Proceedings of the 4th International Conference on Environmental Geoscience and Earth Ecology
DOI: 10.54254/2753-8818/2026.34583

Grid-Scale Ecological Security Assessment of a Semi-Arid Inland River Basin Using a DPSIR-CRITIC Framework

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Abstract. Ecological security assessment is needed to identify degradation risk in arid and semi-arid inland river basins where water availability, grassland condition and human disturbance are tightly coupled. This study developed a 1 km grid-scale ecological security index for the Wulagai River Basin in northern China by integrating a DPSIR indicator system with the CRITIC objective weighting method. Twenty-three indicators covering driving force, pressure, state, impact and response dimensions were harmonized for seven benchmark years from 1990 to 2020 at five-year intervals. The results show that ecological security followed a fluctuating downward trajectory, with persistent west-low and east-high spatial differentiation. The strongest decline occurred during 1990-2005, and low-security areas remained concentrated in the western basin and around Gaobi. The state layer contributed the largest share of total weight, followed by pressure and impact indicators, indicating that vegetation condition, water-related ecosystem services and landscape fragmentation jointly shaped ecological security. The framework provides a transferable approach for long-term ecological monitoring and restoration-oriented management in data-limited grassland inland river basins.

Keywords: ecological security, DPSIR model, CRITIC method, Wulagai River Basin, arid and semi-arid grassland

1. Introduction

Ecological security refers to the ability of an ecosystem to maintain structural integrity, functional stability and the sustained provision of services under natural disturbance and human pressure. It has become an important concept for regional sustainability assessment because ecological degradation, land-use change, hydrological alteration and socioeconomic pressure usually interact across both administrative and biophysical boundaries [1]. In arid and semi-arid inland river basins, this issue is particularly prominent because vegetation growth, wetland persistence and grassland productivity are strongly constrained by water availability.

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Indicator-based ecological security assessment has been widely applied to grasslands, lakes, oases and inland river basins [2-4]. The DPSIR framework is useful for such assessments because it links driving forces, environmental pressures, ecosystem states, ecological impacts and policy responses in a coherent structure. However, many studies still rely on administrative units or short observation periods, which limits their ability to detect fine-scale spatial differentiation. Weighting also remains a methodological challenge, especially when indicators differ in variability and partial redundancy [5].

The Wulagai River Basin in Inner Mongolia is an important ecological barrier in northern China and a typical semi-arid grassland inland river basin. The basin supports grassland productivity, wetland ecosystems, water conservation and sand-fixation functions, but previous studies have reported wetland shrinkage, grassland degradation, landscape fragmentation and land-cover change in recent decades [6,7]. These features make the basin a representative case for testing an integrated ecological security assessment framework.

This conference paper extracts the ecological-security assessment component from a broader basin study and focuses on three questions. First, how can multi-source spatial indicators be integrated into a grid-scale DPSIR-CRITIC ecological security index? Second, what temporal and spatial pattern characterized ecological security in the Wulagai River Basin from 1990 to 2020? Third, which indicator dimensions contributed most to the basin-scale ecological security pattern?

2. Materials and methods

2.1. Study area and data sources

As shown in Fig. 1a-e, the Wulagai River Basin is located in the northeastern part of Xilingol League, Inner Mongolia, China. It has a temperate continental climate with arid and semi-arid characteristics. The terrain is generally higher in the northeast and lower in the southwest, and the landscape is dominated by grassland, unused land, wetland and river-related habitats. The river, reservoir and surrounding wetland-grassland systems form a sensitive ecological unit in which hydrological connectivity is closely related to local ecological quality.

