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Ecosystem Health Assessment of Honghu Lake Wetland of China Using Artificial Neural Network Approach

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Abstract: Honghu Lake, located in the southeast of Hubei Province, China, has suffered a severe disturbance during the past few decades. To restore the ecosystem, the Honghu Lake Wetland Protection and Restoration Demonstration Project (HLWPRDP) has been implemented since 2004. A back propagation (BP) artificial neural network (ANN) approach was applied to evaluatinig the ecosystem health of the Honghu Lake wetland. And the effectiveness of the HLWPRDP was also assessed by comparing the ecosystem health before and after the project. Particularly, 12 ecosystem health indices were used as evaluation parameters to establish a set of three-layer BP ANNs. The output is one layer of ecosystem health index. After training and testing the BP ANNs, an optimal model of BP ANNs was selected to assess the ecosystem health of the Honghu Lake wetland. The result indicates that four stages can be identified based on the change of the ecosystem health from 1990 to 2008 and the ecosystem health index ranges from morbidity before the implementation of HLWPRDP (in 2002) to middle health after the implementation of the HLWPRDP (in 2005). It demonstrates that the HLWPRDP is effective and the BP ANN could be used as a tool for the assessment of ecosystem health.

Keywords: ecosystem health; artificial neural network; wetland restoration; Honghu Lake

1 Introduction

Ecosystem health (EH) is a newly developed concept for environmental management (Rapport, 1992; 1995; Costanza et al., 1992). It is often used to assess the integration of the social and natural sciences rather than to directly measure individual biological processes (Costanza et al., 1992; Rapport et al., 1998). Several studies have been conducted to investigate the ecosystem health regarding definition, index and assessment methods. Rapport (1995) proposed that the domain of ecosystem health is large including not only biophysical dimensions but also socio-economic and human aspects, thereby pointed out the shortcomings of traditional indicator species method. Jørgensen (1995) measured ecosystem health using exergy, structural exergy and ecological buffer capacity. Over the past years more and more assessment methods and frameworks have been put forward (Levins, 1995; Schaeffer et al., 1998; Xu et al., 1999; Francis et al., 2005; Suo et al., 2008). In the wetland assessment of China, Cui and Yang (2002) assessed the ecosystem health of wetlands employing the indicators of ecological identity, functional integrity, and the indicators associated with socio-economic conditions. Most of the studies on wetland evaluation used Analytical Hierarchy Process (AHP) approach in the past. The current research methods are still not perfect and are still in the exploratory stage.

Artificial neural network (ANN) is a powerful tool for multivariate and nonlinear analysis, and offers an alternative to traditional statistical methods for optimal monitoring and determination of dynamic systems. ANN uses the machine learning approaches to quantify and model complex behaviors and patterns (Pijanowski

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et al., 2002), especially data pattern recognition. It has advantages in observing relationships among parameters by imitating the brain's ability to sort patterns through the interconnected systems of many neurons (Dai et al., 2005). Recently, ANN has become very popular for forecasting purposes in various fields including finance, power generation, medicine, water resources and environmental science. Many ANN methods have been used to evaluate ecological environment, but researches on ecosystem health using ANNs are not common. Among various ANN models, the back propagation (BP) training algorithm has been most widely used (Salomon and Hemmen, 1996), particularly in ecology and environment assessment. So it also can be used to evaluate ecosystem health.

This study used BP ANN to evaluate the ecosystem health condition of the Honghu Lake wetland, Hubei Province, China. Specifically, an optimal BP ANN was selected after a set of BP ANNs were trained and evaluated using various ecological and social-economic parameters. The optimal BP ANN was then used to evaluate the wetland ecosystem health from 1990 to 2008. This study will be helpful to formulate regional sustainable development strategies and restore wetland, at the same time it can be extended to other lake wetlands.

2 Methodology

2.1 Study area

The Honghu Lake wetland (central situation 29°48'N, 113°17'E) is located in Honghu City and Jianli County of Hubei Province, China (Fig. 1). Honghu Lake, with a water area of 344km^2, is the largest natural lake among thousands of water bodies in the Jianghan Plain in the north of the middle reaches of the Changjiang (Yangtze) River (Yao et al., 2006). It is also the seventh largest freshwater lake in China. The ecological environment in the Honghu Lake wetland deteriorated seriously from the 1990s to 2003 because of rapid population growth and associated human activities, such as cultivation and fishing (Yang and Cai, 1995; Qin and Lu, 2005; Cheng and Li, 2006). In order to prevent the Honghu Lake wetland from degeneration, Honghu Lake Wetland Protection and Restoration Demonstration Project (HLWPRDP) has been implemented by the support of State Forestry Administration, P. R. China and World Wild Fund for Nature (WWF) since 2004. This project is to provide a demonstration and to obtain experiences for wetland protection and restoration.

