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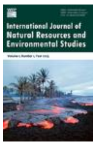
International Journal of Natural Resources and Environmental Studies
ISSN: 3006-2012 (Print), ISSN: 3006-0834 (Online) | Volume 8, Number 3, Year 2026
DOI: https://doi.org/10.62051/ijnres.v8n3.11
Journal homepage: https://wepub.org/index.php/IJNRES/index



Ecological Suitability Assessment and Protection Strategies for the Upper Hanjiang River Basin Based on the Analytic Hierarchy Process

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ABSTRACT

Against the backdrop of accelerating socio-economic development, regional ecosystems are increasingly exposed to pressures such as air pollution, soil erosion, and water scarcity, highlighting the need for more robust ecological protection. Taking the upper Hanjiang River Basin as the study area, this study integrates the Analytic Hierarchy Process with GIS-based spatial overlay to assess ecological suitability. An indicator system comprising elevation, slope, aspect, mean annual precipitation, river-buffer conditions, vegetation distribution, and land-use type was constructed, and indicator weights were determined through expert judgment and pairwise comparison matrices that passed the consistency test. The results show that areas rated suitable or above account for approximately 70% of the study area, indicating an overall favorable level of ecological suitability. Spatially, suitability is relatively low in the Qinling and Daba mountain belts and comparatively high in the central Hanjiang valley and around urbanized areas. Localized high-suitability clusters, such as meadow valleys near the Baohe Basin, are closely associated with favorable vegetation cover and relatively stable ecological conditions, whereas strip-like low-suitability belts between the northern Daba Mountains and the Hanjiang main stem are strongly constrained by slope and aspect and should therefore be prioritized in soil-erosion control. On this basis, targeted strategies are proposed for biodiversity conservation, water-resource protection, and rational land-use planning so as to support ecological restoration, environmental governance, and sustainable development in the upper Hanjiang River Basin.

KEYWORDS

Analytic Hierarchy Process; upper Hanjiang River Basin; ecological suitability assessment; ecological protection; spatial analysis.

1. INTRODUCTION

Rapid socio-economic development has intensified environmental degradation in many river basins, generating ecological, economic, and social spillover effects. Protecting riverine ecosystems has therefore become a major task in contemporary environmental governance. Scientifically grounded ecological assessment is indispensable for balancing resource utilization, environmental protection, and regional development.

Ecological suitability refers to the degree to which land can sustain a given use under the combined influence of topography, hydrology, climate, biological conditions, and human activities. The concept is used to assess whether regional environmental conditions can support specific forms of development, protection, or restoration over the long term. In ecology and environmental science, it usually emphasizes the adaptability of organisms and ecosystems to environmental conditions; in planning and land-use studies, it is more often used to evaluate the compatibility between human activities and the natural environment.

Research on ecological suitability emerged in the context of ecological planning. In Design with Nature, Ian L. McHarg proposed an evaluative approach that integrated natural constraints with human land use and laid an important foundation for later suitability studies [1]. Subsequent research further developed indicator systems and evaluation procedures by incorporating terrain, soil, hydrology, vegetation, and land-use conditions into comprehensive assessment frameworks. In China, Jing Song discussed the theory and methods of land ecological suitability evaluation in suburban counties of large cities and developed a relatively complete framework combining questionnaires, expert scoring, and qualitative–quantitative analysis [2].

With the development of remote sensing, GIS, and spatial modeling, ecological suitability research has become increasingly refined and methodologically diverse. Recent studies have combined AHP, principal component analysis, resistance modeling, and other spatial decision-making techniques to improve indicator weighting, classification, and spatial differentiation [4–5]. Among these approaches, the AHP–GIS framework remains widely used because it can translate complex ecological relationships into a hierarchical indicator system and combine expert judgment with spatial analysis in a comparatively transparent manner.

The upper Hanjiang River Basin is the largest tributary basin of the Yangtze River and an important ecological security barrier as well as a crucial water-source area for the Middle Route of the South-to-North Water Diversion Project. The basin is characterized by complex topography, strong environmental heterogeneity, and rich biodiversity, while also facing increasing pressure from urbanization, land-use change, and resource exploitation. These features make it a representative case for ecological suitability assessment in mountainous river-basin regions.

In recent years, Zhang Jiayu and others analyzed the ecological impacts affecting the middle and lower Hanjiang River through indicator-based studies, paying particular attention to changes in aquatic ecosystems and the influence of the South-to-North Water Diversion Project. Their work highlighted the fragility of the ecological environment in the middle and lower reaches and proposed a series of improvement measures [6]. Zhao Zuoping et al. evaluated the upper Hanjiang River using hydrological monitoring data and ecological indicators, showing that severe soil erosion is one of the major regional problems and relating low ecological suitability to economic underdevelopment, poverty, and population growth [8].

On the basis of map overlay analysis and the AHP–GIS framework [8], this study evaluates ecological suitability in the upper Hanjiang River Basin using multiple spatial datasets and spatial analysis tools. Beyond identifying the spatial pattern of suitability, it further discusses the main ecological constraints and proposes targeted protection strategies, thereby providing a scientific reference for environmental governance and ecological restoration in the basin.

2. STUDY AREA AND DATA SOURCES

2.1. Regional Ecological Background

The Hanjiang River is the largest tributary of the Yangtze River. It flows through Hubei, Shaanxi, Henan, Jiangxi, and Anhui and is about 1,532 km long. The basin has complex terrain, diverse climatic conditions, and rich ecological environment types, including extensive wetlands, forests, grasslands, lakes, and rivers. It is also an important water-source area for the Middle Route of the South-to-North Water Diversion Project.

In recent years, the Chinese government has introduced a series of policies and measures to protect the Hanjiang River and the Yangtze River, including plans related to ecological protection and green development in the Yangtze Economic Belt. At the same time, extensive scientific research and technological innovation have been carried out to improve understanding of the ecological environment of the Hanjiang River Basin and to strengthen conservation capacity.

With rapid economic development, ecological problems affecting river systems have become increasingly prominent. As an important component of the Yangtze River Basin, the upper Hanjiang River has long attracted attention because of its water quality and ecosystem health. Accelerating economic growth and population increase have intensified ecological pressures in the basin, making ecological suitability evaluation and conservation research in the upper Hanjiang River particularly important.

