-weight evaluation. Subsequently, in combination with the characteristics of the geological environment and socioeconomic conditions, the parameters in Equation (2) were selected as: $a = 0.5$, $b = 0.3$, $c = 0.2$, $\lambda = 0.2$, $\alpha = 0.4$, $\beta = 0.6$, $k = 1.5$, and $\mu = 0.8$. Therefore, the state variable-weight vector can be expressed as:

$$S_i = \begin{cases} 0.2\ln\frac{0.2}{x_j} + 0.5 & x_i \in (0, 0.2] \\ -x_j + 0.7 & x_i \in (0.2, 0.4] \\ 2.5{x_j}^2 - 3x_j + 0.2 & x_i \in (0.4, 0.6] \\ 0.2 & x_i \in (0.6, 0.8] \\ 0.3\ln\frac{0.2}{1-x_j} + 0.2 & x_i \in (0.8, 1) \end{cases} \tag{3}$$

The graph of the state function is shown in Figure 3. It can be seen that when selecting this set of parameters, the trend of the function changes gently without abrupt inflection point, and the penalty level and incentive level are moderate. In line with the principle that penalty should be stronger than incentive, this set of parameters is selected.

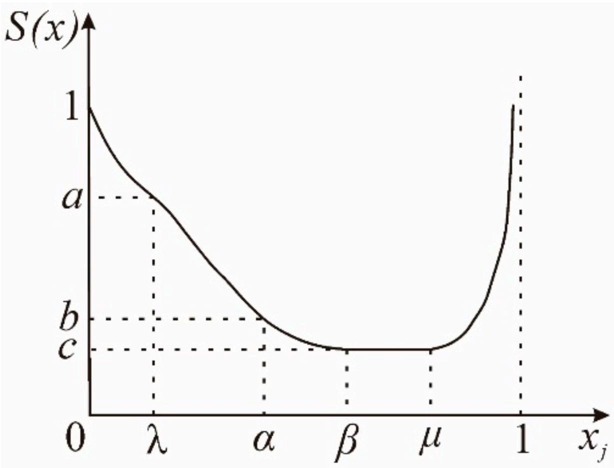


Figure 3. Penalty-incentive variable weight function S_i.

Combined with the above variable-weight model, by means of the combined index method, a variable-weight integrated evaluation model of the suitability of underground space development is established ($X_i = (x_1, \ldots, x_m)$, $S_i = (S_1, \ldots, S_m)$, $W_i = (W_1, \ldots, W_m)$ are abbreviated as X_i, S_i,W_i in the formula):

$$\mathbf{Z_i} = \sum_{i=1}^{m} \frac{\mathbf{W_i} \cdot \mathbf{S_i}}{\sum_{i=1}^{m} (W_i \cdot S_i)} \cdot \mathbf{X_i} \tag{4}$$

Here, Z_i is the vector of the suitability composite evaluation scores; X_i represents the state value vector of index *i*.

3.2. Construction of Evaluation System

The suitability evaluation of underground space development is a comprehensive multilevel and multi-index problem. To solve such problems, it is appropriate to adopt the AHP to construct the evaluation index system. The specific steps are as follows:

(1) The design and development of the underground space is influenced by geological environment and socioeconomic condition, which are integrated and divided into three layers: the target layer, the guideline layer and the indicator layer (Figure 4).
(2) Constructing the judgment matrix. This step is to determine the relative importance of each factor in pairs, for which the 1–9 scale method has been applied.
(3) Performing the hierarchical single ranking and total ranking and passing the consistency test; then, the constant-weight weights can be calculated (as shown in Table 1).

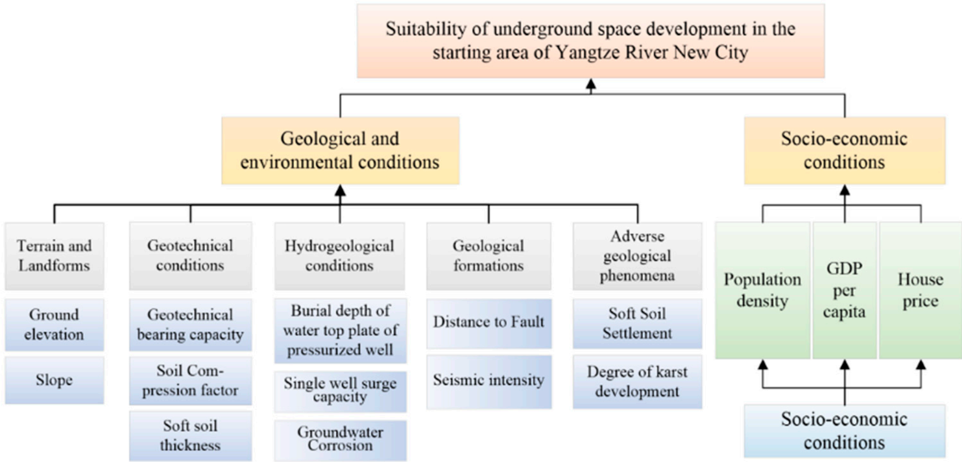


Figure 4. Suitability evaluation index system of underground space development.

Table 1. Constant weights of the suitability evaluation indicators of underground space development.

