# Site selection for municipal solid waste landfills in arid regions based on fuzzy decision-making A Case Study in the Hexi Corridor of China

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**Research Article**

**Keywords:** FAHP, MSW, Landfill site selection, Hexi corridor, Group fuzzy MULTIMOORA

**Posted Date:** March 29th, 2021

**DOI:** https://doi.org/10.21203/rs.3.rs-305236/v1

# Site selection for municipal solid waste landfills in arid regions based on fuzzy decision-making： A Case Study in the Hexi Corridor of China

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**Abstract:** The rational and scientific selection of Municipal Solid Waste (MSW) landfill sites is becoming increasingly important, due to the continuous growth of MSW worldwide. Multi-source information is employed to ensure the accuracy of the evaluation criteria, including hydrogeological, morphological, environmental, climatic and socio-economic data. In the fuzzy logic environment, a Fuzzy Analytic Hierarchy Process (FAHP) and GIS spatial technique have been utilized to locate potential landfill sites. Landfill Site Selection Results (LSSR) were divided into three categories: suitable, less suitable, and unsuitable. Suitable areas were further divided into high, moderate, and low levels. We used the field investigations of 28 standardized landfill sites in the Hexi Corridor of China that comply with the China National Standard (CNS) to verify the LSSR. These sites are then ranked utilizing group fuzzy MULTIMOORA. These methods were more feasible and accurate in assessing the suitability of MSW landfills. The highlights of our methods were as follows: (1) The uncertainty of AHP expert

scoring reduced by employing the fuzzy membership function, and the decision efficiency of spatial analysis improved as well. (2) Verification results showed that the main LSSR met the CNS perfectly and located suitable areas, with an accuracy of 93% (26 out of 28 sites). (3) In the highly suitable areas, 11 candidate areas were selected for the MSW landfill site construction in the Hexi Corridor. Furthermore, technical countermeasures for the standardized management of MSW landfills were proposed for the Hexi Corridor, which is critical for ecological/environmental protection.

**Keywords:**

FAHP

MSW

Landfill site selection

Hexi corridor

Group fuzzy MULTIMOORA

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**Declaration**

**Funding:** This work was supported by [the National Key R&D Program of China] (Grant numbers [2018YFC1903700]).

**Conflicts of interest/Competing interests:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Ethics approval**: All authors have read this manuscript and would like to have it considered exclusively for publication in **ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH.** None of the material related to this manuscript has been published or is under consideration for publication elsewhere, including the internet. These articles report original research with broad scientific significance and importance. Consequently, this article is Research Articles.

**Consent to participate** All authors have read this manuscript and would like to have it considered exclusively for publication in **ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH.**

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**Availability of data and material:** Agree with transparent.

**Code availability:** Agree with transparent.

**Authors' contributions**: Data curation: [JiaMin Liu]; Software: [JiaMin Liu]; Formal analysis: [JiaMin Liu]; Visualization: [JiaMin Liu]; Writing - original draft: [JiaMin Liu]; Methodology: [Bin Xiao]; Resources: [Bin Xiao]; Writing - review &

editing: [Yueshi Li, Jizong Jiao]; Supervision: [Jizong Jiao, Xiaoyun Wang]; Conceptualization: [Jizong Jiao, Jian Bi]; Validation: [Jizong Jiao, Xiaoyun Wang]; Funding acquisition: [Jizong Jiao].

**Acknowledgments:** We would like to thank the data providers, authors and funders.

## 1. Introduction

While urbanization promotes higher anthropogenic living standards, it also creates a series of significant challenges, such as increased waste production (Hoo et al., 2018); thus, the management of MSW is of great concern on a global scale (Turcott Cervantes et al., 2018). According to Chinese statistics, the annual growth rate ranges from 8%~11.5%, where 2/3 of cities are surrounded by MSW sites (Luo et al., 2018), which can hinder economic development to a certain extent (Liu et al., 2014).

The composition of MSW is complex and is typically separated by domestic waste, industrial solid waste, agricultural solid waste, and other waste (Han et al., 2019). Although China has experimented with waste classification and harmless treatment policies in Shanghai and other developed cities since 2018, landfills remain the most important and efficacious means for the disposal of most MSW (Zhang et al., 2019). Over time, the leachate produced by chemical degradation in landfills tend to

contaminate surface water and groundwater (Calabro et al., 2018). Further, the ambient atmosphere, soil, and water are contaminated by microbial decomposition releases of $NH_3$, $H_2S$, and harmful hydrocarbon gases (Peng et al., 2018). Meanwhile, landfills require large tracts of land; thus, existing landfills in most areas of China cannot meet the ever-growing demand for MSW. Consequently, it is imperative that the locations of landfill sites be prudently selected based on the best science and rationale (Kamdar et al., 2019).

In recent years, a variety of Multi-Criteria Decision Analysis (MCDA) methods have been employed for the Landfill Site Selection (LSS) research (Davami et al., 2014), encompassing the Analytic Hierarchy Process (Asefi et al.) (Torabi-Kaveh et al., 2016), Fuzzy Analytic Hierarchy Process (FAHP) (Hanine et al., 2016), Preference Ranking Organization Method (PROMETHEE) (Hamzeh et al., 2015), Analysis Network Process (ANP) (Bahrani et al., 2016), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Asefi and Lim, 2017), and Fuzzy TOPSIS (Beskese et al., 2015).

Integrated MCDA and GIS are the more commonly used models for LSS. AHP utilizes relative importance to compare qualitative and quantitative criteria, which can minimize the inconsistency of judgments (Torabi-Kaveh et al., 2016). Fuzzy logic provides a broad set of fuzzy membership functions, including linear, triangular, trapezoidal, Sigmoidal, Gaussian and Gamma functions (Al-Ruzouq et al., 2018). FAHP introduces fuzzy logic on the basis of AHP to resolve complex multi-criteria/

multi-level decision-making challenges (Rezaeisabzevar et al., 2020). The emergence of massive quantities of data has enabled modeling research and analysis based on spatial data and other tools, where the application of GIS has become commonplace (Afzali et al., 2014).

Fuzzy membership functions and GIS tools have been widely employed in LSS (Spigolon et al., 2018) , and several researchers used 13 evaluation criteria and a triangular fuzzy membership function to select optimal landfill sites (Karimi et al., 2020). Other researchers utilized 10 criteria and fuzzy logic space modeling methods to identify landfills (Soroudi et al., 2018). However, a few studies in the literature describe the combination of more than 20 evaluation criteria with multiple fuzzy membership functions. The adoption of multiple sets of fuzzy membership functions for scenario simulation can better transform the logical relation of criterion attributes to membership degree, effectively reducing the uncertainty of decision-making (Eskandari et al., 2016). As relates verifications, nighttime satellite imagery and sensitivity analysis have been exploited to verify the LSSR (Karimi et al., 2020). However, no reports to date have employed existing standard landfill locations to verify the LSSR. In addition, we discuss several Fuzzy MULTIMOORA tools for ranking to produce the final rankings and clarifying the robustness of the MCDA method.

The Hexi Corridor comprises one of the most arid areas in China (Huang et al., 2017). The ecological environment is extremely fragile, with a poor anti-interference capacity, and is one of the strategic regions for environmental development and

protection in Northwest China (Williams et al., 2009). Nevertheless, existing research has concentrated primarily on the LSS in humid areas, and few reports exist on the study of arid areas with fragile ecological environments (Osra and Kajjumba, 2020). Therefore, it is of particular importance to scientifically and rationally select landfill sites for MSW that minimize negative environmental impacts (Uyan, 2014).

To encapsulate, taking the Hexi Corridor in China as a case study, we endeavored to integrate FAHP-GIS methods, select 20 valuation criteria, and determine multiple fuzzy membership functions, toward the identification of new suitable and scientifically vetted landfill areas. The LSSR was employed to provide reliable and technological support for the scientific management of solid waste in this region, while guiding effective urban planning.

## 2. Materials and methods

### 2.1. Study area

The Hexi Corridor **(Fig. 1)** is located in the northwest of Gansu Province, China (93°20'E—104°00'E, 37°10' N—42° 50' N) (Zhang et al., 2016). The improper disposal of MSW is one of the most important factors leading to increasingly serious environmental pollution in this area (Huang et al., 2017). According to statistics from the Gansu Environmental Statistics Bulletin (GESB, 2009), it was estimated that the Hexi Corridor generated 0.6825 million tons of domestic waste, 19.2056 million tons of industrial solid waste and 1.6031 million tons of agricultural solid waste annually. In

2018, the Hexi Corridor produced 1.1894 million tons of domestic waste, 43. 2496 million tons of industrial solid waste, and 2.6082 million tons of agricultural solid waste.

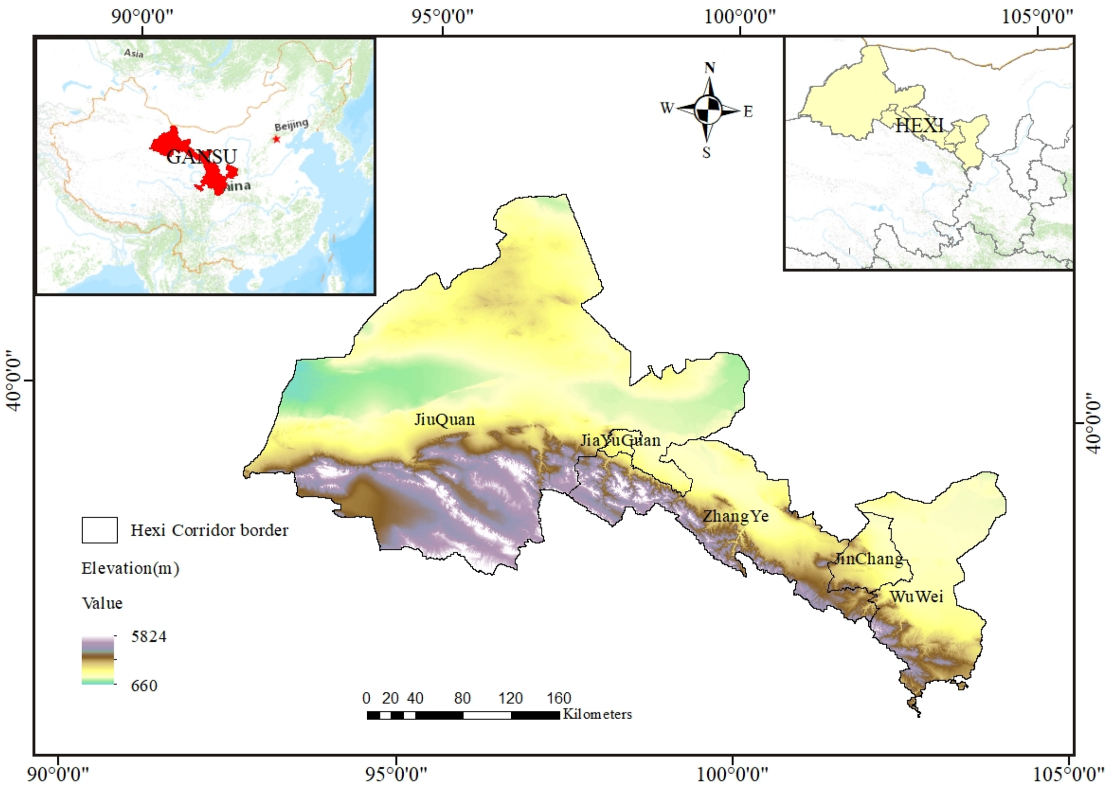



**Fig. 1.** Elevation of the study region. The Hexi Corridor includes five cities (Jiuquan, Jiayuguan, Zhangye, Jinchang, Wuwei), and twenty counties (districts), with a total area of $2.7\times 10^5$ $km^2$. Elevation data is from the USGS - SRTM dataset, which provides elevation data at a 30-meter resolution. The elevation of the study area ranged from 660 to 5842 meters.

## 2.2. Data collection

Source data for groundwater depth and quality was provided by the Gansu Water Resources Department (GWRD, 2019). The groundwater richness content and faults source data were obtained from the Gansu Bureau of Geology and Mineral Hydrogeology Engineering Geological Exploration Institute (GBGMHEGEI, 2015).

Earthquake related data was accessed from the Gansu Earthquake Agency online portal (GEA, 2015). Normalized vegetation index (NDVI) of MOD13Q1 products was derived from the online MODIS data website (MODIS, 2018). We obtained surface water, settlements and roads data from the National Catalogue Service for Geographic Information (NCSGI, 2015). Ecological function reserves data was obtained from the Gansu Forestry and Grass Bureau (GFGB, 2015). Shuttle Radar Topography Mission (SRTM) digital data were obtained from the online website of USGS Earth Explorer, with a spatial resolution of 30m (USGS, 2015). The landform, soil, and 30m land use types, as well as temperature, precipitation meteorological, economic, population, administrative division and basic geographic space data were acquired from the Resource and Environmental Science and Data Center, Chinese Academy of Sciences (RESDC, 2015). All of the criterion data sets used in this study, as well as their formats and sources are described in **Table A1** in Appendix A.

### 2.3. Method framework

We describe the specific process employed for this study inclusive of multi-source data collection and preprocessing in **Fig. 2**: (1) Groundwater depth and quality data were interpolated via the kriging interpolation method, whereas the vector point, polyline, and polygon data were converted to raster data, imported into the GIS spatial database and unified spatial reference in the WGS_Albers_System projection coordinate system. (2) FAHP was employed to establish an evaluation criteria system and obtain the weight of evaluation criteria, construct a judgment matrix, check for

consistency, as well as to set up membership functions of the S-function, Triangular function, and Gamma function. (3) GIS spatial analysis and modeling involved the establishment of buffer zones for faults, earthquake points, surface water, settlements, roads, and ecological function reserve evaluation criteria. The model builder in ArcGIS was used for modeling to achieve a weighted overlay of layers and neighborhood smoothing, to obtain the results of landfill site selection through GIS visualization. (4) The LSSR were verified by the coordinates of the landfill sites that conformed to the CNS, these sites are then ranked utilizing group fuzzy MULTIMOORA.

