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Original Research

A PSR-Framework-Based Health Assessment of Ulansuhai Lake in China

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Abstract

A Pressure-State-Response (PSR) framework was developed to realize a holistic health assessment of the Ulansuhai Lake in the Inner Mongolia. A total of 25 indicators including ecological character indicators, ecological function indicators and social environment indicators were organized to assess the lake ecosystem health. The Ulansuhai Lake was regionalized into three sub-regions (I, II, and III) in the consideration of ecological and environmental characters the lake. Results indicate the lake is in the state of Alert or Worse. The comprehensive health indices (CHI) of three sub-regions are 0.346, 0.385, and 0.445, respectively, reflecting obvious regional differences in ecosystem health of the lake. The current study may provide useful information for valid wetland restoration and management

Keywords: health assessment, PSR framework, Ulansuhai Lake

Introduction

Since the concept of ecosystem health emerged in the 1980s, environmental managers have increasingly begun to consider the protection of ecosystem health as one of their primary goals in environmental management. Health information is extremely important for effective management of ecosystems. As a result, a large number of ecosystem health assessments have been attempted to provide qualitative and quantitative information for ecosystem management [1-4].

Health assessment indicators provide an important source of information for policy makers and help to guide decision-making as well as monitoring and evaluation, because they can provide valuable information on complex issues in a relatively accessible way. Historically, ecosystem health was measured using indices for a particular species of the system, and many species, e.g., zooplankton communities [5], microbes [6], and aquatic macroinvertebrates [7] are still used for reflecting the condition of ecosystem health. However, it cannot be denied that single sensitive species somewhat lack complete information of the system as a whole [8]. Now more indicators have been proposed to depict ecosystem complexities, e.g., gross ecosystem product [9], ecosystem stress indicators [10], biotic integrity [11], network ascendancy [12, 13], eco-exergy, structural eco-exergy, and ecological buffer capacities [14, 15]. Some new methods have appeared to address ecosystem health assessment, such as the ecological modelling method (EMM) [8], ecosystem health index methodology [16], and the structurally dynamic model method [17], which provide great technical support for health assessment.

Most often health assessment is restricted to the instant biological state of ecosystems, and cause-response indicators are often ignored and therefore fail to complement a holistic assessment to ecosystems. For example, one can easily find that the above health indicators focused on the state of ecosystems, which is monitoring biological changes

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in the natural environment. Generally, these indicators reflect mostly the biological condition of ecosystems. These indicators may provide information that something is going wrong, but it does not provide information on why something is going wrong and what we have done to ameliorate the situation. Stresses from human activities have been more deeply involved in ecosystem functioning than ever before. Human activities exert pressures on the ecosystems, which can induce changes of the health state of ecosystems. Society then responds to changes with environmental and economic policies and programs that prevent, reduce, or mitigate pressures on ecosystems. Although biological changes have appeared with great meanings to confirm the state of significant ecosystem pathology, holistic level assessment should encompass indicators depicting both the above negative stresses and positive responses from anthropogenic activities. Negative stresses will damage the health of ecosystems while positive responses will improve the health of ecosystems. Thus health assessment indicators should comprise not only biophysical indicators, but also social, economic, and human aspects as well [18]. The different indicators cover different aspects of ecosystem health, a more complete picture of ecosystem health may require the simultaneous application of several indicators [15]. The current difficulty is to find a method that can deal with the holistic-level assessment on ecosystems.

Pressure-state-response (PSR) framework was first proposed by Rapport and Friend [19], which was further developed by the Organization for Economic Co-operation and Development [20]. It is now widely used in describing and quantifying the environment quality, sustainability, ect. [21-26]. The PSR framework is established from three aspects (pressures from population growth, environmental resources assumption, the state of the eco-environment, and measures and policies to be adopted to solve eco-environmental issues) that affect or relate to ecosystem heath, which can be readily utilized for holistic assessment of ecosystems. This paper was intended to assess the health of freshwater Ulansuhai Lake in a spatial scale. Pressure indicators, state indicators, and response indicators were selected for a more holistic characterization of the practical health state aiming to providing scientific information for restoration and management of Ulansuhai Lake.

Material and Methods

Study Area

Ulansuhai (N40º36′~41º03′, E108º43′~108º57′) is a typical plant-dominanted lake in Ulate County, Inner Mongolia, China. The lake covers an area of 292 km^2, with a drainage area of 11,800 km^2. The average elevation of the lake is 1,018.8 m and hydraulic mean depth is 0.7 m [27]. The lake is 35.4 km in length and mean 6.6 km in width, so that it looks like an inclined carrot (Fig. 1).