2.2. Overview of the Study Area

The Hanjiang River originates on the southern slope of the Qinling Mountains in Shaanxi Province. The whole river is about 1,532 km long and drains an area of 166,000 km². This study focuses on the basin upstream of the Baihe Hydrological Station in the upper Hanjiang River [9], located between 106°–110°E and 32°–34°N. The study area accounts for about 31.7% of the total Hanjiang Basin. The northern part is adjacent to the Qinling Mountains, while the south is dominated by the western Hubei Mountains, Badong Mountains, and related ranges. Topographic relief is substantial and elevation generally increases from south to north. The basin belongs to the humid northern subtropical monsoon climate zone, with clear north–south climatic differentiation. Precipitation decreases from south to north and is highly uneven both spatially and seasonally; more than 80% of annual rainfall occurs from May to October, and more than 80% of annual runoff is concentrated between April and October. The southern area is warm and humid, with a mean annual temperature of about 16°C, whereas the northern area is relatively cool and dry, with mean annual temperatures of about 10–14°C.

The upper Hanjiang ecosystem is one of the important ecological systems in central China. It contains rich biodiversity and valuable ecological resources. According to the survey data cited in the manuscript, the upper Hanjiang region contains more than 3,000 plant species and over 1,000 animal species, including a number of rare and endangered taxa. Aquatic plants are abundant, though species richness is relatively limited. Aquatic animals include approximately 161 species in 7 orders, 16 families, and 69 genera, and the fish community is represented by species such as silver carp, bream, and common carp.

With industrial development and accelerating urbanization, the ecological environment of the upper Hanjiang River has faced a number of challenges. Monitoring data indicate that excessive wastewater discharge and industrial pollutants have negatively affected local water quality and threatened aquatic ecosystems. At the same time, large-scale land development and deforestation have added pressure to ecological balance. In response, government authorities have adopted a range of measures, including stricter environmental regulations, the promotion of cleaner energy use and energy saving, and strengthened supervision of industrial effluent and urban sewage treatment.

2.3. Data Sources

All spatial analyses in this study were conducted within a unified projected coordinate system. Before analysis, the datasets were checked for spatial consistency, resampled after pixel-size verification, and clipped to the study-area boundary. The principal data sources are as follows:

1) Geospatial data, including the 2022 point dataset of Chinese cities, 2022 provincial, municipal, and county administrative boundaries, the distribution of meteorological stations, and national river polyline data. These datasets were used to provide accurate geographic positioning and spatial zoning, to delineate the study area through county-level administrative-unit merging, and to identify the upstream and downstream extent of the target river. The data were obtained from the Resource and Environment Science and Data Center of China (www.resdc.cn).

2) Land-use data. This study mainly used the 2020 land-use raster data and classified it into six categories: cropland, forest land, grassland, water bodies, construction land, and unused land. The data were obtained from the Resource and Environment Science and Data Center of China (www.resdc.cn).

3) DEM data. The digital elevation model used in this study has a spatial resolution of 90 m and was obtained from the National Earth System Science Data Center (http://www.geodata.cn/).

4) Vegetation-cover data. The 2020 vegetation-cover dataset used here was derived from MODIS NDVI data and downloaded from Geospatial Data Cloud (www.gscloud.cn).

5) Monthly precipitation raster data. The study used the nationwide monthly precipitation raster dataset for 2020, released through climate datasets provided by the European Union, the European Centre for Medium-Range Weather Forecasts, and related organizations (https://cds.climate.copernicus.eu).

3. ECOLOGICAL SUITABILITY ANALYSIS

3.1. Principles for Establishing the Ecological Suitability Evaluation System

The scientific selection of indicators is a prerequisite for ensuring the reliability of ecological suitability assessment. To characterize environmental conditions in the upper Hanjiang River Basin more comprehensively, this study constructed the evaluation system from geographic, climatic, hydrological, ecological, and land-use perspectives. The indicator system was developed according to the following principles:

1) High precision. To understand environmental conditions in the upper Hanjiang River more accurately, a high-precision evaluation system is required. Measurement and recording of each indicator should therefore meet a high standard so as to ensure the accuracy and reliability of the assessment results.

2) Multidimensionality. The environment of the upper Hanjiang River is shaped by many interacting factors. The indicator system should therefore be multidimensional and cover geography, hydrology, ecology, and related aspects in order to evaluate ecological suitability more comprehensively.

3) Timeliness. As technology advances and research progresses, ecological indicators for the same region may vary across time. In river ecological monitoring, for example, real-time systems can provide continuously updated environmental information. The indicator system should thus be able to reflect environmental change in a timely way and support adaptive management.

3.2. Construction of the Ecological Suitability Indicator System

Based on the ecological background of the upper Hanjiang River Basin, the factors affecting ecological suitability can be grouped into two broad dimensions: natural conditions and socio-economic conditions. Following the principles of ecological suitability assessment, this study established a hierarchical indicator system in which the first level distinguishes the two dimensions and the second level specifies the corresponding indicators in light of regional environmental conditions and development characteristics.

First, from the perspective of topographic and geomorphological conditions, the upper Hanjiang River lies in a transition zone of plateaus, hills, and mountains. High elevation, relatively low temperature, short sunshine duration, dry climate, and strong wind erosion contribute to a complex geomorphic pattern and strong terrain undulation. Topographic factors therefore exert a pronounced influence on the regional ecological environment. Slope and aspect help evaluate how terrain affects ecological processes and thus provide strong support for suitability assessment.

Second, hydrological factors are also crucial. As the largest tributary of the Yangtze River, the hydrological characteristics of the Hanjiang River are closely related to ecological conditions throughout the basin. Upstream of the Baihe Hydrological Station in Ankang, average slopes are relatively steep, making the land more vulnerable to erosion and degradation. Steep terrain also makes hydrological processes more complex and contributes to frequent flood disasters, landslides, and debris flows. At the same time, some areas have relatively abundant water resources and favorable irrigation conditions, so hydrological indicators can help guide rational water-resource use and water-environment protection.

In addition, land cover is of great importance because it describes the degree and type of vegetation or other cover on the earth's surface and plays a key role in maintaining ecosystem functions, biodiversity, and hydrological cycles. Climate factors are likewise a major driving force of ecosystem operation, and climatic variation directly affects ecosystem stability and sustainability. A combined assessment of land-cover types and climate factors can therefore provide a more complete understanding of ecological conditions and climate-change trends in the Hanjiang Basin and support the formulation of ecological protection and climate-adaptation strategies.

Accordingly, this study selected elevation, slope, aspect, mean annual precipitation and runoff, river buffer factors, land-use type, and vegetation distribution as the secondary indicators for ecological suitability assessment in the upper Hanjiang River Basin, and then constructed the evaluation system shown in Table 1.