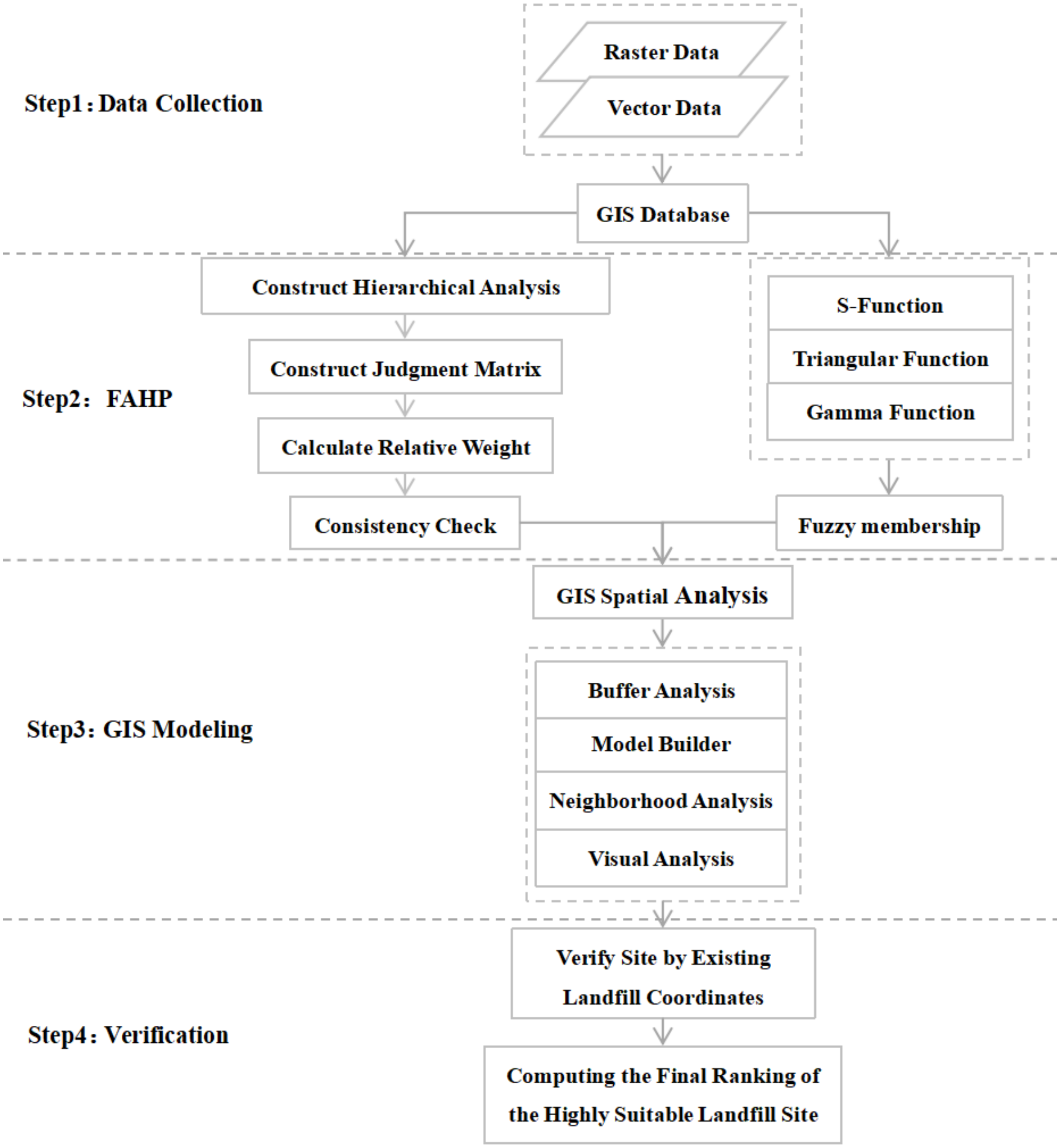



**Fig. 2.** Method framework chart including the four main steps: Data Collection, FAHP, GIS Modeling, and Verification.

## 2.4. Criteria selection

The extraction of reasonable evaluation criteria determines the appropriateness and reliability of LSSR (De Feo and De Gisi, 2014). After discussing with authoritative professors and experts and referring to the relevant literature in strict accordance with

the CNS, the selected qualitative and quantitative evaluation criteria ($C_1$, $C_2$, $C_3$, $C_4$……$C_{20}$) for landfill sites were established. Since LSS is a complex task in MSW, one should consider hydrogeological, morphological, environmental, climatic, and socio-economic factors for the overall situation (Soltani et al., 2015).

Hydrogeological aspects should be considered to avoid potential groundwater contamination caused by the leakage of landfill leachate, while ensuring the safety of construction and operation (Karakus et al., 2020). Morphological aspects were taken into account to reduce construction costs and increase stability during construction(Bahrani et al., 2016). Environmental aspects were taken into consideration to minimize impacts on surrounding residents, and land/water resources (Ozkan et al., 2019). Climatic issues were reviewed to reduce potential threats and damage to the surrounding environment posed by various pollutants released from the landfill through leachate or waste gas (Lima et al., 2018). Socio-economic impacts were considered to prevent the landfill from adversely affecting the surrounding ecological reserves and regional economic development (Asefi et al., 2020a). Further detailed information on the criteria selection is contained **in Table B1** in Appendix B. The interval from 0 to 1 was adopted for normalization, where the larger the value, the better the suitability (**Fig. C1, C2, C3, C4, and C5** in Appendix C).

The specific CNS for reference include: "Standard for Pollution Control on the Landfill Site of Domestic Waste" (GB16889-2008), "Technical Specifications for Sanitary Landfill of Domestic Waste" (GB50869-2013), "Standard for Pollution on the

Storage and Disposal Site for General Industrial Solid Waste" (GB18599-2001), "Water Pollution Prevention Law of the People's Republic of China", "Regulations of the People's Republic of China on Nature Reserves, " Technical Regulations for Investigation of Land Use Status", and " Urban and Rural Planning Law of the People's Republic of China". All CNS are available at the National Standard Full Text Open System (NSFTOS, 2017).

### 2.4.1. Hydrogeological factors

The contamination of groundwater from landfills is dependent on the groundwater depth and the permeability of the aquifers, with shallower groundwater being more likely to be polluted. Consequently, landfills should developed at locations with sufficient groundwater depth (Rezaeisabzevar et al., 2020). Groundwater quality is an important factor that affects the LSSR (Przydatek and Kanownik, 2019) (refer to the comprehensive evaluation method in "Groundwater Quality Standard" GB/T 14848-2017). Contingent on the composition of its chemical components, groundwater quality is separated into five categories, from high to low. The suitability of groundwater quality was divided according to the actual situation of the study area. The more water-rich the groundwater aquifer, the more difficult it is to build landfills and the higher the cost (Sener et al., 2011). According to the actual status of the study area, the water inflow from a single well classified the suitability of groundwater richness. The establishment of landfills should be avoided in areas with active geological structures or other underground terrain (Yousefi et al., 2018). As the permeability of rocks in

geological faults and earthquake zones increases, the resulting leachate may contaminate groundwater (Eskandari et al., 2012). **Table B1** in Appendix B displays the classification of groundwater depth, groundwater quality, groundwater richness, distance from faults, and earthquake points. Normalized suitability maps are shown in **Fig. C1** in Appendix C.

2.4.2. Morphological factors

The greater the elevation and slope, the more difficult it is to carry out the main body and auxiliary projects of the landfill, and the higher the construction costs (Motlagh and Sayadi, 2015). The terrain of the study area contained a complex and diverse topography, with lower elevations considered to have reduced construction costs. We combined the above conditions to assess the suitability of elevation and slope. The basin landform is surrounded by mountains on three sides and with "S" or "Y" gullies extending in the open direction, which is conducive to reducing pollution risks, providing sufficient space, while extending landfill service and resource utilization (Sureshkumar et al., 2017).The bottom of the basin or valley is gentle and wide, and the landfill space is sufficient, which is conducive to extending the landfill service (Sureshkumar et al., 2017). For the LSSR, the reduction of excessive damage to surface vegetation should be considered (Kara and Doratli, 2012). In the study area, the vegetation distribution is affected by natural factors such as climate, soil, hydrology, and landform, showing obvious meridional and vertical zonal distribution. Considering the impacts of different soil types on landfills, we classified soil type suitability. **Table**

**B1** in Appendix B shows the classification of elevation, slope, landform type, NDVI, and soil type suitability, and got its normalized suitability map (**Fig. C2**, Appendix C).

2.4.3. Environmental factors

Landfills should not be located near ambient surface water such as ponds, lakes, rivers, and streams to avoid their contamination (Torabi-Kaveh et al., 2016). In the study area, the water all originates from the Qilian Mountains; thus, landfill sites should be built downstream of the water source area as far as possible. Based on the above situation, we assessed the suitability of surface water. Land use type directly reflects the anthropogenic utilization of land and natural environment, as well as the current status of land use on the surface, which provides a powerful basis for decision-making in LSS planning (Motlagh and Sayadi, 2015). We classified the suitability of land use types according to the available value of the study area. The development of landfills is likely to initiate social conflicts and the "neighbor effect", as well as various environmental problems (Khan et al., 2018). In the study area, the settlements were concentrated in the oasis area of the corridor plain, with sufficient water resources, convenient transportation, and high population carrying capacity. The LSS must also consider road requirements, where the closer to the roads, the more convenient the transportation conditions and the lower the cost of waste transfer (Ersoy et al., 2013). **Table B1** in Appendix B reveals the division of the suitability of surface water, land use type, settlements, and roads, whereas a normalized suitability map is shown in **Fig. C3** in Appendix C.

### 2.4.4. Climatic factors

Precipitation and temperature are critical factors in the LSS process (Aksoy and San, 2016). Areas with less precipitation and mild temperatures are more suitable for construction landfills. Our study area belonged to a typical continental arid climate, with a complex precipitation distribution and an average temperature of ~ 7.06°C. The suitability of precipitation and temperature were segregated according to the above conditions (**Table B1** in Appendix B) to obtain a normalized suitability map (**Fig. C4**, Appendix C).

### 2.4.5. Socio-economic factors

Ambient ecological function reserves primarily include entities that require protection such as natural ecosystems, rare/endangered wild animal and plant species, and natural relics of special significance. It is always the least desirable option to develop landfills in close proximity to natural reserves (Sener et al., 2010). Concomitant with higher population densities is more extensive urbanization (Farahbakhsh and Forghani, 2019). Further, the higher the GDP in a given location, the higher its economic level and the higher the added value of land will be (Aracil et al., 2018). Indirect ecosystem service values reflect the value of land use, while the suitability of landfills gradually decreases with higher ecosystem service values (Alavi et al., 2013). We classified the ecological function reserves, population density, GDP, and ecosystem service value suitability according to the status quo of the study area (**Table B1** in Appendix B) to obtain a normalized suitability map (**Fig. C5** in Appendix C).

## 2.5. FAHP Model

A hierarchical analysis structure was constructed by selecting reasonable criteria and sub-criteria **(Fig. 3).**

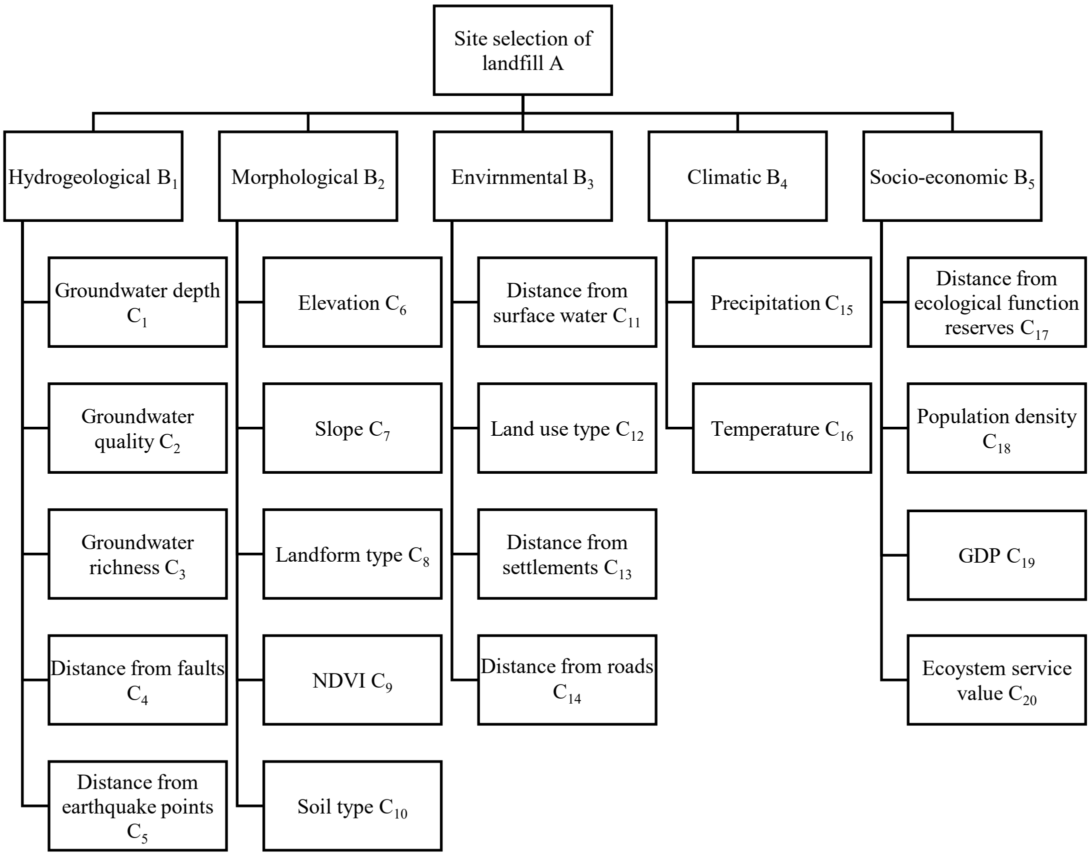



**Fig. 3.** The hierarchical analysis structure is comprised of three layers (decision, primary, and secondary evaluation factor layers). Decision layer A is the site selection of landfill, primary layer B contains five criteria, secondary layer C includes 20 sub-criteria.