As the biggest lake in the same latitude on earth, Ulansuhai plays an important role in maintaining the ecological balance of arid and semiarid areas. Historically, the lake is rich in fish and over 230 species of birds have been observed on and around the lake. However, it is facing severe ecological and environmental problems due to rapid population growth and fast economic development in recent decades. Return water of farmland irrigation, industrial sewage, and municipal wastewater from upstream contribute an annual average of 5.38×108 m^3 input water of the lake. About $1,088.59\times10^3$ kg nitrogen and 65.75×10^3 kg phosphorus were thus discharged into the lake each year, resulting in superfluous growth of aquatic plants, such as *Potamogeton pectinatus* and *Phragmites communis* Trin. Ecosystem health of the lake is now facing great pressure and challenge, which has become a major concern of local managers and scholars.

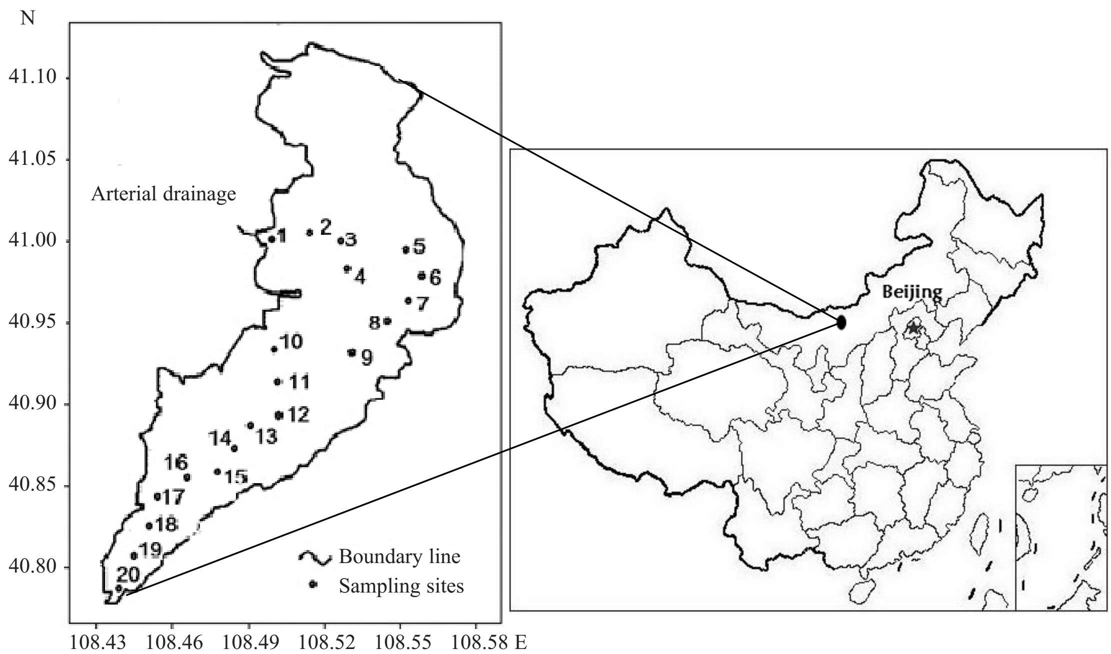

Fig. 1. Location of Ulansuhai Lake.

Regional Division of Ulansuhai Lake

The northwestern arterial drainage is the largest inlet channel of the lake and nearly 90% of input water comes from this drainage [28]. The only outlet is located southwest of the lake. Drainage water flows slowly from north to south with an average speed of 0.007 m/s-0.057 m/s. After a series of physical, chemical and biological processes, the concentration of some pollutants (e.g., total nitrogen (TN) and total phosphorus (TP)) can be greatly decreased.

Different regions of the lake will present different health states due to ecological and environmental differences. To provide a more precise health assessment on the lake, three sub-regions of the lake were classified in the current study. Spatial form is the primary criteria for the regional division of the lake. Besides, the concentrations of pollutants (e.g., TN and TP) of water bodies are also considered into the regional division since ecosystem health is closely related to water quality. There is no obvious geographical boundary between any two regions, while each region has distinct geographical characters that are depicted in Table 1.

Table 1. Partitions of Ulansuhai Lake.

Division	Region I	Region II	Region III
Sampling sites	1, 2, 3, 4, 5, 6, 7, 8	9, 10, 11, 12, 13, 14	15, 16, 17, 18, 19, 20
Area	140 km^2	89 km^2	54 km^2
Description	Close to the arterial drainage	In the middle of the lake	Close to the outlet of the lake

Assessment Method

The PSR Framework

The pressure-state-response (PSR) framework was developed by OECD to promote a common set of environmental performance indicators [29]. The PSR indicators allow evaluating the pressures of human activities on environmental states and to provide social responses in order to come back to a "desirable state."

Health state of a lake is also closely related to pressures from human activities. Human activities exert pressures on the environment and change its quality and quantity of natural ecosystems (State). To some extent, positive social responses will alleviate a human's negative impact on lakes (Response). Thus the health of a lake is the result of joint action from negative human pressures and positive social responses. The PSR framework can be extended to evaluate the health state of ecosystems, including pressures from human activities and social responses trying to control the impact from damaging human activities. This framework also highlights the relationships between social and economic dimensions of ecosystem health (Fig. 2).