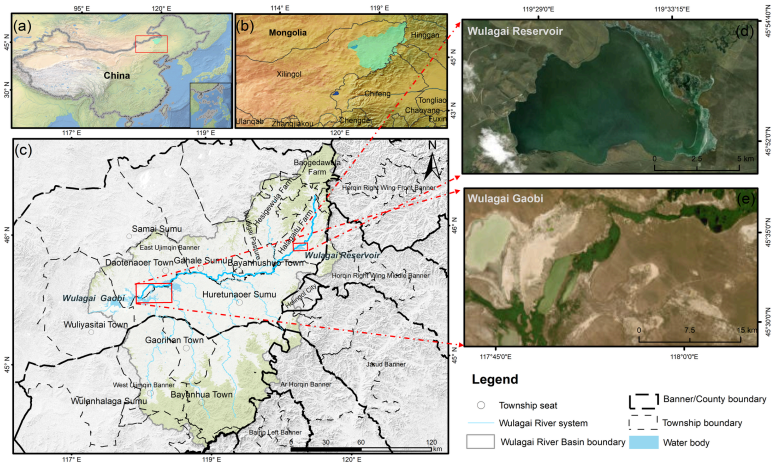


Figure 1. Geographic setting of the Wulagai River Basin. (a) Location of the study area in China. (b) Provincial context showing the position of the basin in Inner Mongolia. (c) Basin boundary, major river network, and associated water bodies in the Wulagai River Basin. (d) ESRI satellite image of the Wulagai Reservoir. (e) ESRI satellite image of the Wulagai Gaobi.

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Multi-source data were used, including remote-sensing imagery, meteorological datasets, land-cover maps, digital elevation data, socioeconomic statistics and hydrological information. All spatial layers were clipped to the Wulagai River Basin, projected to a common coordinate reference system and harmonized to a 1 km by 1 km grid. Seven benchmark years were analysed: 1990, 1995, 2000, 2005, 2010, 2015 and 2020. Static terrain variables were repeated across benchmark years, whereas climate, vegetation, water-related and socioeconomic indicators were updated according to the corresponding year or period.

2.2. DPSIR indicator system and CRITIC weighting

The indicator system was constructed according to the DPSIR framework. Driving-force indicators described climate and demographic background; pressure indicators represented human activities and environmental hazards; state indicators captured topography, vegetation condition and ecosystem-service capacity; impact indicators measured landscape fragmentation and heterogeneity; and response indicators represented socioeconomic and restoration-related responses. In total, 23 indicators were selected according to ecological relevance, data availability and consistency across the 1990-2020 study period.

All indicators were range-standardized according to their ecological direction. For positive indicators, higher standardized values indicate better ecological security. For negative indicators, higher raw values indicate greater ecological pressure and were therefore transformed inversely. The CRITIC method was used to derive objective weights because it considers both the contrast intensity of each indicator and its conflict with other indicators [8]. In simplified form, the information content of indicator j can be expressed as $C_j = s_j \Sigma (1 - r_{ij})$, where s_j is the standard deviation of indicator j and r_{ij} is the correlation coefficient between indicators i and j. The weight was calculated as $w_j = C_j / \Sigma (C_j)$. The ecological security index of grid cell i was then calculated as $ESI_i = \sum (w_j z_{ij})$, where z_{ij} is the standardized value of indicator j. Higher ESI values indicate higher ecological security. The indicator system and CRITIC weights are reported in Table 1.

Table 1. Ecological security indicator system and CRITIC weights in the Wulagai River Basin

Criterion layer	Code	Indicator	Effect	Weight (%)
Driving force (D, 10.328)	D1	Annual mean temperature	−	4.402
	D2	Annual precipitation	+	5.380
	D3	Population growth rate	−	0.546
Pressure (P, 22.932)	P1	Urban-industrial land area	−	1.022
	P2	Population density	−	0.626
	P3	Livestock density	−	12.618
	P4	Snow hazard risk	−	4.171
	P5	Drought hazard risk	+	4.495
	S1	Slope	−	4.923
	S2	Elevation	−	3.598

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Table 1. (continued)

State (S, 40.654)	S3	NDVI	+	4.169
	S4	FVC	+	7.099
	S5	NPP	+	3.887
	S6	Carbon storage	+	6.289
	S7	Soil retention	+	0.865
	S8	Water yield	+	2.843
	S9	Snowmelt	+	3.820
	S10	Water-network density index	+	3.161
Impact (I, 22.586)	I1	Patch density	−	4.685
	I2	Splitting index	−	9.981
	I3	Shannon diversity index	+	7.920
Response (R, 3.500)	R1	GDP	+	1.262
	R2	Grain-for-Green and grassland restoration area	+	2.238

Note: '+' indicates a positive indicator, for which higher values imply better ecological security, whereas '-' indicates a negative indicator, for which higher values imply lower ecological security.