Ten experts were invited to fill out questionnaires to score the criteria. Among them were five professors who have been engaged in solid waste research for more than ten years, and five experts involved in urban planning. To improve the accuracy and

rationality of the evaluation, a numerical scale of 1-9 **(Table 1)** was employed to quantify the evaluation criteria of the constraint factor layer, which were used to construct pairwise comparison judgment matrices, respectively.

$$\begin{array}{c|cccc} A & B_1 & B_2 & \cdots & B_n \\ B_1 & a_{11} & a_{12} & \cdots & a_{1n} \\ B_2 & a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ B_n & a_{n1} & a_{n2} & \cdots & a_{nn} \end{array}$$

**Table 1**

Relative importance scale.

| Scaling $a_{ij}$ | 1 | 3 | 5 | 7 | 9 |
|---|---|---|---|---|---|
| The degree to which the $i$ factor is stronger than the $j$ factor | Equal | Slightly stronger | Strong | Very strong | Absolutely strong |

Among these, 2, 4, 6, and 8 corresponded to the importance of 1, 3, 5, 7, and 9 respectively.

The essence of calculating a relative weight is to calculate the normalized value $\overline{W}_i$ and the maximum eigenvalue $\lambda_{\max}$ of the eigenvector of the judgment matrix(Eq. 1-3) (Vaverkova et al., 2018).

$$W_i = n\sqrt{\prod_{j=1}^{n} a_{ij}} \quad i = 1,2,...,n \tag{1}$$

$$\overline{W}_i = \frac{W_i}{\sum_{i=1}^{n} W_i} \quad i = 1,2,\ldots n \tag{2}$$

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(A\overline{W})_i}{n\overline{W}_i} \quad i = 1,2,\ldots n \tag{3}$$

Where, $W_i$ represents the eigenvector of the judgment matrix, $\overline{W}_i$ represents the normalized value of the eigenvector and satisfies $0 < \overline{W}_i \leq 1$, $\lambda_{\max}$ represents the maximum eigenvalue of the judgment matrix, and $n$ represents the number of criteria.

Calculation for the consistency metric $CI$ (Eq. 4):

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

When $\lambda_{\max} = n$, $CI = 0$ means that the matrix is completely consistent. When $\lambda_{\max} \neq n$, and the average random consistency metric $RI$ **(Table 2)** is introduced to determine the size of $CI$. The higher the value of $CI$, the greater the probability of random deviation from consistency.

**Table 2**

Mean random consistency index.

| Matrix order | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *RI* | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 | 1.51 | 1.54 | 1.56 |

Calculation for the consistency ratio $CR$ (Eq. 5):

$$CR = \frac{CI}{RI} \tag{5}$$

When $CR < 0.1$, it denotes that the degree of inconsistency of the judgment matrix is within the controllable range, and its normalized eigenvector can be used as the weight vector through the consistency test; if $CR > 0.1$, it means that the consistency of the judgment matrix deviates too much, the judgment matrix should be adjusted.

We employed MATLAB software to calculate the relative weight, maximum eigenvalue, consistency index and consistency ratio of each evaluation criterion, where after the criterion weight was obtained **(Table 3)**. Further details are presented in **Tables D1 through D6** in Appendix D.

**Table 3**

Evaluation Criterion Weight.

| Criteria B | Relative weight $W_{B_i}$ | Sub-criteria C | Relative weight $W_{C_i}$ | Normalized weight $\overline{W}_{C_i}$ |
|---|---|---|---|---|
| Hydrogeological $B_1$ | 0.3192 | Groundwater depth $C_1$ | 0.3984 | 0.1272 |
| | | Groundwater quality $C_2$ | 0.1072 | 0.0342 |
| | | Groundwater richness $C_3$ | 0.2443 | 0.0780 |
| | | Distance from faults $C_4$ | 0.1392 | 0.0444 |

| | | | | |
|---|---|---|---|---|
| | | Distance from earthquake points $C_5$ | 0.1109 | 0.0354 |
| | | Elevation $C_6$ | 0.1769 | 0.0325 |
| | | Slope $C_7$ | 0.4543 | 0.0836 |
| Morphological $B_2$ | 0.1840 | Landform type $C_8$ | 0.0960 | 0.0177 |
| | | NDVI $C_9$ | 0.0960 | 0.0177 |
| | | Soil type $C_{10}$ | 0.1769 | 0.0325 |
| Environmental $B_3$ | 0.3192 | Distance from surface water $C_{11}$ | 0.3509 | 0.1120 |
| | | Land use type $C_{12}$ | 0.1890 | 0.0603 |
| | | Distance from settlements $C_{13}$ | 0.3509 | 0.1120 |
| | | Distance from roads $C_{14}$ | 0.1091 | 0.0348 |
| Climatic $B_4$ | 0.0683 | Precipitation $C_{15}$ | 0.6667 | 0.0455 |
| | | Temperature $C_{16}$ | 0.3333 | 0.0228 |
| Socio-economic $B_5$ | 0.1094 | Distance from ecological function reserves $C_{17}$ | 0.4554 | 0.0498 |
| | | Population density $C_{18}$ | 0.1409 | 0.0154 |

| | | |
|---|---|---|
| GDP $C_{19}$ | 0.1409 | 0.0154 |

Mapping and analysis of criteria attributes based on fuzzy logic, S-shape, triangular shape, and Gamma shape are commonly employed fuzzy membership functions to determine fuzzy information in fuzzy logic (as shown in **Table 4**) (Barakat et al., 2017). The effects of the 7 scenarios applied were investigated, aiming to obtain the most suitable scenario to improve the accuracy of the results and optimize the uncertainty of the evaluation criteria.

Scenario 1: All criteria employ the nonlinear fuzzy membership function (S shape) to calculate the fuzzy membership.

Scenario 2: All criteria employ the linear fuzzy membership function (Triangular shape) to calculate the fuzzy membership.

Scenario 3: All criteria employ the linear fuzzy membership function (Gamma shape) to calculate the fuzzy membership.

Scenario 4: Criteria employ S and Triangular shapes to calculate the fuzzy membership.

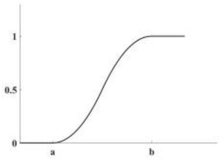
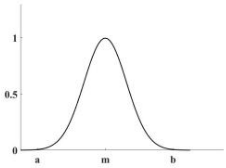
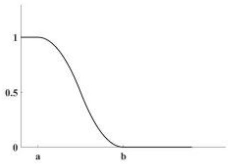
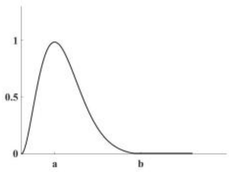
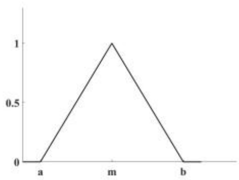
Scenario 5: Criteria employ S and Gamma shapes to calculate the fuzzy membership.

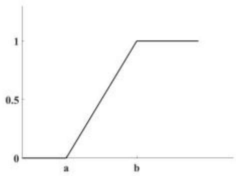
Scenario 6: Criteria employ Triangular and Gamma shapes to calculate the fuzzy membership.

Scenario 7: Criteria employ S, Triangular, and Gamma shapes to calculate the fuzzy membership.

**Table 4**

Fuzzy membership function.

| **Fuzzy Membership Function** | | Figure | Formula |
|---|---|---|---|
| S-shape | S-shape (increasing) |  | $\mu_i = \begin{cases} 0 & x_i \le a \\ 2(\frac{x_i - a}{b - a})^2 & a < x_i < b \\ 1 & x_i \ge b \end{cases}$ |
| | S-Shape (general) |  | $\mu_i = \begin{cases} 0 & x_i \le a \\ 2(\frac{x_i - a}{m - a})^2 & a < x_i \le m \\ 2(\frac{x_i - b}{b - m})^2 & m < x_i < b \\ 0 & x_i \ge b \end{cases}$ |
| | S-shape (decreasing) |  | $\mu_i = \begin{cases} 1 & x_i \le a \\ 2(\frac{x_i - b}{b - a})^2 & a < x_i < b \\ 0 & x_i \ge b \end{cases}$ |
| | S-shape (individual) |  | $\mu_i = \begin{cases} 2(\frac{x_i - a}{a})^2 & x_i \le a \\ 2(\frac{x_i - b}{b - a})^2 & a < x_i < b \\ 0 & x_i \ge b \end{cases}$ |
| Triangular shape | Triangular shape (general) |  | $\mu_i = \begin{cases} 0 & x_i \le a \\ \frac{x_i - a}{m - a} & a < x_i \le m \\ \frac{b - x_i}{b - m} & m < x_i < b \\ 0 & x_i \ge b \end{cases}$ |

| | | | |
|---|---|---|---|
| Gamma shape | Gamma shape (increasing) |  | $\mu_i = \begin{cases} 0 & x_i \le a \\ \frac{b-x_i}{b-a} & a < x_i < b \\ 1 & x_i \ge b \end{cases}$ |

In **Table 4**, $x_i$ denotes the attribute feature value of the $i$ evaluation sub-criteria, $\mu_i$ represents the degree of membership, and $a, b$ represents the interval value of the $i$ evaluation criteria with different suitability grades, $m = \frac{a+b}{2}$.

For this study, we established an overlay model of multi-source layers by using the GIS spatial analysis tool. The weight of the evaluation criteria was multiplied by the fuzzy membership degree to obtain the Landfill Suitability Index ($LSI$) of the Hexi Corridor landfill site by a weighted average. The specific formula is as follows (Eq. (6)):

$$LSI = \sum W_i \bullet \mu_i \tag{6}$$

Where, $LSI$ denotes the suitability index, $W_i$ denotes the comprehensive weight of the evaluation sub-criteria, and $\mu_i$ denotes the fuzzy membership degree of the evaluation criteria.

2.6. GIS spatial analysis

On the basis of a unified projected coordinate system, the application of GIS buffer analysis, network analysis, data reclassification, neighborhood analysis, overlay analysis, raster calculator, model builder, and other extended tools were used for data

processing.

#### 2.6.1. Buffer analysis

The primary purpose of buffer analysis is to restrict the range of vector data through the establishing of a special distance radius or boundary. Vector data is segmented by point, polyline, and polygon elements (Khan et al., 2018). According to the requirements of urban construction planning, the specified range is utilized as the radius of influence to establish buffer zones for faults, earthquake points, surface water, settlements, roads, and ecological function reserves, such that the suitable construction area is within a reasonable distribution range.

#### 2.6.2. Model builder modeling overlay

Initially, we utilized the raster calculator input function and map algebra grammar in ArcGIS to calculate the evaluation criteria and obtain the attribute grading results. Secondly, the optimal weight was obtained by expert scoring, and the fuzzy evaluation matrix was determined by the membership degree. Finally, the Model builder tool was employed to model according to the $LSI$, superposition the attribute grading results of the evaluation criterion, determine the optimal weight and the fuzzy evaluation matrix, and obtain the LSSR **(Fig. 4)**. According to the CNS, classified areas smaller than the waste disposal area were unsuitable. Therefore, once the LSSR are smoothed, area screening was required to eliminate areas that did not meet the requirements to ensure the accuracy and rationality of the results.

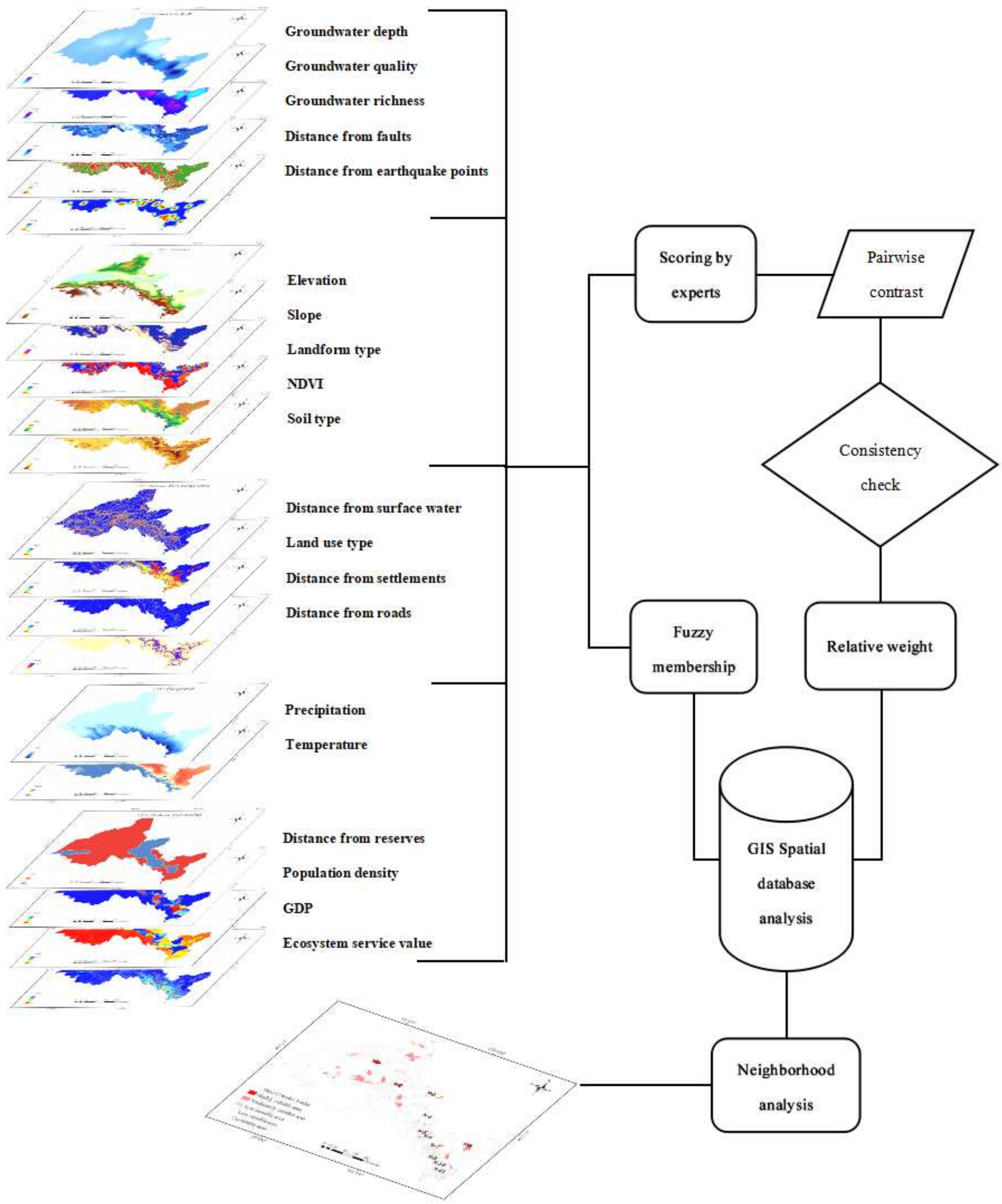



**Fig. 4.** Flow chart of LSS modeling, which includes 20 normalized layers of criteria. GIS spatial analysis was used to calculate its weight and fuzzy membership degree, and obtain the LSSR.