Table 1. Evaluation indicators for ecological suitability in the upper Hanjiang River Basin

Ecological factors	**Secondary indicator**	**Significance**
Natural factors	Elevation	Absolute elevation is the most intuitive macroscopic indicator for describing topographic variation within a region.
	Slope	Slope represents the inclination of the land surface relative to the horizontal plane; it reflects suitability for human production and living and is also an indicator of natural-hazard risk.
	Aspect	Aspect describes the orientation of the land surface, usually by azimuth, and—when combined with prevailing wind direction—helps evaluate resistance to land erosion.
	Mean annual precipitation	Reflects the natural water-supply capacity of the region.
	Vegetation distribution	Reflects the condition of vegetation cover and artificial surface cover in the study area.
	River buffer zone	A buffer zone within a certain distance of rivers reflects the degree of protection of river ecosystems, helps reduce natural-hazard risk, and indicates appropriate land-use patterns, thus providing a scientific basis for ecological protection and the stability of socio-economic activities.
Socio-economic factors	Land use	Reflects the effects of land-cover types and socio-economic activities on the ecological environment.

3.3. Workflow of Ecological Suitability Evaluation

Using the collected datasets and ArcGIS, the study area was divided into raster cells with a spatial resolution of 30 m, which were used as the basic analytical units. This gridded approach improves the precision of spatial analysis and enables micro-scale geographic variation to be incorporated more effectively into the evaluation process.

According to the requirements of different indicators, the study employed spatial overlay, neighborhood analysis, and buffer analysis to evaluate ecological and social suitability based on both natural-environment and socio-economic indicators. Comprehensive ecological suitability was then classified into five levels: most suitable, relatively suitable, suitable, unsuitable, and least suitable. Finally, corresponding ecological protection measures were proposed in light of the suitability results and the region's environmental and socio-economic conditions.

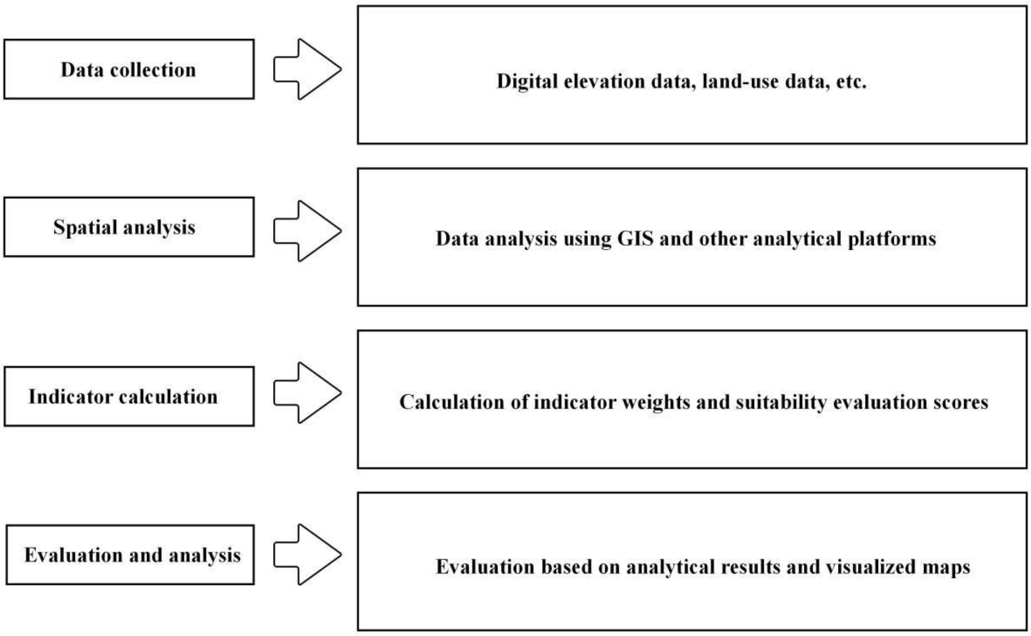

Figure 1 Research framework

3.4. Models and Methods of Ecological Suitability Evaluation

3.4.1. Comprehensive Evaluation Model

A multi-factor comprehensive evaluation model was adopted to synthesize the effects of the selected indicators and calculate the overall ecological suitability of each spatial unit. The model is expressed as follows:

$$E = \sum_{i=1}^{n} \omega_i \times I_i \tag{1}$$

In the formula, E denotes the comprehensive ecological suitability index, wi denotes the weight of factor i, and Si denotes the evaluation score of factor i.

3.4.2. Suitability Grades

In this study, suitability was assessed from the perspective of ecological constraints and land-development requirements. The grading framework mainly considers natural environmental factors, including vegetation cover, climatic conditions, and land use, while also reflecting whether the surrounding ecological setting can sustain human activity under the premise of ecological protection.

Evaluation of construction-related land suitability generally needs to take into account natural conditions, socio-economic conditions, and ecological protection requirements defined by local laws and regulations. In this study, the region was classified into five grades—most suitable, relatively suitable, suitable, unsuitable, and least suitable—so as to produce a comprehensive evaluation, as shown in Table 2. Areas in the highest class meet relatively favorable development conditions while still maintaining ecological capacity, whereas the least suitable areas should be treated as basic ecological control zones and should not be used for development.

Table 2. Ecological suitability classification system

Class	Suitability	Description
S1	Most suitable	Ecological interactions are highly favorable and the area may be considered first for development under controlled conditions.
S2	Relatively suitable	Ecological interactions are relatively favorable and the area is comparatively suitable for development.
S3	Suitable	The ecological environment is generally good, but some ecological constraints remain.
S4	Unsuitable	The ecological environment is relatively poor and the area is generally unsuitable for development.
S5	Least suitable	The ecological environment is severe and the area is unsuitable for development.

3.4.3. Determination of Indicator Weights

3.4.3.1. Principle of weight determination

This study identifies four groups of factors—topography, hydrology, land cover, and the natural environment—as the principal influences on ecological suitability. Within these groups, seven secondary indicators were selected: elevation, slope, aspect, mean annual precipitation, river buffer, land-use type, and vegetation distribution. The Analytic Hierarchy Process was then used to compare indicator importance across different levels.

Following the logic of the research problem, AHP decomposes the evaluation into the target layer, criterion layer, and indicator layer. Pairwise comparison matrices are then constructed for each level, and mathematical methods are used to calculate the relative weights of the indicators. Finally, the weighted values are overlaid to obtain the composite score and to rank suitability classes in the upper Hanjiang River Basin. In this study, the arithmetic progression scoring method assigns values of 9, 7, 5, 3, and 1 to the five suitability classes from most suitable to least suitable, respectively.