Primary Indicators		Weights	Secondary Indicators	Weights	Total Ranking Weight
Geological and environmental conditions	Terrain Landforms	0.040	Ground elevation Terrain slope	0.5 0.5	0.0201 0.0201
	Geotechnical conditions	0.210	Geotechnical bearing capacity Soil compression factor Soft soil thickness	0.539 0.297 0.164	0.1132 0.0624 0.0344
	Hydrogeological conditions	0.140	Burial depth of top plate of pressurized water Single-well surge capacity Groundwater corrosion	0.230 0.648 0.122	0.0322 0.0907 0.0171
	Geological formations	0.089	Distance to fracture Seismic intensity	0.8 0.2	0.0714 0.0179
	Adverse geological phenomena	0.396	Degree of rock development Soft soil settlement	0.5 0.5	0.1978 0.1978
Socioeconomic conditions		0.125	Population density GDP per capita Ground price	0.142 0.429 0.429	0.0178 0.0536 0.0536

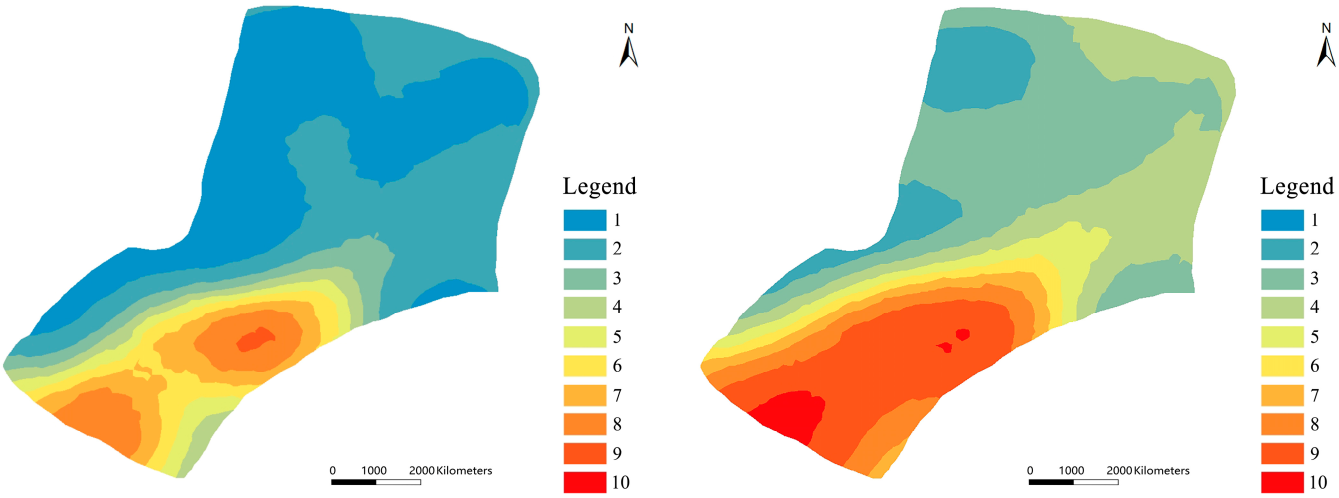
Referring to the standard of land construction and combined with the geological and economic conditions of the study area, one must act according to circumstances. The quantitative criteria of the evaluation index of the study area are clarified, and the suitability of the underground space development can be divided into four grades: superior (level I), good (level II), inferior (level III), and worse (level IV).

3.3. Constant-Weight Evaluation Process

Using the comprehensive index method, the index-weighted average based on the zoning map of the quantified values of each index factor was calculated to obtain the synthetical suitability score, and an integrated suitability evaluation grading map under constant weights was drawn. The population density and per capita GDP distribution were obtained through Kriging interpolation from Wuhan's Yearbook (Figure 5a,b). Regarding the house prices, basic data were obtained from Wuhan Statistic Bureau first, then the real-time house prices of the buildings in the study area were obtained from the house transaction website. Since the house prices in a certain area are often the same [41], Tyson polygon (as shown in Figure 6) was generated from the location points of each building to represent the house price distribution in the study area. The evaluation model can be expressed as:

$$S_j = \sum_{j=1}^{n} X_{ij} W_j \tag{5}$$

where S_j is the suitability index of the evaluation unit i; X_{ij} is the suitability score of the evaluation unit i for the evaluation factor j; W_j is the weight of the evaluation factor j; n is the total number of evaluation factors; i is the evaluation unit i. (The variable weight matrix (see Table 2) takes the evaluation factors as columns and the divided evaluation units as rows. "i" is the order of evaluation units and "j" is the order of evaluation factors).



(**a**) Distribution of population density (**b**) Distribution of GDP per capita

Figure 5. Distribution of population density and GDP per capita in the study area (the numbers 1 to 10 in the legend represent the values from low to high).