## 2.7. Group fuzzy MULTIMOORA

MULTIMOORA presents a robust result by combining the subordination rank based on the dominance theory. There are three methods for MULTIMOORA: Ratio

System, Reference Point Approach, and Full Multiplicative Form. In addition, MULTIMOORA could be beneficial in a general form of a decision-making problem in which “positive “and “negative” sub-criteria exist besides noting to a “robust” final outcome (Hafezalkotob et al., 2019). In this study, the fuzzy group extension of MULTIMOORA is employed, which has the following steps:

Fuzzy ratio system：

Step 1 A fuzzy decision matrix is constructed, ${x_{ij}}^{[k]} = \left({x_{ij1}}^{[k]}, {x_{ij2}}^{[k]}, {x_{ij3}}^{[k]}\right)$represent the response of expert *k* to sub-criteria *j* in place of alternative *i*. The decision matrix should be aggregated as follows.

$$x_{ij} = \left( \frac{1}{h}\sum_{k=1}^{h} {x_{ij1}}^{[k]}, \frac{1}{h}\sum_{k=1}^{h} {x_{ij2}}^{[k]}, \frac{1}{h}\sum_{k=1}^{h} {x_{ij3}}^{[k]} \right) \tag{7}$$

Step 2 The decision matrix is normalized based on the following vector method, where *m* is the number of alternatives.

$$x_{ij}^{*} = \left( \frac{x_{ij1}}{\sqrt{\sum_{i=1}^{m} x_{ij1}^{2}}}, \frac{x_{ij2}}{\sqrt{\sum_{i=1}^{m} x_{ij2}^{2}}}, \frac{x_{ij3}}{\sqrt{\sum_{i=1}^{m} x_{ij3}^{2}}} \right) \tag{8}$$

Step 3 The weighted normalized decision matrix was used to calculate the relative importance of the alternatives (Eq.8). where *g* is the number of positive criteria, *n* is the number of criteria, and *w* is the weight of the sub-criteria *j*.

$$y_i = \left( \sum_{j=1}^{g} \left( w_j \otimes x_{ij}^{*} \right) \right) - \left( \sum_{j=g+1}^{n} \left( w_j \otimes x_{ij}^{*} \right) \right) \tag{9}$$

Step 4 The best alternative and the ranking of this method is obtained as follows.

$$Z_{F\_RS} = \left\{ Z_i \mid \max_i y_i \right\} \tag{10}$$

Fuzzy reference point approach：

Step 1 and Step 2 are the same as Fuzzy ratio system, and the vector of reference point is calculated as follows.

$$x_j = \left\{ \begin{matrix} \left( \max_i x^*_{ij1}, \max_i x^*_{ij2}, \max_i x^*_{ij3} \right), \textit{for positive criteria} \\ \left( \min_i x^*_{ij1}, \min_i x^*_{ij2}, \min_i x^*_{ij3} \right), \textit{for negative criteria} \end{matrix} \right\} \tag{11}$$

Step 3 The weighted normalized decision matrix was used to calculate the relative importance of the alternatives (Eq.11), where *w* is the weight of the sub-criteria *j*.

$$y_i = \max_j d\left[ \left( w_j \otimes x_i \right), \left( w_j \otimes x^*_{ij} \right) \right] \tag{12}$$

Step 4 The best alternative and the ranking of this method is obtained as follows.

$$Z_{F\_RP} = \left\{ Z_i \mid \max_i y_i \right\} \tag{13}$$

Fuzzy full multiplicative form：

Step 1 and Step 2 are the same as Fuzzy ratio system.

Step 3 The weighted normalized decision matrix was used to calculate the relative importance of the alternatives (Eq.13). where *g* is the number of positive criteria, *n* is the number of criteria, and *w* is the weight of the sub-criteria *j*.

$$y_i = \prod_{j=1}^{g} \left( x^*_{ij} \right)^{w_j} \Big/ \prod_{j=g+1}^{n} \left( x^*_{ij} \right)^{w_j} \tag{14}$$

Step 4 The best alternative and the ranking of this method is obtained as follows.

$$Z_{F\_MF} = \left\{ Z_i \mid \max_i y_i \right\} \tag{15}$$

## 3. Results and discussion

Based on the FAHP-GIS model, the LSS of MSW in the ecologically fragile area of the Hexi Corridor was studied for the first time. According to expert judgment in the criteria, hydrogeological and environmental factors were the most important criteria for landfills, with the weights of both being 0.3192. The climatic weight was 0.0683, which had a relatively low impact on the LSSR. In the sub-criteria, the groundwater depth had the greatest impact on site selection, with a weight of 0.1272.

According to the $LSI$, we selected suitable areas for landfills in the Hexi Corridor **(Fig. 5)**. The range of $LSI$ was between 0 and 1, whereas the attribute value was divided by three grades: "suitable area (1-0.8), less suitable area (0.8-0.6), unsuitable area (0.6-0)".

The comparison of the scenarios' application results with the initial results revealed a slight degree of variation. The most suitable area ratios for scenarios 1-7 were 0.06, 0.07, 0.07, 0.05, 0.05, 0.06, 0.03. Furthermore, the Spearman's correlation coefficient values of scenario 1, compared with those of other scenarios, confirmed the similarities. As the results observed suggest, scenario 2, 3 accounted for the highest degree of variation in area ratios, as it reduced Spearman's correlation coefficient value (0.94), the coefficient scores of scenarios 4-7 were all 1. The result demonstrated that

setting the corresponding membership function to reflect its logical relationship and ambiguity according to the different standard attributes can improve the reliability of the results.

We compared the existing location coordinates of 28 landfill sites that conformed to the CNS and the LSSR of Scenario 7. The results revealed that 26 sites were located in suitable areas, one site was located in a less suitable area, and one site was located in an unsuitable area, with an accuracy of 93%. This illustrated the scientific reliability of the LSSR based on the integrated FAHP-GIS model. Suitable areas were characterized as having low groundwater depth, flat terrain, mostly bare land, a 300 m distance from roads, and at least a 2000 m distance from settlements with low land use value. The less suitable areas were characterized by a lack of surface water development, moderate elevation, within 500 m of the traffic line, and distance from settlements of 2000m. The unsuitable areas were characterized by complex terrain, large topographic relief, large soil sediment concentrations, with the distance from surface water of from 50 m to 500 m, and distance from settlements of less than 1000 m, with high land use value.

Encompassing the study region as a whole, the unsuitable areas accounted for the largest proportion (0.67) with an area of $1.80\times10^5 km^2$, which was mainly distributed along the river. The less suitable areas accounted for a relatively large number (0.30), with an area of $8.20\times10^4 km^2$, which was primarily distributed in the central part of the study area. The suitable area occupied a small area (0.03), with an area of $0.8\times10^4 km^2$, scattered across various cities. At the municipal scale (**Fig. E1**, Appendix E), the

unsuitable areas were evenly distributed in each city. Jiuquan accounted for the largest proportion of 0.7, with an area of $1.34\times10^5 km^2$, whereas Zhangye had the lowest proportion. The less suitable areas were mainly distributed in Zhangye with a proportion of 0.46, having an area of $1.88\times10^4 km^2$, with the lowest proportion in Jiuquan. The suitable areas were primarily distributed in Jiuquan with a proportion of 0.05, covering an area of $9.60\times10^4 km^2$, where Zhangye and Jinchang had the lowest proportion.

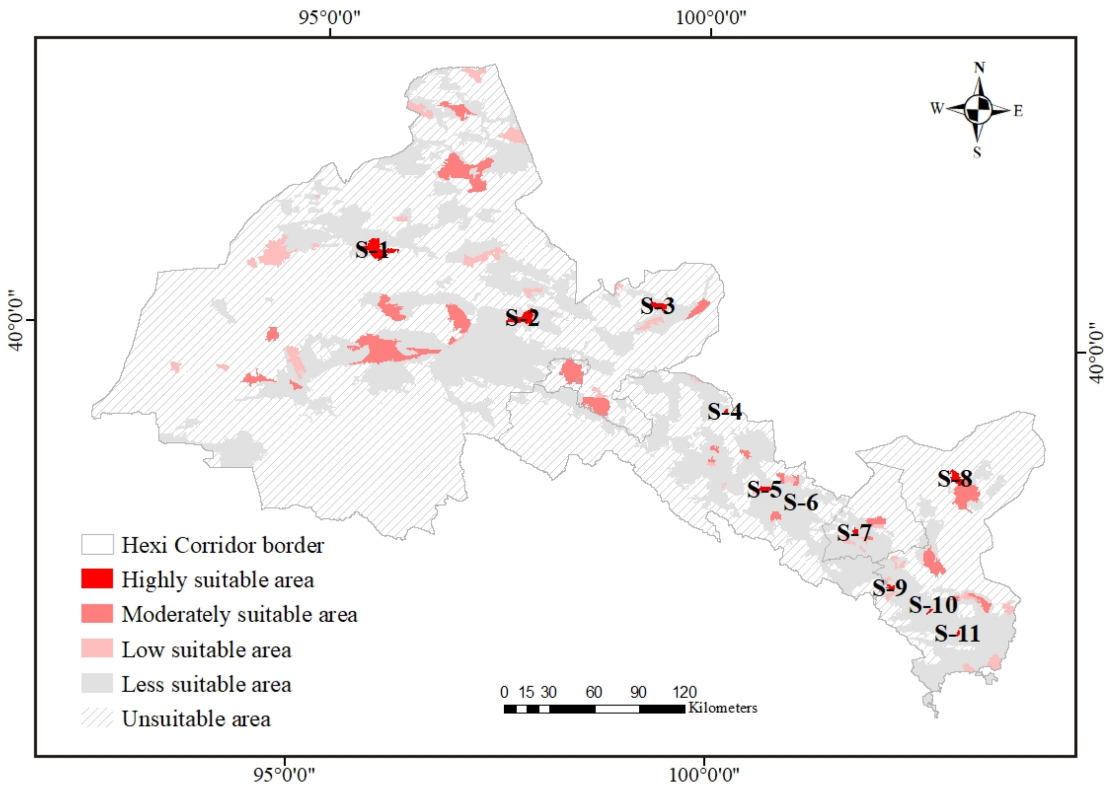



**Fig. 5.** Site selection of MSW landfills in Hexi Corridor. The LSSR are graded according to color brightness. Brighter reds indicate better suitability, gray indicates less suitability, and the line fill indicates the unsuitable. A total of 11 candidate sites were selected in the Hexi Corridor.

The landfill suitability values of the study area were divided into three categories:

highly (1-0.934), moderately (0.934-0.867), and low suitable (0.867-0.800) by employing the equal interval classification method. The results revealed that in the suitable area ($8.0\times10^3km^2$), the area of highly suitable was $2.0\times10^2km^2$ (0.03), the area of moderately suitable was $4.4\times10^3km^2$ (0.55), and the area of low suitable was $3.4\times10^3km^2$ (0.42). We selected 11 candidate landfill sites and location coordinates that conformed to the CNS for the Hexi Corridor. The daily MSW capacity of the candidate sites was calculated according to the "Construction Standard of MSW Landfill Disposal Engineering Project" (**Table F1 and F2**, Appendix F).

There were three candidate landfills (S-1, S-2 and S-3) in Jiuquan. Among these, S-1 and S-2 had a capacity of more than 1200 tons/day of MSW, while S-3 could hold 500 to 1200 tons/Day of MSW. Jiayuguan had no optimal site. There were three candidate landfill sites in Zhangye (S-4, S-5 and S-6), among which S-4 and S-6 had the capacity to contain MSW at less than 200 tons/day, whereas S-5 could contain 500 to 1200 tons/day of MSW. There was one most suitable site (S-7) in Jinchang that could be used as a candidate landfill, with a capacity of 200 to 500 tons/day of MSW. There was a total of four candidate landfills in Wuwei (S-8, S-9, S-10, and S-11). Among these, S-8 had the capacity to accommodate more than 1200 tons/day of MSW, whereas S-9 could absorb 500 to 1200 tons/day of MSW, S-10 could hold less than 200 tons/day of MSW, and S-11 could accommodate 200 to 500 tons/day of MSW (**Table F2**, Appendix F). The rankings for the fuzzy ratio system, fuzzy reference point approach, and fuzzy full multiplicative form are obtained based on Eq. 9, 12, and 14, respectively. The three

subordinate rankings are integrated exploiting the dominance theory. The outcomes of the three approaches and the final ranking are listed in **Table G1** in Appendix G. Based on the three approaches of the group fuzzy MULTIMOORA, the suitable site is S-2. Hence, since the outcomes are consistent, it can be decided that in the face of inconsistent criteria, the methodology used was suitable and robust and the resultant findings of the research logical and accurate.