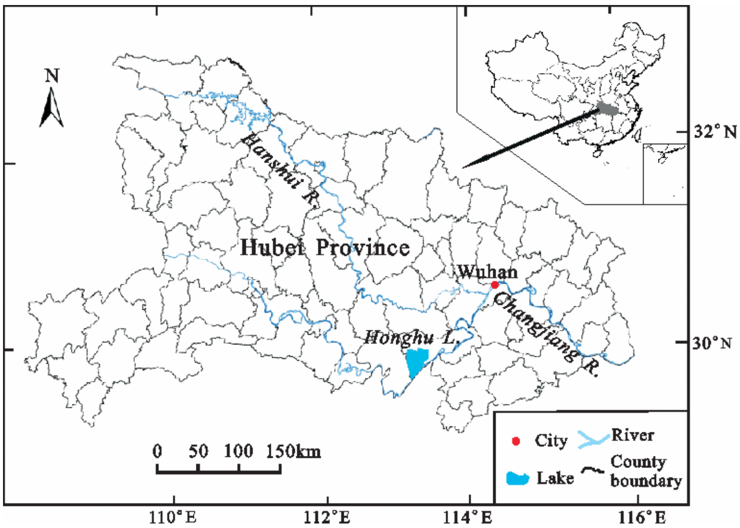

Fig. 1 Location of Honghu Lake wetland

2.2 Index system and data sources

Ecosystem health indices must accurately reflect the target of ecosystem management and evaluation. So the indices must indicate the characteristics of ecosystem structure, ecosystem function and regional social and economic characteristics (Simpson, 1998). Each researcher may choose different indicators depending on his specific interest and expertise. Meanwhile, in specific application, indices should be chosen based on the types of wetland ecosystems and regional environmental differences (Cui and Yang, 2002). The Honghu Lake wetland, as a typical lacustrine wetland and a provincial

Nature Reserve, has the ecosystem service functions of supplying aquatic products, purifying water, maintaining biodiversity, tourism and so on (Wang et al., 2003). According to the principles of selecting indices mentioned above, the following 12 indices were chosen.

(1) Water quality. Dissolved oxygen (DO), permanganate index (COD_{Mn}), ammonia nitrogen (NH_3-N), total nitrogen (TN) and total phosphorus (TP) were selected to determine the water quality. It is measured by gray water quality index calculated according to the National Surface Water Environmental Quality Standards of China (GB3838-2002) (Xia, 1999).

(2) Species diversity. It is measured by the proportion of species of plants and animals in the study area to the total species in the regional wetland ecosystem. If statistical data are not available, it can also be qualitatively described by the changes of species number and their spatial distribution.

(3) Coverage of dominant plants. It is the percentage of the area covered by dominant plants in the whole wetland area.

(4) Aquatic community structure. It is measured by the complexity, stability and dependence on the external energy of community structure.

(5) Stress. It mainly refers to human disturbances including over-fishing, hunting, mowing, reclaiming, hunting waterfowl eggs, etc.

(6) Biomass. It is the annual change rate of plant biomass in Honghu Lake wetland.

(7) Water purifying. It is the rate of sewage purification in the wetland ecosystem.

(8) Food production. It is measured by the annual output of animal and plant products and the annual change rate of the output.

(9) Entertainment value. It reflects the value in the environmental protection, scientific research, and landscape aesthetics.

(10) Index of living. It is the annual per capita net income of residents around the wetland area.

(11) Management level. It reflects the overall level of wetland management organizations and managers′ quality.

(12) Policy and law. It reflects the formulation and implementation of relevant policies and regulations.

Among them, indices (1)–(5) belong to ecosystem structure characteristics, (6)–(9) belong to ecosystem function characteristics and (10)–(12) belong to social and economic characteristics. For each index, the health condition was divided into five categories, i.e., excellent health, health, middle health, morbidity, and illness (Table 1) (Cui and Yang, 2002; Zhang et al., 2008).

