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ORIGINAL PAPER

Comprehensive evaluation and indicator system of land desertification in the Heihe River Basin

Feng Qi · Liu Wei · Xi Haiyang

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Abstract Two landscape evaluation approaches, an integrated model and an ecological analysis method, based on landscape elements and environmental quality, respectively, were used to describe land desertification in the Heihe River Basin of northwestern China, by evaluating the current state of the local ecosystems and environment. Based on national water-quality criteria and fuzzy cluster analysis methods, surface water quality was divided into 5 grades with corresponding evaluation scores (evaluation rating threshold of water pollution), while groundwater quality was divided into 5 grades based on salinity and solute chemistry. For grassland ecosystems, grass yield (biomass) and types were the main indicators used. The soil component was described according to factors including its nutrient content, thickness, texture and degree of desertification, for a total of 11 evaluation indicators. Total vegetation cover is one of the 5 indicators chosen to describe the plant ecosystem. Based on conditions currently prevailing in the study region, evaluation factors such as total output value of agricultural, industrial, forestry and animal husbandry activities, the ratio of irrigation area to farmland area, the mean output return per unit area farmland, the level of education and per capital income were selected among others to characterize the social and economic situation. In total, 32 typical environment evaluation factors were selected, classifying land desertification in the region into four zones.

F. Qi (✉) · X. Haiyang
Alashan Desert Eco-hydrology Experimental Research Station, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, No. 260 West Duong Gang Road, Lanzhou 730000, China
e-mail: qifeng@lzb.ac.cn

F. Qi
Department of Geography, Shaanxi Normal University, Xi'an 710062, Shaanxi, China

F. Qi
Gansu Hydrology and Water Resources Engineering Center, No. 260 West Duong Gang Road, Lanzhou 730000, China

L. Wei
Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, No. 260 West Duong Gang Road, Lanzhou 730000, China
e-mail: Weiliu@lzb.ac.cn

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1 Introduction

The Heihe River Basin is one of three large inland river basins in the Hexi Corridor region of northwestern China (Fig. 1). At present, the main problems affecting land use and occurring in the region's oases are windblown sand, drought and soil salinization. The population's irrational development and use of water, land and biotic resources are among the main reasons for land degradation in the region. This problem has attracted widespread attention from public organizations and scholars (Ma et al. 1998; Dong 1990; Sun 2000; Ding and Gao 2001; Ding and Cui 2001). However, water shortage is the most important factor driving environmental degradation in the inland Heihe River Basin, where it seems the lifeblood of oases and human society. This problem has attracted widespread attention from public organizations and scholars. The ever-increasing demand for water in the upper and middle reaches of the Heihe River Basin has led to a sharp deterioration of downstream ecosystems and a wide range of environmental issues: drying up of lakes within the Ejin oasis, water-quality deterioration, increase in ground water salinity, and soil salinization leading to the death of large areas of riparian forest and shrubs (Gao and Li 1991; Wang and Cheng 1998; Gong et al. 2002). Because of economic expansion and population increases in the whole basin, land-use-related ecological degradation has been very intensive as to constitute a severe threat to regional sustainable development (Cao and Feng 2012; Qin et al. 2002). Many researchers have focused on desertification processes or oasis landscape changes in the Heihe River Basin (Luo et al. 2005; Lu et al. 2003; Jiao et al. 2003). Land-use change and its environmental impacts in the Heihe River Basin have received some attention (Meng et al. 2003; Luo et al. 2005; Qi and Luo 2005); however, a little discussion was paying attention to the indicator systems for the Heihe River Basin. In view of the current situation, remote sensing and field data were used to study the main factors having an impact on the degradation of ecosystems in the Heihe River Basin(Gao and Li 1991; Wang et al. 2001; Wang and Cheng 1999; Wang et al. 2003), to establish the ecosystem degradation indicators and criteria whereby to judge the severity of ecosystem degradation, and provide a theoretical basis for the rational and sustainable use of water and land resources, the control of land desertification, and the restoration and reclamation of desertified lands in the region.

Water, land and biotic resources in the arid zone are closely tied to the region's very limited water resources and its sharing among upper–middle–lower reaches. The excessive use of water resources in the upper and middle reaches of the Heihe River has led to a virtual plundering of the downstream basin's water resources. Clearly, the spatially unbalanced allocation of water resources must be rectified as water resources in the mid-downstream region become increasingly scarce. In the presence of a relative abundance of land resources, the importance of water resources is also manifested by the fact that its efficiency of use depends on the volume of available water and that the carrying capacity of water resources for given land resources is very limited. In addition, the fertility of most soils, lost under desert conditions, is difficult to restore, making these soils prone to sandy desertification. The limited biotic resources in the oases and desert are manifested in the sparse biodiversity, low biomass, simple nutrient-energy structure and food chain, poor self-adjustment and self-restoration capacity, which contribute to the changes caused by human activities and natural fluctuations in the environment to easily upset the existing ecological balance.

