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ASSESSMENT OF WATER RELATED ECOLOGICAL SECURITY UNDER CHANGING ENVIRONMENT IN CHINA

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Abstract

Over the last few decades intensive human activities and climate changing have stressed ecological systems impeding sustainable development of the social economy in many regions in China. The importance of ecological security has gained greater prominence. Sustaining or restoring natural functions of water ecosystems is also crucial for human welfare. To assess water related ecological security (WES), this paper constructed a framework based on the Pressure-State-Response (PSR) model with indicators in terms of society, economy, water resources, water environment and ecology. The Entropy Method was used to determine the weighting of each indicator. Spatial distribution and temporal trend of WES was then analyzed in China. With weighting analyses, dominant factors threatening eco-security were identified. Results show that the basin of Inland Rivers in the Northwest (IRNW) and the basin of Rivers in the Southwest (RSW) are the most ecologically threatened regions in China. In the IRNW basin, the WES is mostly affected by the factors of water consumption ratio and soil erosion area ratio, while in the RSW basin it was influenced by the natural population increase ratio and the investment percent of GDP in environmental pollution treatment. Most WES indexes (WESIs) in the ten basins show an increasing trend, except for that in the basin of Rivers in Southeast (RSE) which has a decreasing trend due to the reduced investment ratio of environmental pollution treatment. These results will provide valuable information to water resources management.

Key words: entropy weighting, Pressure-State-Response (PSR), Water-related Ecology Security (WES)

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1. Introduction

Over the last few decades, ecological challenges both at local and global scales are rapidly arising due to climate change and continued development (Chen et al., 2014; Falkenmark, 2002; Potschin, 2009; Stefu et al., 2017). As ecological security worsens, it has begun to impede the sustainable development of the social economy. Ecological security has been given equal importance with military, economic, political and national security (Farmer, 2005; Ghinea et al., 2017; Huang et al., 2007; Soffer, 2000), that also concentrate the focus of research by many national and international programs (Shi et al., 2006). Ecological security refers to the goal of stakeholders to create a condition where the physical surroundings of a community provide for the needs of its inhabitants without diminishing its natural stock (Chen, 2002; Fortuna et al., 2012; Li and Ren, 2002; Li et al., 2006a, b; Wachernagel et al., 1999; Xiao et al., 2002). It suggests that the state of the ecology does not threaten conditions for human

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existence and the environment for regional development (Brauch, 2007; Li, 2001; Wackernagel, 2002). An environment with a degraded environment and depleted natural resources through over exploitation will weaken or even damage the sustainable development of a region. Water is an important resource in fluvial, lacustrine, basin and wetland ecosystems. Sustaining or restoring the natural functions of water related ecosystems is crucial for human welfare and is also a challenging task with the continuing human population growth and water demands (Barquin and Martinez-Capel, 2011; Postel and Ritcher, 2003). At present, research on water related ecological security (WES) is lacking for quantified assessment results to give effective guidelines to water use (Huang et al., 2010).

The assessment of WES can provide information on the quantity and quality of water alerting to issues and allowing actions to be taken to help reverse the ecological damage (Wu et al., 2005; Yang and Lu, 2002). Some research has explored ecological security assessment, and some methods may be able to apply to the assessment of WES. Two types of approaches available for ecological security assessment are empirical and statistical approaches (Barbiroli et al., 2002; Eisenbeis et al., 1999; Giralt et al., 2007) and pressure-state-response (PSR) models (OECD, 1993; Wang et al., 2010). Empirical and statistical approaches based on regression or probability analysis require a low-cost hardware environment and quick calculation results and have been applied widely to assess regional eco-security (Adriaenssens and Baets, 2004; Enea and Salemi, 2001; Hao nd Zhou, 2002; Park et al., 2004). However, variables used in these approaches are not always easy to acquire. Moreover, methods developed for small spatial scales have been seriously criticized when used at regional level (Li et al., 2006b; Wang et al., 2010). In contrast, the PSR approach is considered to be more effective. It can classify the indicators of eco-security into cause, effect and human response, to understand the extent of anthropogenic impacts on eco-security in a systematic way (Briassoulis, 2001; Crabtree and Bayfield, 1998). However, the PSR approach suggests linear relationships between human activities and the environment, so does not accommodate decision-making support, and the quality and comparability of the existing indicators needs to be improved. To cope with these shortcomings, some statistical approaches such as entropy, AHP (Analytic Hierarchy Process), Expert Decision (Expert System Analyses) have been used to accurately and systematically represent interconnections between indicators. The PSR framework, combined with statistical approaches, has been widely applied (Dai et al., 2001; Wang et al., 2008a; Wolfslehner and Vacik, 2008; Ye et al., 2011). With increasing water resource shortages in China, conflicts between economic and ecological needs are unprecedentedly high and vary between regions. Thus, the assessment of WES across China is important for sustainable water resources management and ecological restoration and protection. In this paper WES was assessed at both national and basin scales based on the PSR framework and entropy method. Spatial patterns and trends were also studied to find out the dominant influencing factors, to help policy-makers and stake-holders effectively protect and restore the environment, to help maintain a sustainable socio-economy.