Assessment Indicators and Weight Identification

The current assessment system was classified into three levels, including target level, subsystem level, and assessment indicator level. As stated above, the index system is established from three aspects that affect or relate to ecosystem health, i.e. ecological pressure (the pressure from population growth, water resources assumption), state of ecosystem (ecological state, environmental state and function state), and response (measures and policies to be adopted to solve eco-environment issues). It is a major challenge to determine the "best" indicators that reflect the health of the lake. With the help of expert consultation and a literature survey, health assessment indicators of three levels are finally determined. We try to select the "best" indicators using the following two methods: first, indicators from health assessment of referring lake ecosystems; second, indicators in environmental sustainability assessment from other PSR models, especially for the pressure and response indicators. All selected indicators and their detailed infromation are listed in Table 2.

Weights of 25 indicators were finally identified by analytic hierarchy process (AHP). The basic process to identify the weight of each indicator can be illustrated as the following example: first, establishing the judgment matrix *A*

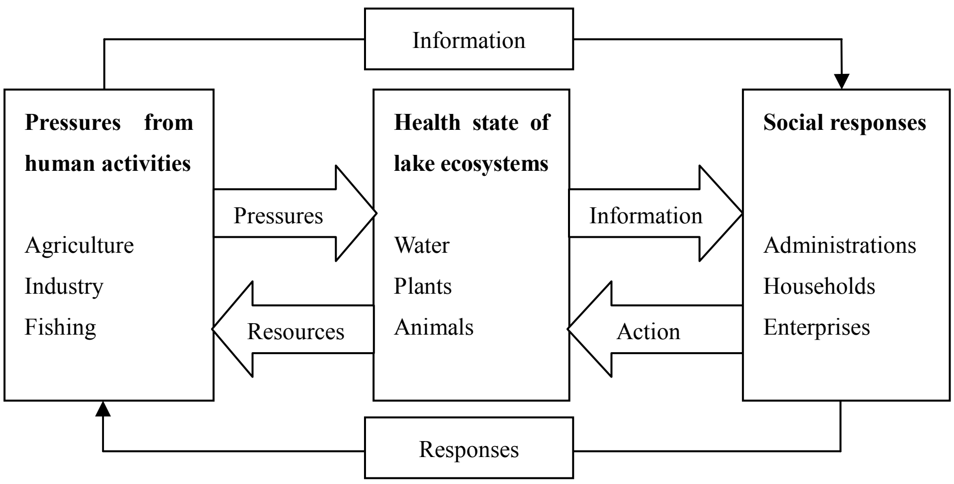

Fig. 2. The basic PSR framework (reconstructed from OECD, 2001 [21]).

Table 2. Details of select health assessment indicators.

Target level	Subsystem level		Indicator level	Detailed information
Health state A	Pressure B1		Population Density C_1	Population per unit area
			Utilization ratio of water resources C_2	Ratio between the actual water use amounts (P=50%) and basin mean annual water resources.
			Pest density C_3	Annual use of pesticides per hectare
			Fertilizer density C_4	Annual use of fertilizers per hectare
			COD emission per 10,000 Yuan GDP C_5	Industrial COD emissions
			Water resources ownership per capita C_6	Water resources ownership per capita
	State B_2	Ecological state B_{21}	Wetland plants C_7	Types of wetland plants
			Primary productivity C_8	Primary productivity of local dominant species
			Fish richness C_9	Species of fish
			Coverage of dominant species C_{10}	Coverage of dominant species
		Environmental state B_{22}	Water quality classification C_{11}	COD, BOD, pH, and poisonous chemicals
			Eutrophication level C_{12}	Trophic level index calculated by Chla, TP, TN, SD, and CODMn.
			Soil organic matter C_{13}	The organic matter component of soil
			Water-supply guarantee rate C_{14}	Ratio between available supply water and environmental flow requirements of the lake
			Lake deposition degree C_{15}	Ratio between deposition volume and lake volume
		Functional state B_{23}	Material production function C_{16}	Annual harvest of fish of the lake
			Hydrological adjusting function C_{17}	Water exchange period
			Water quality purification function C_{18}	Purification degree of primary pollutants
			Habitat maintenance C_{19}	Degradation rate of dominant plants of the lake
			Scientific studies and tourism C_{20}	Species of rare birds of the lake
	Response B_3		Wastewater treatment index C_{21}	Sewage treatment rate upstream the lake
			Public environmental awareness C_{22}	The proportion of people who have environmental awareness to total population
			Environmental protection investment coefficient C_{23}	The proportion of environmental protection investment and local GDP
			Wetland management level C_{24}	Degree of satisfaction of wetland management
			Research level C_{25}	The proportion of research specialist staff to total number of departments

by making a series of pairwised comparisons of the elements.