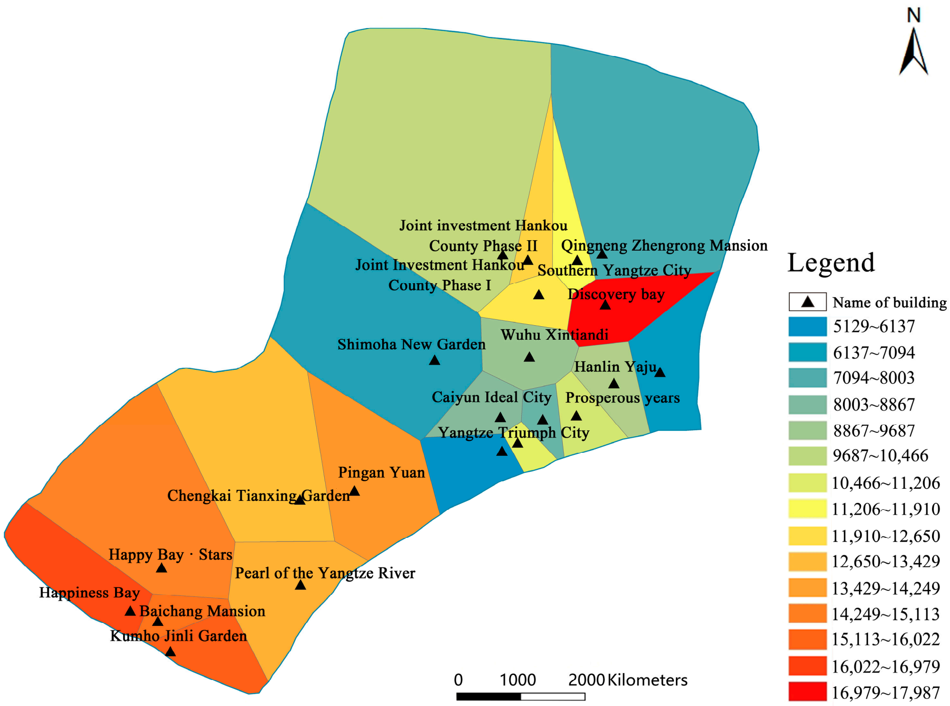


Figure 6. Distribution of housing prices in the study area (unit: 10,000 CNY per sq m).

Table 2. Variable-weight suitability evaluation results of underground space development.

Evaluation Unit	Ground Elevation	Terrain Slope	Rock and Soil Bearing Capacity	Compressibility of Soil	Soft Soil Thickness	Buried Depth of Confined Water Roof	Water Inflow Per Well	Groundwater Corrosion	Distance to Fracture	Seismic Intensity	Degree of Karst Devel-opment	Soft Soil Settlement	Population Density	GDP per Capita	House Price
1	0.0105	0.0213	0.1202	0.0023	0.0365	0.0342	0.1508	0.0182	0.0372	0.0190	0.2100	0.2100	0.0185	0.0558	0.0558
2	0.0105	0.0213	0.1202	0.0023	0.0365	0.0342	0.1508	0.0182	0.0372	0.0190	0.2100	0.2100	0.0185	0.0558	0.0558
3	0.0106	0.0217	0.1223	0.0023	0.0372	0.0171	0.1535	0.0185	0.0378	0.0193	0.2137	0.2137	0.0189	0.0568	0.0568
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0098	0.0200	0.1129	0.0021	0.0343	0.0321	0.0905	0.0171	0.0349	0.0179	0.1973	0.3089	0.0174	0.0524	0.0524
6	0.0111	0.0226	0.1271	0.0024	0.0386	0.0361	0.1018	0.0192	0.0393	0.0201	0.2221	0.2221	0.0196	0.0590	0.0590
7	0.0104	0.0213	0.1199	0.0040	0.0364	0.0341	0.1505	0.0181	0.0371	0.0190	0.2096	0.2096	0.0185	0.0557	0.0557
8	0.0106	0.0217	0.1221	0.0041	0.0371	0.0170	0.1532	0.0184	0.0377	0.0193	0.2133	0.2133	0.0188	0.0567	0.0567
9	0.0098	0.0200	0.1127	0.0038	0.0343	0.0157	0.1415	0.0170	0.1114	0.0178	0.1970	0.1970	0.0174	0.0523	0.0523
……	……	……	……	……	……	……	……	……	……	……	……	……	……	……	……
1759	0.0115	0.0208	0.1171	0.0040	0.0356	0.0184	0.0939	0.0177	0.0739	0.0185	0.2047	0.3206	0.0090	0.0272	0.0272
1760	0.0214	0.0214	0.1206	0.0041	0.0366	0.0189	0.0966	0.0182	0.0373	0.0191	0.2107	0.3299	0.0093	0.0280	0.0280
1761	0.0225	0.0225	0.1268	0.0043	0.0385	0.0199	0.0498	0.0192	0.0392	0.0201	0.2216	0.3470	0.0098	0.0294	0.0294
1762	0.0225	0.0225	0.1268	0.0043	0.0385	0.0199	0.0498	0.0192	0.0392	0.0201	0.2216	0.3470	0.0098	0.0294	0.0294
1763	0.0207	0.0207	0.1168	0.0039	0.0355	0.0183	0.0459	0.0176	0.1153	0.0185	0.2040	0.3195	0.0090	0.0271	0.0271
1764	0.0207	0.0207	0.1168	0.0039	0.0355	0.0183	0.0459	0.0176	0.1153	0.0185	0.2040	0.3195	0.0090	0.0271	0.0271
1765	0.0207	0.0207	0.1168	0.0039	0.0355	0.0183	0.0459	0.0176	0.1153	0.0185	0.2040	0.3195	0.0090	0.0271	0.0271
1766	0.0207	0.0207	0.1168	0.0039	0.0355	0.0183	0.0459	0.0176	0.1153	0.0185	0.2040	0.3195	0.0090	0.0271	0.0271
1767	0.0207	0.0207	0.1165	0.0063	0.0354	0.0183	0.0458	0.0176	0.1151	0.0184	0.2035	0.3188	0.0090	0.0270	0.0270