2. Methodology

2.1. Study area

The mean annual precipitation for China is 645 mm. Precipitation in the south is much more than that in the north as it is affected by the East Asia Monsoon climate. In some southern areas, the mean annual precipitation exceeds 2000 mm while it is less than 400 mm in some northern parts. Of China's water resources, there is 2, 711.5 km^3 in rivers and 828.8 km^3 in the ground. However, available water resources are only 2, 821. 4 km^3, and 80% are in the south of China.

To facilitate the management of water resources, the whole area of China is divided into ten water resource basins (Fig.1). Among those basins, the Songhua River, the Liao River, the Hai River, the Yellow River, the Huai River, and the northwest inland river basins are located in the north where the total annual surface water resources average 20% of the whole of China. In contrast, the Yangtze River, the Pearl River, and the southeast and southwest rivers basins are located in the south, where the total annual surface water resources average over 80%. The water resource distribution in the ten basins is shown as Table 1. In recent years, water problems including water shortages, water pollution and water quality deterioration have been increasing as a result of the growing population, rapid economic development and lax environmental oversight. In return, these problems have placed great barriers for sustainable development for society.

China has the fifth largest amount of internal renewable water resources in the world but has lower water resources per capita and severe regional water crises. China is about 21% of the world population but only about 6% of the freshwater and 9% of farmlands. Total renewable water resource per capita in China in 2010 is 2, 310.4 m^3, while the global average is 6, 466 m^3 per capita (World Bank, 2010). Water shortages are largely concentrated in the dry north area, including the Yellow River basin, the Liao River basin, the Hai River basin and the Huai River basin, which contain 65% of China’s cultivated cropland, but have only 20% of China’s water. Meanwhile, over exploitation of rivers has resulted in negative impacts to the rivers and lakes. One serious example is the natural flows of the Yellow River have been greatly reduced by dams and other irrigation infrastructure, which has threatened to dry up the river in the past 50 years. The cessation of river flows, or flow stoppages has surged since the 1980s. The situation improved after 2000 with the adoption of uniform water allocation and management across the whole Yellow River Basin.

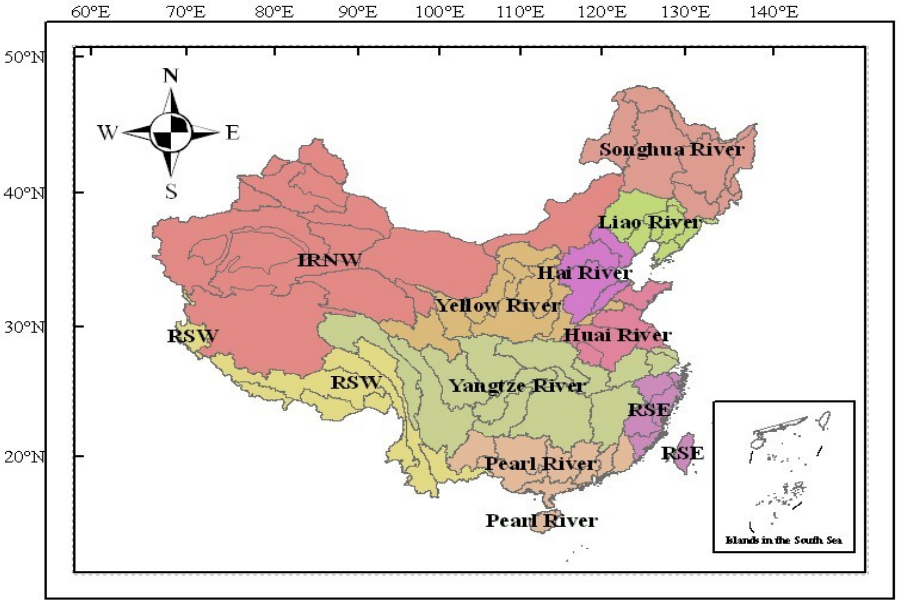

Fig. 1. The ten water-resource basins in China

Table 1. Water resources in the ten water resource basins*

GradeIwater resources regions	*Population (10^8)*	*Area (10^4km^2)*	*Total water resources (10^8m^3)*	*Total water use (10^8m^3)*
The Songhua River	0.65	90.34	1537.2	503.5
The Liao River	0.57	34.50	716.9	205.8
The Hai River	1.42	31.82	436.7	371.8
The Yellow River	1.12	79.47	771.8	388.6
The Huai River	1.99	32.92	746.2	647.7
The Yangtze River	4.42	180.85	10807.0	2002.8
The Pearl River	1.82	58.06	5077.2	864.7
Rivers in the Southeast(RSE)	0.79	23.98	2749.4	337.0
Rivers in the Southwest (RSW)	0.21	85.14	5256.2	108.0
Inland Rivers in the Northwest(IRNW)	0.31	332.17	1430.4	701.3
Total	13.29	949.26	29528.8	6131.2

**Data in Table 1 are from China Water Resource Bullet (2012) and China Water Statistic Yearbook (2013)*

The groundwater is also greatly over-extracted, especially in the north of China. In the Hai River Basin, groundwater use accounts for 64% of the total water use. In the Songhua River basin, the Liao River basin and the Yellow River basin, the groundwater in 2012 was made up 43%, 54%, and 32%, respectively. The intensive use of groundwater resources has resulted in the lowering of water tables and the rapid depletion of groundwater reservoirs. The depletion of groundwater resources in turn dried up lakes and wetlands and salinized the groundwater.