$$A=\begin{bmatrix} 1 & 1/3 & 3 \\ 3 & 1 & 5 \\ 1/3 & 1/5 & 1 \end{bmatrix}$$

Second, a matrix B was calculated from matrix A by the normalized process (we divide each element of the matrix A with the sum of its column).

$$B=\begin{bmatrix} 3/13 & 5/23 & 3/9 \\ 9/13 & 15/23 & 5/9 \\ 1/13 & 3/23 & 1/9 \end{bmatrix}$$

Third, the normalized principal Eigen vector can be obtained by averaging across the rows.

$$w=\frac{1}{3}\begin{bmatrix} 3/13 + 5/23 + 3/9 \\ 9/13 + 15/23 + 5/9 \\ 1/13 + 3/23 + 1/9 \end{bmatrix}=\begin{bmatrix} 0.258 \\ 0.637 \\ 0.105 \end{bmatrix}$$

...where w = (0.258 0.637 0.105)^T is the weight vector. Finally, we check the consistency of the matrix B by CR (CR=CI/RI. CI=(λ_{max} – n)/(n – 1), RI=0.58); If CR≦0.1, then the consistency is satisfied. Otherwise, we reconstructed the judgment matrix A until satisfying results were achieved.

Health Condition Classification

The comprehensive health index (CHI) was used to classify the health state of the lake, which is depicted in Equation (1)

$$CHI = \sum_{i=1}^{n} W_i \times X_i \tag{1}$$

...where W_i is the integrated weight of different indicators; and X_i is the score of assessment indicators. The *CHI* was classified into five levels including very good (0.8, 1.0], good (0.6, 0.8], fair (0.4, 0.6], poor (0.2, 0.4], and very poor (0, 0.2].

Data Sources

Assessment data were collected in three ways: first, survey and monitoring data from 20 sampling sites of the lake from April 2011 to October 2013; second, statistical yearbooks, statistical data from the *Fisheries Management Station,* and the *Nature Conservation Bureau* of Ulansuhai Lake; third, Questionnaire survey data from tourists, local residents, and the internet.

Table 3. Weights of different assessment indicators.

Indicators	System weight	Integrated weight	Indicators	System weight	Integrated weight
C_1	0.052	0.013	C_{14}	0.174	0.027
C_2	0.219	0.056	C_{15}	0.136	0.022
C_3	0.317	0.082	C_{16}	0.152	0.039
C_4	0.317	0.082	C_{17}	0.239	0.063
C_5	0.072	0.018	C_{18}	0.302	0.078
C_6	0.023	0.006	C_{19}	0.219	0.057
C_7	0.218	0.047	C_{20}	0.088	0.022
C_8	0.439	0.096	C_{21}	0.259	0.028
C_9	0.187	0.042	C_{22}	0.168	0.020
C_{10}	0.156	0.034	C_{23}	0.222	0.023
C_{11}	0.264	0.042	C_{24}	0.196	0.021
C_{12}	0.317	0.049	C_{25}	0.155	0.016
C_{13}	0.109	0.017	-	-	-

Results

Weights of Various Assessment Indicators

Weights of pressure subsystem, state subsystem, and response subsystem are 0.258, 0.637 and 0.105, respectively. In the state subsystem, weights of ecological state indicator, environmental state indicator, and functional state indicator are 0.345, 0.245, and 0.408, respectively. The integrated weights of all indicators are listed in Table 3.

According to the results of the weight analysis, state-related indicators are still the most important factors reflecting the health status of the lake. The pressure indicators get the second important position, followed by the response indicators. In pressure indicator, pesticide use intensity (C_3-0.818) and fertilizer use intensity (C_4-0.818) have the same weight since irrigation return flows are primary pollution sources of the lake. Primary productivity reflects the ability to stabilize organic carbon and exhibits the vigor of the lake ecosystem. Eutrophication level will conduct negative impact ecosystem function to a large extent, especially in eutrophic Ulansuhai Lake. Water purification function is a prerequisite for the restoration of healthy aquatic ecosystems [30]. Hence, primary productivity (C_8-0.096), eutrophication level (C_{12}-0.496), and water purification function(C_{18}-0.078) share the maximum weight in ecological state indicator, environmental state indicator, and functional state indicator, respectively.

Indicator Normalization

Since every original indicator has a different dimension, it is necessary to non-dimensionalize each indicator. The standardized score of each indicator was graded into five classes set between 0-1 (0 represents the worst state, a representative of the best state). Each class corresponds to a specific score range depicted in Table 4. Scores of an indicator can be achieved by calculating its specific position in the corresponding range.