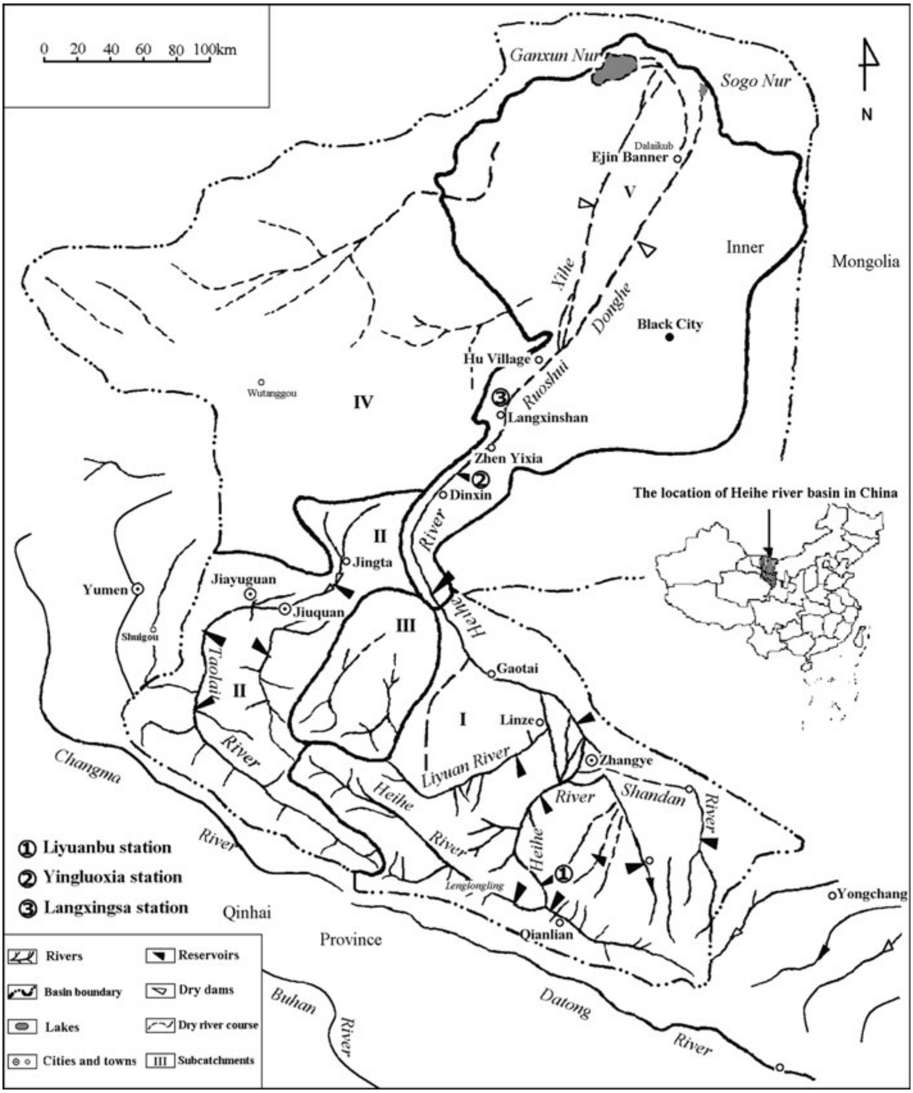

Fig. 1 Sketch of the Heihe River Basin

The environment is a resource and yet is larger than individual resources, in the sense that resources such as natural materials are dependent on the environment and also a component of the environment. The environment is the basis for the existence and regeneration of resources and, therefore, a resource on which mankind must rely for its existence and development.

2 Methods of land desertification evaluation and mathematical model

The methodology used to obtain and evaluate information on the status of land type in the basin was based on Landsat TM images of the year 2003 and field investigations.

The primary information for this study was obtained from the false color composites of the whole basin. These composites were made up of bands 4, 3 and 2 (R, G, B) of Lansat TM (Thematic Map) imagery from July 2003, and the detailed explanation is in the paper (Qi and Cai 2007). The degraded land map was compiled following the recommendations of Chen and Qu (1992) and Xiao (1999). Based on the reference of previous evaluation indicators (Chen and Qu 1992; Del et al. 1998), accompanied with the physical and social conditions of the Heihe River Basin, the physiographic parameters of degraded land in this study were soil characteristics, vegetation cover, grass yield, area of shifting sands and sand dunes, and slope gradient.

High correlation scores indicate that the corresponding landscape indices provide information about landscape patterns with particular importance to an ecological process. This approach seems to have become common practice, supported by the increasing availability of remotely sensed landscape data, Geographic Information Systems and computer programs to calculate landscape indices (Tischendorf 2001). Two methods of evaluating the elements and quality of the environment making up the region under study, an integrated model and a landscape ecology analysis, were used to estimate the severity of land desertification (Fortlage 1990; He et al. 2002). The distribution of land desertification and various environmental factors (environmental impact on factors which include water environment, soil ecosystem, forest ecosystem, grassland ecosystem, and socioeconomic environmental indicators) contributing to it was comprehensively analyzed. The integrated model approach effectively reflects the contribution of various factors which play a decisive role in the basin, as well as how ecosystem elements have an impact on a region's overall land quality. This model can also adopt and integrate expert opinions into the evaluation of non-quantitative factors (Howarth and Wickware 1981; Turner 1997). Land desertification evaluation indicators should also be representative of the whole basin, their basic purpose being to numerically represent a region's integrated ecosystem status. A landscape ecology approach can provide a quantitative description of the overall ecosystem structure and medium-scale spatial pattern (Wang et al. 1999).

