Postprint: Health Assessment and Early Warning of Linghe Estuary Wetland Ecosystem Based on the PSR Model

Authors: Xu Haotian, Zhou Linfei, Cheng Qian

Date: 2018-01-09T00:00:00+00:00

Abstract

The Linghekou Wetland Nature Reserve constitutes a major wetland protection area within the Liao River Basin. TM imagery from 1995, 2000, 2005, 2009, and 2014 was selected as the data source for this study. A spatial information database for the Linghekou Wetland was constructed utilizing a 3S technology platform, and landscape pattern indices for five temporal periods were acquired. Employing the PSR mathematical model, ten evaluation indices were selected across three dimensions: pressure, state, and response, to establish an ecosystem health assessment index system for the Linghekou Wetland. The Analytic Hierarchy Process (AHP) method was adopted to determine the weight indices for each indicator, the Logistic growth model was applied to conduct single-factor evaluations for each individual indicator, and finally, a comprehensive evaluation method based on the CEI was utilized to comprehensively assess the ecological health status of the wetland across the five periods. The results demonstrated that the ecosystem health indices for 1995 and 2000 were 0.642 and 0.617, respectively, indicating that the Linghekou Wetland ecosystem was in a relatively healthy state; the ecological health indices for 2005, 2009, and 2014 were 0.524, 0.436, and 0.405, respectively, placing the Linghekou Wetland ecosystem in a sub-healthy state, necessitating timely implementation of ecosystem protection measures for the study area. Finally, by selecting a prediction model based on grey system theory, the GM(1,1) ecological health prediction model for the Linghekou Wetland was constructed. Model accuracy validation was performed, revealing that the precision test grades for grey absolute correlation degree, posterior difference ratio, and small error probability were all Grade I, indicating that the prediction model accuracy was relatively ideal. Therefore, the GM(1,1) model was employed for ecosystem health prediction research on the Linghekou Wetland. The prediction results indicated that the wetland ecological health values for the next 20 years would be 0.357, 0.321, 0.291, and 0.267, respectively, with the study area in a generally unhealthy state and showing a trend

toward further deterioration. The ecological health is facing increasingly severe threats, making wetland protection and management imperative.

Full Text

Preamble

ACTA ECOLOGICA SINICA ChinaXiv Partner Journal
Vol. 37, No. 24 Dec., 2017
DOI: 10.5846/stxb201611152317

Study on Ecosystem Health Evaluation and Early Warning for Linghekou Wetlands Based on a PSR Model

XU Haotian, ZHOU Linfei*, CHENG Qian
College of Water Conservancy, Shenyang Agricultural University, Shenyang 110866, China

Abstract

The Linghekou Wetland Nature Reserve represents a major wetland protection area in the Liao River Basin. Using TM imagery from 1995, 2000, 2005, 2009, and 2014, we constructed a spatial information database for Linghekou Wetland under 3S technology support and extracted landscape pattern indices for five periods as our data source. We established a Linghekou Wetland ecosystem health evaluation index system based on the Pressure-State-Response (PSR) model.

The Analytic Hierarchy Process (AHP) method was employed to determine indicator weights. We applied the logistic growth model for single-factor evaluation of each indicator and conducted comprehensive assessments of wetland ecological health across four periods. The ecosystem health indices were 0.642 and 0.617 for 1995 and 2000 respectively, indicating relatively healthy conditions. For 2005, 2009, and 2014, the values were 0.524, 0.436, and 0.405, showing sub-healthy status that requires immediate conservation measures.

Finally, we selected the grey system theory-based GM(1,1) prediction model for Linghekou Wetland ecosystem health forecasting. Model accuracy testing revealed that the grey absolute correlation degree, posterior difference ratio, and small error probability all achieved first-grade precision levels, indicating satisfactory model performance. Prediction results for 2019, 2024, 2029, and 2034 yielded health values of 0.357, 0.321, 0.291, and 0.267 respectively, all indicating generally morbid conditions with a trend toward further deterioration. The wetland ecosystem faces increasingly severe threats, making protection and management efforts extremely urgent.