Weighted score of an indicator was calculated by multiplying its score with its integrated weight. Generally, indicators' scores and weighted scores varied in a similar tendency, which is obviously reflectedg in a comparison between scores and weighted scores of the first region in the lake (Fig. 3). We can also clearly observe that there are still some exceptions against the above tendency. For example, indicators C_2 (utilization ratio of water resources) and C_5 (COD emission per ten thousand Yuan GDP) got the highest and the lowest scores, respectively. When weights of indicators are considered, however, C_4 instead of C_5 got the highest scores in the Pressure level. In the State level, indicators C_8 (water quality purification function), C_{12} (eutrophication level), and C_{18} (primary productivity) ranked top three in weighted scores. In contrast, indicators C_9 and C_{20} got relatively low weighted scores. Weighted scores of indicators in the Response level are generally lower than those in the Pressure and State levels since the Response level has the least weight among all three levels.

Although no single indicator can reflect the health state of the whole lake, it is also important to distinguish different indicators with respect to their weighted scores. Using cluster analysis, we categorized all these indicators of region III into four clusters. The first cluster includes indicators C_1, C_2, C_6, C_9, C_{13}, C_{14}, C_{17}, C_{20}, C_{22}, C_{23}, C_{24}, and C_{25}. The weighted scores of these indicators range from 0.002-0.010 in weighted score. Indicators C_3, C_4, and C_{11}, ranging

Table 4. Scores of different assessment indicators.

Indicator	Unit	Class I (0.8, 1.0)	Class II (0.6, 0.8)	Class III (0.4, 0.6)	Class IV (0.2, 0.4)	Class V (0, 0.2)
C_1	person/km^2	<100	(100, 250)	(250, 400)	(400, 600)	>600
C_2	%	<15	(15, 25)	(25, 35)	(35, 40)	>40
C_3	kg/hm^2	<2.5	(2.5, 3.0)	(3.0, 5.0)	(5.0, 7.0)	>7.0
C_4	kg/hm^2	<175	(175, 225)	(225, 275)	(275, 325)	>325
C_5	kg	<1.5	(1.5, 2.25)	(2.25, 3.0)	(3.0, 5.0)	>5.0
C_6	m^3 per captia	>3000	(1700, 3000)	(1000, 1700)	(500, 1000)	<500
C_7	species	>200	(150, 200)	(100, 150)	(50, 100)	<50
C_8	g/m^2·a	>70	(60, 70)	(50, 60)	(30, 50)	<30
C_9	-	>3.0	(2.5, 3.0)	(2.0, 2.5)	(1.5, 2.0)	<1.5
C_{10}	%	>70	(60, 70)	(50, 55)	(30, 50)	<30
C_{11}	-	I	II	III	IV	V
C_{12}	-	<30	(30, 50)	(50, 60)	(60, 70)	>70
C_{13}	%	>0.7	(0.6, 0.7)	(0.5, 0.6)	(0.4, 0.5)	>0.4
C_{14}	%	>90	(65, 90)	(35, 65)	(20, 35)	>20
C_{15}	%	<10	(10, 25)	(25, 40)	(40, 60)	>60
C_{16}	ton/a	>1000	(700, 1000)	(400, 700)	(100, 400)	>100
C_{17}	day	<90	(90, 180)	(180, 270)	(270, 360)	>360
C_{18}	%	>90	(75, 90)	(60, 75)	(45, 60)	>45
C_{19}	%	<10	(10, 20)	(20, 30)	(30, 40)	>40
C_{20}	-	>10	(8, 10)	(4, 8)	(2, 4)	< 2
C_{21}	%	> 95	(85, 95)	(75, 85)	(60, 75)	<60
C_{22}	%	> 50	(40, 50)	(25, 40)	(15, 25)	<15
C_{23}	%	>0.8	(0.4, 0.8)	(0.1, 0.4)	(0.05, 0.1)	<0.05
C_{24}	%	>80	(60, 80)	(50, 60)	(30, 50)	<30
C_{25}	%	>50	(40, 50)	(30, 40)	(20, 30)	<20

from 0.010-0.020 in weighted scores, were categorized into cluster II. Category III includes indicators C_5, C_7, C_{10}, C_{15}, C_{16}, C_{19}, and C_{21} ranging from 0.030-0.040 in weighted scores. The last category includes C_8, C_{12}, and C_{18} ranging from 0.050-0.055 in weighted scores, indicating they are relatively important indicators reflecting the state of the lake. With limited time and money, ecological restoration of the lake may be started with the above three indicators.

Limit data allow us only to make a distinction in indicators C_{10}, C_{11}, C_{12}, C_{15}, and C_{16} among three sub-regions. Nevertheless, most of the above indicators exhibit large differences in weighted scores. For example, weighted scores of indicator C_{10} in three regions are 0.0058, 0.0133, and 0.0166, respectively. The maximum value almost triples the minimum value, indicating there may be huge ecological and environmental differences among three sub-regions of the lake. Many factors may result in the above differences, such as aquatic plants, landform, velocity of water flow, and so on.