## 4. Conclusion

For this study, we initially developed the proper criteria for evaluating the suitability of the LSSR in the Hexi Corridor. The main conclusions were as follows:

The uncertainty of AHP expert scoring was reduced and the decision efficiency of spatial analysis was improved. The synthesis of 20 multi-source data and multiple fuzzy membership functions proved a new model for the rational planning of MSW landfill sites in arid areas with fragile ecological environments, to realize LSSR within the Hexi Corridor. To reduce the uncertainty of AHP, proper membership functions were selected for each evaluation criterion, including the S-shape (increasing), (decreasing), (general), (individual), Triangular shape (general), and Gamma shape (increasing). From the analysis of the results, it was shown that the spatial distribution characteristics differed greatly as to the suitability of Hexi Corridor landfills.

The verification results based on field investigations revealed that this strategy was feasible and highly accurate. Specifically, among 28 landfills, 26 were located in

suitable areas, with an accuracy of 93%. There were two possible reasons why two landfills did not conform to the verification results. Urban growth leads to changes in regional population density, economy, and land use. The ecological environment is extremely fragile in the study area, and the ecological function reserve was expanded.

A number of ideal MSW landfill sites were located, with 11 landfill site candidates in total selected, according to the CNS. Among them, three candidates were located in Jiuquan and Zhangye, one candidate in Jinchang, and four candidates in Wuwei. The group fuzzy MULTIMOORA method was applied because of its high practicality in solving decision making problems to reach the optimal alternative. Consequently, Group fuzzy MULTIMOORA can effectively result in a reliable ranking of the candidate landfill sites. From an economic perspective, the accessibility of landfills based on spatial clustering could reduce transportation costs, while providing a scientific basis for optimizing the transport of waste.

This research method might also be employed to address MSW disposal problems in other similar areas, while providing decision support for waste disposal and environmental protection. This study incorporated three innovations for the LSS process. Initially, 20 multi-source data items were collected and multiple fuzzy membership functions were introduced to reduce the uncertainty of expert scoring. Secondly, the Hexi Corridor, which is extremely vulnerable to ecological fragility, was selected for case studies. A total of 11 candidate landfill sites were identified that conformed to the CNS, which demonstrated that this method was applicable in arid

areas. Finally, the LSSR were compared with existing landfill sites in accordance with the CNS, and the accuracy was higher. Consequently, we illustrated the appropriateness and reliability of this novel siting mode, which evaluated the suitability of landfill sites from the perspective of environmental health risks, while providing scientific references for decision-makers to support urban planning and environmental protection.

## Appendix Supplementary data

## Appendix A

**Table A1**

Data Format and Source.

| Dataset | Format | Data Source |
|---|---|---|
| Groundwater depth、Groundwater quality | Vector (Point) | Gansu Groundwater Report (Gansu Water Resources Department) (http://slt.gansu.gov.cn/) |

| | | |
|---|---|---|
| Groundwater richness | Vector (Polygon) | " Gansu Hydrogeological Map " (Gansu Bureau of Geology and Mineral Hydrogeology engineering Geological Exploration Institute) (http://www.gssgy.com/) |
| Faults | Vector (Polyline) | " Gansu Hydrogeological Map " (Gansu Bureau of Geology and Mineral Hydrogeology engineering Geological Exploration Institute) (http://www.gssgy.com/) |
| Earthquake points | Vector (Point) | "China Historical Earthquake Catalog" (Gansu Earthquake Agency) (http://www.gsdzj.gov.cn/) |
| 30m SRTM Elevation | Raster | USGS Earth Explorer (https://earthexplorer.usgs.gov/) |
| Landform type | Raster | "Landscape Atlas of the People's Republic of China (1: 1 million)" Resource and Environmental Science and Data Center, Chinese Academy of Sciences (http://www.resdc.cn/) |
| NDVI | Raster | MODIS (https://modis.gsfc.nasa.gov/) |

| | | |
|---|---|---|
| Soil type | Raster | "The Soil Atlas of the People's Republic of China (1: 1 million)" Resource and Environmental Science and Data Center, Chinese Academy of Sciences (http://www.resdc.cn/) |
| surface water | Vector (Polyline) | National Catalogue Service for Geographic Information (https://webmap.cn/) |
| 30m Land use type | Raster | Resource and Environmental Science and Data Center, Chinese Academy of Sciences(http://www.resdc.cn/) |
| Settlements | Vector (Point) | National Catalogue Service for Geographic Information (https://webmap.cn/) |
| Roads | Vector (Polygon) | National Catalogue Service for Geographic Information (https://webmap.cn/) |
| Precipitation | Raster | Resource and Environmental Science and Data Center, Chinese Academy of Sciences (http://www.resdc.cn/) |
| Temperature | Raster | Resource and Environmental Science and Data Center, Chinese Academy of Sciences (http://www.resdc.cn/) |
| Ecological function reserves | Vector (Polygon) | Portal website of Gansu Forestry and Grass Bureau and its administrative departments(http://lycy.gansu.gov.cn/) |

| | | |
|---|---|---|
| Population density | Raster | Resource and Environmental Science and Data Center, Chinese Academy of Sciences(http://www.resdc.cn/) |
| GDP | Raster | Resource and Environmental Science and Data Center, Chinese Academy of Sciences(http://www.resdc.cn/) |
| Ecosystem service value | Raster | Resource and Environmental Science and Data Center, Chinese Academy of Sciences(http://www.resdc.cn/) |

## Appendix B

**Table B1**

Suitability grade of evaluation criterion and Fuzzy membership function.

| Criteria B | Sub-criteria C | Unsuitable | Less suitable | Suitable | Fuzzy membership function |
|---|---|---|---|---|---|
| Hydrogeological $B_1$ | Groundwater depth $C_1$（m） | <15 | 15-30 | >30 | S-Function (increasing) |
| | Groundwater quality $C_2$ | V | III、IV | I、II | S-Function (decreasing) |

| | | | | | |
|---|---|---|---|---|---|
| | Groundwater richness $C_3$ (m³/L) | >1000 | 100-1000 | <100 | S-Function (decreasing) |
| | Distance from faults $C_4$ (m) | <1000 | 1000-6000 | >6000 | Gamma Function (increasing) |
| | Distance from earthquake points $C_5$ (m) | <500 | 500-5000 | >5000 | Gamma Function (increasing) |
| | Elevation $C_6$ (m) | >2200 | 1500-2200 | <1500 | S-Function (decreasing) |
| | Slope $C_7$ | >20% | 5%-20% | 8% | S-Function (individual)c |
| Morphological $B_2$ | Landform type $C_8$ | Mountains | Terraces, hills | Plains | S-Function (decreasing) |
| | NDVI $C_9$ | >0.8 | 0.2-0.8 | <0.2 | S-Function (decreasing) |
| | Soil type $C_{10}$ | Aquatic soil, leached soil, | Alpine soil, desert soil, | Saline soil | S-Function |

| | | | | | |
|---|---|---|---|---|---|
| | | anthropogenic soil | semi-aqueous soil, rock soil, calcareous soil, arid soil, primordial soil, semi-leached soil | | (decreasing) |
| | Distance from surface water $C_{11}$ (m) | <150 | 150-1000 | >1000 | Gamma Function (increasing) |
| Environmental $B_3$ | Land use type $C_{12}$ | Water, snow, farmland, woodland | Grassland, shrubland, wetland | bare land | S-Function (decreasing) |
| | Distance from settlements $C_{13}$ (m) | <800 | 800-3000 | >3000 | Gamma Function (increasing) |
| | Distance from roads | <500 ｜ >1 | 500-1500 | 1000 | S-Function |

| | | | | | |
|---|---|---|---|---|---|
| | $C_{14}$（m） | 500 | | | (general) |
| | Precipitation $C_{15}$（mm） | >300 | 180-300 | <180 | S-Function (decreasing) |
| Climatic $B_4$ | Temperature $C_{16}$（℃） | <2 \| >10 | 2-10 | 6 | Triangular Function (general) |
| | Distance from ecological function reserves $C_{17}$（m） | <3000 | 3000-9000 | >9000 | Gamma Function (increasing) |
| Socio-economic $B_5$ | Population density $C_{18}$ | >200 | 50-200 | <100 | S-Function (decreasing) |
| | GDP $C_{19}$ | <200 ｜>1000 | 200-1000 | 600 | S-Function (general) |
| | Ecosystem service value $C_{20}$ | >15000 | 5000-15000 | <5000m | S-Function (decreasing) |

## Appendix C

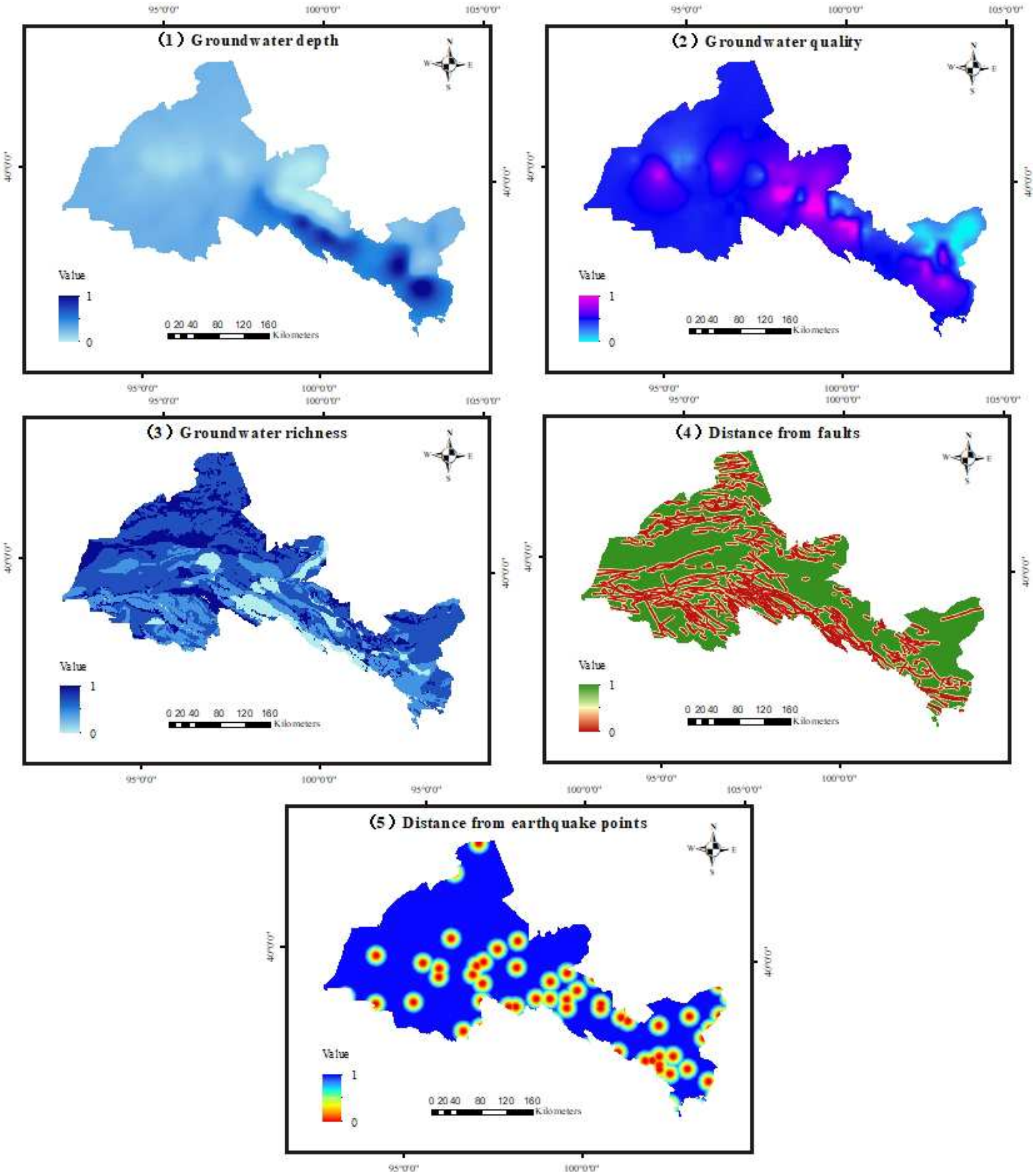



**Fig. C1.** Hydrogeological factors. (1) groundwater depth, (2) groundwater quality, (3) groundwater richness, (4) distance from faults, (5) distance from earthquake points.