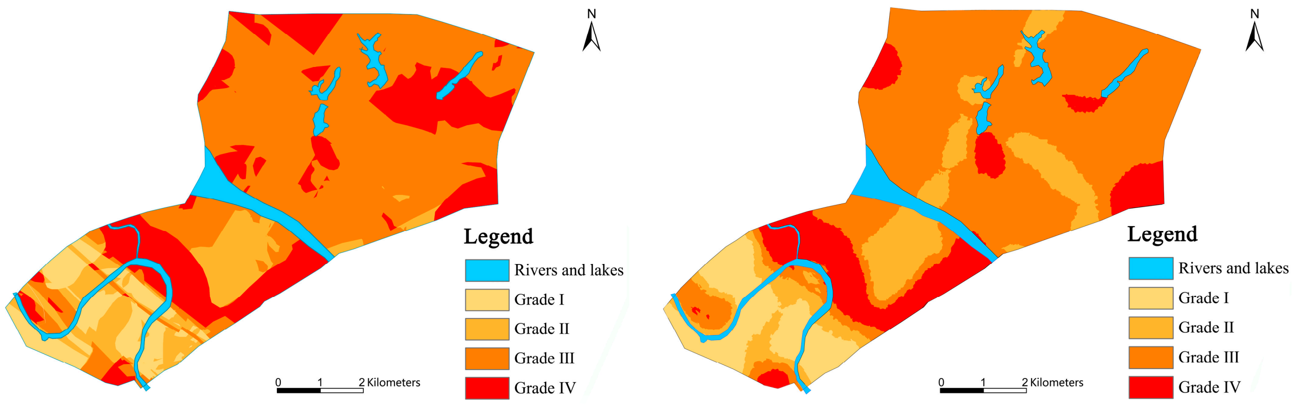
3.4. Variable-Weight Evaluation Process

The study area was divided into evaluation cells, and a total of 1767 effective evaluation grids are acquired. The scores of each evaluation index in the constant-weight evaluation process were assigned to the 1767 grids to obtain the quantified scores of each factor of the corresponding grid, which was combined with the determined state variable-weight function to calculate the variable weight of each index and normalizing to calculate the final variable weight (Table 2). Based on the variable-weight evaluation model, the variable weights and the quantitative scores of each evaluation index being integrated, the variable-weight evaluation results of the underground space development in the study area were obtained using the spatial superposition analysis function in the GIS software.

4. Comparative Analysis of Suitability Evaluation Results

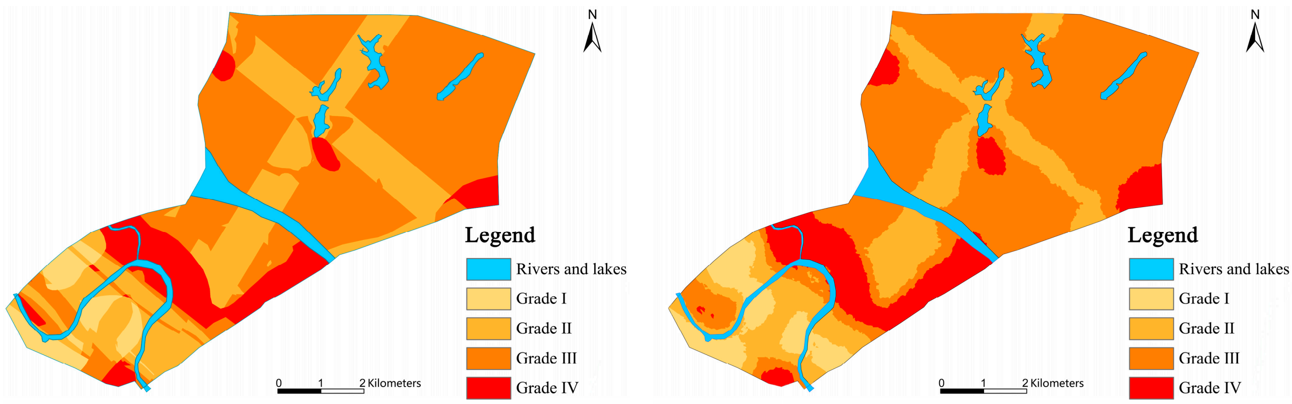
4.1. Result Comparison of Variable- and Constant-Weight Evaluations

Figures 7 and 8 show the grading diagrams of the comprehensive suitability evaluation with constant weight, variable weight, and whether socioeconomic factors are considered. Three sample points A, B and C were selected in areas with levels III, II, and I of the underground space development suitability in the study area, respectively, and the relationship between the state values of the sample points and the values of the constant and variable weights was compared and analyzed (Figure 8). Combined with the comprehensive evaluation grading diagram and sample point comparison diagram, it can be seen that: (1) Considering the socioeconomic factors, the areas with superior suitability (level I), good suitability (level II), inferior suitability (level III), and worse suitability (level IV) account for 13.07%, 68.44%, 5.03%, and 13.46% of the study area under the constant weight, respectively, indicating that the vast majority of the starting area, particularly Wuhu area, is suitable for underground space exploitation and utilization, while the area around Shenjiaji, on both sides of Zhujiahe is of poor suitability for development due to the development of karst strips, thick soft soil layer, and groundwater development. The corresponding areas, in the context of the variable-weight weights, cover 10.97%, 49.25%, 30.19% and 9.59% of the total area. In contrast to the constant-weight evaluation, the variable-weight evaluation has softer grading boundaries and more conservative evaluation results. While the area of poor suitability grows, the area of good suitability reduces. Highlighting the influence of units with poorly-performing indicators on the comprehensive analysis, it is beneficial to overcome the adverse impact of the cask effect on evaluation results. (2) When the state value of the evaluation indicator is poor to a certain extent, the variable weight of the index is distinctly greater than the constant weight; when the state value of the evaluation indicator is particularly fine, the variable weight of the index is slightly greater than the constant weight. This suggests that the penalty force of the variable-weight synthetical model is stronger than the incentive force; moreover, it indicates that the variable-weight evaluation can consider the internal imbalance of the index, producing more objective and reasonable evaluation results. (3) Figure 9 shows that from the region with poor suitability to the region with good suitability, the penalty/incentive force of the variable-weight model on the weak/excellent index increases in turn, while the penalty/incentive force on the moderate index is the same. This indicates that the neutralization effect of the variable-weight evaluation model on the region with good suitability is more significant. This also shows that the differences between indicators of the better suitability areas are greater than those of poor suitability areas.