The CHI of Ulansuhai Lake

Results of PSR-framework-based health assessment of Ulansuhai Lake are shown in Fig. 4. The average CHI of the lake is 0.392, indicating that the lake is in a state of Poor health condition. Relevant restoration measures should be taken to improve the ecological and environmental condition and to restore ecological functions of the lake. With the process of water flowing from north to south, pollutants were reduced by physical, chemical, and biological processes. Thus, the CHI of three regions is gradually increased from 0.346 to 0.385, and finally to 0.445. Considering the above differences, different restoration

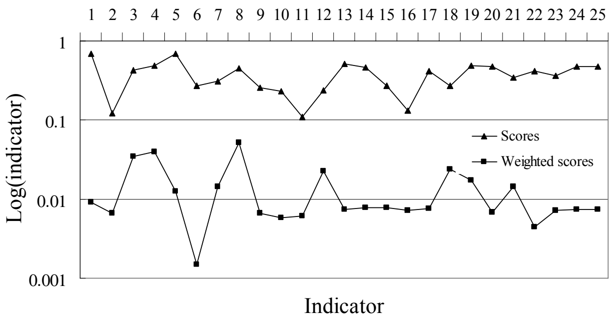

Fig. 3. Comparisons between scores and weighted scores.

measures should be implemented in three different sub-regions.

We can also find that indicators of state level are much larger than indicators in pressure level and response level, which share 59%, 63%, and 68% of three sub-regions' CHI, respectively. Obviously, pressure indicators and response indicators share smaller ratios in the CHI for two reasons: first, they have lower weights in assessment system; second, we made no difference toward three regions. However, we cannot say the state indicator of the lake is good. More detailed information should be considered to draw more accurate conclusions. For example, the average scoring rates of state indicators in three sub-regions are only 31%, 37%, and 47%, respectively. The corresponding results of pressure and response indicators are equally 39%. In regions I and II, at least, the average scoring rates of pressure and response indicators are better than that of state indicators.

Overall, the average scoring rate of three types of indicators are lower than 50%, indicating that Ulansuhai is facing great challenges in health recovery. In the pressure level, we suggest reducing the intensity of pesticide and fertilizer use. In the response level we suggest increasing investments in environmental protection and upgrading the sewage treatment rate of upstream lakes. In the state level, chemical and biological measures should be taken with respect to different sub-regions. For example, we can take physical or chemical measures in region I for a rapid recovery of environmental state, while for region III we may focus on improving its functional status, such as habitat maintenance and tourism function.

Sensitive Analysis

To test the sensitivity of the PSR framework-based health assessment model we applied sensitivity analysis to the current model. Using formula $CHI' = \sum_{i=1}^{n} W_i \times X_i (1 + \Delta K)$, we realized the analysis by adjusting coefficient K (-10%, +10%; -20%, +20%, -30%, +30%). Percentage variation of the CHI was calculated by formula (*CHI' – CHI*)/*CHI*×100%, which is shown in Fig. 5.

In regions I, the average percentage variations of CHI in three pressure-related changes (P±10%, P±20%, P±30%) are 3.1%, 6.1%, and 9.3%, respectively. The corresponding results in regions II and III are 2.7%, 5.3% and 8.3%, 2.1%, 4.2%, and 7.3%, respectively. Obviously, the CHI in region I is more robust to the changes of pressure indicators. A similar tendency was exhibited in response-related changes (R±10%, R±20%, R±30%); however, its percentage variations of CHI are smaller than that of pressure-related changes. As depicted above, region I is close to the arterial drainage, which contribute almost 90% input water of lake. Ecosystems in this region suffer the most direct impact from