2.1 Integrated model method

For that concerning the integrated model method, the establishment of judgment matrix H and its general mathematical form is:

$$H = \overset{n}{\underset{i=1}{V}} (s_i \Lambda x_i) \tag{1}$$

where x_i is the evaluation vector, and s_i is its weight of the ith factor (or subsystem). The equation can include one of the two operations, V: (1) a summation multiplying operation ($V = \Sigma, \times$) yielding a linear integrated model (Eq. 2), or (2) a continuous multiplying exponential operation ($V, \otimes E$) yielding a nonlinear integrated model (Eq. 3)

$$H = (a_1, a_2, \ldots a_h) = \begin{vmatrix} S_1 \\ S_2 \\ \cdots \\ S_h \end{vmatrix}^T \cdot \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1h} \\ a_{21} & a_{22} & \cdots & a_{2h} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nh} \end{bmatrix} \tag{2}$$

$$H = (a_1, a_2, \ldots a_h) = \begin{vmatrix} S_1 \\ S_2 \\ \cdots \\ S_h \end{vmatrix}^T \cdot \begin{bmatrix} \ln a_{11} & \ln a_{12} & \cdots & \ln a_{1h} \\ \ln a_{21} & \ln a_{22} & \cdots & \ln a_{2h} \\ \cdots & \cdots & \cdots & \cdots \\ \ln a_{n1} & \ln a_{n2} & \cdots & \ln a_{nh} \end{bmatrix} \otimes E \tag{3}$$

where the operational sign $\otimes E$ is defined as: $(a_1, a_2, a_3, \ldots ah) \otimes E = \left(e^{a1}, e^{a2}, \ldots e^{ah}\right)$; a_i is a component of H, and a_{ij} is a component of x_i, and the T is the transposed matrix.

The AHP (analytical hierarchy process) method was used to establish the factor weights, Si, describing the hierarchical structure of the ecosystem's quality evaluation and allowing pairwise comparison of elements in different layers (Picketl and Cadanasso 1995; Wang and Xu 1989; Dyer 1990). Using the square root method to calculate the normalized eigenvectors and eigenvalues of H until the consistency test met, calculation feature vector is the sort of factor weights in the relative weights in the AHP structural layer.

The structural layers can be used to judge the matrix, and this judgment can be quantified according to a ratio scale established through the subjective opinion of decision makers, generally a group of experts coming to a consensus regarding the ratio. Once the characteristic value of the matrix has been assigned, the weight values of various factors of the single ordination layer can be determined. The combined weight values of the factors of the upper layer are then used to obtain the combined weight values of the factors of the lower layer. Thus, through a layer-by-layer calculation, the total ordination weight value of the whole hierarchical structure can be obtained and the weight value is taken as the value of s_i. The specific calculation processes are as follows:

Arbitrarily taking a normalized initial vector W^o of the same order as the judgment matrix B, one finds where $\vec{W}^{k+1} = \beta W^k$, $k = 0, 1, 2, \ldots n$. If one let $\beta = \sum_{i=1}^{n} \vec{W}^{k+1}$, then one can calculate $W^{k+1} = \frac{1}{\beta}\vec{W}^{k+1}$, for the probability-given accuracy ε, when $\left|\vec{W}^{k+1} - \vec{W}^{k}\right|$ is valid for i = 1, 2, …, then $W = W^{k+1}$ is the required characteristic vector. The maximum characteristic root of vector $\lambda_{\max}$ is

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{\vec{W}^{k+1}}{\vec{W}^{k}} \tag{4}$$

W can be solved by using the $\beta W = \lambda_{\max}$ formula. After W being normalized, we can obtain a value of the relative importance of the corresponding element of the same layer to a factor in the upper layer, thus allowing consistency, CR, to be tested. The CR can be calculated as:

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

where $\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1}$ represents the consistency index, and RI represents the mean random consistency index drawn from the data sheet. When the random consistency ratio, *CR,* is less than 0.10, the above ordination is believed to have satisfactory consistency; otherwise, one needs to check and judge the element value of the matrix.