Deterioration of drinking water quality is also a great challenge in China. According to FAO, 80% of the 50,000 km of major rivers in China is so degraded that they no longer support fish (FAO Disclaimer, 2010). Around urban areas 90% of rivers are seriously polluted, especially in the north where heavy industry is concentrated. 65% of the Hai River, 64% of the Huai River and 45.5% of the Yellow River are classified as polluted, where water quality is lower than Grade III of national water quality standards (water resources bullet, 2012).

Furthermore, these water quality issues, coupled with seasonal water scarcity, spark endemic water shortages and therefore negatively affect peoples' daily life. Continuous waste emissions from manufacturing are the largest contributor to the degraded water quality. Additionally, introduction of poorly treated sewage, industrial spills, and extensive use of agricultural fertilizers and pesticides have proven to be major contributors as well (FAO Disclaimer, 2010). According to the China Statistical Yearbook (2011), there are 79.2 billon tons of waste water discharge, in that the industrial waste water is about 23.75 billion tons, 30% of the total discharge; and the domestic waste water discharge come to 38 billion tons, 48% of the total discharge. High frequency river pollution incidents, such as the drinking water source pollution by algae in the Tai Lake, Wuxi in May 2007, Jilin chemical plant explosions in 2005 (Meng, 2010), also threaten the water supply security and increase the risk of water resources.

2.1. Method

2.1.1. Pressure-State-Response (PSR) model

The key problem of WES assessment is how to describe the status of an ecosystem in reasonable and qualified ways. Ecological security indicators representing a numerical or a descriptive categorization of environmental data have been suggested as useful tool. A series of typical indicators give information about the condition of a system, and simplify the communication of its components (OECD, 1993). The usefulness of indicators can be enhanced by putting them into the pressure-state-response (PSR) framework proposed by OECD (OECD, 1993, 1997), which has been widely used as a tool to model human–environmental systems (OECD, 1999, 2004). The PSR model, consisting of a feedback system of pressures, states and responses, is built on the linkages among the human activities, the state of the ecology, and the societal and economic responses to the ecology change (Linser, 2002). It provides a mechanism to monitor the status of the eco-environment and serves as a framework for investigation and analysis, in which indicators of environmental, ecological, social, economic, and institutional characteristics are considered. In combination with appropriate indicators, the particular components and their developments can be assessed.

The selection of indicators plays a key role in the application of PSR model to WES assessment. Based on the concept of causality, three categories of indicators expressing the condition of "pressure, state, response" are therefore distinguished in this paper, as follows. First, pressure indicators are used to describe pressures on the water related ecology from human activities and climate change. In China the most severe WES problems are the over exploitation of water resources and the deterioration of ecology of water systems. The latter is usually caused by water exploitation and waste water emission. So the principal pressure indicators comprise population increase, economy, water utilization and wastewater emission. Second, state indicators describe the status quo of the natural eco-security. Herein, we choose some indicators depicting the condition of water quality, quantity and water eco-environment for the status quo. Third, response indicators show the degree to which society responds to eco-environmental changes and concerns. This could be the number and kind of measures taken, the efforts of implementing measures, or the effectiveness of those measures (Linser, 2001; Wolfslehner and Vacik, 2008).

In this paper, the indicators are chosen from the measures of water-saving, water pollution treatment and economic investment. In total, 19 independent indicators were chosen to represent water related eco-security principal traits. Four levels (target level, project level, factor level, and indicator level) were classified in an adapted PSR framework, as shown in Table 2.

Table 2. Indicators of the PSR framework

Project	***Factors***	***Indicators***	***Depicts***
Pressure (P)	Environment pressure (P1)	Water use per capita (m^3/ per capita) (X1)	Gross amount of water resources divided by total population; the pressure from population.
		Wastewater emissions ratio (%) (X2)	Waste water emission amount into rivers divided by surface water resources amount**;** pressure from pollution with economic development
		Farming fertilizer use (kg/per hectare) (X3)	Consumption of chemical fertilizer divided by total sown areas of farm crop; pressure from farming pollution
		Water consumption ratio (%) (X4)	Water consumption amount divided by total water use amount; pressure from water efficiency
	Economic pressure (P2)	Water uses per GDP (m^3/10^{4}yuan) (X5)	GDP divided by total water use amount; pressure from economic water use, reflecting the relationship between water resources and society, economic
	Population pressure (P3)	Natural population increase ratio (%) (X6)	Pressure from population increasing
State (S)	Water Resource state (S1)	Water resources exploitation and utilization ratio (%) (X7)	Water supply divided by gross water resources
		Surface water exploitation and utilization ratio (%) (X8)	Surface water supply divided by surface water resources
		Groundwater exploitation and utilization ratio (%) (X9)	Groundwater supply divided by groundwater resources
		Underground funnel area ratio (%) (X10)	Underground funnel area divided by plain area
	Water Environment state (S2)	Percentage of I-III river length (%) (X11)	I-III river length divided by total river length
		Eutrophication percentage of lake and reservoir (%) (X12)	Eutrophicated lake and reservoir divided by total lake and reservoir
	Water ecology state (S3)	Soil Erosion Area ratio (%) (X13)	Soil erosion area divided by total area