Keywords: PSR model; ecosystem health evaluation; grey prediction; Linghe River estuary wetlands

1. Study Area Overview

The Linghekou Wetland (40°45 –41°00 N, 121°00 –121°30 E), covering approximately 69 km^2 in Linghai City, Liaoning Province, constitutes a primary wetland conservation target in the Liao River Basin. The Linghekou Wetland Nature Reserve possesses a typical coastal wetland mixed ecosystem. Located in the Liaodong Bay area of the Bohai Sea, the wetland is influenced by northern Liaodong Bay tides and waves, forming extensive mudflats. The suitable ecological environment supports rich flora and fauna, with 1,024 species of plants and animals. Approximately migratory birds pass through annually, making it an internationally important stopover site and breeding ground for migratory birds, including the endangered Saunders' s Gull (*Larus saundersi*) and Red-crowned Crane (*Grus japonensis*) [6-7].

2. Data Sources

The primary data source consisted of satellite remote sensing imagery obtained from the official website, with 30m resolution TM imagery for 1995, 2000, 2005, 2009, and 2014. Geographic Information System software (ArcGIS) and ERDAS 8.6 were used to perform radiometric correction, radiometric calibration, atmospheric correction, and image enhancement preprocessing. Additional collected materials included water system maps, administrative boundary maps, and previous survey data for the Linghekou Wetland study area, as well as relevant geological, geomorphological, hydrometeorological, and socioeconomic data.

Based on the Liaoning Province land use classification system and field survey data from Linghekou Wetland, the study area' s land use landscape types were classified into eight categories: forest land, dry land, paddy field, culture ponds/lakes, residential area, reed swamp, mudflat, and river. Visual interpretation information extraction methods were employed to extract ground object information, establish primary interpretation indicators, and conduct field verification of interpretation accuracy. Using the Summary Statistics tool in ArcGIS 10.0 software, we analyzed the corrected imagery to obtain remote sensing information data for five periods.

3. Linghekou Wetland Ecosystem Health Assessment

3.1 Conceptual Model Selection

The Pressure-State-Response (PSR) model, developed by Tony Friend and David Rapport and later modified by the Organisation for Economic Cooperation and Development (OECD) for environmental reporting, analyzes the relationships between natural environmental pressures, current status, and responses. The PSR model' s advantage lies in its clear logical relationships among environmental impact factors, enabling thorough analysis of human disturbance pressures and corresponding environmental indicator changes and responses within the study area.

Based on Linghekou Wetland survey data and internal conditions, we introduced the PSR model into the ecosystem health evaluation. [Figure 1: see original paper] illustrates the PSR model framework for Linghekou Wetland.

3.2 Evaluation Index System Construction

Wetland ecosystem health assessment must integrate ecological, economic, and social factors while considering natural wetland characteristics to understand dynamic changes under different management policies and maintain system sustainability [10]. Based on Linghekou Wetland' s ecological problems and considering representativeness and operability, we selected 10 evaluation indicators from ecological composition and socioeconomic impacts to construct the Linghekou Wetland ecosystem health evaluation index system ().

Pressure Indicators: Human disturbance represents the primary pressure on natural wetland ecosystems, with most wetlands suffering anthropogenic damage [11]. Field investigations revealed that wetland ecological health is mainly affected by human activities including deforestation, large-scale reclamation, and wastewater discharge, causing severe landscape fragmentation and threatening wetland health. We selected population density index and human interference index as pressure indicators.

- *Population Density Index:* Population per unit area (people/km^2 or people/hectare), calculated as: Study Area Population / Wetland Total Area
- *Human Interference Index:* (Urban Residential Area / Wetland Total Area) × 100%

State Indicators: These reflect environmental element changes and ecosystem status, including biological, physicochemical characteristics, and ecological functions [12-13]. We selected six indicators from landscape, biological, and physicochemical perspectives:

1. **Landscape Diversity Index (H):** Measures diversity in spatial structure, functional mechanisms, and temporal dynamics of different landscape elements. Higher H values indicate greater heterogeneity. Formula: $H = -\sum_{i=1}^{m} P_i \log_2 P_i$, where P_i is the area proportion of landscape type i, and m is the number of landscape types.

2. **Mean Patch Area (MPS):** Reflects landscape fragmentation level. Formula: $MPS = \sum_{i=1}^{m} S_i/N_i$, where N_i is the number of patches and S_i is the total area of landscape type i.

3. **Hydrological Regulation Index:** Wetlands' crucial ecosystem service for flood attenuation and water storage. Calculated as: Wetland Area / Total Area × 100%

4. **Landscape Dominance Index (D):** Indicates the dominance degree of landscape types. Formula: $D = H_{max} - H$, where $H_{max} = \log_2 m$ when

all landscape types have equal area proportions.