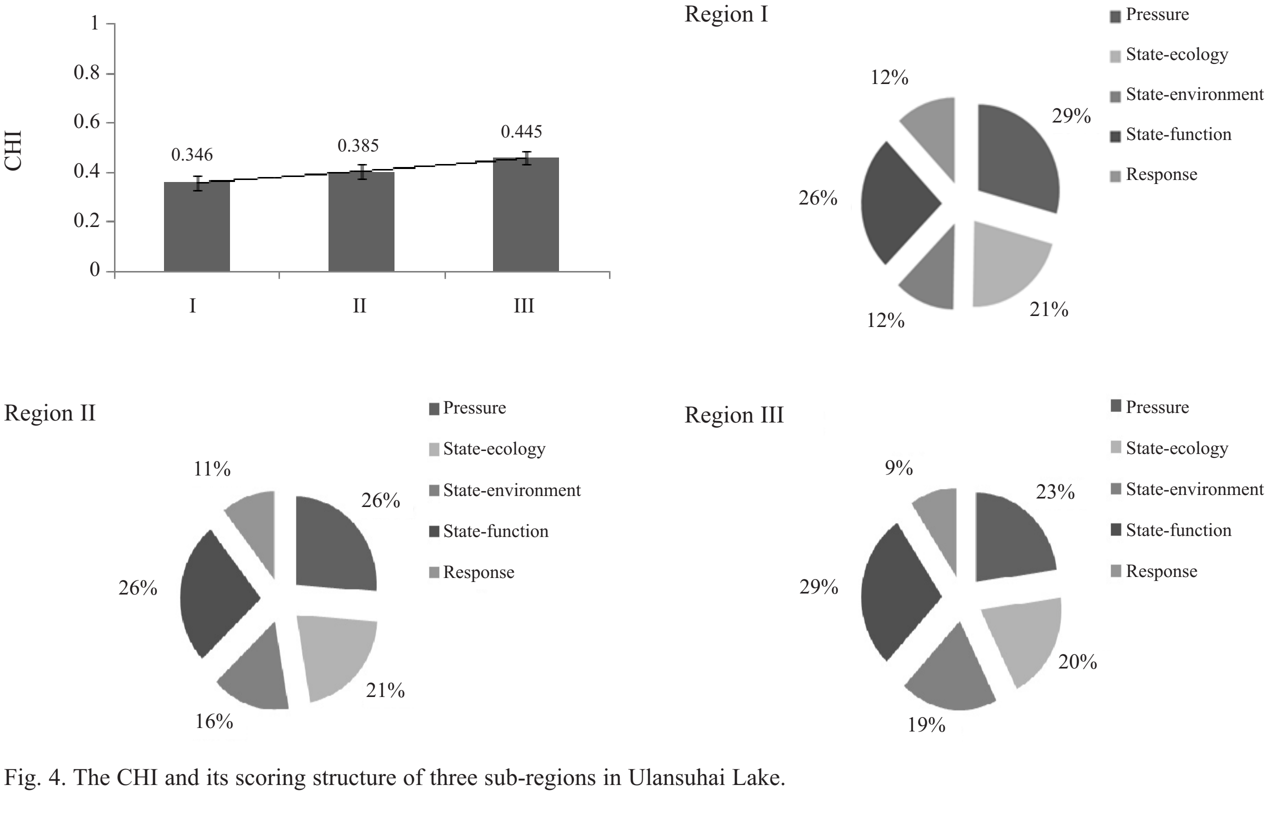

Fig. 4. The CHI and its scoring structure of three sub-regions in Ulansuhai Lake.

outside pressures. In contrast, regions II and III are relatively far from arterial drainage. After a series of physical, chemical, and biological processes the concentrations of primary water pollutants were greatly decreased. To some extent self-purification capacity will counteract the effects of pressures in regions II and III. Therefore, the CHI in region I is more robust to the changes of pressure indicators.

It is interesting that an opposite tendency was found in state-change related scenarios (S±10%, S±20%, and S±30%). Region III presents the largest percentage changes in response to state-related changes. Region III is far from arterial drainage. After a certain time of self-purification process, water quality in this region is much better than that of the other two regions. Thus, state indicators in region III got the highest scoring rate among three regions, which can clearly be found in Fig. 4. The CHI index is more sensitive to the changes of state indicators. That is why region III presents the largest percentage changes in response to state-related changes.

We further calculated the sensitivity index ($\beta=|\Delta CHI/\Delta X_i|$) to show the model's sensitivity toward different indicator levels. Results show that the average sensitivity index for pressure, state, and response is 4.7, 1.8, and 11.7, respectively. In other words, the CHI of the lake is sensitive to outside pressures and social responses. If we reduce the pressures and take active actions, the CHI of Ulansuhai Lake may get a rapid promotion. As to the state level, different measures should be considered with respect to ecological and environmental characteristics of different subregions to restore the ecological, environmental, and functional states of the whole lake.

Discussion of Results

The PSR framework allows an evaluation of human activities, in both positive and negative sides, that resulted in health changes, which is one of the easiest frameworks to use. It has proven valuable in highlighting the cause-effect relationships between human activities and health conditions. As it only shows where linkages exist among ecological, economic, and social issues, it can help decision-makers and the public see how these issues are interconnected. Thus, it can also help policy makers design policies that address the key problems at the different levels. It therefore provides a means of selecting proper indicators in a way that is useful for decision-makers and the public.

Despite its many advantages, discussions of the PSR model have generally revealed some limitations or challenges [24]. For example, it is insufficient to describe, understand, and manage social and ecological interactions. Due to its simplicity, the PSR framework tends to suggest linear relationships in the human activity-ecological health interaction. In other words, the index system is established from three aspects that affect or relate to lake ecological health, but these indicators cannot indicate precisely how