Response (R)	Society response (R1)	Sewage and rainfall reuse rate (%) (X14)	Sewage and rainfall reuse divided by total water use
		Water-saving Irrigated Area ratio (%) (X15)	Water-saving irrigated area divided by total irrigated area
		Urban water Reuse Rate (%) (X16)	Urban Water reuse divided by total urban water use amount
		Industrial Wastewater Ratio Meeting Discharge Standards (%) (X17)	Industrial waste water meeting discharge standards divided by industrial waste water
		Natural reserve area ratio (%) (X18)	Natural reserve area divided by total area
	Economic response (R2)	Investment percent of GDP in Environmental Pollution Treatment (%) (X19)	Investment of GDP in environmental pollution treatment divided by GDP

2.1.2. Data processing

Large differences in dimension and magnitude usually exist among. the indicators of a multiple criteria decision-making model. Even for the same indicator, there is sometimes great disparity in magnitude among various evaluated samples. In order to effectively execute multiple criteria decision-making, the influences derived from dimension and magnitude of indicators should be eliminated. A large number of approaches have been utilized to fulfill such intention (Hsu, 1983; Reese and Schwalbe, 1993; Zhao et al., 2006). Eqs. (1-2) are used to standardize the data from various sources.

(1) Standardization of positive index:

$$y_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \quad (i=1, n;\ j=1, m) \tag{1}$$

(2) Standardization of negative index:

$$y_{ij} = \frac{x_{\max} - x_{ij}}{x_{\max} - x_{\min}} \quad (i=1, n;\ j=1, m) \tag{2}$$

Among that, n is the number of the indicators, m is the number of years, x_{ij} is the original data; y_{ij} is the standardized data; x_{max} and x_{min} is the maximum and minimum values. For the indices in Eq. (1), the higher their values are, the greater the positive effect they will bring to the WES. Conversely in Eq. (2), the higher values bring more negative effect to the WES. The value of y always lies between 0 and 1. And a larger y means a greater impact on eco-security.

2.1.3. Indicator-weighting determination by the entropy method

In the PSR framework, the weighting of each indicator is of great significance and complication. It determines the efficiency and precision of the assessment results. The entropy method proves an appropriate method for deriving the weighting assigned to each indicator objectively and has been applied widely in environmental evaluation and sustainable management (Dong and Liu, 2011; Mon et al., 1994; Zhang et al., 2003; Zhou and Wang, 2005).

Information entropy represents uncertainties, it can measure effective information from the data provided. The entropy and entropy weighting decrease with the reduction of the amount of information, and vice versa (Ye and Ke, 2006). The computation of entropy and entropy weighting is as Eqs. (3-4), where: H_j is the entropy of the index j (Wan, 2009):

$$H_j = -K\sum_{i=1}^{m}(f_{ij}\ln f_{ij}) \tag{3}$$

$$K = \frac{1}{\ln n} \tag{4}$$

Here, we assume that when f_{ij} is zero, $\ln f_{ij}$ equals to zero. Then, the weighting of the index j can be calculated by Eq. (5).

$$w_j = \frac{1 - H_j}{\sum_{j=1}^{n}(1 - H_J)} \quad \left(0 \le w_j \le 1, \sum_{j=1}^{n} w_j = 1\right) \tag{5}$$

After the weightings have been determined, the water related eco-security index (WESI) can be calculated by Eq.(6):

$$WESI = \sum_{j=1}^{n} y_j w_j \tag{6}$$

where: $WESI$ is the index of the ecology security; w_i is the weighting of the index j; y_i is the indicator transformed into the comparable scale.

3. Results and discussion

3.1. Temporal and spatial distribution pattern of WESI

3.1.1. Spatial distribution of the WESI

Averaged WESI value in 2010-2012 is used to depict the current condition of the ecology security in the ten basins in China, ranked as Table 3. Results show that the safer ecological basins are the Pearl River basin and the Liao River basin (with WESI of 0.49 and 0.44); the riskier ecological basins are the IRNW basin and the RSW basin (WESI: 0.23, 0.20).

In the IRNW basin, the WES is mostly affected by the factors of water consumption ratio, water use per GDP and soil erosion area ratio. The factors of Water consumption ratio and water use per GDP stand for the water use efficiency in a region. In the IRNW basin Water consumption ratio is up to 68%, and ranks the first in the ten basins; water use per GDP almost reaches 700 $m^3/\ 10^4$yuan, more than national mean value (118) fatherly.