(**a**) Evaluation results by constant-weight method (**b**) Evaluation results by variable-weight method

Figure 7. Evaluation results of UUS suitability in the study area with respect to socioeconomic factors.



(**a**) Evaluation results by constant-weight method (**b**) Evaluation results by variable-weight method

Figure 8. Evaluation results of UUS suitability in the study area with respect to geological environment factors.

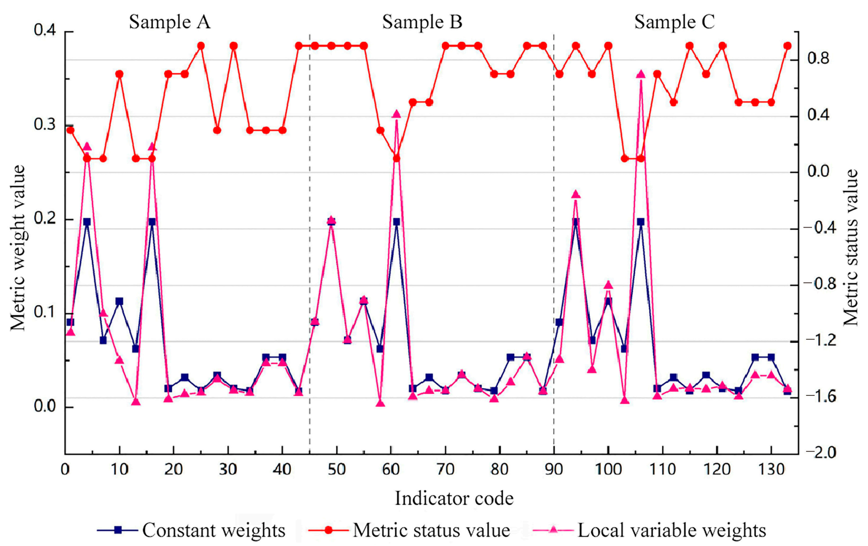


Figure 9. Comparison of sample point state values with constant- and variable-weight values.

4.2. Comparison of Results with and without Considering Socioeconomic Factors

Environmental conditions represent the physical characteristics of underground space, determining the complexity and mode of underground space utilization, while socioeconomic factors embody the degree of economic development and synthetically reflect the land cost and population distribution in the underground space. A high population density, per capita GDP, and surface housing price drive the development of underground spaces [35,42]. More construction requires more construction costs. From the comparison chart of the evaluation results, due to the high population density, per capita GDP, and housing price in Zhujiahe basin, the development cost of regions with developed socioeconomic conditions is high. Hence, after considering the socioeconomic factors, the suitability of Zhujiahe basin, particularly the southwest of the study area, is appropriately reduced; socioeconomic factors gradually decrease from southwest to northeast. Therefore, the suitability of the study area becomes more orderly compared with the suitability when only the geological environment factors from southwest to northeast are taken into consideration. Attributed to the dense distribution of communities in the eastern part of Shenjiaji area, there is a high-value area corresponding to the housing price, and the development cost of this high-value area is high, and areas with poor suitability expand.

5. Correction of Evaluation Results Based on Development Requirements

5.1. Revision of Evaluation Results Considering Development Demand

The development requirements are positively correlated with the suitability of underground spaces. The higher the development demand is, the greater the economic benefits. Therefore, the suitability evaluation results of underground space development can be modified from the perspective of development benefits. Moreover, the demand for underground space development is closely related to the ground function: the higher the above-ground function positioning, the lower the existing construction restriction [43], while what follows is that the stronger the development demand, the greater the development value. Figures 10 and 11 show the details of the existing building restrictions and functional zoning of ground buildings in the study area. The existing building restriction is divided into three levels, and the above-ground functional positioning is divided into five levels. The correction coefficient is determined by the level. The lower the level is, the lower the correction coefficient. When the correction coefficient is less than 1, the correction result is to weaken the suitability; otherwise, the suitability is enhanced. The correction coefficients m and n are selected from these two aspects (Tables 3 and 4), and the expressions are as follows:

$$\mathbf{L_i} = m \times n \times \mathbf{Z_i} \tag{6}$$

Here, $\mathbf{L_i}$ is the modified suitability score vector of the underground space development; m is the ground function correction coefficient; n is the existing building restriction correction coefficient; $\mathbf{Z_i}$ is the suitability variable-weighted comprehensive evaluation score vector.

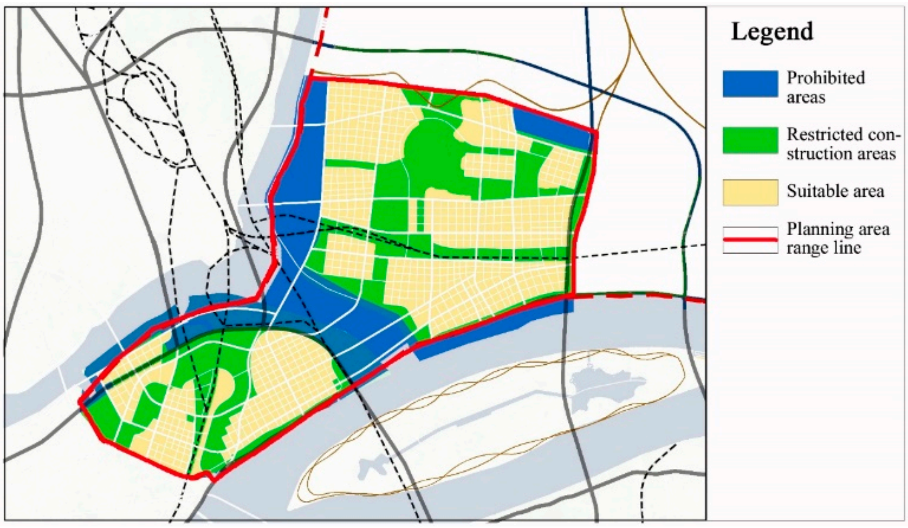


Figure 10. Restricted zoning of existing buildings.