Table 3. Classification of ecological suitability analysis factors

Influencing factor	**Secondary indicator**	**Classification criterion**				
		Most suitable (9)	**Relatively suitable (7)**	**Suitable (5)**	**Unsuitable (3)**	**Least suitable (1)**
Natural factors	Elevation (m)	<200	200-400	400-800	800-1200	>1200
	Slope (°)	<5	5-10	10-15	15-25	>25
	Aspect	SW/H	S/W	NW/SE	N/E	NE
	River buffer (m)	>200m	140-200m	100-140m	60-100m	<60m
	Vegetation distribution	Meadow	Cropland vegetation	Shrub–grass vegetation	Shrubland	Coniferous, broadleaved, or mixed forest
Socio-economic factors	Land-use type	Construction land	Dry cropland	Grassland	Forest land	Paddy fields / water bodies

3.4.3.2. Determination of weights

The determination of indicator weights begins with the construction of a hierarchical structure model and an analysis of the relationships among indicators, thereby forming a multi-level index system. The hierarchy generally includes a target layer representing the overall objective, a criterion layer representing the intermediate dimensions, and an indicator layer representing the specific variables used in the assessment [10]. The resulting framework is shown in Figure 1.

Figure 1. Ecological suitability evaluation framework of the Hanjiang River Basin

A pairwise comparison judgment matrix was then constructed for the indicators, and a local ranking was performed. Indicators at the same level were compared two by two to determine their relative weights. Let aij denote the relative importance between factor ai and factor aj.

$$A = \begin{bmatrix} a_{11} & \dots & a_{n1} \\ \dots & \dots & \dots \\ a_{1m} & \dots & a_{nm} \end{bmatrix} \tag{2}$$

Based on the matrix above, the indicators were compared pairwise, and their relative importance was determined through literature consultation and expert scoring. The geometric mean method was then used for aggregation and averaging.

Table 4. Ecological suitability judgment matrix

Ecological factor	Elevation	Slope	Aspect	Vegetation distribution	River buffer	Mean annual precipitation	Land-use type
Elevation	1	2	2	3	3	3	3
Slope	1/2	1	1	2	3	3	3
Aspect	1/2	1	1	2	2	3	3
Vegetation distribution	1/3	1/2	1/2	1	2	2	3
River buffer	1/3	1/3	1/2	1/2	1	1	1
Mean annual precipitation	1/3	1/3	1/3	1/2	1	1	1
Land use	1/3	1/3	1/3	1/3	1	1	1

A consistency test was then performed for the derived results. First, the maximum eigenvalue λmax and the consistency index CI were calculated. Next, the average random consistency index RI was obtained, and finally the consistency ratio CR = CI/RI was calculated. When CR < 0.1, the matrix is considered to have passed the consistency test and the results are regarded as acceptable.

Using MATLAB, the matrix above was first normalized to obtain the normalized matrix shown in Table 5.

Table 5. Normalization Processing Matrix

	Elevation	Slope	Aspect	Vegetation distribution	River buffer	Mean annual precipitation	Land-use type
Elevation	0.3000	0.3636	0.3529	0.3214	0.2308	0.2143	0.2000
Slope	0.1500	0.1818	0.1765	0.2143	0.2308	0.2143	0.2143
Aspect	0.1500	0.1818	0.1333	0.2143	0.2000	0.2857	0.2143
Vegetation distribution	0.1000	0.0909	0.0667	0.1071	0.2000	0.1905	0.2143
River buffer	0.1000	0.0606	0.0667	0.0536	0.1000	0.0952	0.0714
Mean annual precipitation	0.1000	0.0606	0.0444	0.0536	0.1000	0.0952	0.0714
Land use	0.1000	0.0606	0.0444	0.0357	0.1000	0.0952	0.0714

Matrix operations on the data above show that the sum of the characteristic-vector weights yields λmax = 7.028.

The consistency index CI is then calculated as follows:

$$CI = (\lambda_{\max} - n)/(n - 1) \tag{3}$$

$$CR = CI / RI \tag{4}$$

In the formula, CI is the consistency index and λmax is the maximum eigenvalue. Because the matrix order is 7, n = 7 and the random consistency index is RI = 1.32. According to the calculation, CI is about 0.047 and satisfies CR < 0.1, indicating that the matrix passes the consistency test and can be used as a reference for weighting.

According to the AHP procedure, the final indicator weights are shown in Table 6.

Table 6. Evaluation Index Weight System

Influencing factor	Weight	Secondary indicator	Local weight	Final weight	
Natural factors	0.75	Elevation	0.3036	0.2277	CR = 0.047
		Slope	0.2318	0.1739	
		Aspect	0.2241	0.1681	
		River buffer	0.1132	0.0849	
		Vegetation	0.2558	0.1919	
		Precipitation	0.1169	0.0877	
Socio-economic factors	0.25	Land-use class	0.2632	0.0658	

4. APPLICATION AND RESULTS OF ECOLOGICAL SUITABILITY EVALUATION

4.1. Analysis of Major Ecological Factors

4.1.1. Elevation Factor

In this study, elevation was classified into 0–200 m, 200–400 m, 400–800 m, 800–1,200 m, and above 1,200 m, and the corresponding scores of 9, 7, 5, 3, and 1 were assigned to derive the elevation factor map (Figure 2). Elevation is the most intuitive indicator for representing regional topographic and geomorphic characteristics and also provides an important basis for geological research and land-use planning.

Elevation in the study area is mainly concentrated between 100 and 1,500 m and shows a clear altitudinal gradient. The overall pattern is high in the north and south and low in the middle. High-elevation areas are mainly distributed in the northern Qinling Mountains and the southern Daba Mountains, whereas low-elevation areas are concentrated in the southern plains. Overlay analysis also suggests a close relationship between vegetation type and elevation. At relatively low elevations, shrublands, grasslands, and cultivated land are dominant, while grassland gradually transitions into forest with increasing altitude.