Table 3. The Pressure-State-Response of 2010-2012 in the ten basins

Basin	***Pressure***	***State***	***Response***	***WESI***
The Pearl River	0.37	0.70	0.76	0.52
The Liao River	0.17	0.33	0.53	0.44
The Songhua River	0.50	0.41	0.70	0.43
The Yangtze River	0.52	0.42	0.30	0.41
The Hai River	0.16	0.22	0.83	0.39
The Yellow River	0.30	0.31	0.53	0.37
RSE	0.21	0.79	0.39	0.29
The Huai River	0.23	0.30	0.22	0.27
IRNW	0.34	0.02	0.34	0.23
RSW	0.65	0.87	0.18	0.20

This is because the drier climate leads to the higher evapotranspiration; the bigger ratio of high-water-consuming industries and less developed irrigation technology lead to lower water use efficiency. Soil erosion area ratio (53% in IRNW basin) also ranks the first among the ten basins.

The reason is that the lower but intensive precipitation erodes the soil lacking of vegetation protection. In the RSW basin, the natural population increase ratio and the percent of GDP investment in environmental pollution treatment greatly contribute the WESI. The natural population increase rate ranks the first in the ten basins with the ratio of 0.66% and the investment percent of GDP in environmental pollution treatment (0.46%) ranks the last in the ten basins. Dominated by these factors, the comprehensive WESI ranks the last.

3.1.2. Temporal change trend

WESI can be divided into the pressure security index, state security index and response security index according to the PSR framework. WESI in the ten basins from 2003 to 2012 are calculated, as shown in Fig. 2. Most WESIs in the ten basins show more or less an increasing trend except for that in the RSE basin of which WESI reveals a decreasing trend. That suggests the WES condition in most basins has been improving and is better than the earlier years.

Among the ten basins, the most remarkable increasing trend of the WESI appears in basins of the Yangtze River, the Liao River, and the Songhua River, with WESI-increase-slope of 0.44/10a, 0.37/10a and 0.24/10a, respectively. In the Yangtze River basin, the WESI increases from 0.19 to 0.54 during the period from 2003 to 2012 which benefits from the decrease of underground funnel area ratio. Water resources in the Yangtze River basin are relatively abundant, with the groundwater utilization in the whole basin lower compared to the northern basins.

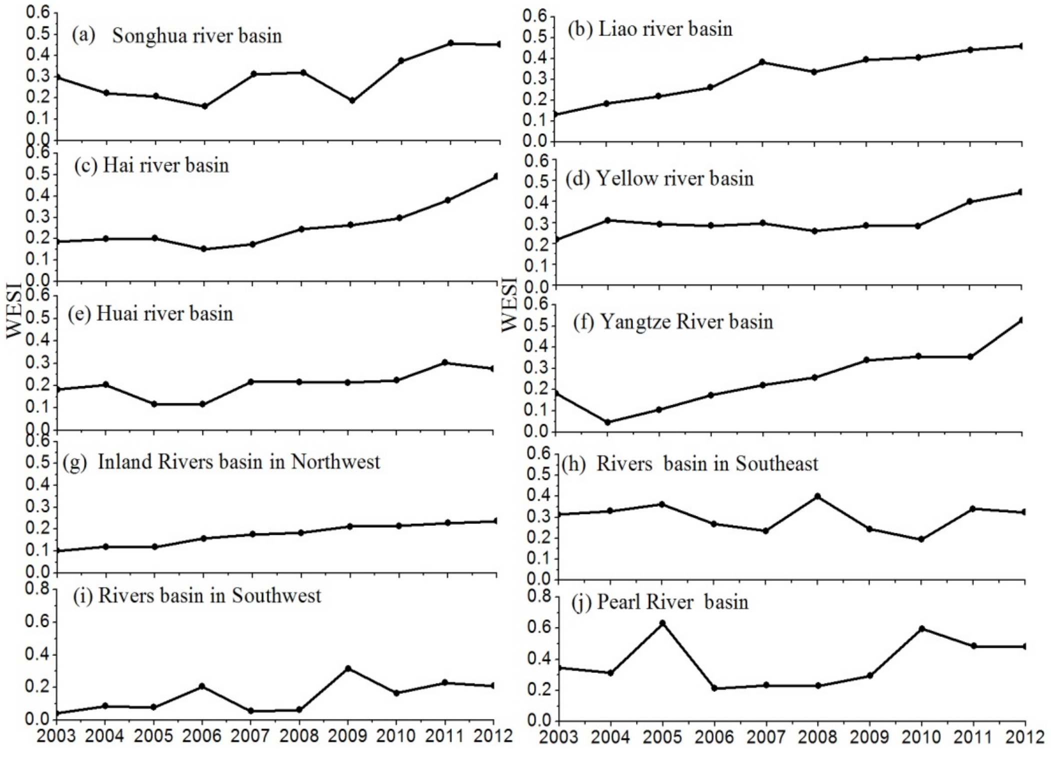

Fig. 2. WESI variations over time in the ten basins

However, in some regions of the basin, especially for the Yangtze River Delta, severe over-exploitation of groundwater has led to the decline of the groundwater level, which resulted in the higher underground funnel area ratio. In 2003 the underground funnel area is 12,369.58 km^2, accounting for 41% of total plain area in the Yangtze River basin, and in 2012 the area has decreased to 6,714.39 km^2, 22.5% of total plain area (Wang, 2012). In the Liao River basin, the WESI value changes from 0.13(in 2003) to 0.46 (in 2012). This increase was mainly attributed to the sewage and rainfall reuse rate changing from 0.16% to 1.7% during the period from 2003 to 2012. The increase can effectively alleviate the pressure from water use. Also, the improvement in river water quality with the increasing percentage of I-III river length, increasing from 28% to 44.1%, is another important reason for the rising trend of WESI. In recent years, some effective measures have been adopted to control water pollution in Liao river basin, and waste water emission amount is decreasing. So, the water quality in rivers and lakes is also getting better. Further, the increasing water-saving irrigated area ratio (from 36.5% to 70.4%) contributes to the improving ecology security of the Liao River basin to some degree. The development of technology for water-saving improves ecology security.

