Data processing and model building specific process

1. Data processing

Based on the index conversion outlined in section 2.2, the five attributes of geomorphic type, engineering geological rock group, active fracture distance, karst development degree, and land use degree were transformed into intuitionistic fuzzy numbers. This transformation yielded the initial numerical table for evaluating the carrying capacity of the geological environment in Meishan City, as shown in Table S1.

Table S1 Initial data sheet of Geo-environmental carrying capacity evaluation of Meishan City

Geomorphological units	C1	C2	C3	C4	C5	C6	C7	C8
A1-1	[1000,1500]	[0.6,0.2]	[0.8,0.05]	[0.3,0.4]	[0.1,0.65]	[1200,1200]	[0.1,0.65]	[0.15,0.15]
A2-1	[300,480]	[0.6,0.2]	[0.8,0.05]	[0.6,0.2]	[0.6,0.2]	[1200,1200]	[0.3,0.4]	[0.15,0.15]
A2-2	[500,500]	[0.6,0.2]	[0.8,0.05]	[0.6,0.2]	[0.1,0.65]	[1200,1200]	[0.3,0.4]	[0.15,0.15]
A3-1	[500,500]	[0.6,0.2]	[0.8,0.05]	[0.8,0.05]	[0.1,0.65]	[800,1200]	[0.6,0.2]	[0.1,0.15]
A3-2	[200,400]	[0.6,0.2]	[0.8,0.05]	[0.8,0.05]	[0.1,0.65]	[650,800]	[0.6,0.2]	[0.1,0.15]
A3-3	[180,220]	[0.6,0.2]	[0.8,0.05]	[0.8,0.05]	[0.3,0.4]	[700,800]	[0.6,0.2]	[0.05,0.05]
B1-1	[100,130]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[800,900]	[0.6,0.2]	[0.1,0.1]
B1-2	[100,140]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[700,800]	[0.8,0.05]	[0.1,0.1]
B1-3	[100,120]	[0.3,0.4]	[0.8,0.05]	[0.3,0.4]	[0.1,0.65]	[650,750]	[0.8,0.05]	[0.1,0.1]
B1-4	[100,160]	[0.3,0.4]	[0.8,0.05]	[0.6,0.2]	[0.1,0.65]	[700,700]	[0.6,0.2]	[0.05,0.1]
B1-5	[150,180]	[0.3,0.4]	[0.8,0.05]	[0.8,0.05]	[0.1,0.65]	[650,800]	[0.8,0.05]	[0.065,0.05]
B2-1	[60,60]	[0.3,0.4]	[0.8,0.05]	[0.8,0.05]	[0.1,0.65]	[800,1000]	[0.6,0.2]	[0.1,0.12]
B2-2	[50,60]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[850,850]	[0.8,0.05]	[0.1,0.1]
B2-3	[50,80]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[1200,1200]	[0.8,0.05]	[0.1,0.15]
B2-4	[60,80]	[0.3,0.4]	[0.8,0.05]	[0.8,0.05]	[0.1,0.65]	[800,900]	[0.6,0.2]	[0.06,0.2]
B2-5	[50,50]	[0.3,0.4]	[0.8,0.05]	[0.3,0.4]	[0.1,0.65]	[700,800]	[0.8,0.05]	[0.1,0.1]
B2-6	[40,60]	[0.3,0.4]	[0.8,0.05]	[0.6,0.2]	[0.1,0.65]	[600,800]	[0.6,0.2]	[0.05,0.05]
B2-7	[50,90]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[600,800]	[0.8,0.05]	[0.05,0.05]
B3-1	[20,40]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[800,900]	[0.8,0.05]	[0.1,0.1]
B3-2	[20,40]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[800,1100]	[0.8,0.05]	[0.1,0.1]
B3-3	[30,30]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[800,900]	[0.8,0.05]	[0.1,0.1]
B3-4	[20,40]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[800,900]	[0.8,0.05]	[0.1,0.1]
B3-5	[20,40]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[750,750]	[0.8,0.05]	[0.1,0.1]
B3-6	[40,40]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[700,800]	[0.8,0.05]	[0.05,0.05]
B3-7	[40,40]	[0.3,0.4]	[0.8,0.05]	[0.1,0.65]	[0.1,0.65]	[650,800]	[0.8,0.05]	[0.05,0.05]
C1-1	[10,20]	[0.1,0.65]	[0.3,0.4]	[0.1,0.65]	[0.1,0.65]	[1200,1200]	[0.8,0.05]	[0.15,0.15]
C1-2	[10,20]	[0.1,0.65]	[0.3,0.4]	[0.1,0.65]	[0.1,0.65]	[1100,1100]	[0.8,0.05]	[0.1,0.1]
C1-3	[20,20]	[0.1,0.65]	[0.3,0.4]	[0.1,0.65]	[0.1,0.65]	[1100,1100]	[0.8,0.05]	[0.1,0.1]
C1-4	[20,20]	[0.1,0.65]	[0.3,0.4]	[0.1,0.65]	[0.1,0.65]	[1200,1200]	[0.8,0.05]	[0.1,0.11]
C1-5	[10,20]	[0.1,0.65]	[0.3,0.4]	[0.1,0.65]	[0.1,0.65]	[700,800]	[0.8,0.05]	[0.1,0.1]
C1-6	[20,20]	[0.1,0.65]	[0.3,0.4]	[0.1,0.65]	[0.1,0.65]	[800,1000]	[0.8,0.05]	[0.1,0.1]
C2-1	[15,20]	[0.1,0.65]	[0.3,0.4]	[0.1,0.65]	[0.1,0.65]	[800,1000]	[0.8,0.05]	[0.1,0.1]
C2-2	[15,15]	[0.1,0.65]	[0.3,0.4]	[0.3,0.4]	[0.1,0.65]	[850,850]	[0.8,0.05]	[0.1,0.1]