2.2 Analytical method of landscape spatial pattern assessment

The Heihe River Basin was divided into landscape unit patches according to their different ecological structures. Through the quantitative analysis of the landscape's spatial patterns

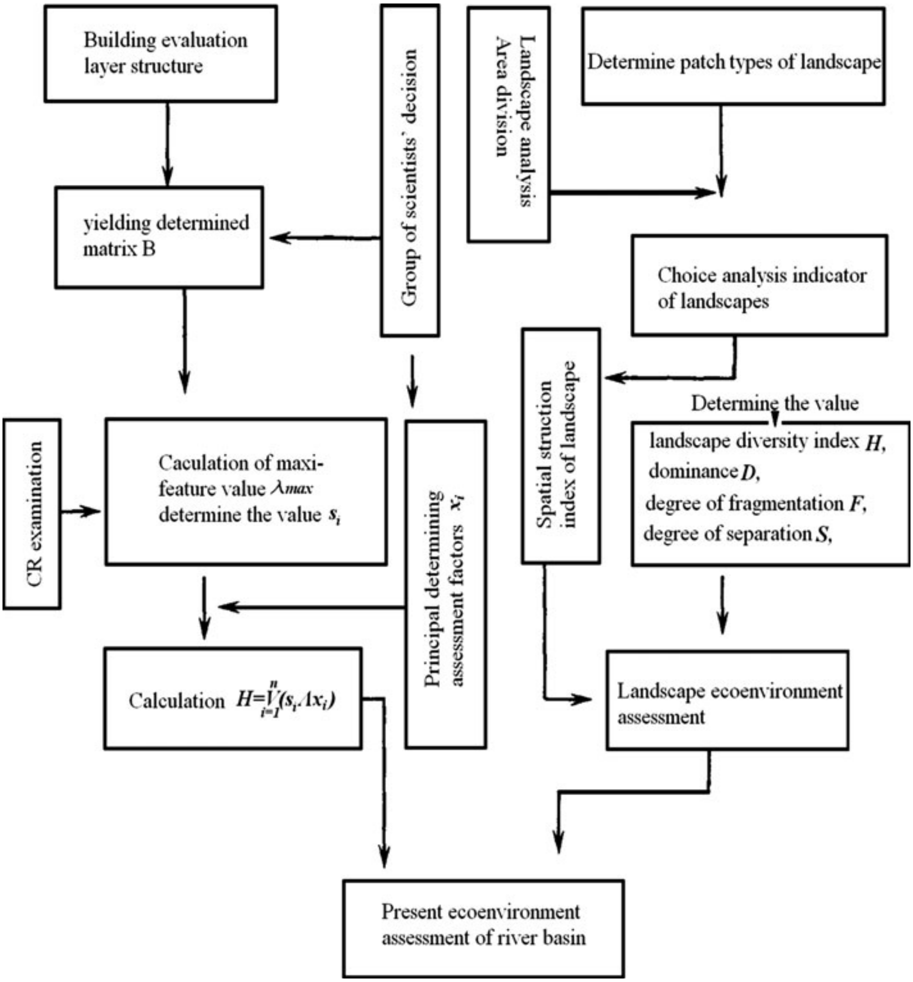

Fig. 2 The weight taxis hierarchy of AHP method

and heterogeneity, regional environmental regimes can be drawn out and viewed from a macroscopic perspective (Fig. 2). The spatial theory of ecosystems recognizes that their spatial patterns determine the components and distribution of biotic resources in the geographical environment, control various ecological processes and are closely tied to ecosystems' ability to resist disturbance resistance and remain stable. The assemblage of ecosystems in a region is termed the ecological landscape; landscape spatial patterns and spatial elements, especially the barrier passage and the assemblage of high-heterogeneity regions, contribute to the landscape heterogeneity (Picketl and Cadanasso 1995; Gong et al. 2002). The quantitative index of the landscape spatial pattern can be expressed according to patch area (A), patch perimeter (P), patch density (G), patch shape and patch separation. Patch area can be expressed as total patch area, A_{tot}, or as a mean for patches of a specific type, A_{avg}, while the mean patch perimeter is P_{avg}. Patch density can represent the total number of patches of a given type per unit area, G_A, the ratio of the number of a specific patch type to the total patch number, $G_{n/\mathrm{tot}}$, and the ratio of one type of patch's area to the total area, $G_{A/A\mathrm{tot}}$ (William et al. 1994). Patch shape, P, is generally expressed through its fractal dimension D, given by:

$$P = R\left(A^{D/2}\right) \tag{6}$$

Function (6) is used to measure the degree of complexity of the patches, where R is a constant, and P is the perimeter of the patch; when the patch is square, then, as $P = 4(A^{D/2})$, $D = [2\log(P/4)]/\log(A)$.

The degree of landscape separation is given as:

$$S_K = D_K/S_K \quad K = 1,\ 2,\ 3, \ldots n \tag{7}$$

where K is the landscape type, and

$$D_K = \frac{1}{2}\sqrt{\frac{n_K}{A_K}} \tag{8}$$

where n_K is the patch number of the Kth landscape type, and A_K is the area of the Kth landscape type. B_K is the area index of the Kth landscape type, $B_K = A_K/A_{\mathrm{tot}}$.

The index of landscape spatial heterogeneity generally includes several aspects:

Landscape diversity and evenness: According to the principle of information theory, the landscape diversity index, H, is given as:

$$H = -\sum_{i=1}^{n}\left(\frac{A_i}{A_{\mathrm{tot}}}\right)\cdot\log\left(\frac{A_i}{A_{\mathrm{tot}}}\right) \tag{9}$$

where A_i is the area of the ith patch.