In the Songhua River basin, the WESI increased from 0.30 (2003) to 0.45 (2012). The factor that contributed most was the increasing percentage of I-III river length which changed from the 45.6% (2003) to 56.9% (2012). Also, the eutrophication percentage of lake and reservoirs changed from 14.81% in 2003 up to 23.5% in 2008 and decreased to 9.1% in 2012. The bettering water quality of rivers/lakes can be explained by the changing investment percent of GDP in environmental pollution treatment from 1.17% (2003) to 1.54% (2012). The investment in the environment is important to provide the economic security for environment protection. Greater attention is also being paid to pollution treatment.

Conversely, the WESI is descending in the basin of the southeast rivers because of the reduction of investment ratio of environmental pollution treatment. During the period of 2003-2012, the investment ratio in 2008 is the highest, up to 1.854%, while it is only 0.89% in 2011 and 1.11% in 2012. Additionally, farming fertilizer use amount is also an important factor leading to the descending water related ecology security. In RSE basin, the fertilizer use appearing the increasing trend from 38.73 kg/per hectare (2003) to 45.65 kg/per hectare (2012). Non-point pollution caused by the farming fertilizer is the major contributor of eutrophication of lake and reservoir. And the eutrophication percentage of lake and reservoir in the RSE basin is also increasing. The trend of WESI can be explained by its components – the pressure security index (PSI), the state security index (SSI) and the response security index (RSI),

A smaller PSI value means a higher pressure. Comparisons among the basins show that pressure value and the trend vary in the different basins (Fig. 3). In IRNW and RSE, the PSI is rising which means the pressure is decreasing. This is because of the decrease of the population increase rate and economic water use. According to Water Resources Bullets of China (2003-2012), in RSW basin water use per 10, 000 RMB GDP changes from 1,114 m^3 to 299m^3 and the value in IRNW basin also changes from 2,288 m^3 to 576 m^3. This means water use efficiency has been greatly enhanced and ecology security is alleviated by the reduction in pressure. However, the adverse effect of pressure in the Huai River and the Hai River has been strengthened. The assessment shows a declining trend of pressure security index in those basins. In the Huai River basin, the pressure is mainly caused by the increase of waste water emission, fertilizers use and water consumption.

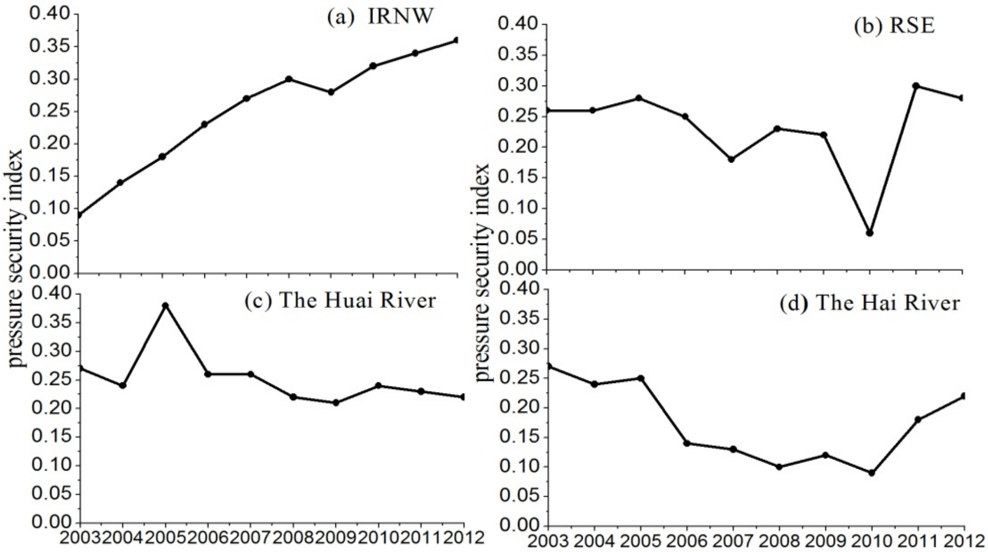

Fig. 3. Variation of PSI over time in four typical basins

With the development of agriculture, industry and urbanization, more and more polluted water and sewage were poured into rivers, and lots of fertilizers were adopted to farming caused more non-pointed pollution. In 2003, waste water emission sums up to 4.978 billion-ton, accounting for 3.27% of the total surface water resources, and the ratio increases to 17.33%in 2012. The fertilizer use per hectare also increases 18%. In addition, water consumption ratio is increasing from 65% to 68% in the Huai River, as well as 67% to 69% in the Hai River. As to SSI, the protection of environment and ecosystems has received more attention with the rapid development of society. Therefore, the SSI in most basins takes up an unchanged or rising trend.