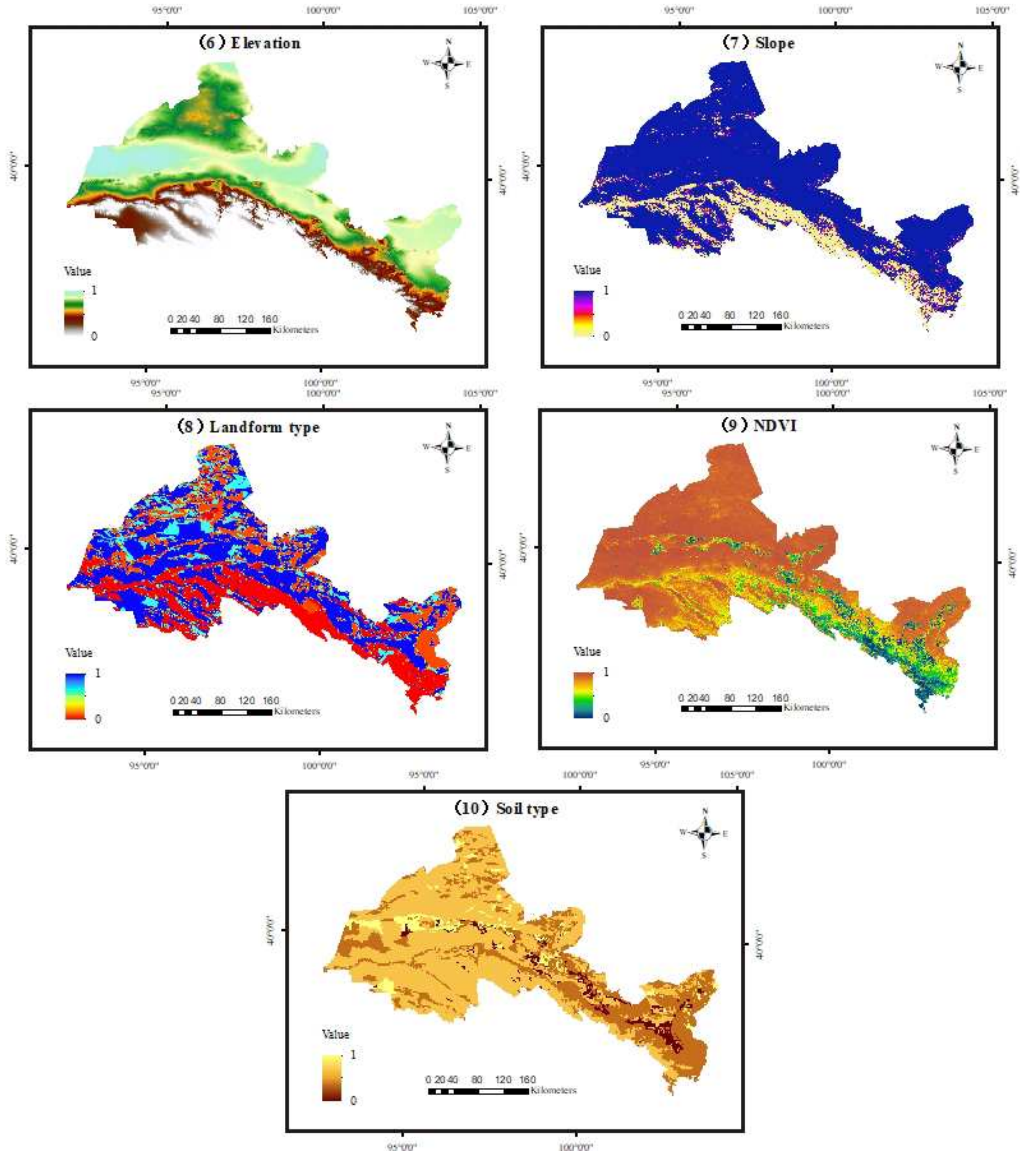



**Fig. C2.** Morphological factors. (6) elevation, (7) slope, (8) landform type, (9) NDVI, (10) soil type.

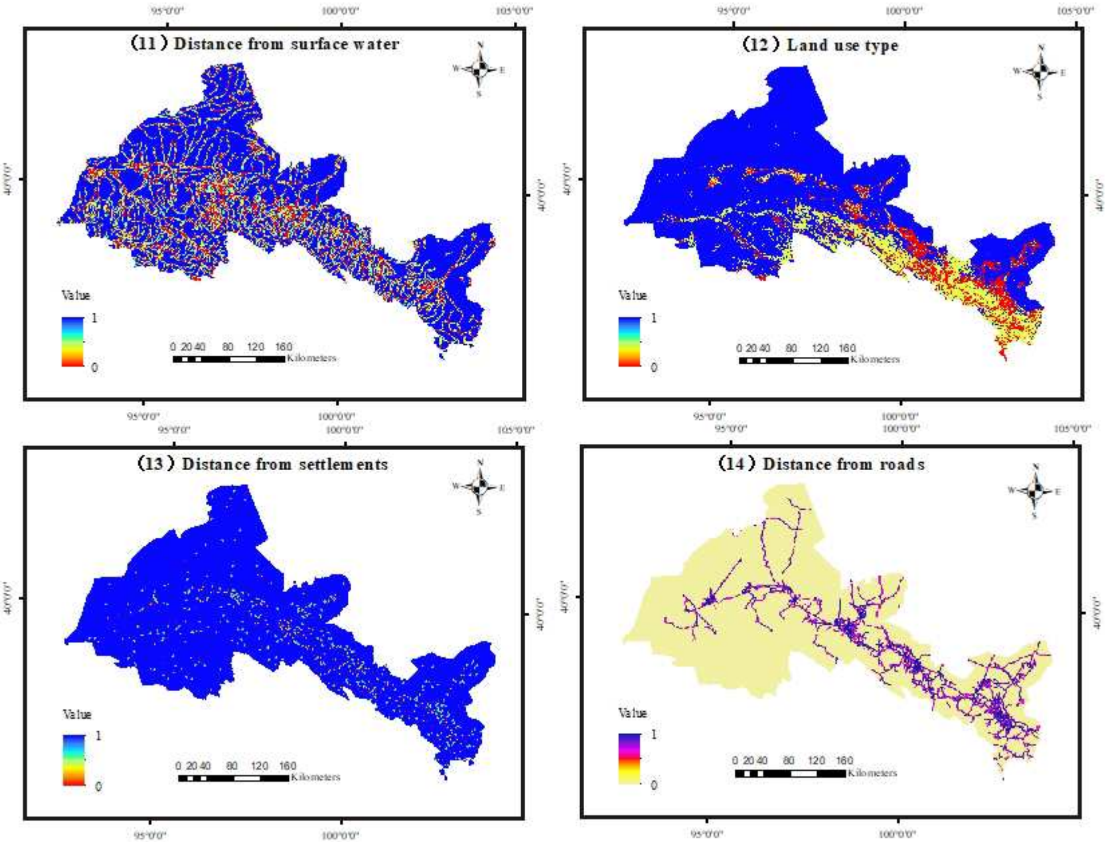



**Fig. C3.** Environmental factors. (11) distance from surface water, (12) land use type, (13) distance from settlements, (14) distance from roads.

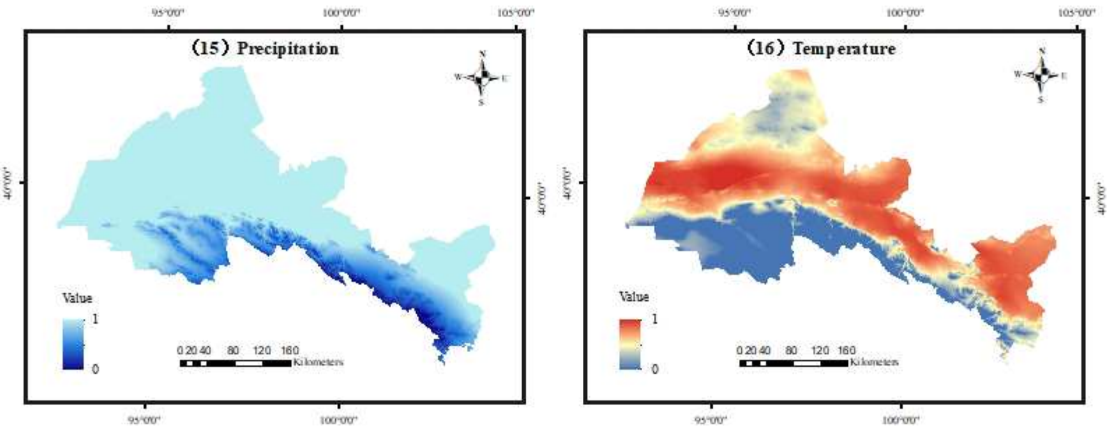



**Fig. C4.** Climatic factors. (15) precipitation, (16) temperature.

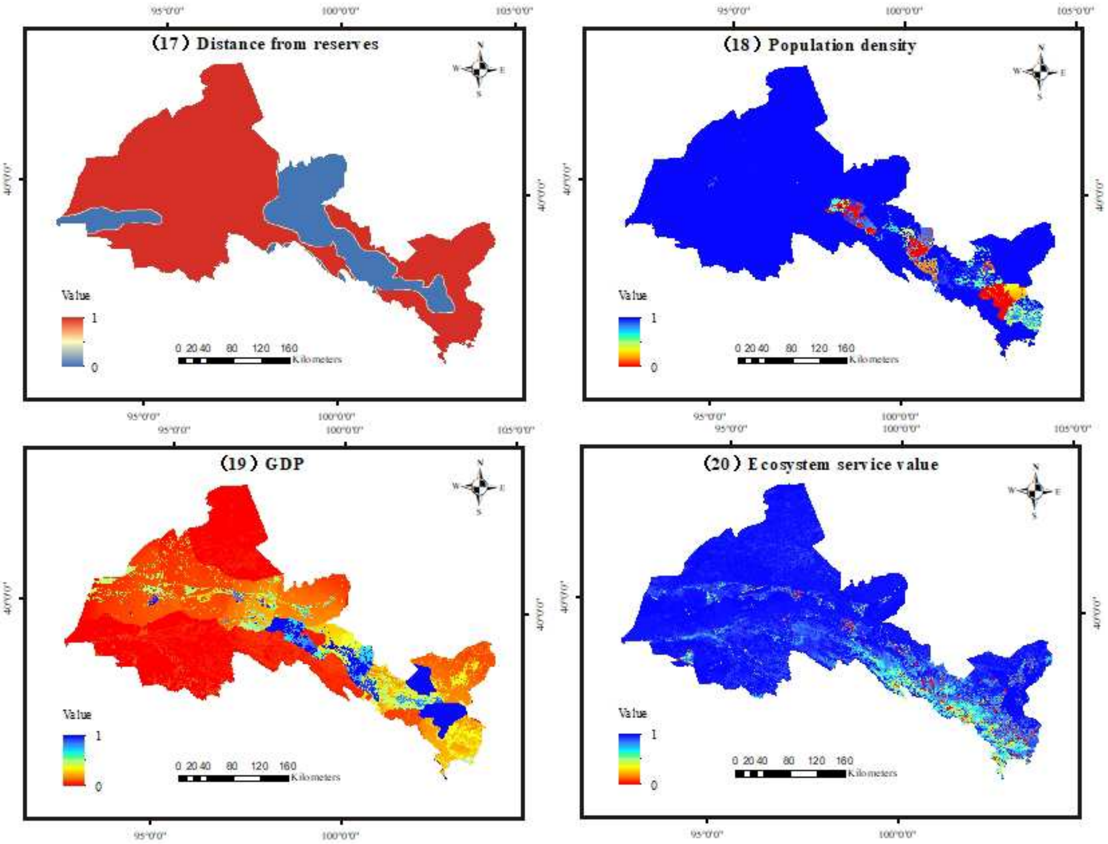



**Fig. C5.** Socio-economic factors. (17) distance from ecological function reserves, (18) population density, (19) GDP, (20) ecosystem service value.

# Appendix D

**Table D1**

Judgment matrix table of objective A and Criteria $B_{1\text{-}5}$.

| Site selection of | Hydrogeological $B_1$ | Morphological $B_2$ | Environmental $B_3$ | Climatic $B_4$ | Socio-economic $B_5$ | Relative weight $W_{B_i}$ |
|---|---|---|---|---|---|---|

| landfill A | | | | | | |
|---|---|---|---|---|---|---|
| Hydrogeological $B_1$ | 1 | 2 | 1 | 4 | 3 | 0.3192 |
| Morphological $B_2$ | 1/2 | 1 | 1/2 | 3 | 2 | 0.1840 |
| Environmental $B_3$ | 1 | 2 | 1 | 4 | 3 | 0.3192 |
| Climatic $B_4$ | 1/4 | 1/3 | 1/4 | 1 | 1/2 | 0.0683 |
| Socio-economic $B_5$ | 1/3 | 1/2 | 1/3 | 2 | 1 | 0.1094 |

$\lambda_{max}$ = 5.0364，CI=0.0091，RI=1.12，CR=0.0081

**Table D2**

Criterion $B_1$ and Criteria $C_{1-5}$ Judgment Matrix.

| Hydrogeological $B_1$ | Groundwater depth $C_1$ | Groundwater quality $C_2$ | Groundwater richness $C_3$ | Distance from faults $C_4$ | Distance from earthquake | Relative weight $W_{C_i}$ | Normalized weight $\overline{W}_{C_i}$ |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | points $C_5$ | | |
| Groundwater depth $C_1$ | 1 | 3 | 2 | 3 | 4 | 0.3984 | 0.1272 |
| Groundwater quality $C_2$ | 1/3 | 1 | 1/2 | 1 | 1/2 | 0.1072 | 0.0342 |
| Groundwater richness $C_3$ | 1/2 | 2 | 1 | 2 | 3 | 0.2443 | 0.0780 |
| Distance from faults $C_4$ | 1/3 | 1 | 1/2 | 1 | 2 | 0.1392 | 0.0444 |
| Distance from earthquake points $C_5$ | 1/4 | 2 | 1/3 | 1/2 | 1 | 0.1109 | 0.0354 |
| $\lambda_{max}$ =5.1944，CI=0.0486，RI=1.12，CR=0.0434 | | | | | | | |

**Table D3**

Criterion $B_2$ and Criteria $C_{6-10}$ Judgment Matrix.

| Morphological $B_2$ | Elevation $C_6$ | Slope $C_7$ | Landform type $C_8$ | NDVI $C_9$ | Soil type $C_{10}$ | Relative weight $W_{C_i}$ | Normalized weight $\overline{W}_{C_i}$ |
|---|---|---|---|---|---|---|---|
| Elevation $C_6$ | 1 | 1/3 | 2 | 2 | 1 | 0.1769 | 0.0277 |
| Slope $C_7$ | 3 | 1 | 4 | 4 | 3 | 0.4543 | 0.0497 |
| Landform type $C_8$ | 1/2 | 1/4 | 1 | 1 | 1/2 | 0.0960 | 0.0851 |
| NDVI $C_9$ | 1/2 | 1/4 | 1 | 1 | 1/2 | 0.0960 | 0.0150 |
| Soil type $C_{10}$ | 1 | 1/3 | 2 | 2 | 1 | 0.1769 | 0.0851 |
| $\lambda_{max} = 5.0264$，CI=0.0066，RI=1.12，CR=0.0059 | | | | | | | |

**Table D4**

Criterion $B_3$ and Criteria $C_{11\text{-}14}$ Judgment Matrix.