The evenness, E, is then defined as:

$$E = (H/H_{\max}) \times 100\,\% \tag{10}$$

where $H_{\max}$ is the maximum diversity index and equals $\log(n)$.

Landscape dominance, D, is used to measure the degree of control one or more landscape types have over the overall landscape structure:

$$D = H_{\max} + \sum_{i=1}^{n}\left(\frac{A_i}{A_{\mathrm{tot}}}\right)\cdot\log\left(\frac{A_i}{A_{\mathrm{tot}}}\right) \tag{11}$$

If the summation $= -H$, then D is simply $= H_{\max} - H$

It can also be expressed as the relative dominance:

$$RD = 100 - (D/D_{\max}) \times 100\,\% \tag{12}$$

The degree of landscape fragmentation, F, is used to express how fragmented the landscape is.

$$F = \sum n_i/A \quad i = 1,\ 2,\ 3, \ldots n \tag{13}$$

Landscape richness is used to express the degree of abundance of a given landscape type in a larger landscape and can be expressed by the mean richness T_a and relative richness T_r:

$$T_a = T/S \quad T_r = T/T_{\max} \times 100\,\% \tag{14}$$

where T is the frequency of the particular landscape type in the larger landscape, and $T_{\max}$ is the largest possible type frequency.

The AHP method was used to evaluate the landscape indices of desertified lands in the Heihe River Basin. Their results need cross-checked and considered from different theoretical and experiential angles, so as to give an objective evaluation of the overall status of the environment.

Ecosystem stability problems caused by land desertification and degradation are the result of ecological disturbances arising from the influence of excessive crop production, forestry and animal husbandry (He et al. 2001). Therefore, a quantitative or qualitative evaluation of ecosystems' capacity to adapt along with knowledge of their degradation/regeneration processes is needed to establish a risk indicator (Table 1). A cluster analysis method of the environment's carrying capacity should be based on determining the extent of irrigation based on available water resources and the maintenance of a "water-land balance." Shifts in water resource allocation drive both changes in land desertification and agricultural land development. Over the years, the development pattern in the middle reaches of the Heihe River Basin has been one dominated by the construction of man-made oases, while the downstream portion of the basin has been dominated by livestock breeding.

Based on the preceding analysis and evaluation of the status of the environment, a number of evaluation method were given and classification indicators were established (Table 2). In terms of national water-quality standards, a fuzzy cluster analysis method was used to divide surface water quality into 5 grades with corresponding evaluation scores. Ground water quality was classified according to two indicators: salinity and chemical type of groundwater. According to domestic water and irrigation water standards and considering the present situation in the study region, groundwater quality was divided into 5 grades (Fig. 1). BOD and COD in the paper mean biochemical oxygen demand and chemical oxygen demand. For forest ecosystems, four evaluation indicators were selected, that is, the ratio of the area of forested land to the total land area, forest cover, stocking volume of wood, and the ratio of mid-young forest. For grassland ecosystems, five evaluation indicators were selected, that is, the ratio of the area of grasslands to the total land area, a quality grading, the livestock density, grass biomass yield and grass cover. The soil environment was described in terms of soil nutrition and degree of desertification, with a total of 11 evaluation indicators, as suggested by Bai and Zhao (2001). Among indicators regarding vegetation ecosystem, there is the surface cover, classified into 5 grades of cover. Based on current conditions in the study region, 10 socioeconomic indicators were selected, that is, total value of agricultural output, total value of industrial output, values of forestry and animal husbandry output, ratio of irrigated farmland area to total farmland area, mean output return per unit area (including mean return in RMB of m^3 of water and the output value of water consumption), industrial sewage volume, infective ratio of local disease, level of education popularization (% having completed a junior school level of education) and per capita income (Table 2). In total, 32 environmental evaluation factors were selected, each with an evaluation indicator system.

3 Comprehensive evaluations of environmental quality zones within the Heihe River Basin

Environmental zoning of the basin land desertification degree served to define the systems targeted. Subzones were identified according to the principles that: (1) A single subzone should be geomorphologically and climatically uniform, showing only small macroscopic and spatial differences in ecological characteristics, particularly with respect to vegetation

Table 1 Landscape indices for eco-environmental system in the Heihe River Basin of northwestern China