5. **Evenness Index (SHEI):** Reflects uneven distribution of patch types. Formula: $SHEI = -\sum_{i=1}^{m} P_i \log_2 P_i / \log_2 m$
6. **Primary Productivity:** Indicated by Normalized Difference Vegetation Index (NDVI), positively correlated with vegetation productivity.

Response Indicators: Management measures taken to maintain healthy wetland development. We selected:

1. **Wetland Degradation Index:** (Reduced Wetland Area / Original Wetland Total Area) × 100%
2. **Patch Fragmentation Index:** Measured by patch density ($PD = \sum N_i / A_i$), where higher PD indicates greater fragmentation.

3.3 Single Factor Evaluation

The logistic growth curve model (Lotka-Volterra equation) is widely used in ecology for population growth studies. Since individual indicator test values cannot linearly reflect wetland ecosystem health status, we applied this model for single-factor evaluation. The evaluation model is:

$P = \frac{1}{1+e^{(a-bR)}}$

Where P is the single indicator evaluation value, R is the measured indicator value. Parameters were determined as: when R = 0.001, P 0.01; when R = 0.99, P 0.999, yielding a = 4.595 and b = 9.19. The final model becomes:

$P = \frac{1}{1+e^{(4.595-9.19R)}}$

Using remote sensing interpretation data and indicator formulas, we calculated single-factor values for 2005 and 2014 ().

3.4 Comprehensive Evaluation

Based on single indicator evaluation values, we calculated the Comprehensive Evaluation Index (CEI) using weighted averages:

$CEI = \sum_{i=1}^{n} W_i \times P_i$

Where P_i is the evaluation value of indicator i, and W_i is its weight.

3.5 Evaluation Standards

Using continuous real number intervals [0,1] to represent health status levels (1 = best, 0 = worst), we established a five-level classification system combining literature and Linghekou Wetland characteristics [17-19] ():

- **0.8–1.0:** Very Healthy
- **0.6–0.8:** Healthy

- **0.4–0.6:** Sub-healthy
- **0.2–0.4:** Generally Morbid
- **<0.2:** Sick

3.6 Evaluation Results Analysis

The comprehensive evaluation yielded Linghekou Wetland ecosystem health indices of 0.642 (1995), 0.617 (2000), 0.524 (2005), 0.436 (2009), and 0.405 (2014). According to the classification standards, the wetland was healthy in 1995–2000 and sub-healthy in 2005–2014.

Pressure Analysis: Human activity interference is the primary degradation driver. Population density increased from 834.57 people/km^2 in 2005 to 1026.52 in 2014, while wetland area decreased by nearly 100 km^2, showing negative correlation. Increasing human pressure has reduced original wetland area, decreased functionality, lowered biodiversity, and intensified fragmentation.

State Analysis: Mean patch area decreased from 2.908 km^2 to 2.569 km^2, while landscape diversity declined from 2.664 to 2.631, indicating increasing landscape heterogeneity and severe fragmentation. Wetland function levels are degrading, threatening ecological health.

Response Analysis: Natural wetland area decreased from 368.587 km^2 to 276.440 km^2 (92.147 km^2 reduction, ~25% of original area). Landscape fragmentation increased as wetlands were converted to residential or construction land, shrinking waterfowl habitats and reducing biodiversity. The wetland' s functional stability has declined, requiring urgent protection and restoration measures.

4. Linghekou Wetland Ecosystem Health Early Warning Study

Based on the health evaluation results (1995: 0.642, 2000: 0.617, 2005: 0.524, 2009: 0.436), we employed grey system theory for predictive modeling.

4.1 Grey Prediction GM(1,1) Model

Following Deng Julong and Zhu Weihong' s methodology [20-23], we established the GM(1,1) model using the original data sequence $X^{(0)}$ = (0.6424, 0.6172, 0.5244, 0.4363, 0.4051).

Step 1: Accumulated Generating Operation (1-AGO) $X^{(1)}$ = (0.6424, 1.2596, 1.7840, 2.2203, 2.6254)

Step 2: Smoothness Test Using the smoothness ratio formula, we verified the original sequence meets smoothness conditions.

Step 3: Quasi-exponential Law Test The sequence ratio test confirmed quasi-exponential properties, validating GM(1,1) applicability.

Step 4: Model Construction We established the mean generation sequence $Z^{(1)}$ and constructed data matrices B and Y. Using least squares estimation, we obtained parameters: development coefficient a = -0.1608, grey action quantity b = 0.7529.