| Environmental $B_3$ | Distance from surface water $C_{11}$ | Land use type $C_{12}$ | Distance from settlement s$C_{13}$ | Distance from roads $C_{14}$ | Relative weight $W_{C_i}$ | Normalized weight $\overline{W}_{C_i}$ |
|---|---|---|---|---|---|---|
| Distance | 1 | 2 | 1 | 3 | 0.3509 | 0.1120 |

| | | | | | | |
|---|---|---|---|---|---|---|
| from surface water $C_{11}$ | | | | | | |
| Land use type $C_{12}$ | 1/2 | 1 | 1/2 | 2 | 0.1890 | 0.0603 |
| Distance from settlements $C_{13}$ | 1 | 2 | 1 | 3 | 0.3509 | 0.1120 |
| Distance from roads $C_{14}$ | 1/3 | 1/2 | 1/3 | 1 | 0.1091 | 0.0348 |
| $\lambda_{\max} = 4.0104$，CI=0.0035，RI=0.90，CR=0.0039 | | | | | | |

**Table D5**

Criterion $B_4$ and Criteria $C_{15-16}$ Judgment Matrix.

| Climatic $B_4$ | Precipitation $C_{15}$ | Temperature $C_{16}$ | Relative weight $W_{C_i}$ | Normalized weight $\overline{W}_{C_i}$ |
|---|---|---|---|---|
| Precipitation $C_{15}$ | 1 | 2 | 0.6667 | 0.0455 |
| Temperature $C_{16}$ | 1/2 | 1 | 0.3333 | 0.0228 |

$\lambda_{max}=2$，CI=0，RI=0，CR=0

**Table D6**

Criterion $B_5$ and Criteria $C_{17-20}$ Judgment Matrix.

| Socio-economic $B_5$ | Distance from ecological function reserves $C_{17}$ | Population density $C_{18}$ | GDP $C_{19}$ | Ecosystem service value $C_{20}$ | Relative weight $W_{C_i}$ | Normalized weight $\overline{W}_{C_i}$ |
|---|---|---|---|---|---|---|
| Distance from ecological function reserves $C_{17}$ | 1 | 3 | 3 | 2 | 0.4554 | 0.0498 |
| Population density $C_{18}$ | 1/3 | 1 | 1 | 1/2 | 0.1409 | 0.0154 |
| GDP $C_{19}$ | 1/3 | 1 | 1 | 1/2 | 0.1409 | 0.0154 |
| Ecosystem service value $C_{20}$ | 1/2 | 2 | 2 | 1 | 0.2628 | 0.0287 |

**$\lambda_{max}=4.0104$，CI=0.0035，RI=0.90，CR=0.0039**

## Appendix E

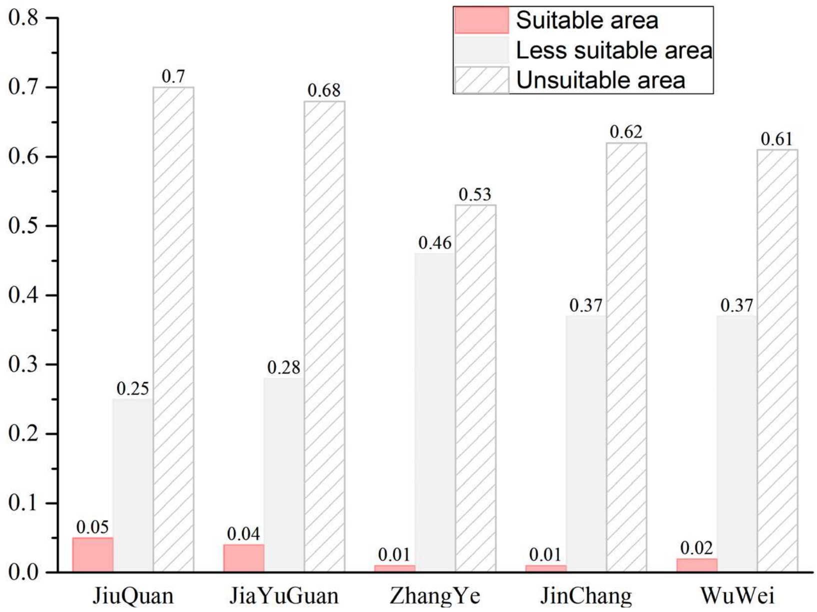



**Fig. E1.** The proportion of suitability grade in Hexi Corridor.

## Appendix F

**Table F1**

"Construction Standard of MSW Landfill Disposal Engineering Project". The landfill is divided into four levels according to the area of the landfill. The smaller the area, the higher the level, and the lower the amount of MSW to be disposed.

| Landfill | I | II | III | IV |
|---|---|---|---|---|
| Area（Km$^2$) | >12 | 5-12 | 2-5 | 1-2 |
| Amount of MSW（Tons/day） | >1200 | 500-1200 | 200-500 | <200 |

**Table F2**

Candidate site latitude, longitude, area, and MSW disposal capacity. S-1 and S-2 had the highest MSW disposal capacities, S-4, S-6, and S-10 had the lowest MSW disposal capacities.

| City | Candidate site | Longitude | Latitude | Area（Km$^2$) | Amount of MSW（Tons/day） |
|---|---|---|---|---|---|
| JiuQuan | S-1 | 95°46′40″E | 40°56′28″N | 41.83 | >1200 |
| | S-2 | 97°40′19″E | 40°20′40″N | 25.98 | >1200 |
| | S-3 | 99°22′45″E | 40°29′38″N | 10.67 | 500-1200 |
| JiaYuGuan | - | - | - | - | - |
| ZhangYe | S-4 | 100°14′10″E | 39°29′08″N | 1.73 | <200 |
| | S-5 | 100°43′27″E | 38°44′18″N | 5.50 | 500-1200 |
| | S-6 | 101°02′42″E | 38°37′06″N | 1.83 | <200 |
| JinChang | S-7 | 101°50′21″E | 38°19′07″N | 4.85 | 200-500 |

| | | | | | |
|---|---|---|---|---|---|
| | S-8 | 103°05′06″E | 38°19′30″N | 15.00 | >1200 |
| | S-9 | 102°15′17″E | 37°47′01″N | 5.19 | 500-1200 |
| WuWei | S-10 | 102°43′16″E | 37°32′41″N | 1.94 | <200 |
| | S-11 | 103°04′07″E | 37°19′51″N | 2.48 | 200-500 |

## Appendix G

**Table G1**

Assessment values as well as subordinate and final rankings of alternative sites utilizing the Fuzzy MULTIMOORA method.

| Alternatives | Fuzzy ratio system | | Fuzzy reference point | | Fuzzy full multiplicative form | | Fuzzy MULTIMOORA |
|---|---|---|---|---|---|---|---|
| | $y_i$ | Rank | $y_i$ | Rank | $y_i$ | Rank | Rank |
| S-1 | (-0.128,-0.128,-0.125) | 3 | 0.611 | 3 | (6.233,6.195,6.158) | 2 | 3 |
| S-2 | (-0.045,-0.043,-0.039) | 1 | 0.339 | 1 | (7.325,7.386,7.331) | 1 | 1 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| S-3 | (-0.174,-0.173,-0.171) | 4 | 0.652 | 4 | (5.391,5.474,5.252) | 4 | 4 |
| S-4 | (-0.369,-0.364,-0.362) | 10 | 0.797 | 10 | (3.392,3.438,3.287) | 10 | 10 |
| S-5 | (-0.221,-0.216,-0.214) | 5 | 0.689 | 5 | (4.990,4.925,4.871) | 6 | 5 |
| S-6 | (-0.380,-0.375,-0.373) | 11 | 0.822 | 11 | (2.954,2.869,2.711) | 11 | 11 |
| S-7 | (-0.299,-0.292,-0.292) | 7 | 0.732 | 7 | (4.771,4.857,5.040) | 7 | 7 |
| S-8 | (-0.089,-0.083,-0.083) | 2 | 0.558 | 2 | (5.771,5.934,5.886) | 3 | 2 |
| S-9 | (-0.266,-0.261,-0.259) | 6 | 0.715 | 6 | (5.174,5.378,5.221) | 5 | 6 |
| S-10 | (-0.315,-0.311,-0.308) | 8 | 0.769 | 9 | (4.240,4.587,4.328) | 8 | 8 |
| S-11 | (-0.341,-0.341,-0.339) | 9 | 0.755 | 8 | (3.870,3.929,3.965) | 9 | 9 |

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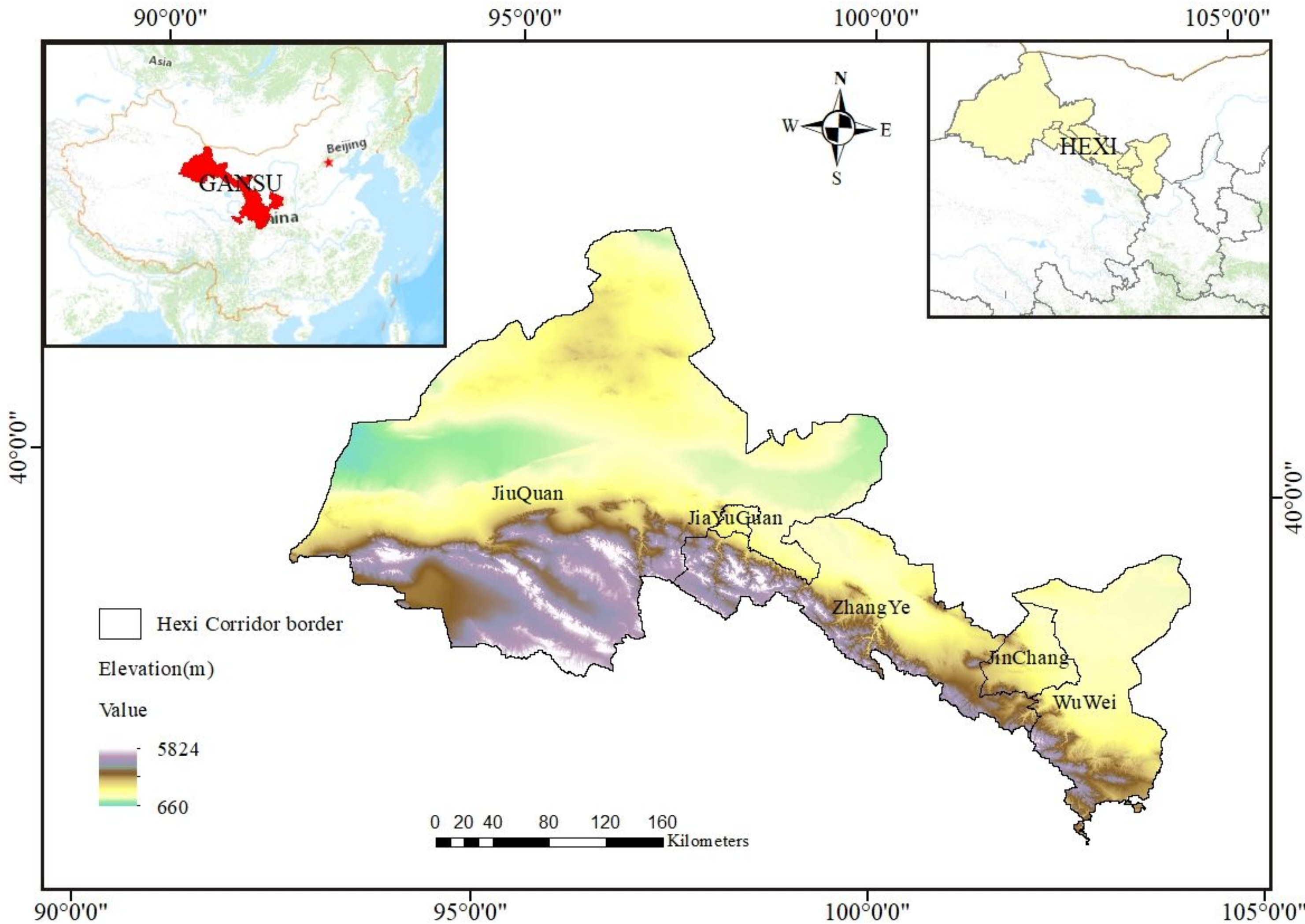
# Figures




## Figure 1

Elevation of the study region. The Hexi Corridor includes five cities (Jiuquan, Jiayuguan, Zhangye, Jinchang, Wuwei), and twenty counties (districts), with a total area of 2.7× 105 km2. Elevation data is from the USGS - SRTM dataset, which provides elevation data at a 30-meter resolution. The elevation of the study area ranged from 660 to 5842 meters. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

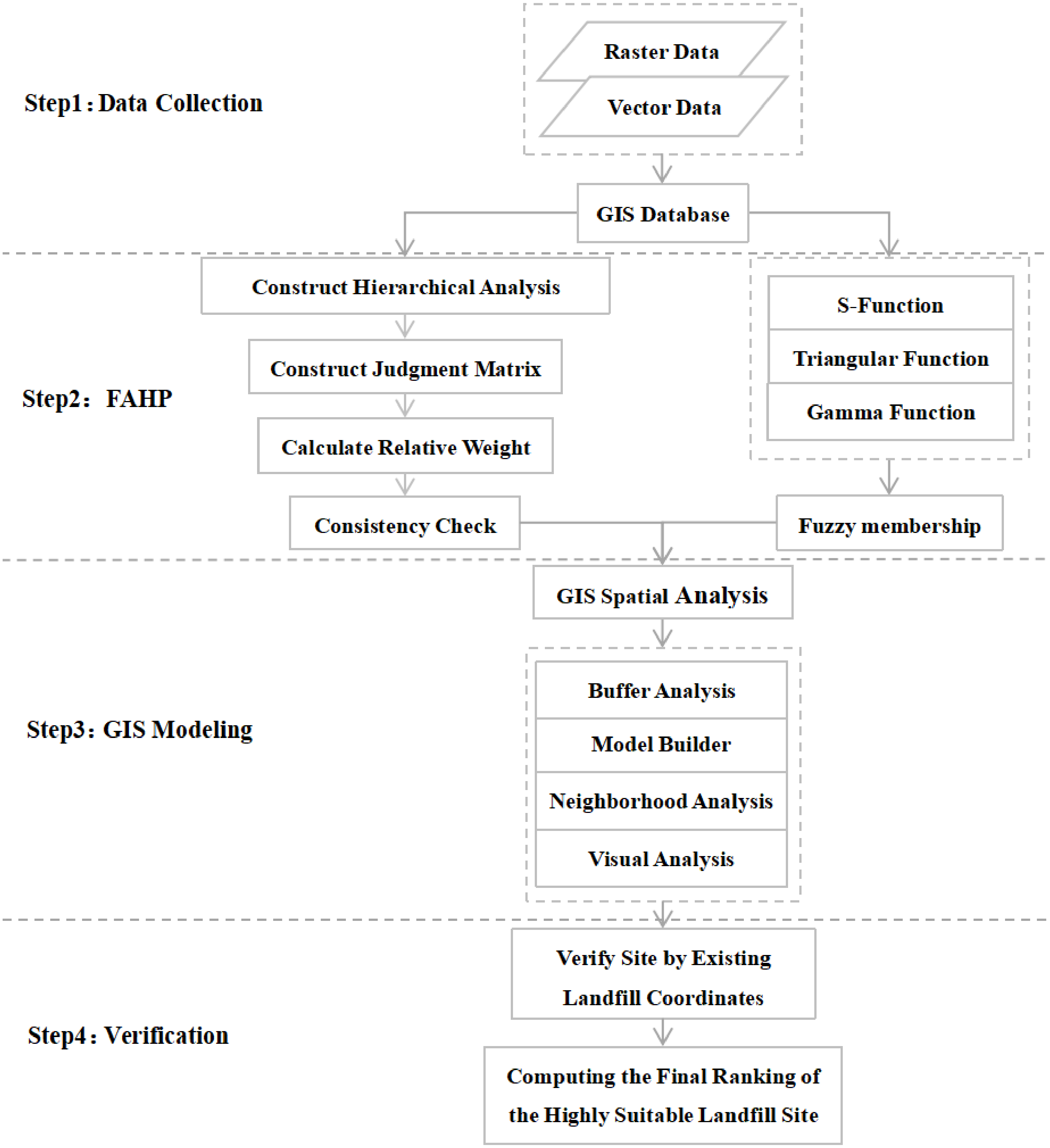



**Figure 2**

Method framework chart including the four main steps: Data Collection, FAHP, GIS Modeling, and Verification.