Data collected here include ecological, social, and economic indices from 1990 to 2008. The water quality index (1) was acquired from Environmental Monitoring Center of Hubei Province; the indices (9), (11) and (12) were obtained from Honghu City Municipal Government Work Report; the indices (8) and (10) were obtained from *Jingzhou Statistical Yearbook* (Jingzhou Statistical Bureau, 2001–2008) and Honghu Statistical Bureau; the indices (3), (6) and (7) were from the monitoring data of Institute of Geodesy and Geophysics, Chinese Academy of Sciences; and indices (2), (4) and (5) from the Report of Scientific Survey for Honghu Lake Wetland Nature Reserve of Hubei Province (IGG and HWNRAB, 2005).

2.3 Calculation method

2.3.1 Data normalization

To evaluate the ecosystem health using BP ANN method, the evaluation criteria were converted to numerical values (Table 2). Some indices were calculated directly and others are equivalently assigned a score from 0–10. The criteria and thresholds of the related 12 indices were divided into five categories. So were the five ecosystem health standard which was normalized. The value of 0–0.2 belonged to illness, 0.2–0.4 to morbidity, 0.4–0.6 to middle health, 0.6–0.8 to health and 0.8–1.0 to excellent health.

All indices were further normalized to 0–1 before BP ANN analysis. The normalization can reduce the impacts of different dimensions or large gaps of samples. The indices that the smaller values represent better ecosystem health are normalized by the Equation (1):

$$x'_{ij} = \begin{cases} 1 & x_{ij} \le m_j \\ \dfrac{x_{ij} - M_j}{m_j - M_j} & m_j < x_{ij} < M_j \\ 0 & x_{ij} \ge M_j \end{cases} \qquad (1)$$

On the other hand, the indices which are positively related to the ecosystem health are normalized by the Equation (2):

Table 1 Ecosystem health assessment criteria in Honghu Lake wetland

No.	Indicator	Excellent health	Health	Middle health	Morbidity	Illness
1	Water quality	I	II	III	IV	V
2	Species diversity	>40%	30%–40%	20%–30%	10%–20%	<10%
3	Coverage of dominant plant	>45%	25%–45%	15%–25%	10%–15%	<10%
4	Aquatic community structure	Complex nutrition relationship, reasonable biology age structure, good self-stability capability	A little complex nutrition relationship, reasonable biology age structure, good self-stability capability	A little complex nutrition relationship, stability depending on human being to some extent	Linear nutrition relationship, few species, stability depending on human being a little strongly	Single linear nutrition relationship, imbalanced biology age structure, stability depending on human being strongly
5	Stress	No over-fishing, hunting, mowing, reclaiming, and gathering waterfowl eggs	Few or suitable fishing, mowing	Over-fishing, hunting, mowing, but no reclamation	Intensive fishing, hunting, mowing, reclaiming	Over-fishing, hunting, mowing, reclaiming and gathering waterfowl eggs
6	Biomass	Biomass increasing, increasing rate>10%	Biomass increasing or no change, increasing rate being 0–10%	Biomass decreasing or no change, decreasing rate being 0–10%	Biomass decreasing, decreasing rate being 10%–50%	Evident biomass decreesing, decreasing rate being>50%
7	Water purifying	Enhanced purifying, enhancing rate≥5%	Enhanced purifying, enhancing rate<5%	Declined purifying, diminishing rate being 5%–10%	Evident declined purifying, diminishing rate being 10%–20%	Evident declined purifying, diminishing rate >20%
8	Food production	Annual output increasing, increasing rate>5%	Annual output increasing, increasing rate being 2%–5%	Stable annual output, variety rate being 0	Annual output decreasing, decreasing rate being 0–5%	Annual output decreasing, decreasing rate>5%
9	Entertainment	Higher aesthetics value, much many entertainment days	High aesthetics value, many entertainment days	Low aesthetics value, some entertainment days	Lower aesthetics value, less entertainment days	No aesthetics value, no entertainment days
10	Index of living	>4000 yuan	3000–4000 yuan	2000–3000 yuan	1000–2000 yuan	<1000 yuan
11	Management level	Rational management organizations, high quality managers	Acceptable management organizations, and managers	Having management organizations, absence of essential training for managers	Having management organizations, low quality managers	No management organizations, lower quality managers
12	Policy and law	All-round laws and regulations, fulfilling completely	Some laws and regulations, fulfilling mostly	Some laws and regulations, fulfilling partly	Few laws and regulations, simply copying with them	Few laws and regulations, no fulfilling