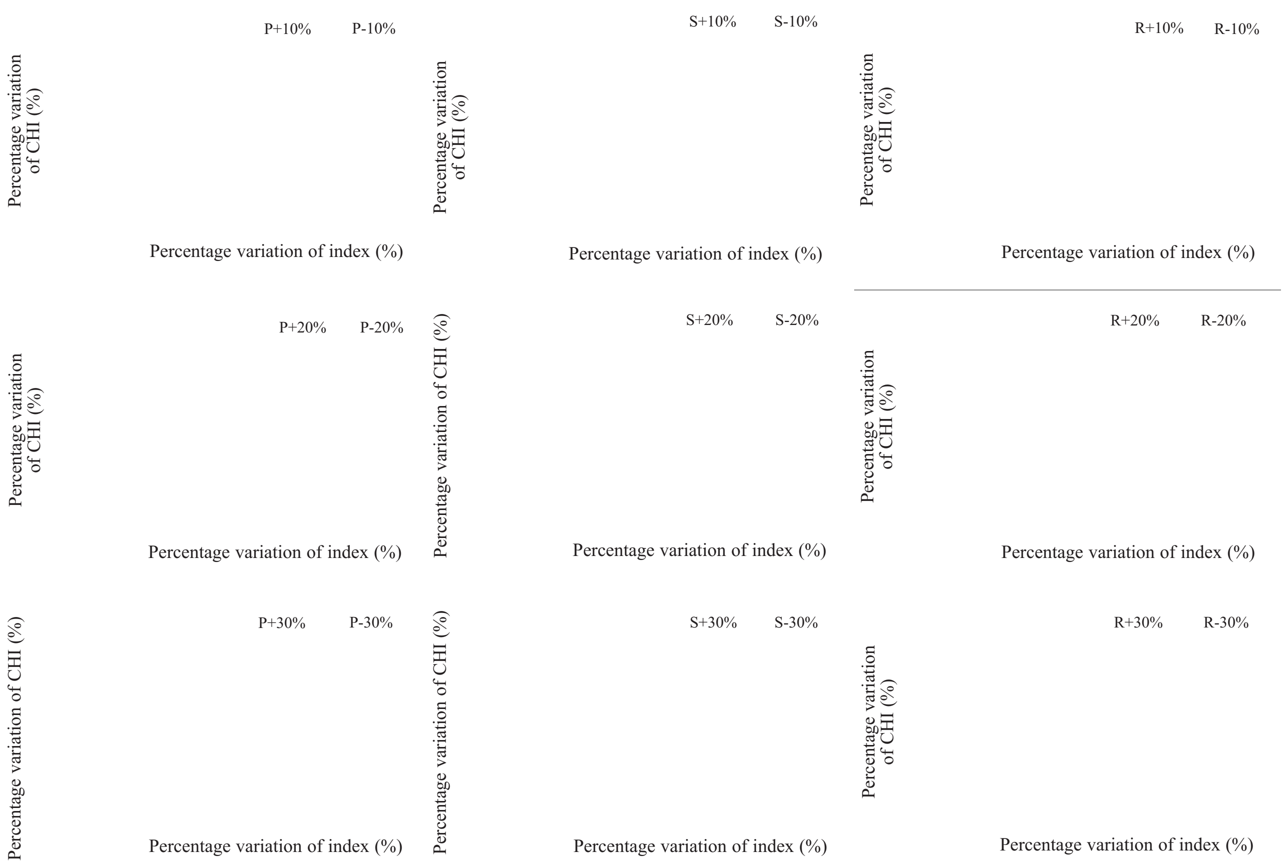

Fig. 5. Sensitivity analysis for the PSR assessment framework of Ulansuhai Lake.

social and ecological issues are related [31]. It cannot handle more complex relationships in ecosystems and in environment-economy interactions. When trying to use the PSR framework for health assessment, these weaknesses need to be given further consideration. A potential solution is introducing new tools to tackle with the complex relationships among ecosystems and social-economic systems. For example, by constructing a causal network for a particular problem, it is possible to identify relevant indicators in a structured manner [32]. Ideally, each indicator in an indicator system should have a particular function in analysis of the ecosystem health issues. A challenge of the PSR framework is to select ideal indicators to represent pressure, state, and response of a lake. The expert panel method was usually chosen to select the "best" indicators [33]. To facilitate future research, formal selection criteria should be constructed to direction indicators selection [34]. More empirical data should be collected to help identify effective and efficient indicators.

A limitation of the current study is that we made no difference in three sub-regions' pressure and response indicators. This may result in a low dipartite degree among three sub-regions. As stated above, more empirical data from long-term field monitoring should be collected to get more accurate assessment results.

Conclusions

As a typical wetland in an arid and semiarid area, Ulansuhai Lake has the characteristics of sensitivity and vulnerability. PSR-framework-based health assessment provides a scientific basis for targeting restoration, which depicts the causes and degrees of ecological degradation of lake ecosystems. Moreover, health assessments of different regions increased the accuracy of lake health diagnosis. Analysis demonstrates the following conclusions with respect to the current study.

(1) The PSR framework is a useful and simple tool to formalize overall lake health assessment.
(2) New added pressure and response indicators may provide a more complete picture for ecosystem health assessment since the cause-effect relationship between human activities and lake health can be explored more clearly.
(3) To get a more accurate assessment, future study may focus on developing new methods to tackle the complex relationships among ecosystems and social-economic systems.

Despite some limitations, this study introduced a new framework that can easily assess the health state of lake ecosystems from the perspective of causal-state-effect. We hope the current results provide more valuable information for the management of wetlands.

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