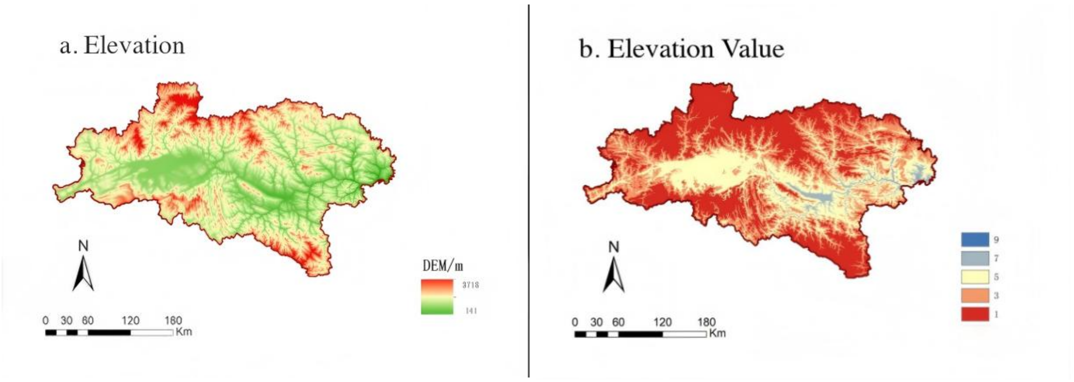

Figure 2. Classification of the elevation factor

4.1.2. Slope Factor

Slope is one of the main factors affecting the regional ecological environment. It is closely related to soil and water conservation and directly influences the suitability of vegetation growth. Areas with slope classes of 0–5°, 5–10°, 10–15°, 15–25°, and above 25° were assigned scores of 9, 7, 5, 3, and 1, respectively, to produce the slope factor map (Figure 3). The study area is dominated by slopes greater than 15°, accounting for about 60%–70% of the total area, with 23° being the most frequent value. Steeper slopes often aggravate soil erosion and thus influence ecological conditions.

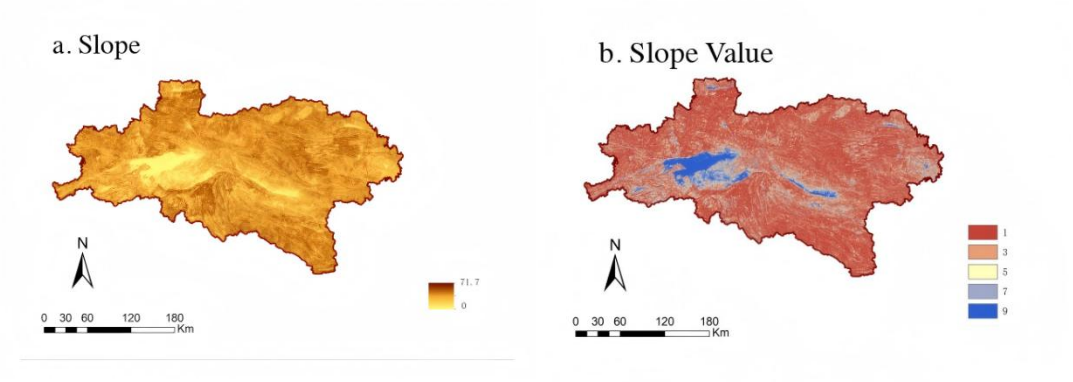

Figure 3. Analysis of the slope factor

4.1.3. Aspect Factor

The aspect map was derived from the DEM using the aspect tool. After reclassification and masking by the study-area polygon, aspect values within the region were obtained. Because the prevailing wind direction in this region is from the northeast, southwest-facing slopes or flat land, south- or west-facing slopes, northwest- or southeast-facing slopes, north- or east-facing slopes, and northeast-facing slopes were assigned values of 9, 7, 5, 3, and 1, respectively. The resulting aspect factor map is shown in Figure 4.

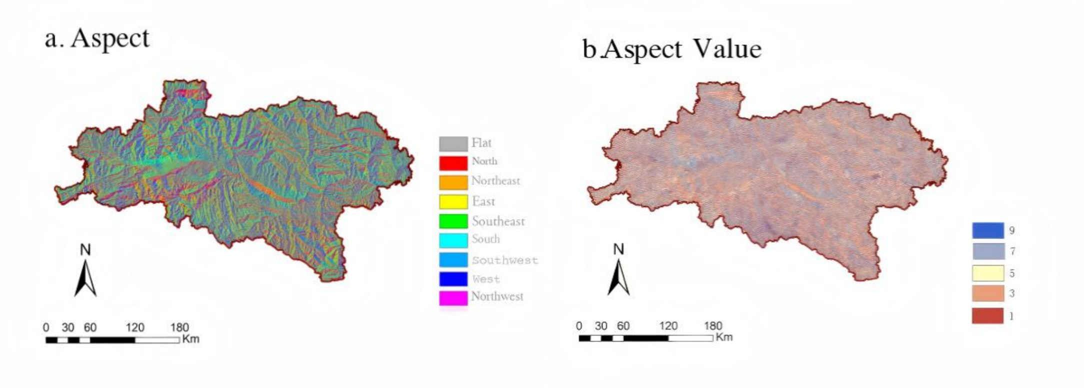

Figure 4. Aspect factor

The aspect pattern in the region can be roughly divided into two parts. One is the long-slope area of the Hanzhong Basin, where aspect varies little and the surrounding slopes generally point toward the basin floor. In the rest of the region, except for the riverfront areas where slope directions tend to face the main rivers, aspect is largely perpendicular to ridge and valley alignments, which also makes the mountain contours visible. Notably, the high-scoring areas do not show a very obvious regularity, but medium-to-low scoring areas (scores below 5), which are more vulnerable to erosion, form several northwest–southeast belts, suggesting priority areas for soil-loss prevention and ecological protection.

4.1.4. River Buffer Factor

The DEM was first processed with a fill tool to remove the influence of depressions on river-network extraction. Flow direction and flow accumulation were then derived, after which river channels were extracted according to threshold conditions and vectorized to obtain the target river network. Multi-ring buffer zones of 60 m, 100 m, 140 m, and 200 m were created around the river network. After raster conversion, the scores 7, 5, 3, and 1 were assigned to the buffer belts, while the remaining area was assigned a score of 9, producing the river buffer map shown in Figure 5.

The river network is dense and highly interconnected, and tributaries of the Hanjiang River radiate outward through surrounding valleys. The main channel is concentrated in the corridor between the Qinling Mountains and their southern foothills, where the river lines are denser and thicker, indicating more abundant water resources and more confluences. Upstream parts of the main stem have a higher network density than downstream parts and should therefore be prioritized for water-resource protection and pollution prevention. Some areas have low river-network density, probably because high mountain barriers impede runoff development, and these areas require greater attention to water replenishment and watershed conservation.