Table 2 Ecosystem health assessment numerical criteria of Honghu Lake wetland

No.	Indicator	Excellent health	Health	Middle health	Morbidity	Illness	Method
1	Water quality	(1.0, 1.5]	(1.5, 2.5]	(2.5, 3.5]	(3.5, 4.5]	(4.5, 5.5]	Gray index
2	Species diversity	[0.50, 1.00]	[0.30, 0.50)	[0.20, 0.30)	[0.10, 0.20)	[0, 0.10)	Directly calculating
3	Coverage of dominant plant	[0.45, 1.00]	[0.25, 0.45)	[0.15, 0.25)	[0.10, 0.15)	[0, 0.10)	Directly calculating
4	Aquatic community structure	[8, 10]	[6, 8)	[4, 6)	[2, 4)	[0, 2)	Experts scoring
5	Stress	[8, 10]	[6, 8)	[4, 6)	[2, 4)	[0, 2)	Experts scoring
6	Biomass	[0.8, 1.0]	[0.6, 0.8)	[0.4, 0.6)	[0.2, 0.4)	[0, 0.2)	Directly calculating
7	Water purifying	[0.9, 1.0]	[0.75, 0.9)	[0.6, 0.75)	[0.45, 0.6)	[0, 0.45)	Directly calculating
8	Food production	[0.8, 1.0]	[0.6, 0.8)	[0.4, 0.6)	[0.2, 0.4)	[0, 0.2)	Directly calculating
9	Entertainment	[8, 10]	[6, 8)	[4, 6)	[2, 4)	[0, 2)	Experts scoring
10	Index of living	[4000, 8000]	[3000, 4000)	[2000, 3000)	[1000, 2000)	[0, 1000)	Directly calculating
11	Management level	[8, 10]	[6, 8)	[4, 6)	[2, 4)	[0, 2)	Experts scoring
12	Policy and law	[8, 10]	[6, 8)	[4, 6)	[2, 4)	[0, 2)	Experts scoring

$$x'_{ij} = \begin{cases} 1 & x_{ij} \geq M_j \\ \dfrac{x_{ij} - m_j}{M_j - m_j} & m_j < x_{ij} < M_j \\ 0 & x_{ij} \leq m_j \end{cases} \quad (2)$$

In the equations, x'_{ij} is the normalized attribute value of the ith sample and the jth index; x_{ij} is the specific attribute value of the ith sample and the jth index; m_j and M_j represent minimum and maximum values of the jth index, respectively.

2.3.2 Identification of network structure

A BP ANN structure of three layers was used. According to Kolmogorov theorem, a 3-layer BP ANN can capture any nonlinear function of the approximation. In BP ANN, 12 indices were chosen as input variables for the assessment of ecosystem health and the output was the value of ecosystem health. Thus the input layer units n_1=12 and output layer unit n_3=1. The numbers of hidden nodes (n_2) were calculated from the equation n_2=2×n_1+1 and then taken by node expansion approach. The optimal assessment BP ANN was determined after the network models were trained and tested. Specifically, the optimal network is the one with the fastest convergence and the smallest prediction error. Training sample matrixes were generated from the criteria and thresholds of ecosystem health categories. Five categories level were defined and its average value was between 0 and 1. To do this, samples of evaluation indices of ecosystem health were obtained by randomly extracting values between the low and high thresholds.

2.3.3 BP ANN assessment processing

The BP ANN was processed by using Matlab 7.0, particularly, its Neural Network Toolbox and corresponding functions. "Rand" function was used to generate training and testing samples. Function "newff" is running BP ANN in MATLAB. "tansig" is the transfer function of hidden layer. "logsig" is the transfer function of input layer, and "trainlm" is for training function using Levenberg-Marquardt algorithm to train. Training epochs are set to 3000 and goal of training error is set to 0.00001. Thus, seven network models of BP ANN were established by using 60 training data and tested by 15 testing data. The forecast value and prediction error were analyzed.

3 Results and Analyses

3.1 Optimal BP ANN model

From the errors produced from seven BP ANN models for 15 testing samples, all models produce small errors and predict ecosystem health correctly. Relatively, the largest error occurs in the model of 12-23-1 while the smallest error is produced from the network structure of 12-28-1 (Table 3). Therefore, the network structure of 12-28-1 is selected to be the model for evaluating the ecosystem health in the Honghu Lake wetland.