3. Results

3.1. Weight structure of ecological security indicators

The CRITIC results in Table 1 indicate that the state layer had the largest contribution to the ecological security index, accounting for 40.654% of the total weight. This result suggests that ecological security in the Wulagai River Basin was primarily shaped by vegetation condition, topographic constraints and water-related ecosystem-service capacity. The pressure and impact layers also contributed substantially, with total weights of 22.932% and 22.586%, respectively. These results imply that ecological degradation risk in the basin cannot be explained by vegetation greenness alone, but reflects the combined effects of environmental pressure, ecosystem state and landscape fragmentation.

At the individual-indicator level, livestock density, landscape splitting, Shannon diversity index, fractional vegetation cover and carbon storage were among the indicators with relatively high weights. Their importance is ecologically meaningful for a grassland inland river basin. Livestock pressure is directly related to grazing intensity, landscape splitting reflects fragmentation, vegetation cover describes surface ecological condition, and carbon storage represents an integrated ecosystem-service property

3.2. Spatiotemporal evolution of ecological security

The long-term ESI results in Figure 2 show a fluctuating downward trajectory from 1990 to 2020. Spatially, the basin displayed a persistent west-low and east-high pattern. Lower ecological security

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was concentrated in the western basin and around Gaobi, while relatively higher ecological security was mainly distributed in the northeastern and southeastern areas where forest-meadow composites, wetlands and river-related habitats are more developed. This spatial contrast indicates that ecological security was strongly constrained by both hydrogeomorphic background and land-cover structure.

The distributional results show that the ESI did not shift smoothly in a single direction. Instead, the middle part of the study period showed a stronger movement toward lower ESI values, especially during 2005-2010. Although partial recovery occurred after 2010, the mean and median ESI did not return to the initial 1990 level. This pattern suggests that ecological degradation in the basin had stage-dependent characteristics and that later recovery was not sufficient to fully offset earlier decline.

From a management perspective, the results indicate that the western basin and Gaobi area should be considered priority zones for ecological security improvement. These areas showed persistent low-security conditions and are likely to be sensitive to combined hydrological stress, grassland degradation and land-cover disturbance. In contrast, the relatively high-security zones in the northeastern and southeastern basin should be managed as ecological source areas that help maintain basin-scale stability.

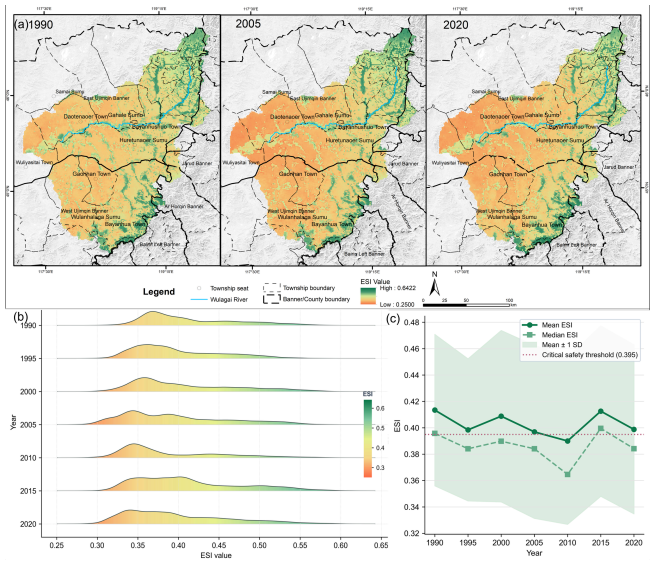


Figure 2. Spatiotemporal evolution of ecological security in the Wulagai River Basin from 1990 to 2020. (a) The spatial distribution of the continuous ecological security assessment index in 1990, 2005 and 2020 under a unified basin-wide color scale; (b) Ridgeline distribution of ESI values across years. Horizontal peak position indicates the dominant ESI range, ridge height reflects the relative density of grid cells, and the internal color gradient represents ESI magnitude under the unified basin-wide scale. (c) The temporal evolution of mean and median ESI, together with the mean ± 1 standard deviation envelope and the critical safety threshold.