2 Determination of indicator weights and analysis

2.1 Determination of subjective weights

The degree of influence of the k-th indicator on the carrying capacity of the geo-environmental is denoted by $D_j = [u_k, v_k], j = 1, 2, \cdots, m; k = 1, 2, \cdots, j$, while u_k represents the degree of affiliation of the k-th indicator to the geo-environmental carrying capacity, and v_k represents the degree of non-affiliation of the k-th indicator to the geo-environmental carrying capacity. Using the consistent scoring of the eight indicators on the geo-environmental carrying capacity provided by three experts and the intuitionistic fuzzy conversion formula outlined in Table 3 of the main text, Table S2 was obtained.

Table S2 Expert weights converted to intuitionistic fuzzy numbers

Indicators	Linguistic variables	Intuitionistic fuzzy data
Terrain undulations (I_1)	Average level of impact	[0.5,0.45]
Geo-morphological type (I_2)	Average level of impact	[0.5,0.45]
Engineering geological rock group (I_3)	High level of impact	[0.75,0.2]
Active fracture distance (I_4)	High level of impact	[0.75,0.2]
Karst development degree (I_5)	Average level of impact	[0.5,0.45]
Annual average rainfall (I_6)	High level of impact	[0.75,0.2]
Earthquake peak acceleration (I_7)	Negligible impact	[0.35,0.6]
Land use degree (I_8)	Average level of impact	[0.5,0.45]

In order to accurately represent the influence of each indicator on the geoenvironmental carrying capacity based on the weight information provided by the experts, this study employs the principle of maximum affiliation (Wang et al., 2015). The following formula is used to calculate the subjective weights of each indicator:

$$\omega_j = \frac{u_k + (u_k / (u_k + v_k))}{\sum_{j=1}^{m} (u_k + (u_k / (u_k + v_k)))} \quad j = 1, 2, \cdots, m; k = 1, 2, \cdots, j \tag{1}$$

The weights of the 8 index systems were obtained by the above formulae in Table S3 below.

Table S3 Results of weight calculation by expert scoring method

Indicators	Weighting (expert scoring method)
Terrain undulations (I_1)	0.1087
Geo-morphological type (I_2)	0.1087
Engineering geological rock group (I_3)	0.1630
Active fracture distance (I_4)	0.1630
Karst development degree (I_5)	0.1087
Annual average rainfall (I_6)	0.1630
Earthquake peak acceleration (I_7)	0.0761
Land use degree (I_8)	0.1087

And record the subjective weight as:

$$\omega_j = (0.1087, 0.1087, 0.1630, 0.1630, 0.1087, 0.1630, 0.0761, 0.1087)$$

2.2 Determination of objective weights

The specific steps of the intuitive logistic modulus entropy weighting method are as follows:

(1) Data standardization

According to the original data of geological environment bearing capacity index of Meishan City, the standardized data can be obtained by using the method of standardization of index data in Chapter 3 of the main text. See Table 1.

(2) Calculation of intuitive fuzzy entropy

The more information provided, or the greater the variability of the attribute index values among the evaluation units, the greater the objective weight will be, so that the differences among the evaluation units can be distinguished more effectively (Mohammed et al., 2022). The intuitive fuzzy entropy can be calculated by the following formula.