In the Yangtze River basin and Hai River basin, there is an obvious increase in the SSI (Fig. 4). This is because of the decrease of the underground water funnel area in the Yangtze River, and the reducing exploitation and utilization ratio of water resources contributes the rising trend of SSI in Hai River basin. In 2005 and 2006, the SSI of the Huai River declined because a sudden water contamination event led to the water resources' deterioration and lakes' severe eutrophication. In recent years, effective control measures greatly improved water quality. However, in IRSW basin, a drier climate and less water resources along with unreasonable water exploitation led to severe soil erosion, thus the state security has been declining since 2003.

In respect to RSI, the response measures sustaining the ecological health have brought a positive effect. Most basins' RSI appears to an increasing trend. In the Pearl River basin, the RSI experiences a change from 0.33 in 2003 to 0.88 in 2010, and then 0.73 in 2012, which was mainly caused by the increasing investment on pollution treatment (Fig. 5).

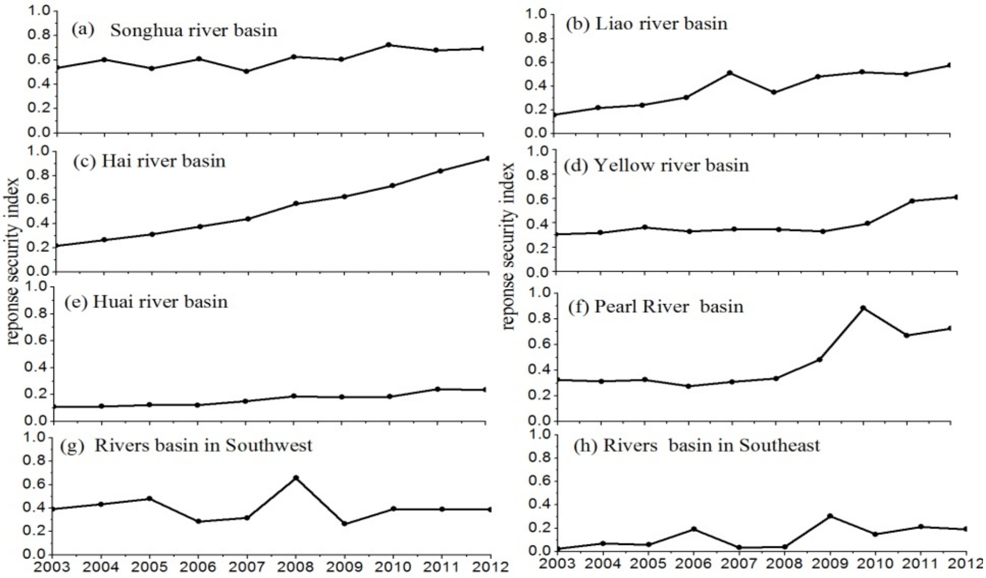

Fig. 4. Variation of SSI variations over time in seven typical basins

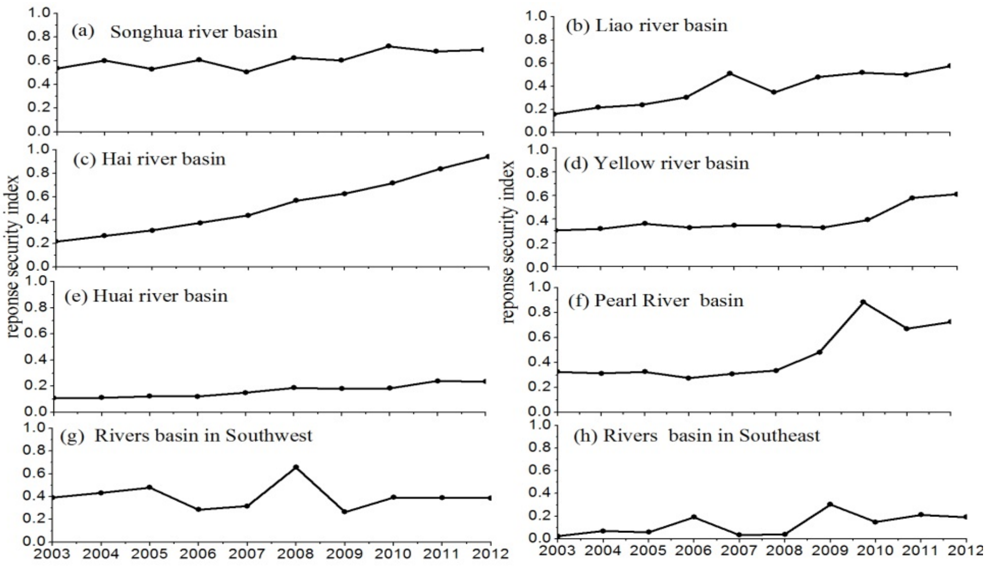

Fig. 5. Variation of RSI over time in eight typical basins

The Liao River basin has the same trend of RSI with the value of 0.16 in 2003, and up to 0.58 in 2012. Also in the Hai River, it is 0.22 in 2003, up to 0.94 in 2012 with multi-fold increases. Besides the investment increase, the application of water–saving technology was also beneficial, such as the increase of sewage and rainfall reuse rate and water-saving irrigated area ratio