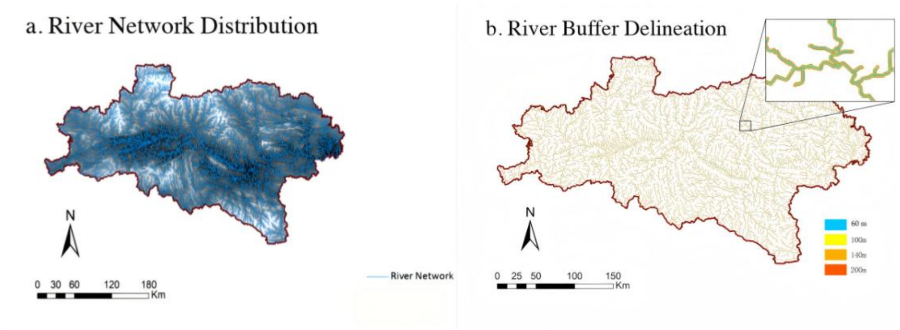

Figure 5. River buffer factor

4.1.5. Vegetation-Cover Factor

The vegetation-cover raster data were processed to identify the vegetation types present in the study area. Through reclassification, sub-codes were aggregated to first-level categories according to the vegetation code table, thereby producing the vegetation-cover distribution map (Figure 6). Meadow, cropland vegetation, shrub–grass vegetation, shrubland, and coniferous/broadleaved/mixed forest were assigned scores of 9, 7, 5, 3, and 1, respectively.

Temperature varies most obviously along elevation gradients, and vegetation type, quantity, and growth conditions also vary accordingly, closely reflecting the influence of altitude on environmental factors. Extensive coniferous forests, broadleaved forests, and mixed forests occur in the high-elevation Qinling region in the north, while various grass and shrub communities are more common at lower elevations in the south and northeast. In the high mountains of the north, steep terrain is associated with relatively sparse vegetation cover. In the high-elevation parts of the Daba Mountains, coniferous and broadleaved forests surround lower-elevation grassland and shrubland. Along the transition from low to high elevation, forests gradually replace grassland. In the central part of the region, large areas of cropland vegetation are distributed along the Hanjiang River valley, which is closely related to abundant water resources and intensive human activity.

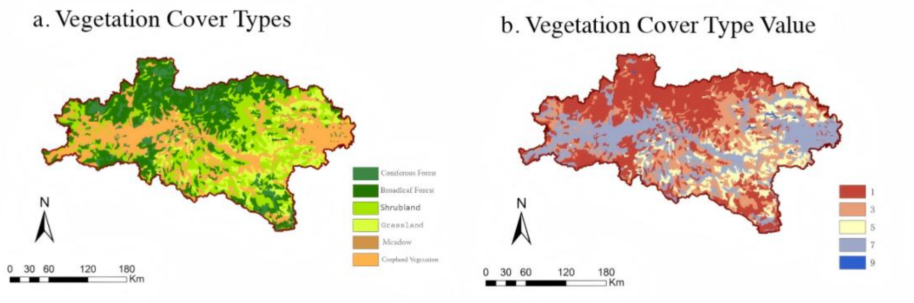

Figure 6. Vegetation-cover factor

4.1.6. Land-Use Factor

The collected land-use raster dataset was reclassified by merging second-level land-use codes other than cropland into broader first-level categories while keeping paddy fields and dry cropland as separate indicators. This produced the land-use distribution map shown in Figure 7. Industrial/mining land, construction land, dry cropland, grassland, forest land, and paddy fields/water bodies were then assigned scores for suitability analysis.

The dominant land-use types in the region are forest land and grassland, while water bodies are concentrated along the main stem of the Hanjiang River. The Hanzhong Basin and the urban area of Ankang contain relatively large areas of cultivated land, including both paddy fields and dry cropland. Urban centers and scattered towns embedded in the agricultural matrix appear as clustered construction land.

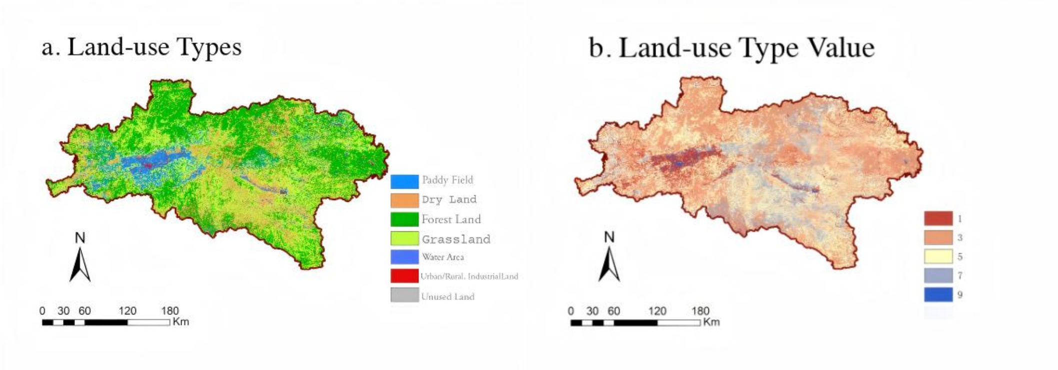

Figure 7. Land-use factor

4.2. Comprehensive Regional Analysis

4.2.1. Spatial Differentiation of Ecological Suitability

After weighted overlay of the individual ecological factors, the resulting suitability scores are concentrated mainly in the range of 2.90–3.72, accounting for approximately 60% of the total area. The overall spatial pattern exhibits a clear altitudinal gradient: suitability is relatively low in the northern and southern mountain belts and comparatively high in the Hanjiang River valley and adjacent basin areas.

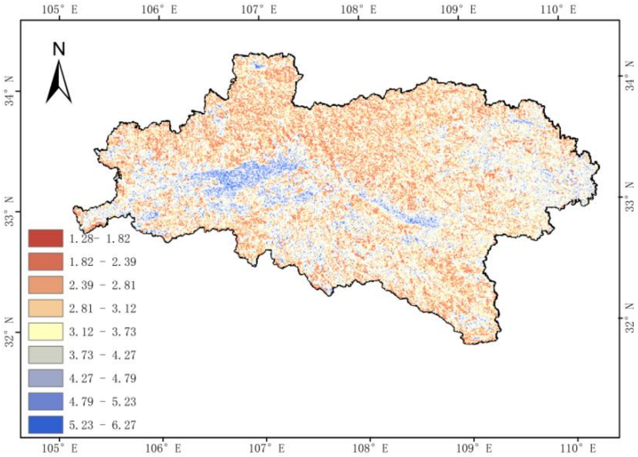

Figure 8. Range of weighted overlay scores

Ecological suitability in the region is most closely related to elevation. The lowest-suitability areas are concentrated in the continuous high-mountain zones in the north and the Daba Mountains in the south, such as the Xunhe and Baohe basins. High values are clustered around the Hanzhong Basin, with additional concentrations in the Lengshuihe and Shuangmahe basins. The higher-suitability areas also show strong correspondence with the Hanjiang main valley and cultivated zones. Vegetation distribution is again closely associated with elevation: lower areas are dominated by shrubland, grassland, and cropland, whereas grassland gradually transitions to forest at higher altitudes. In the steep cliff zones of the southwest and much of the north, suitability is poor because of rugged terrain, sparse vegetation, and the greater risk of hazards such as landslides. By contrast, some southeastern areas are flatter and have richer soil and water resources and therefore receive higher suitability scores.