Main ecological processes		Ecological assessment indicators
Negative ecological effects	Positive ecological effects	
Lakes dried up, river channels shrank; vegetation in plains and riparian forest/shrubland area decreased; grasslands were degraded, species diversity was destroyed; farmlands became salinized, land desertification processes accelerated; frequency of dust storms increased Predatory and destructive land resource development activities, such as over reclamation, overgrazing, overcutting, broad sowing but meager harvest and extensive management causes land desertification	Rivers and water resources are managed and distributed in an environmentally friendly manner; farmland, grassland and river protection systems are constructed; desert culture is developed; desert oasis reserves are established A newly emerging desert culture (green industry) is developing to use desert environment resources (solar energy, wind energy, water resources and land resources), to protect the environment and to readjust the traditional industrial structure	River annual discharge; groundwater table, percentages of sand-buried and salinized farmland areas; vegetation cover, grassland area and livestock density; Water use efficiency indicators: unit water resource output value Grassland species and community dominance indicator: important value of species Grassland soil improvement effect indicator: soil capillary porosity, land cover, increased organic matter, total N, available P contents Light energy use efficiency indicator: biomass and heat value Farming–grazing region protective forest indicator: the protective range of forest net system, decreased wind velocity and sand transport rate; humidity, temperature, surface and ground temperature adjustment effect of microclimate

and soil type, (2) a single subzone's land-use patterns, water resource allocation and water usage should be roughly the same (i.e., farming and grazing regions, or swampy lowland/spring zones and hyperarid desert zones would not be included in the same subzone) and differences in the condition of the main resources should be small, (3) two areas facing the same environmental problems (e.g., land desertification and salinization) should be in the same subzone unless the spatial distribution features of the main ecological problems are radically different, and (4) the basin's current economic development plan should take into account the key environmental protection sites. This requires that agricultural production and the direction of further development in the zone should be similar. According to these principles the study basin was divided into five environmental evaluation zones.

1. Southern piedmont of the Qilian Mountains and the upper alluvial fan of the Heihe River, including Dahuang Mountain and the cool, oil-grain producing region, a product of economic development planning. The Zhangye region has about 20 villages and a total land area of 3,835 km^2, of which forest and cultivated land accounted for 1,269 km^2. The natural forest (159 km^2) is mainly concentrated in the Dahuang Mountain region. Along with planted forests, the total forested land area is 255 km^2. Annual precipitation varies between 149.1 mm and 328.2 mm and gradually decreases from the south to the north. Annual mean air temperature ranges from warm to cool.

Table 2 Identification factors for the degree of land degradation

Evaluation factors	Classification and quantification of indicators				Methods for evaluation	
Water environment						
Water body COD	Grade 1	Grade 2	Grade 3	Grade 4	Below Grade5	Calorimetric method which has sample digested by XJ- I COD
Water body BOD	Grade 1	Grade 2	Grade 3	Grade 4	Below Grade5	
Sewage discharge(10^4 T) per year	<1,000	1,000–1,500	1,500–2,000	2,000–2,500	>2,500	
River channel shrinkage increase ratio (%)	>30	30–20	20–10	10–5	<5	Investigation by TM image
Lake shrinkage ratio (%)	>40	40–30	30–20	20–10	<10	Investigation by TM image
Forest ecosystem						
Forest land area ratio (%)	>90	90–80	80–65	65–30	<30	Investigation by TM image
Forest cover (%)	>7.0	7.0–6.0	6.0–5.0	5.0–3.0	<3.0	Field investigation
Stocking volume of wood (10^4 m^3)	>30	30–20	20–10	10–5	<5	Field investigation
Mid-young forest ratio (%)	>60	60–45	45–25	25–15	<15	Field investigation
Grassland ecosystem						
Grassland area ratio (%)	>60	60–45	45–25	25–10	<10	Field investigation
Grass grade	1–2	3–4	5–6	7–8	>8	Field investigation
Live stocking rate (10^4 sheep units per hm^2)	>6.0	6.0–4.0	4.5–2.0	2.0–1.5	<1.5	Field investigation
Grass yield (kg hm^{-2})	>1,000	1,000–700	700–400	400–100	<100	Sample plot analysis
Grass cover (%)	>70	70–30	30–20	20–10	<10	Sample plot analysis
Socioeconomic environmental indicators						
Total agricultural output (10^8 yuan)	>5	5–3	3–2	2–1	<1	Sample plot analysis
Guaranteed irrigation ratio (%)	>90	90–70	70–50	50–30	–	Sample plot analysis
Mean return (in RMB) per m^3 water	>1.5	1.5–1.0	1.0–0.7	0.7–0.4	<0.4	Sample plot analysis with market
Unit area output efficiency (15 × Yuan/hm^2)	>600	600–500	500–350	350–200	<200	Sample plot analysis with market
Total industrial output value (10^8 yuan)	>25	25–15	15–10	10–5	<5	Sample plot analysis with market