Step1: Column normalized decision matrix

Drawing on the conversion of interval-type variables to intuitionistic fuzzy numbers in Chapter 3 of the main text, Let $X = (x_{ij})_{n \times m}$ be the intuitionistic fuzzy decision matrix, then the normalized decision matrix is $Y = (y_{ij})_{n \times m}$, $i = 1, 2, \cdots, n; j = 1, 2, \cdots, m$.

$$f_{ij}^{L} = (y_{ij}^{l}) / \sum_{i=1}^{n} (y_{ij}^{l}) \quad i = 1, 2, \cdots, n; j = 1, 2, \cdots, m \tag{2}$$

$$f_{ij}^{U} = (y_{ij}^{u}) / \sum_{i=1}^{n} (y_{ij}^{u}) \quad i = 1, 2, \cdots, n; j = 1, 2, \cdots, m \tag{3}$$

Where f_{ij}^{L} and f_{ij}^{U} are the intuitionistic fuzzy number endpoint values after normalization of the decision matrix, where i is each evaluation unit and j is each evaluation index.

Step 2: Calculate the information entropy of the intuitionistic fuzzy number endpoint output respectively.

$$H_{j}^{L} = -\frac{1}{\ln m} \times \sum_{i=1}^{n} f_{ij}^{L} \ln(f_{ij}^{L}) \quad (j=1,2,\cdots,m) \tag{4}$$

$$H_{j}^{U} = -\frac{1}{\ln m} \times \sum_{i=1}^{n} f_{ij}^{U} \ln(f_{ij}^{U}) \quad (j=1,2,\cdots,m) \tag{5}$$

Step 3: Calculate the entropy value interval for each attribute

$$\omega_{j}^{1} = (1 - H_{j}^{L}) / (m - \sum_{j=1}^{m} H_{j}^{L}) \tag{6}$$

$$\omega_{j}^{2} = (1 - H_{j}^{U}) / (m - \sum_{j=1}^{m} H_{j}^{U}) \tag{7}$$

$$\begin{aligned} \omega_j^L &= min(\omega_j^1, \omega_j^2) \\ \omega_j^U &= max(\omega_j^1, \omega_j^2) \\ \overline{\omega} &= (\omega_j^L, \omega_j^U) \end{aligned} \tag{8}$$

(3) Calculate the weight of each indicator

Using the intuitionistic fuzzy matrix R_{ij}, the intuitionistic fuzzy entropy of each attribute is calculated by applying formula (3) as described in the text. To minimize the fuzzy degree of attribute evaluation information, a linear programming solution model is established, which is expressed as follows:

$$\begin{aligned} & minE_{\omega} = \sum_{i=1}^{n} E_{\omega}(R_{ij}) = \sum_{i=1}^{n}\sum_{j=1}^{m} \omega_j \sum_{i=1}^{n} E_{\omega}(r_{ij}) \\ & s.t.\begin{cases} \omega_j \in (\omega_j^L, \omega_j^U) \\ \sum_{j=1}^{m} \omega_j = 1 \qquad (j = 1, 2, \cdots, m) \\ \omega_j \geq \eta \end{cases} \end{aligned} \tag{9}$$

where η is a sufficiently small real number, and

$$E_{\omega}(r_{ij}) = \frac{min(u_{r_{ij}}(x), v_{r_{ij}}(x)) + \pi_{r_{ij}}(x)}{max(u_{r_{ij}}(x), v_{r_{ij}}(x)) + \pi_{r_{ij}}(x)} \tag{10}$$

The optimized objective weight value of each attribute can be obtained by solving Eq. 9 and denoted as $\omega_j^* = arg\ minE_{\omega}$.

Using the intuitionistic fuzzy entropy objective weight calculation method described above, the indicator values of 8 attributes in the decision matrix of geological environment carrying capacity evaluation of Meishan City are entered into Eqs. (2, 3, 4, 5, 6, 7, 8). The objective weight of each attribute is then obtained within the following value interval:

$$\begin{aligned} \overline{\omega} = (&[0.0777, 0.6650], [0.0171, 0.0381], [0.0135, 0.1386], [0.0520, 0.0855], \\ &[0.0034, 0.0361], [0.0030, 0.7290], [0.0090, 0.1227], [0.0009, 0.0177]) \end{aligned}$$

According to the decision matrix R_{ij}, the intuitive fuzzy entropy of each attribute is calculated using Eqs. (10) to form a fuzzy entropy matrix $E(r_{ij})$.