4.2.2. Zoning of Ecological Suitability Grades

Using the weighted overlay function in ArcGIS, all factor layers were overlaid according to their weights. The resulting polygons were merged, geometric area was calculated through a new field, and the region was classified into five grades, S1–S5, according to the evaluation criteria (Figure 9).

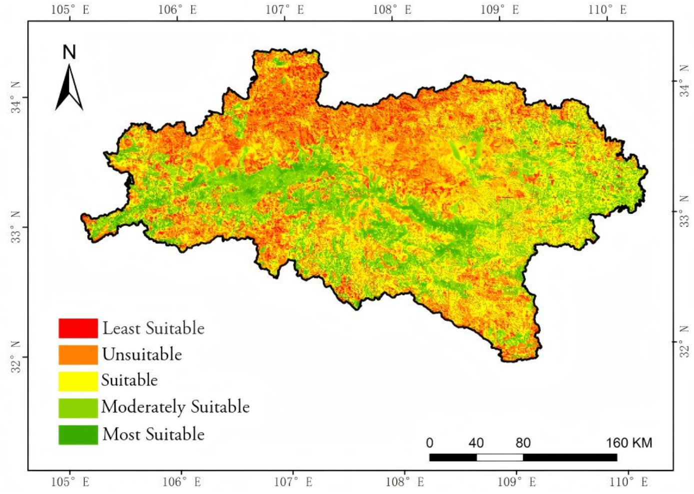

Figure 9. Distribution of ecological suitability in the upper Hanjiang River Basin

Combined with the results above and Table 7, the area classified as suitable or above reaches 45,517 km², accounting for about 70% of the total study area of 65,697 km². Overall, the upper Hanjiang River Basin shows a generally favorable level of ecological suitability. The two extreme classes occupy comparatively small shares: the least suitable class covers 4,593 km², whereas the most suitable class covers 5,633 km².

The least suitable areas (S5) are concentrated mainly in the Qinling Mountains in the north, especially on high mountain summits and steep mountain slopes. These areas cannot be regarded as favorable ecological-suitability zones in terms of elevation, slope, or vegetation cover. Ecological interactions are weak, climatic conditions fluctuate strongly, and steep slopes limit vegetation growth and soil accumulation, thereby intensifying soil erosion and increasing habitat fragility. Vegetation is dominated by coniferous and broadleaved forests with relatively simple structure, which is not advantageous for ecosystem stability.

The most suitable areas (S1) are concentrated in parts of the Hanzhong Basin, valley sections near river channels, and the surroundings of urban Ankang, and they display a degree of spatial autocorrelation. The Hanzhong Basin did not receive as high a score as expected. Comparison with the land-use factor map shows that the basin contains a certain amount of paddy land. Although paddy fields are usually well managed and favorable for crop growth, their soils are rich in organic matter and moisture and are therefore relatively soft and unstable from the perspective of construction and intensive human activity. In addition, because these paddy fields depend on water supply from tributary basins and lie close to rivers, they are exposed to flood, waterlogging, and debris-flow risk, which reduces their suitability in development-oriented terms.

It is also worth noting that the Yuehe Basin in Ankang forms an east–west belt of relatively high suitability along the Hanjiang main stem. This is related to the local land-use pattern, where dry cropland and water bodies are interwoven, allowing vegetation to adapt well to drier conditions while still benefiting from rich water resources. Large areas of cropland vegetation and long-term human management have also enhanced resistance to natural hazards. In the densely mountainous Qinling area, some low-elevation valley zones still show relatively high suitability in clustered patches, partly because they include ecologically favorable meadow areas near the Baohe Basin. Abundant water supply, adequate rainfall, and well-drained soils there support plant growth and reproduction and therefore raise suitability scores. Meanwhile, the surrounding high mountains act as natural barriers that help stabilize the local ecological environment, although attention should still be paid to soil erosion and landslide prevention in the surrounding mountain areas. The Danjiang Basin and the Jinqianbao Basin in the northeast also show generally high suitability because of lower elevation, abundant water resources, and dense cropland vegetation.

Areas classified as unsuitable are similar in environmental constraints to the least suitable areas but are distributed more extensively across the northern Qinling Mountains and the southern Daba Mountains. Constrained by high elevation and dominance of coniferous and broadleaved forests, these areas require targeted mountain ecological protection measures. In addition, some unsuitable areas south of the Hanjiang main stem form northwest–southeast belts, which may be related to slope and aspect. These areas include large and steep northeast-, east-, and north-facing slopes and are therefore prone to landslides and erosion, deserving special attention from environmental protection authorities.

Because ecological restoration and transformation are more difficult in high-altitude areas, the lower-altitude suitable zones should be regarded as the primary targets for ecological protection. These areas occupy a relatively large share of the region, and ecological protection there is likely to generate comparatively high returns.

Table 7. Area of each suitability class

Suitability class	Area (km²)
S1	4593
S2	19205
S3	21719
S4	14547
S5	5633
Total	65697

4.2.3. Analysis of Influencing Factors

In recent years, the upper Hanjiang River Basin has faced increasingly prominent ecological challenges. Multiple pressures, including intensive human activities, irrational land use, water pollution, biodiversity loss, and frequent natural hazards, have weakened ecosystem stability and posed growing constraints on sustainable regional development.

First, biodiversity loss is one of the most serious ecological problems in the upper Hanjiang River. High-altitude mountain areas such as the Qinling and Daba ranges are rich in biodiversity and contain many rare plants and animals. However, human disturbance and habitat destruction have caused habitat loss and fragmentation for many endangered species, increasing extinction risk, weakening the regional gene pool, and reducing the stability and resilience of ecosystems. Environmental monitoring and assessment are also insufficient. The lack of a sound monitoring network and a robust scientific evaluation system hinders the timely detection and treatment of environmental problems and makes it difficult for government departments to formulate effective protection policies.

Second, water-resource management and protection need to be strengthened. As the main regional water source, the Hanjiang River has been severely affected by industrial and agricultural pollution. Water pollution threatens both local ecosystems and human health. In addition, overexploitation and irrational use of water resources have intensified scarcity and put sustainable development at risk. With accelerating urbanization, population growth and economic development continue to raise demand for water beyond the renewable supply capacity, while climate change further alters precipitation patterns and the hydrological cycle. Water degradation and scarcity restrict biodiversity, damage ecological balance, and also create serious challenges for drinking water supply and agricultural production.