Table 2 continued

Evaluation factors	Classification and quantification of indicators				Methods for evaluation	
Water consumption output per 10^4 yuan output value	<200	200–260	260–300	300–350	>350	Evaluation
Forest output value (10^6 yuan)	>10	5–10	2–5	0.8–2	<0.8	Sample plot analysis with market
Animal husbandry output value (10^6 yuan)	>200	200–150	150–100	100–50	<50	Sample plot analysis with market
Education popularization ratio (%)	>90	90–80	80–60	60–50	<50	Strict analysis
Per capita income (10^3 yuan yr^{-1} per adult)	>5	5–4	4.0–3.0	3.0–1.5	<1.5	Strict analysis
Effective soil layer thickness (m)	>1.2	1.2–0.9	0.9–0.6	0.6–0.3	<0.3	Field analysis
Soil texture	Clay	Silt	Coarse silt	Sandy	Coarse sandy	Mechanical analyses
Organic matter content (%)	>4	4–2	2–1	1–0.6	<0.6	Oil bath-heated $K_2Cr_2O_7$ volumetric method
Soil ecosystem						
Total N content (%)	>0.2	0.2–0.15	0.1–0.15	0.06–0.1	<0.06	Se powder-$CuSO_4$–H_2SO_4 method using a KDN-2CAzotometer
Soil desertification area ratio (%)	<1.0	1.0–10.0	10.0–20.0	20.0–30.0	>30.0	Investigation by TM image
Potential soil desertification area ratio (%)	<1.0	1.0–10.0	10.0–30.0	30.0–50.0	>50.0	Investigation by TM image
Severe desertification area rate (%)	<5.0	5.0–15.0	15.0–30.0	30.0–50.0	>50.0	Investigation by TM image
Desertification area expansion rate (%)	<0.05	0.05–0.5	0.5–1.0	1.0–2.0	>2.0	Investigation by TM image

2. Downstream, the modern Ejin delta zone is dominated by terraces on both sides of the Ruoshui river and is part of the ancient channel of the alluvial plain. It includes the towns of Dalaihub, Subo Nur, Saihantailai and Gelangtu Sumu, part of a state-owned farm, woodlands and pasture land, for a total area of 38,528 km^2. This area houses the most important riparian forest and shrub meadow lands at the tail end of the lower Heihe River. Here are concentrated about two-thirds of the Ejin region's forest-grass lands and over 87 % of the region's excellent pasturelands. Due to the influence of river water, this region has relatively adequate water resources and a higher forest-grass cover than other regions. It is the socioeconomic center of the Ejin region and houses about 92 % of its population.
3. Desert and Gobi ecological zone in the northwest of the Hexi Corridor: including the region north of the Shandan River, Zhangye, Linze to the north of the Heihe irrigation district, as well as Gaotai Yanchi, Sunan Minghua and Jiant counties. The main geomorphologic units are the denuded residual hills of the Longshou, Heli and Mazong Mountains and the adjacent Gobi dunes and saline lands. The total land area is 27,080 km^2, of which farmland accounts for 268 km^2 (0.9 %). The region is characterized by large areas of desertified land where vegetation is sparse. Over 95 %, the Hexi Corridor's present-day desertification occurs in this region, and it is housed in one of the most severely degraded soil environments.
4. Desertification zone in the downstream lake basin: including Sumus, Guninai and Wentugaole counties. It covers an area of 34,193 km^2, within which natural grasslands, mainly occurring in the Guaiz and Guninai Lake basins and suffering from blown sand hazards, account for 24.9 % of the Ejin region's total land area.
5. Mazong Mountain, low-mountains and hills, and a Gobi desert zone are located in the western portion of the Ruoshui delta and cover an area of 29,740 km^2, of which natural grasslands make up 14.7 % of area. Surface wind erosion is severe, the soil layer is thin, and an arid Gobi desert landscape prevails due to the extremely dry climatic conditions.

4 Calculating the value of a comprehensive environment evaluation factor and its analysis

In order to use previously described integrated model in quantitatively evaluating environmental quality, the existing values of various environmental factors and corresponding identifying scales must be obtained (Fig. 2). The existing values of various evaluation factors and the qualitatively scaled values, X_i, were determined in terms of the monomial evaluation results presented in Table 3. Due to different zoning types evaluated, the existing values of the evaluation factors are different. For example, in Zone I, the comprehensive evaluation gave an environment evaluation factor of 4.725, while the score obtained for the environment's indicative factor was 2.034 (Table 4). Similarly, the scores for the other four evaluation zones are presented in Table 4.

The evaluation showed that environmental conditions in Zone I and Zone II were good, their evaluation scores being 7.596 (4.725 + 2.871). The main environment type in Zone II is fir trees, and its score varies between 3 and 4. Environmental conditions in Zone IV were poor, its score varying between 2 and 3. Environmental conditions in Zone V were very poor, as its score was <2.0. The evaluation results obtained by using targeted environmental factors and those obtained from the comprehensive evaluation were in good agreement and yielded similar conclusions.

Table 3 Comprehensive evaluation factors and weights for the assessment of environmental quality in the Heihe River Basin of northwest China