Table 3 Testing errors of BP ANNs in assessment of wetland ecosystem health

Testing sample	Expected output	12-22-1	12-23-1	12-24-1	12-25-1	12-26-1	12-27-1	12-28-1
1	0.818200	–0.000700	0.000000	0.001100	0.000001	0.001000	0.000001	0.000700
2	0.881800	0.000700	0.000000	0.001700	0.000003	–0.000600	0.000000	–0.000300
3	0.972700	–0.001900	0.000004	–0.001700	0.000003	0.000000	0.000000	0.001200
4	0.627300	–0.000200	0.000000	0.000500	0.000000	0.001300	0.000002	0.001000
5	0.663600	–0.000400	0.000000	0.000800	0.000001	0.000900	0.000001	0.000800
6	0.745500	0.001700	0.000003	0.002500	0.000006	0.001600	0.000003	0.001100
7	0.463600	0.000100	0.000000	0.000200	0.000000	0.000800	0.000001	0.000400
8	0.518200	0.000600	0.000000	0.001100	0.000001	0.000300	0.000000	0.000600
9	0.581800	0.000800	0.000001	0.001200	0.000001	0.000900	0.000001	0.000800
10	0.227300	0.000300	0.000000	0.000400	0.000000	0.000000	0.000000	–0.001300
11	0.281800	0.000800	0.000001	0.000200	0.000000	0.000000	0.000000	–0.000600
12	0.372700	0.000000	0.000000	0.000800	0.000001	0.000300	0.000000	–0.000700
13	0.027300	0.000800	0.000001	–0.000400	0.000000	0.000400	0.000000	0.000300
14	0.090900	0.000400	0.000000	0.000700	0.000000	0.000500	0.000000	0.000200
15	0.181800	–0.001300	0.000002	–0.000300	0.000000	0.000500	0.000000	–0.000900
Sum of error square	–	1.19E-05	1.84E-05	8.71E-06	9.51E-06	1.75E-05	7.33E-06	6.39E-06

3.2 Assessment of ecosystem health restoration project

Figure 2 shows the change of the ecosystem health value of single indicator before and after restoration project. The indicator with a normalized value of 0.8–1.0 is in excellent health state, while with a normalized value of 0–0.2 is in illness state. After wetland restoration project, water quality in Honghu Lake was obviously improved. It changed from class IV to class III in demonstration region due to the fact that prohibiting fish farming reduces the pollutants from fishing boats and manual fish feeding. Moreover, the restoration of aquatic vegetation gradually improved the purifying capability of water body.

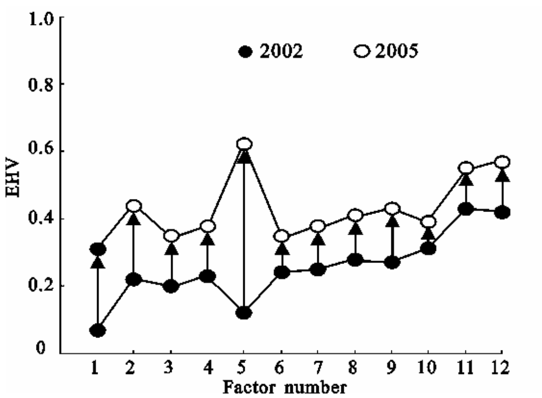

Fig. 2 Change of ecosystem health value (EHV) of single indicator of Honghu Lake wetland in 2002 and 2005

After the implementation of a series of engineering projects, such as clearing up mud in shallow water, dismantling fences of fish farm, cultivating aquatic plants, the species diversity has restored gradually. The main aquatic plant species increased from 10 in 2002 to 15 in 2005. Correspondingly, animal habitat has also improved. Moreover, the annual net income of farmers in Honghu City increased from \$350 in 2002 to \$450 in 2005 according to the *Jingzhou Statistical Yearbook* (Jingzhou Statistical Bureau, 2001–2008).

Taking the normalized data as the input data, the ecosystem health value (EHV) produced from BP ANN was 0.224 in 2002 (before HLWPRDP) and 0.433 in 2005 (after HLWPRDP). It increased by 0.209. Correspondingly, the ecosystem health condition improved from morbidity to middle health. It means that the project is effective in the restoration of ecosystem.