$$E(r_{ij}) = \begin{bmatrix}
0.0059 & 0.5000 & 0.2105 & 0.8571 & 0.3889 & 0.1478 & 0.3889 & 0.1084 \\
0.0198 & 0.5000 & 0.2105 & 0.5000 & 0.5000 & 0.1478 & 0.8571 & 0.1084 \\
0.0119 & 0.5000 & 0.2105 & 0.5000 & 0.3889 & 0.1478 & 0.8571 & 0.1084 \\
0.0119 & 0.5000 & 0.2105 & 0.2105 & 0.3889 & 0.2217 & 0.5000 & 0.1626 \\
0.0298 & 0.5000 & 0.2105 & 0.2105 & 0.3889 & 0.2917 & 0.5000 & 0.1626 \\
0.0334 & 0.5000 & 0.2105 & 0.2105 & 0.8571 & 0.2709 & 0.5000 & 0.4075 \\
0.0608 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.2317 & 0.5000 & 0.1712 \\
0.0607 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.2709 & 0.2105 & 0.1712 \\
0.0610 & 0.8571 & 0.2105 & 0.8571 & 0.3889 & 0.2958 & 0.2105 & 0.1712 \\
0.0605 & 0.8571 & 0.2105 & 0.5000 & 0.3889 & 0.2791 & 0.5000 & 0.3424 \\
0.0603 & 0.8571 & 0.2105 & 0.2105 & 0.3889 & 0.2917 & 0.2105 & 0.3638 \\
0.1053 & 0.8571 & 0.2105 & 0.2105 & 0.3889 & 0.2276 & 0.5000 & 0.1668 \\
0.1264 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.2204 & 0.2105 & 0.1712 \\
0.1242 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.1478 & 0.2105 & 0.1626 \\
0.1035 & 0.8571 & 0.2105 & 0.2105 & 0.3889 & 0.2317 & 0.4082 & 0.2642 \\
0.1282 & 0.8571 & 0.2105 & 0.8571 & 0.3889 & 0.2709 & 0.2105 & 0.1712 \\
0.1580 & 0.8571 & 0.2105 & 0.5000 & 0.3889 & 0.3160 & 0.5000 & 0.4075 \\
0.1234 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.3160 & 0.2105 & 0.4075 \\
0.3277 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.2317 & 0.2105 & 0.1712 \\
0.3277 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.2244 & 0.2105 & 0.1712 \\
0.2269 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.2317 & 0.2105 & 0.1712 \\
0.3277 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.2317 & 0.2105 & 0.1712 \\
0.3277 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.2563 & 0.2105 & 0.1712 \\
0.1638 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.2709 & 0.2105 & 0.4075 \\
0.1638 & 0.8571 & 0.2105 & 0.3889 & 0.3889 & 0.2917 & 0.2105 & 0.4075 \\
0.7376 & 0.3889 & 0.8571 & 0.3889 & 0.3889 & 0.1478 & 0.2105 & 0.1084 \\
0.7376 & 0.3889 & 0.8571 & 0.3889 & 0.3889 & 0.1632 & 0.2105 & 0.1712 \\
0.3688 & 0.3889 & 0.8571 & 0.3889 & 0.3889 & 0.1632 & 0.2105 & 0.1712 \\
0.3688 & 0.3889 & 0.8571 & 0.3889 & 0.3889 & 0.1478 & 0.2105 & 0.1688 \\
0.7376 & 0.3889 & 0.8571 & 0.3889 & 0.3889 & 0.2709 & 0.2105 & 0.1712 \\
0.3688 & 0.3889 & 0.8571 & 0.3889 & 0.3889 & 0.2276 & 0.2105 & 0.1712 \\
0.4917 & 0.3889 & 0.8571 & 0.3889 & 0.3889 & 0.2276 & 0.2105 & 0.1712 \\
0.5366 & 0.3889 & 0.8571 & 0.8571 & 0.3889 & 0.2204 & 0.2105 & 0.1712
\end{bmatrix}$$

To determine the extent of influence of each indicator on the geoenvironmental carrying capacity and simultaneously minimize the fuzzy information of each attribute evaluation, the following linear programming model is established:

$$min\ E_{\omega} = 7.4978\omega_1 + 22.3968\omega_2 + 12.1203\omega_3 + 14.0806\omega_4 + 13.4127\omega_5 + 7.6340\omega_6 + 10.6429\omega_7 + 7.0038\omega_{8s}$$

$$s.t.\begin{cases} 0.0777 \le \omega_1 \le 0.6650 \\ 0.0171 \le \omega_2 \le 0.0381 \\ 0.0135 \le \omega_3 \le 0.1386 \\ 0.0520 \le \omega_4 \le 0.0855 \\ 0.0034 \le \omega_5 \le 0.0361 \\ 0.0030 \le \omega_6 \le 0.7290 \\ 0.0090 \le \omega_7 \le 0.1227 \\ 0.0009 \le \omega_8 \le 0.0177 \\ \sum_{j=1}^{8} \omega_i = 1 \\ \omega_j \ge 0.0001\ (j = 1, 2, \cdots, 8) \end{cases}$$

The optimal objective weights of the eight indicators were obtained as shown in Table S4.