3.3. Spatial clustering

The global Moran's I's results in Fig. 3a show that ESI in the Wulagai River Basin exhibited significant positive spatial autocorrelation in all study years from 1990 to 2020, indicating a stable spatial clustering pattern of ecological security. Global Moran's I reached its lowest value in 1995 (0.620) and its highest value in 2005 (0.725), and rem ained high in 2015 and 2020 at 0.717 and 0.719, respectively. Permutation-test p values were 0.002 in all years. These results indicate that

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high- and low-ESI values were spatially clustered rather than randomly distributed, and that the spatial dependence of ecological security remained strong over time.

The local spatial cluster maps for each year (Fig. 3b~h) further reveal the spatial differentiation of ESI. Overall, non-significant cells accounted for the majority of grid cells. Among significant cells, however, low-low clusters consistently exceeded high-high clusters, with their proportions remaining approximately within 17.87%-20.68% and 14.22%-16.87%, respectively, whereas low-high and high-low outliers remained close to 1%. This pattern indicates that the ESI landscape was dominated by contiguous high-value and low-value areas rather than numerous isolated outliers, and that low-ESI aggregation was a persistent component of basin ecological security.

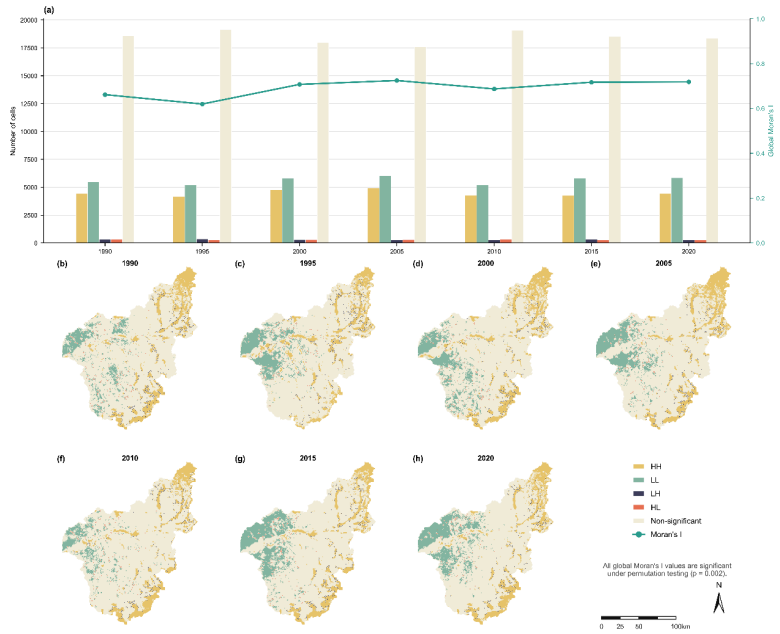


Figure 3. Integrated figure showing global spatial autocorrelation and local clustering patterns of ESI; (a) temporal changes in global Moran's I and in the numbers of different local spatial association classes from 1990 to 2020, where bars represent High-High (HH), Low-Low (LL), Low-High (LH), High-Low (HL), and non-significant cells, and the line denotes global Moran's I; (b)-(h) local clustering patterns of ESI in 1990, 1995, 2000, 2005, 2010, 2015, and 2020, respectively

4. Conclusion

This study developed a DPSIR-CRITIC ecological security assessment framework for the Wulagai River Basin at a 1 km grid scale. The results show that ecological security declined in a fluctuating manner from 1990 to 2020 and displayed persistent spatial differentiation, with lower security in the western basin and higher security in the northeastern and southeastern basin. The state, pressure and impact layers dominated the index structure, indicating that vegetation condition, water-related ecosystem services, environmental hazards and landscape fragmentation were key components of basin ecological security.

The framework is suitable for long-term ecological monitoring in arid and semi-arid inland river basins where ecological processes are closely coupled with water availability and land-use change. For ecological management, the findings suggest that restoration should not rely only on vegetation greenness or land-cover area, but should integrate grassland quality, wetland-river connectivity, landscape fragmentation and water-related ecosystem services. Future work should incorporate

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annual dynamic data, field validation and causal analysis of hydrological regulation to support adaptive basin management.

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