The time response function is: $\frac{dx^{(1)}}{dt} - 0.1608x^{(1)} = 0.7529$

The prediction equation becomes: $\hat{x}^{(1)}(k+1) = \left(x^{(0)}(1) - \frac{0.7529}{0.1608}\right) e^{0.1608k} + \frac{0.7529}{0.1608}$

4.2 Model Accuracy Testing

We conducted three precision tests:

1. Relative Error Test: Calculated residuals between predicted and actual values. The average relative error was 0.0029 (0.29%), meeting first-grade precision standards ().

2. Grey Absolute Correlation Degree (O) Test: With residual variance $S_2 = 0.0104$ and sequence variance $S_1 = 0.0944$, the posterior difference ratio $C = S_2/S_1 = 0.1107 < 0.35$, and correlation degree $O = 0.9978 > 0.90$, achieving first-grade precision.

3. Small Error Probability (P) Test: Small error probability $P = P\{|q(k) - \bar{q}| < 0.6745S_1\} = 1 > 0.95$, also first-grade precision ().

All three indicators achieved first-grade precision, confirming the model' s reliability for future predictions.

4.3 Prediction Results Analysis

Using the validated GM(1,1) model, we predicted Linghekou Wetland ecosystem health values: - 2019: 0.3362 - 2024: 0.2896 - 2029: 0.2495 - 2034: 0.2350

All predictions indicate "generally morbid" status with a deteriorating trend toward sickness. [Figure 2: see original paper] shows the declining health curve. Without protective measures, the ecosystem health will continue declining severely. The wetland ecosystem faces increasingly serious threats, necessitating immediate pressure control and restoration measures to guide development toward a benign trajectory.

5. Conclusions

This study established a Linghekou Wetland ecosystem health evaluation index system based on the PSR model. Using AHP for weight determination and logistic growth curves for single-factor evaluation, we calculated comprehensive evaluation indices for 1995–2014. Results showed healthy status in 1995–2000 (0.642, 0.617) and sub-healthy status in 2005–2014 (0.524, 0.436, 0.405), with a trend toward morbidity.

The GM(1,1) grey prediction model achieved high precision (first-grade in all tests) with the equation $\frac{dx^{(1)}}{dt} - 0.1608x^{(1)} = 0.7529$. Predictions for 2019–2034 (0.3362, 0.2896, 0.2495, 0.2350) indicate generally morbid conditions with continued deterioration. The wetland ecosystem faces increasingly severe threats, demanding urgent protection and management actions.

References

[1] KEDDY P A. Wetland Ecology: Principles and Conservation. Cambridge: Cambridge University Press, 2000: 124-238.
[2] Holland M M. Wetlands and environmental gradients // Mulamoottil G, Warnser B G, McBean E A, eds. Wetlands Environmental Gradients, Boundaries, and Buffers. Boca Raton: CRC Press Inc., 1996: 112-131.
[3] [Landscape structure dynamic change and land use ecological security in Jiansanjiang reclamation area]
[4] [Wetland ecosystem health evaluation index system]
[5] [On basic concepts and research content of ecological security]
[6] [Scientific investigation of Linghekou Wetland]
[7] [Landscape pattern change and functional zoning of Linghekou Wetland Nature Reserve]
[8] [Application of PSR model in wetland ecosystem health evaluation]
[9] [Progress and analysis of environmental indicator research]
[10] [Wetland ecological evaluation index system]
[11] [Research progress on wetland ecosystem health]
[12] [Wetland ecological health evaluation supported by RS and GIS in Honghe area]
[13] [Health water cycle evaluation of Zhalong Wetland based on PSR model]
[14] [Application study of landscape ecology method for Lalu Wetland environmental quality evaluation]
[15] [Environmental quality evaluation of Minjiang River estuary wetland area]
[16] [Wetland ecosystem health evaluation in lower Tumen River area]
[17] [Comprehensive evaluation of Dongping Lake wetland ecosystem health]
[18] [Comprehensive evaluation of Yellow River Delta wetland ecosystem health]
[19] [Mangrove wetland ecosystem health evaluation in coastal areas]
[20] [Application scope of GM(1,1) model]
[21] [Grey prediction technology and its application research]
[22] [Application of grey system theory GM(1,1) prediction model]
[23] [Wetland ecological security evaluation and early warning study in Tumen River Basin based on 3S technology]

Note: Figure translations are in progress. See original paper for figures.