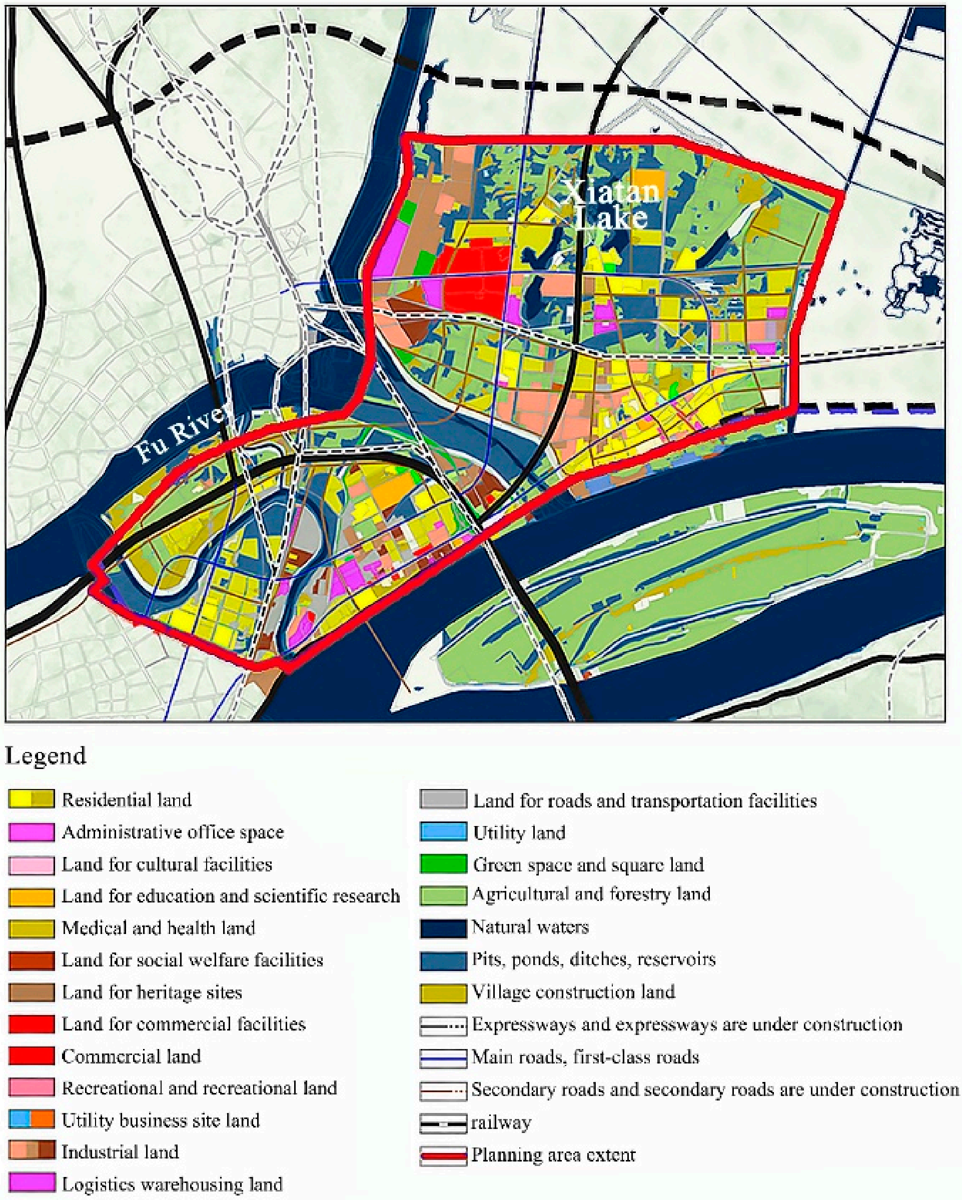


Figure 11. Functional zoning of ground-level buildings.

Table 3. Existing building restriction correction coefficient.

Buildability Zoning	Prohibited Construction	Restricted Construction	Suitable Construction
m	0.8	1	1.2

Table 4. Ground function correction coefficient.

Function of the Ground	n
Mixed-use land for administration, business, tourism, and services	1.4
Road and transportation land, public green space, medical land	1.2
Housing, culture and education, innovation and research and development, sports, social welfare, and public facilities land	1
Logistics warehousing, industry, innovative mixed land, agricultural and forestry land	0.8
Ecological green space, strategic reservation, water area, and township construction land	0.6

5.2. Verification of Underground Space Planning for the Study Area

The variable-weight comprehensive suitability evaluation of underground space development is based on the strength of the comprehensive analysis of geological environment conditions and the cost brought by socioeconomic conditions to the underground space development. Subsequently, modifications were carried out from the perspective of development benefits. Figure 12 shows the final evaluation results. Unlike the existing underground space planning of the study area (Figure 13), the amended suitability zoning has the following characteristics compared with the unmodified one: (1) With the suitable construction area being widely distributed, the development demand and development benefit in the great mass of areas of Shenjiaji will be greater, where the sites are planned for administrative, commercial, and service purposes. Thus, there are evidently more areas with superior suitability, and the underground space in the corresponding area is also mostly planned for administrative, commercial, and service lands; it indirectly verifies that the reliability of the modified suitability partition is high. (2) The west side of the study area has a continuous strip-like distribution; therefore, the suitability is one grade lower than it was before the modification, which also corresponds to the distribution of the ecological green space with a low development benefit in the planning map. (3) Owing to the wide area distribution of road transportation and medical treatment land in the two banks of Zhujia River, areas with superior suitability are accordingly higher, which corresponds to the development of public facilities and public green spaces with good benefits in underground space planning.