Third, the region suffers from pronounced problems of irrational agriculture and land use. Unsuitable agricultural and land-use practices have intensified soil erosion and land degradation in high-altitude areas, while excessive reclamation and overuse of farmland have damaged soils and threatened agricultural productivity. At the same time, rapid urbanization, industrial expansion, and urban sprawl have fragmented ecosystems and destroyed habitats for wildlife.

In summary, the upper Hanjiang River Basin remains under substantial ecological pressure. Irrational land use, insufficient water-resource management, biodiversity loss, and inadequate environmental monitoring and assessment constitute the principal constraints on regional ecological security. At the same time, clarifying the structure and spatial expression of these problems provides an empirical basis for the formulation of more targeted protection measures.

4.3. Ecological Protection Strategies

4.3.1. Biodiversity Conservation and Ecological Restoration

To mitigate biodiversity loss, a coordinated set of measures is required to protect and restore biodiversity in the upper Hanjiang River Basin, thereby maintaining ecological balance and ecosystem resilience.

Key measures include:

(1) Establishing a network of nature reserves, including core protected areas and wildlife reserves, to protect rare species and important habitats while covering different ecosystem types and ensuring representativeness and integrity.

(2) Restoring habitats through measures such as reforestation, wetland restoration, and water purification so as to provide suitable conditions for survival and reproduction and to support the recovery of wild species.

(3) Strengthening supervision and law enforcement to curb illegal hunting, illegal logging, and the theft and trade of wild plants and animals and thereby protect endangered species.

(4) Promoting environmental education and public awareness through outreach, education, and public participation so as to enhance social support for biodiversity conservation.

(5) Enhancing scientific research and monitoring, collecting and analyzing biodiversity data, and evaluating ecological health and biodiversity trends to support evidence-based policy adjustment.

4.3.2. Water-Resource Protection and Sustainable Use

Given the strategic importance of regional water security, a comprehensive set of measures is required to protect and restore water resources in the upper Hanjiang River Basin and to ensure their sustainable use. Such measures are essential for securing water supply, maintaining water quality, and supporting long-term ecological stability.

Key measures include:

(1) Strengthening supervision and law enforcement against illegal discharge and pollution so as to safeguard water quality and sustainable use, supported by stricter penalties for violations.

(2) Formulating scientific and reasonable water-resource management policies that balance ecological needs with socio-economic development and promote efficient use while avoiding overexploitation and waste.

(3) Implementing integrated water-resource management by coordinating water planning, development, use, and protection and by strengthening monitoring and assessment in order to detect and solve problems in a timely manner.

(4) Promoting the restoration and protection of aquatic ecosystems through wetland conservation and restoration and by protecting rivers, lakes, and water-source areas so as to improve aquatic biodiversity and ecological function.

(5) Advocating water saving and circular use by promoting water-saving technologies and devices, improving efficiency, and reducing waste and pollution.

4.3.3. Rational Land-Use Planning and Sustainable Agricultural Development

To address irrational land use, land-use planning should be strengthened to clarify functional zoning, protect ecologically sensitive areas, promote sustainable agricultural use, and prevent excessive development and exploitation of land resources. At the same time, the pace and form of urbanization should be better regulated so that ecological protection and urban development can be more effectively coordinated.

Through rational land-use planning, the following objectives can be achieved:

(1) Formulating clear regional plans that distinguish farmland, ecological protection zones, and urban construction areas and establish appropriate boundaries and restrictions to prevent excessive land development.

(2) Promoting sustainable agriculture, including organic and ecological agriculture, reducing reliance on fertilizers and pesticides, protecting soil quality and ecosystem health, and improving irrigation efficiency through stronger farmland water-conservancy facilities.

(3) Strengthening the regulation of urbanization and promoting the coordinated development of ecological protection and urban construction through green buildings, eco-cities, rational urban land planning, and protection of natural landscapes and ecological corridors.

(4) Strengthening supervision and law enforcement against illegal land development and non-compliant agricultural activities while establishing a sound monitoring system to detect and handle violations in a timely manner.

(5) Building a network of protected areas and wildlife reserves to safeguard rare species and key habitats and to strengthen biodiversity conservation and habitat restoration.

Overall, ecological protection in the upper Hanjiang River Basin requires the joint participation of government, enterprises, social organizations, and the public. Only through integrated strategies covering land-use planning, water-resource management, biodiversity conservation, and environmental monitoring can a virtuous cycle of ecological protection and sustainable development be achieved. Sustained efforts in these areas will improve regional ecological quality and provide a useful reference for ecological governance in similar river-basin regions.

5. CONCLUSIONS

This study introduced the concept of ecological suitability, selected the upper Hanjiang River Basin as the study area, and employed the Analytic Hierarchy Process to assess regional ecological suitability. A hierarchical indicator system incorporating both natural and socio-economic factors was constructed, indicator weights were determined, and the consistency of the judgment matrix was tested, thereby enabling a quantitative assessment based on expert knowledge and scoring.

The results indicate that the upper Hanjiang River Basin generally exhibits a favorable level of ecological suitability, with areas rated suitable or above accounting for a large share of the total area. Nevertheless, several ecologically fragile zones remain. Areas above 1,200 m show relatively low suitability, whereas low-altitude zones and river valleys along the Hanjiang main stem are generally more suitable. The spatial pattern is highly regular, while some local areas, including the Baohe Basin, Danjiang Basin, and Hanzhong Basin, display distinctive spatial concentrations. Low-elevation meadow valleys adjacent to the Baohe Basin show comparatively high suitability because of favorable interactions with surrounding ecological conditions. By contrast, several strip-like low-suitability zones along the northern flank of the Daba Mountains indicate high risks of water and wind erosion and therefore merit priority conservation attention. The Hanzhong Basin contains soft paddy soils that are less suitable for intensive construction and human activities, which partly explains why it does not fall entirely within the most suitable class.

Future research should further refine ecological suitability assessment methods and develop more systematic evaluation frameworks so as to provide more accurate and comprehensive support for ecological protection. Closer collaboration with local departments and institutions in the upper Hanjiang River Basin will also be necessary to strengthen the practical application of assessment results. Continued efforts in these areas are expected to improve the regional ecological environment and provide a more robust basis for decision-making and subsequent research.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the guidance of the supervisor and the academic support provided by the School of Tourism, Xi'an International Studies University.

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