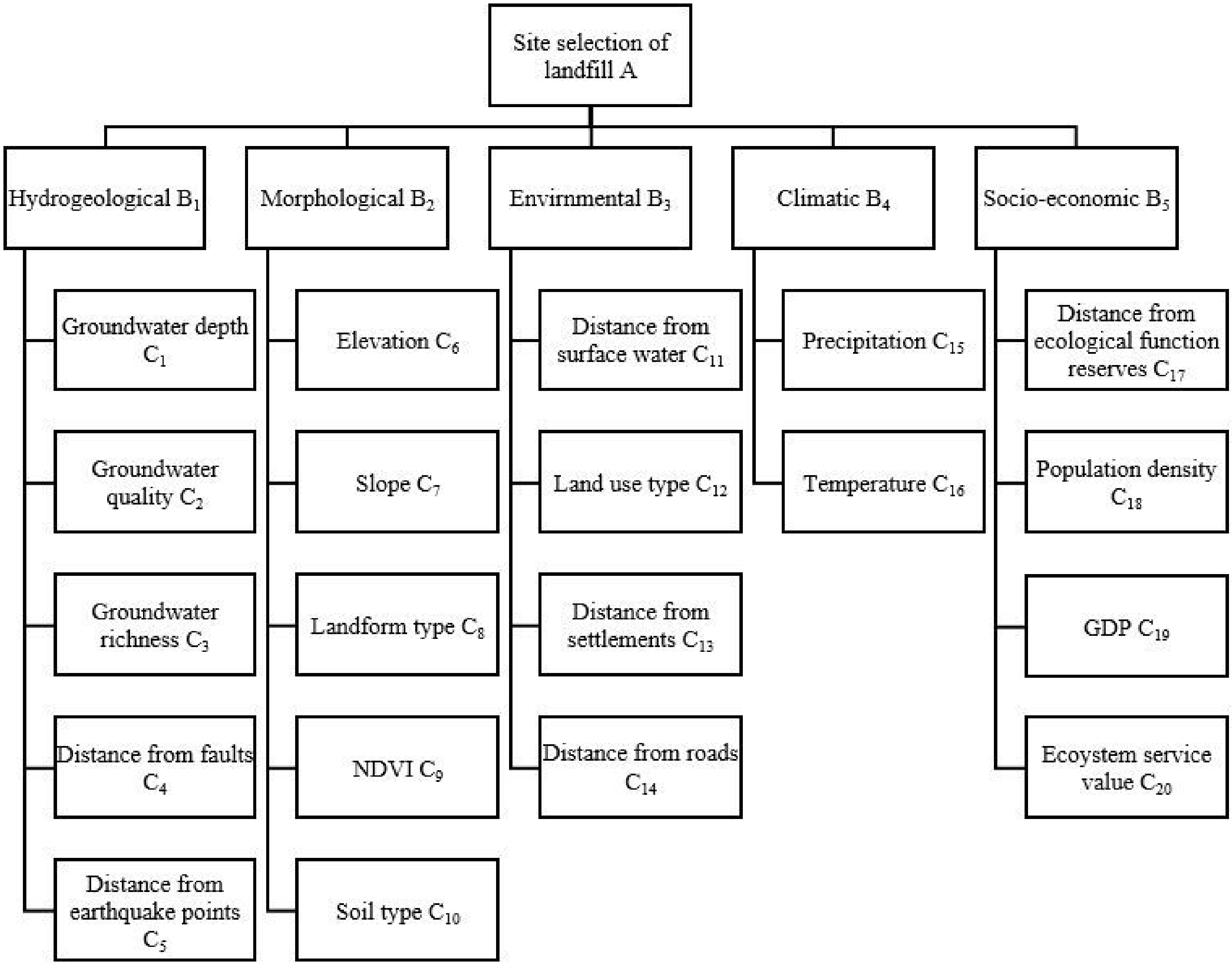
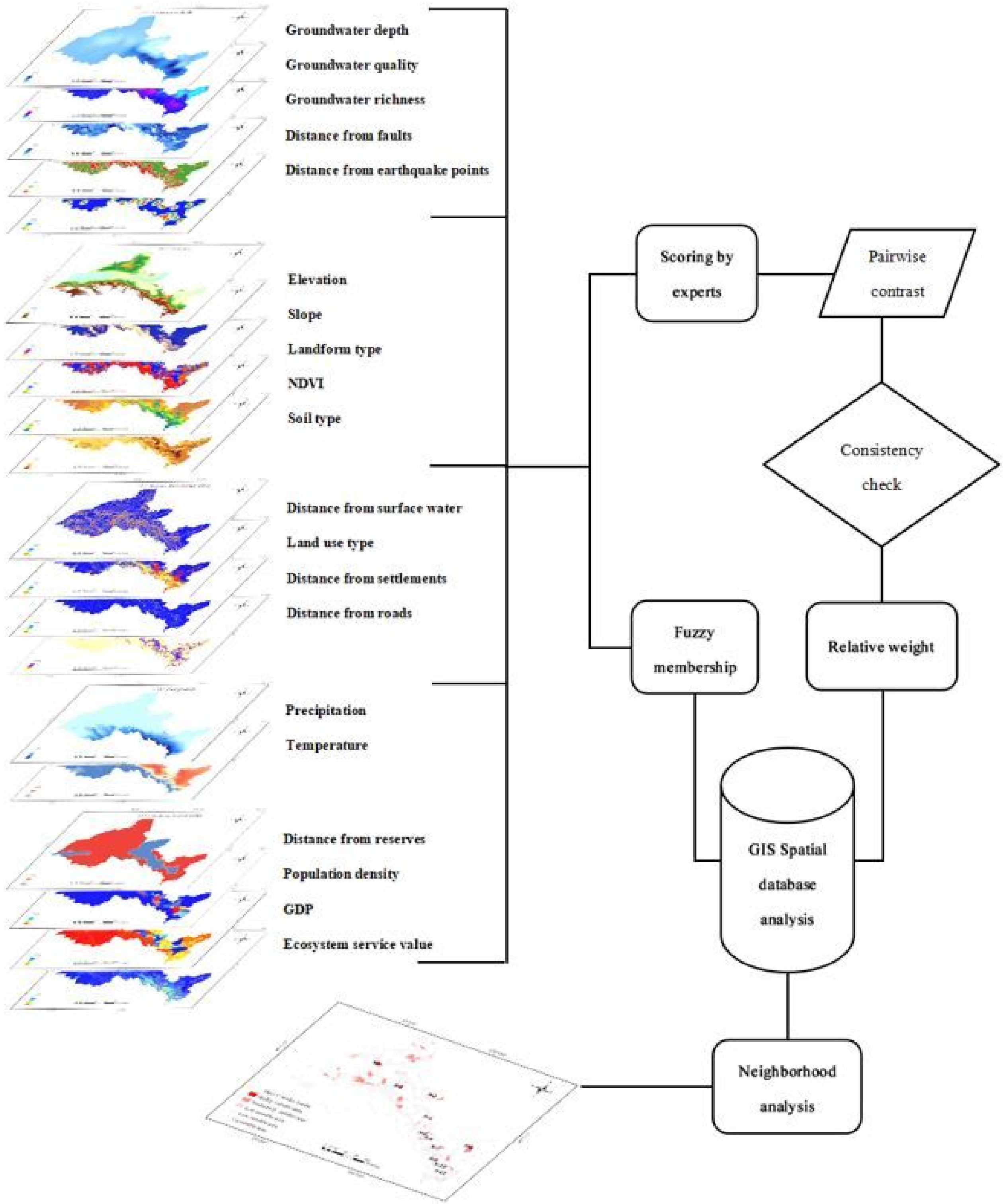



**Figure 3**

The hierarchical analysis structure is comprised of three layers (decision, primary, and secondary evaluation factor layers). Decision layer A is the site selection of landfill, primary layer B contains five criteria, secondary layer C includes 20 sub-criteria.




## Figure 4

Flow chart of LSS modeling, which includes 20 normalized layers of criteria. GIS spatial analysis was used to calculate its weight and fuzzy membership degree, and obtain the LSSR.

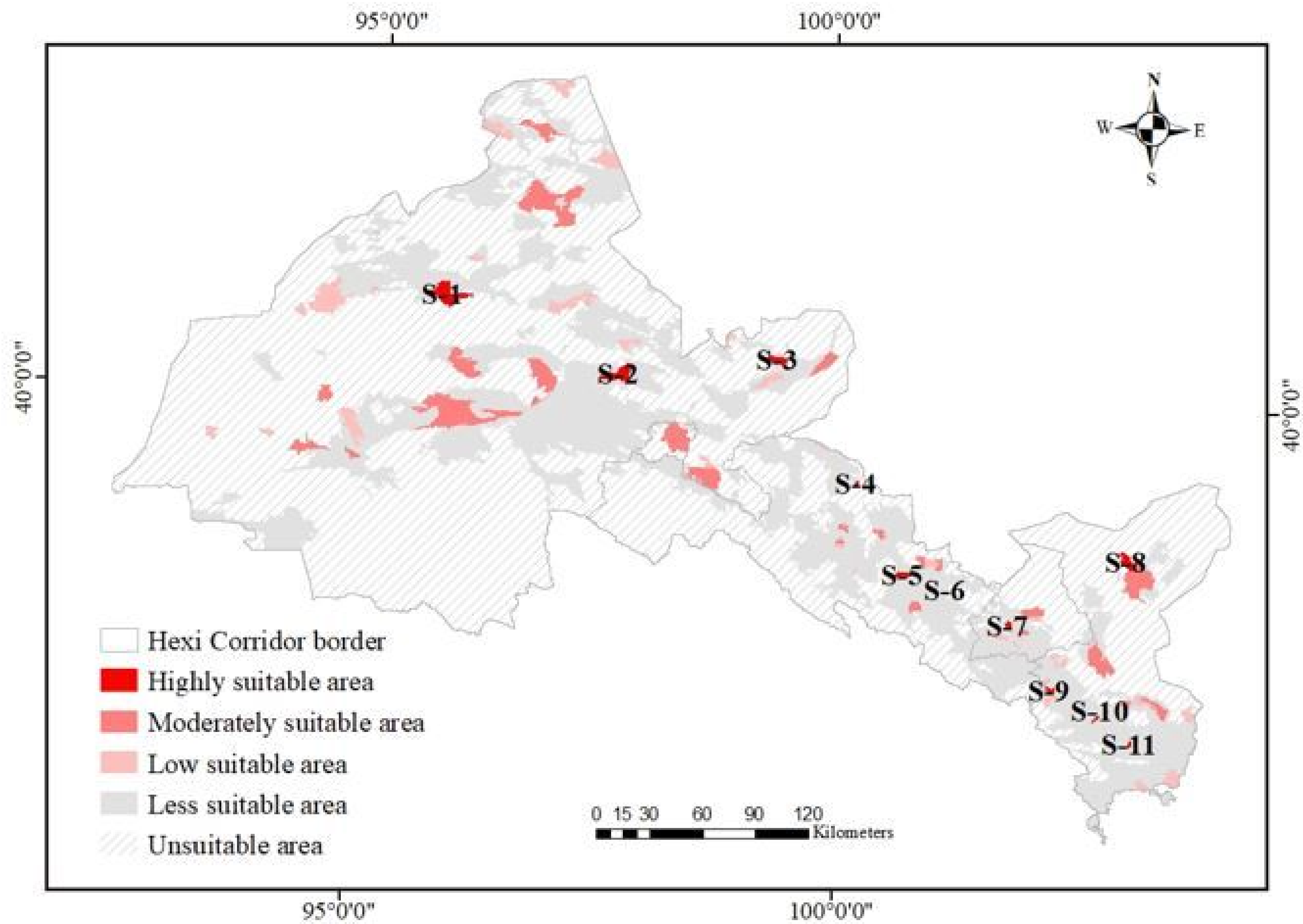



**Figure 5**

Site selection of MSW landfills in Hexi Corridor. The LSSR are graded according to color brightness. Brighter reds indicate better suitability, gray indicates less suitability, and the line fill indicates the unsuitable. A total of 11 candidate sites were selected in the Hexi Corridor. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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