Table S4 Objective weighting calculation results

Indicators	Intuitive fuzzy entropy method
Terrain undulations (I_1)	0.6649
Geo-morphological type (I_2)	0.0171
Engineering geological rock group (I_3)	0.0135
Active fracture distance (I_4)	0.0521
Karst development degree (I_5)	0.2224
Annual average rainfall (I_6)	0.0034
Earthquake peak acceleration (I_7)	0.0089
Land use degree (I_8)	0.0178

And record the objective weights as:

$$\omega_j^* = (0.6649, 0.0171, 0.0135, 0.0521, 0.2224, 0.0034, 0.0089, 0.0178)$$

2.3 Combination weight determination

In this study, the weights of each geo-environmental carrying capacity indicator were determined using both the subjective weight determination method (expert scoring method) and the objective weight determination method (intuitionistic fuzzy entropy value method). The expert scoring method simplifies the complex problem of multiple indicators into a simple intuitionistic fuzzy problem and calculates the weights of each indicator in a concise and clear manner (Finkelstein et al., 2021). On the other hand, the intuitionistic fuzzy entropy method calculates the weights of each indicator based on its variability and degree of influence on the geo-environmental. This method determines the importance of indicators to the results based on their variability, without considering the interconnections between them. It uses the distribution characteristics of indicator data as the basis for judgment, which has a solid theoretical basis (Ni et al., 2022).

To distinguish the degree of influence of each indicator on the bearing capacity of the geo-environmental under different weighting results, the indicators were combined to find the weight using the established indicator system that contains interval-type variables and linguistic variables. To avoid the loss of effective information, this study used the weight proportion to accurately portray the weight of each indicator system in geo-environmental carrying capacity, and the calculation formula is as follows:

$$\omega_j = \omega_j^* \bullet \omega_{jz} / \sum_{j=i}^{m} \omega_j^* \bullet \omega_{jz} \quad j = 1, 2, \cdots, m \tag{11}$$

The results of the obtained combined weights are shown in Table S5.

Table S5 Calculation results of combination weights

Indicators	Combination weights
Terrain undulations (I_1)	0.6442
Geo-morphological type (I_2)	0.0166
Engineering geological rock group (I_3)	0.0196
Active fracture distance (I_4)	0.0757
Karst development degree (I_5)	0.2155
Annual average rainfall (I_6)	0.0049
Earthquake peak acceleration (I_7)	0.0060
Land use degree (I_8)	0.0172

And record the combined weights as:

$\omega = (0.6442, 0.0166, 0.0196, 0.0757, 0.2155, 0.0049, 0.0060, 0.0172)$

2.4 Sensitivity analysis of indicator weights

The weights of the evaluation indexes for geo-environmental bearing capacity are determined using the aforementioned subjective assignment method (expert scoring), objective assignment method (intuitionistic fuzzy entropy value method), and combined weight determination. The results are presented in Exhibit S6 and Figure 1. It is observed that the objective weights and combined weights of each index remain largely consistent. The topographic relief (I1) is identified as the primary factor that affects geo-environmental bearing capacity, followed by the degree of karst development (I5), while other indicators combined impact the bearing capacity of the geological environment in each evaluation unit. Areas with more undulating terrain exhibit lower geo-environmental carrying capacity and higher density of geohazards. Similarly, stronger degrees of karst development indicate a higher likelihood of geohazards. The weight information derived from this study provides a more accurate reflection of the main influencing factors of geo-environmental carrying capacity.

Table S6 Weighting analysis

Indicators	Expert scoring method	Intuitive fuzzy entropy method	Combination weights
Terrain undulations (I_1)	0.1087	0.6649	0.6442
Geo-morphological type (I_2)	0.1087	0.0171	0.0166
Engineering geological rock group (I_3)	0.1630	0.0135	0.0196
Active fracture distance (I_4)	0.1630	0.0521	0.0757
Karst development degree (I_5)	0.1087	0.2224	0.2155
Annual average rainfall (I_6)	0.1630	0.0034	0.0049
Earthquake peak acceleration (I_7)	0.0761	0.0089	0.0060
Land use degree (I_8)	0.1087	0.0178	0.0172

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