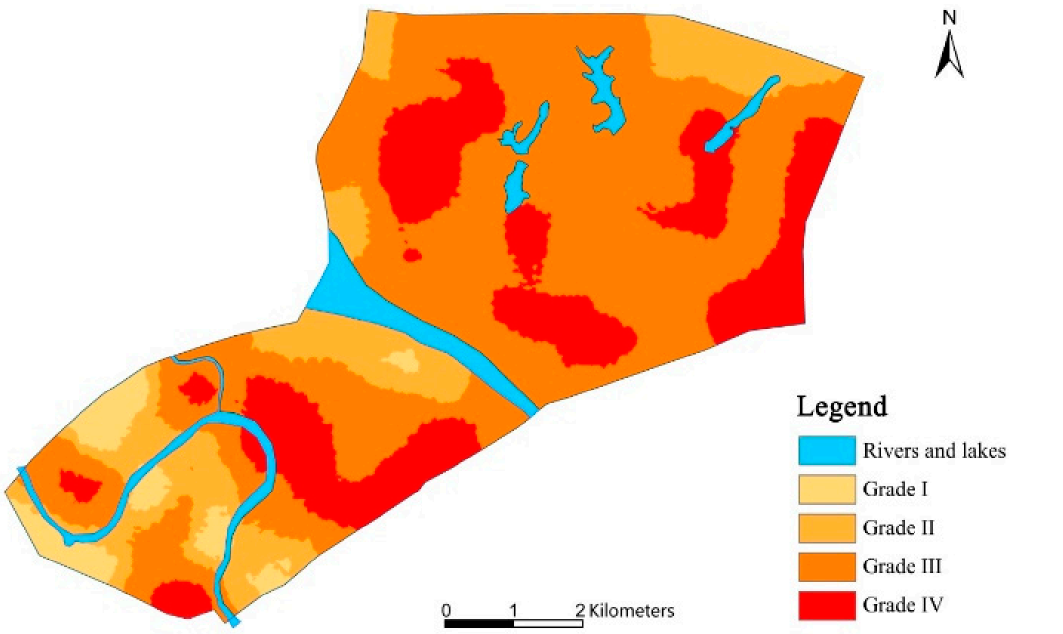


Figure 12. Suitability zoning amendment of the study area.

Overall, the favorable and unfavorable effects of socioeconomic conditions have been fully considered in the revised suitability evaluation of the underground space development in the study area. In the final grading diagram, each grading is no longer distributed continuously, but mostly in blocks, which also corresponds to the existing underground space planning of the study area individually.

The validation shows that the evaluation results are more accurate and make up for the drawbacks of the variable-weight comprehensive evaluation model, which only considers the development cost corresponding to socioeconomic factor.