Evaluation factor	Coded integrated weight ratio W_d		Integrated weight, W_c, of upper-layer factor C_i	
Effective soil layer thickness (cm)	D6	0.0118	C5	0.0157
Soil texture	D7	0.0039		
Organic matter content (%)	D8	0.0344	C6	0.0458
Total N content (%)	D9	0.0114		
Soil desertification area ratio (%)	D10	0.0313	C8	0.1234
Soil potential desertification area ratio (%)	D11	0.0259		
Severe desertification area rate	D12	0.0067		
Desertification area expansion rate	D13	0.0595		
Forest land area ratio (%)	D14	0.0305	C11	0.1427
Forest cover (%)	D15	0.0149		
Stocking volume of wood (10^4 m^3)	D16	0.0067		
Mid-young forest ratio (%)	D17	0.0906		
Grassland area ratio (%)	D18	0.0445	C10	0.1436
Grass grade	D19	0.0217		
Live stocking rate (10^3 sheep unit)	D20	0.0454		
Grass yield (kg hm^{-2})	D21	0.0216		
Grass cover (%)	D22	0.0104		
Total agricultural product	D23	0.0080	C9	0.0127
Guaranteed irrigation ratio (%)	D24	0.0047		
River channel shrinkage increase ratio (%)	D1	0.0411	C1	0.056
Lake dwindled ratio (%)	D2	0.0149		
Water body BOD (mg/L)	D3	0.0498	C4	0.0907
Water body COD (mg/L)	D4	0.0098		
Sewage discharge (kg/year)	D5	0.0311		
Mean return (in RMB) per m^3 water	D31	0.0103	C12	0.0121
Unit area output efficiency (15 × Yuan/hm^2)	D32	0.0018		
Total industrial output value	D25	0.0022	C7	0.0066
Water consumption per 10^4 yuan output value	D26	0.0044		
Forest output value	D27	0.0022	C3	0.0066
Animal husbandry output value	D28	0.0044		
Education popularization ratio	D29	0.0035	C2	0.0133
Per capita income	D30	0.0098		

Table 4 Overall environment evaluation factor for different regions of the Heihe River Basin (due to above calculate from Eqs. 1–14)

Evaluation zoning	I	II	III	IV	V
Environmental factor	4.725	3.543	2.871	2.135	1.786
Environmental indicator score	2.034	2.654	2.341	1.059	0.686

Environmental indicator score means that the index from analytical method of landscape spatial pattern assessment

The AHP (analytical hierarchy process) method shows that the environmental conditions in Zones III, IV and V are poor; this is consistent with the actual situation. Zones III and IV, located in the mid-downstream basin, are suffering from most severe land desertification, and over 87 % of desertified land is concentrated in Zone III; water resource conditions are very poor, the inflow being controlled by the degree of water use in the mid-upstream region, within region runoff yield is very limited, water quality is very poor, and its salinization is continuously worsening. The desertified and salinized land area in the Jinta Yuanyangchi irrigation district is four times larger than the district's total cultivated land area. The annual rate of land desertification once reached 6.4 % and still remains at 0.5 % or more, today. Furthermore, the groundwater table in the irrigation district is lowering and its salinity is increasing at a rate of 0.35–1.7 g L^{-1} yr^{-1}. Zones III and IV are also suffering from severe degradation of their vegetation; some 650 km^2 of river bank meadow vegetation in Jinta County have suffered from sandy desertification. In the Ejin Guninai–Wentugaole Lake basin, the land area with a minimum vegetation cover of 30 % is decreasing at a mean annual rate of 5.1–7.8 %. Zone V including Mazong Mountain, low-mountain, denuded residual hills and Gobi desert region, main vegetation harbor is less than 5 %. Environmental conditions are very poor as soil development is weak to non-existent. The soil type is dominated by brown desert soil or gray-brown desert soil. Water resources are meager; therefore, this zone's environmental conditions are among the worse in the basin. Based on the environmental changes and development strategies in this zone, its poor environment can be attributed mainly to naturally poor conditions and has little relation to human activities or water resource changes. The environmental deterioration in the Zones III and IV is attributable to human activities and spatial and temporal distribution of water resources. Developmental strategies have directly led to the disappearance of residual natural oases and the destruction of mid-stream man-made oases. Hence, their influence was profound and severe in comparison with Zone IV. In this sense, Zones III and V are the environmental deterioration zones worthy of special attention.

5 Conclusions

Through a comprehensive microecological environmental evaluation of its zoning, land desertification in the Heihe River Basin was divided into the southern piedmont desert steppe and dry farming ecological Zone (I), the downstream, modern Ejin delta Zone (II), a desert and Gobi ecological zone in the northwest of the Hexi Corridor (III), a desertification zone in the downstream lake basin (IV), and the Mazong Mountain low-mountain and hill desert Zone (V). The analysis of site data using an integrated model yielded an environment evaluation factor for each zone. Zones with good, moderately good, poor and very poor environmental conditions obtained an evaluation scores of 75.0, 3–4, 2–3 and <2, respectively. Field evaluation results showed environmental conditions in Zones III, IV and V to be poor. The poor environmental conditions in Zone V (i.e., Mazong Mountain, low-mountain and denuded residual hills, and Gobi desert zone) are caused by harsh natural conditions and has little relation to human activities and water resource changes of the basin. Environmental deterioration in Zones III and IV was attributable to human activities, particularly the spatiotemporal redistribution of the basin's water resources, and poorly thought out regional development. This zone's deterioration will lead to the disappearance of its residual natural oases and the destruction of its midstream man-made oases. Hence, the influence of environmental deterioration was much more profound and severe in this zone than in the Zone V and III. In this sense, Zones III and V are the environment deterioration zones worthy of special attention.

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