3.3 Temporal change of ecosystem health state

Based on the same approach and model used, the ecosystem health index of the Honghu Lake wetland from 1990–2008 were calculated (Fig. 3, Table 4). As shown in Fig. 3, in the all 12 indices, the ecosystem health values of management level and policy and law changed very little while that of water quality changed much. The mean health value of stress was biggest and that of index of living was smallest. The results reveal that the ecosystem health values of the Honghu Lake wetland fluctuated from 1990 to 2008 (Table 4). They were all at middle health and morbidity levels. Before 2000, the wetland ecosystem health did not change much; however, it deteriorated dramatically after 2000. According to the ecosystem health assessment (Table 4), four stages can be identified.

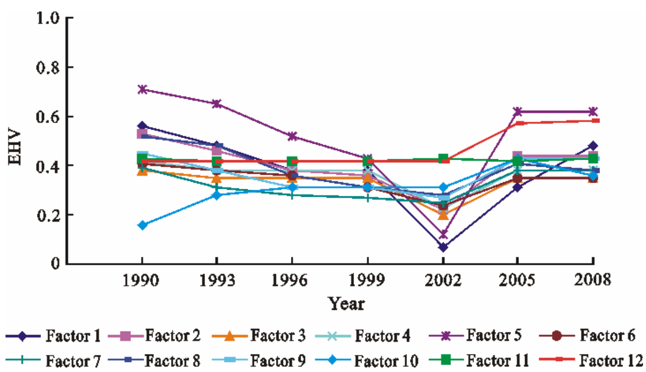

Fig. 3 Ecosystem health value (EHV) of single indicator of Honghu Lake wetland in 1990–2008

Table 4 Ecosystem health value (EHV) of Honghu Lake wetland in 1990–2008

	1990	1993	1996	1999	2002	2005	2008
EHV	0.525	0.421	0.375	0.372	0.224	0.433	0.446
State	Middle health	Middle health	Morbidity	Morbidity	Morbidity	Middle health	Middle health

Stage 1 (1990–1995): The ecosystem health belonged to middle health. The health value was 0.525 in 1990, which was the highest in the following nearly 20 years, and declined a little in this stage. This implies that the ecological environment was relatively good.

Stage 2 (1996–1999): The ecosystem health turned bad and belonged to morbidity. Because of the relatively good environment, human activities increased for effective utilization of wetlands and to prevent lake from swamping. Meanwhile, untreated sewage from industrial and agricultural sources carries large amount of pollutants into the lake due to the growth of population and economic development around the lake. This means that the wetland ecological environment began to decline.

Stage 3 (2000–2003): The ecosystem health value was 0.224 in 2002, which was near to illness. The area for enclosure culture in the lake expanded rapidly in this stage, which accelerated the environment deterioration. During this period, more fish food was put into the lake and more fish excretion was produced. On the other hand, the aquatic plants were harvested as part of fish food, and were put into the enclosure culture area, which weakened the purification ability of the aquatic plants in the lake.

Stage 4 (2004–2008): As the HLWPRDP started in 2004, a series of ecological restoration measures had been implemented. The wetland restoration measures included forbidding fishing in the core area, restoring aquatic vegetation, wetlands habitat rehabilitation and reconstruction engineering, and strengthening connectivity between Honghu Lake and the Changjiang River. Because of the government's attention, the management of the Honghu Lake wetland was strengthened. The enclosure culture area began to be removed, which reduced the barrier for the water movement within the lake. The ecosystem health state in 2005 and 2008 both belonged to middle health, showing efficient recovery of ecosystem function.

4 Conclusions

Comparing with the commonly used AHP and fuzzy comprehensive evaluation methods, the manual calculation steps have been omitted by BP ANN approach. Its calculation is auto-completed by computer's self-organizing and learning, and its accuracy can meet the research requirements. The BP ANN approach is more convenient to environmental management.

BP ANN method is demonstrated to be an effective tool in the evaluation of ecosystem health. In this paper, 12 ecosystem indices were integrated to quantitatively assess the ecosystem health of the Honghu Lake wetland. The optimal model of BP ANN trained using 60 samples produces high precision. The BP ANN indicates that the ecosystem health value increased from 0.224 in 2002 to 0.433 in 2005, which means the ecosystem health in Honghu Lake improved from morbidity to middle health state. This suggests the HLWPRDP which has been implemented since 2004 works effectively in the restoration of ecosystem health. It is expected that the ecosystem health state will become health or excellent health in near future with the continuous implementation of the ecological and engineering projects. Evidently, this restoration project provides an example for the ecosystem restoration of lakes in this region.

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