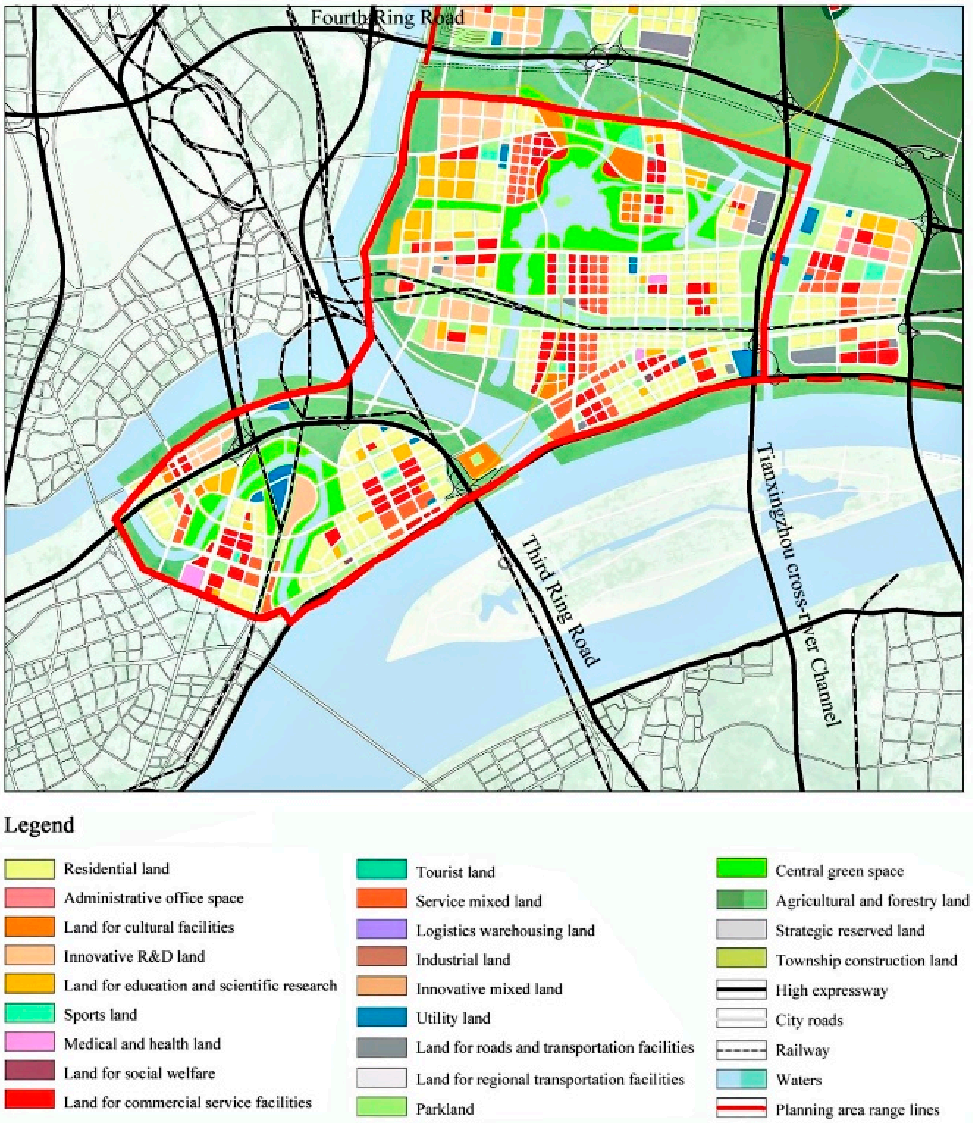


Figure 13. Existing planning of the study area of the underground space.

6. Discussion

The aim of this study has been to explore the influence of socioeconomic conditions on underground space development based on the variable weight comprehensive model. In particular, this study takes socioeconomic factors as an important cost indicator in the suitability evaluation system of underground space, and the evaluation results are modified from the perspective of socioeconomic conditions bringing development benefits. In this way, the positive and negative effects of social and economic conditions on underground space development are comprehensively considered, so the research angle is comprehensive and scientific. In addition, comparisons between the evaluation results of the constant-weight and variable-weight methods showed that the latter can correct the efficaciously determined subjective weight using the AHP and balance the differences within the indicators. Finally, the comprehensive evaluation results were compared with the existing underground space planning for verification. The results showed that the evaluation result comprehensively considered the influence of geological environmental conditions and socioeconomic conditions, and basically coincided with the existing underground space planning, which verified the reasonability of the evaluation results.

Although important discoveries were made in these studies, there are also limitations. First, this study did not reflect the influence of different depths on the development of underground space. Development costs at different depths obviously vary considerably.

We are also carrying out relevant research, which involves examining the idea that various development modes, engineering types and construction techniques of underground space affect the development cost of underground space (there are coupling effects between factors), carrying out macro law analysis and multi-factor correlation analysis of underground space development cost, and putting forward a suitable index system to realize the quantification and evaluation of underground space development cost.

Second, it is not enough to use the variable weight model to weaken the subjectivity of the analytic hierarchy process. Some objective weighting methods are also needed. For example, three indicators of socioeconomic conditions (population density, per capita GDP and house prices) are strongly correlated. We considered the relative importance of each of the two indicators using the analytic hierarchy process, and the variable weight model balanced the differences within the indicators. Combined with the objective weighting method to quantify the correlation between indicators, the final evaluation results will be more scientific and reasonable.

Third, the mutual mechanism between underground space development and socioeconomic conditions is not clearly proposed. In future studies, several combination forms can be suggested based on the mutual influence between the underground space development mode and socioeconomic conditions, and the maximum benefit of underground space development can be realized based on the combination cost and benefit.

Finally, as for socioeconomic conditions, the selected indicators may not be comprehensive enough, such as the impact of urban resilience on underground space development, traffic flow, surface construction, etc. Due to the close relationship between the indicators of socioeconomic factors and the limited space of the paper, we chose three representative indicators. A more diverse set of socio-economic indicators could be selected for future studies.

Once optimized based on the aspects discussed above, the evaluation results can be used as a case study of the interaction between underground space development and socio-economic conditions. A framework can also be constructed to express the benefits and costs of different underground space development depths, development modes and different socioeconomic conditions. This framework can also select the most reasonable evaluation methods according to the range of indicators of different regions, such as subjective and objective combination weighting methods, variable-weight and constant-weight combination weighting methods.

To summarize, this study investigated and clarified the influence of geological environmental conditions and social economic conditions on underground space development. Based on the variable-weight comprehensive model, taking the starting area of Changjiang New Town as an example, the study completed the suitability evaluation of underground space development, and verified it with the existing underground space planning of the starting area, proving its credibility. The study provided an innovative perspective on the suitability evaluation of urban underground space, which is conducive to the optimization of the functional layout and engineering design of underground space, and conforms to the core needs of the society to seek to maximize the overall benefits of environmental economy and promote the coordination and control of urban space optimization. Nevertheless, there is scope to further explore the selection of evaluation methods and the interaction between underground space development and socioeconomic conditions.

7. Conclusions

(1) The penalty-incentive variable-weight state function was adopted to establish a comprehensive evaluation model of underground space utilization, and the evaluation results of the constant-weight and variable-weight applied to the starting area of Changjiang New Town as an analysis case were compared. The results showed that the variable weight evaluation model effectively weakened the influence of state value on suitability, and reduced the subjectivity of AHP.

(2) The results of evaluation with and without consideration of socioeconomic factors were compared and analyzed. The results showed that, in terms of cost, the adverse impact of economic development degree on underground space development was taken into account, which made up for the single angle of the existing suitability evaluation. Furthermore, the development cost of areas with high socioeconomic factors is high.
(3) From the perspective of socio-economic factors bringing development needs and benefits to underground space development, the variable weight comprehensive evaluation results were revised to obtain a more scientific suitability zoning map, which was verified with the existing underground space planning in the study area to prove its credibility. The evaluation method can be extended to the suitability evaluation of similar underground space utilization.
(4) It can provide a reference for existing planning where the evaluation results differ from the existing planning of the underground space in the study area. In future research, the development and stratified evaluation will be considered, aimed at the advancement of rational planning and orderly development of urban underground spaces.

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