3.2. Dominant factors in the ten basins

Weightings of Pressure (P), State (S) and Response (R) demonstrate importance of P, S and R. Thereby; all basins can be classified into three categories: pressure-dominated, state-dominated and response-dominated basins. In pressure-dominated basins there are bigger weighting values for pressure indices and the ecological security is threatened by factors from water exploitation and use, waste water emission and population increase. This means that the persistent pressure from the development of society and economy would deteriorate the eco-environment. It is likely that in state-dominated basins, the ecology security depends mainly on the state of the water resource, water quality and water ecology. The ecological security in response-dominated basins depends on factors of beneficial human activities, economic investment and government policy. Taking the RSW basin as an example, the weighting of response is up to 0.96, which mean that the RSW basin is response-dominated, and therefore beneficial human activities, such as water ecosystem protection and water pollution control, can improve the ecological security to a great degree.

According to the weightings in Table 4, the pressure-dominated basins are the Pearl River and RSE with the weighting of 0.61 and 033; the state-dominated basins consist of the Songhua River, the Hai River, the Yellow River, the Huai River, the Yangtze River, and IRNW with the weighting of 0.92, 0.50, 0.53, 0.60, 0.87, and 0.36 respectively. The response-dominated basins encompass basins of the Liao River and the RSW with the weighting of 0.54 and 0.96.

Comparison among indicators of each factor was conducted to elucidate the influence of different indicators on assessment results (Table 5). As for pressure, the environment pressure (P1) is the most important in northern river basins, and Population pressure(P3) affects a lot in some southern river basins; for State, environment pressure (S2) can be used to explain most of the WESI's variation; for response, half of all basins are focused on the society response index (R1) (the Songhua River, the Liao River, the Hai River, the Yellow River, the Huai River, the Yangtze River) while others focused on the economic response index (R2). Dominated factors of the ecology security in each basin are listed in Table 6. Ecological security results from a variety of ecological, economic and social changes. The WESI provides a scientific foundation for regional eco-environmental management. Government and stake-holders should pay more attention to areas with lower WESI values, especially the high-weighting factors in these areas. Based on the spatial pattern of the WESI and natural condition, practicable measures should be undertaken to control eco-environmental degradation in different basins.

Table 4. Weighting of indices of Pressure (P), State (S) and Response (R)

Basin	*Pressure (P)*	*State (S)*	*Response (R)*
The Songhua River	0.00	0.92	0.08
The Liao River	0.01	0.45	0.54
The Hai River	0.20	0.50	0.29
The Yellow River	0.16	0.53	0.31
The Huai River	0.12	0.60	0.29
The Yangtze River	0.06	0.87	0.07
The Pearl River	0.61	0.02	0.38
RSE	0.61	0.01	0.38
RSW	0.03	0.01	0.96
IRNW	0.35	0.36	0.29

For the northern basins such as the Songhua River, the Huai River, the Hai River and the Yellow River, more attention should be paid to water quality and lake/reservoir eutrophication, thus effective measures for pollution control and treatment should be taken to protect and maintain the ecological environment. In southern basins like the Pearl River, the RSW and the RSE, environmental pollution treatment investment should be emphasized, especially for the RSE. In the IRNW basin, measures should be taken for soil erosion and desertification prevention which are most weighted for ecology security. Due to the arid climate and rare water resources in these areas, it is important to adjust the industrial structure and enhance the water use efficiency. Determination of the assessment factors and their weightings are crucial in the PSR framework process. Although it is useful to have large amounts of information in the assessment model to get useful and comprehensive result, in practice it is impossible to include all the factors affecting eco-security in an evaluation model. As such only indicators reflecting the water quantity, quality, environment and ecology traits were chosen in this paper. Moreover, a slight change in weighting coefficients can have a significant effect on the eco-security analyses results (Saisana and Saltelli, 2008; Wang et al., 2010).

Therefore, this paper took the entropy to obtain the different indicators' weighting. With this method the weighting mainly depends on the changing trend of historical data and therefore weighting results are objective (Basso et al., 2000; Store and Kangas, 2001; Wang et al., 2008b).

Table 5. Weighting of sub-indices of P, S and R

Basin	***Pressure (P)***			***State (S)***			***Response (R)***	
	Environment pressure (P1)	***Economic pressure (P2)***	***Population pressure (P3)***	***Water resource state (S1)***	***Water environment state (S2)***	***Water ecology state (S3)***	***Society response (R1)***	***Economic response (R2)***
The Songhua River	0.59	0.33	0.08	0.01	0.97	0.02	0.31	0.69
The Liao River	0.90	0.06	0.05	0.04	0.92	0.04	0.93	0.07
The Hai River	0.52	0.00	0.48	0.65	0.35	0.00	0.86	0.14
The Yellow River	0.67	0.02	0.31	0.02	0.94	0.04	0.87	0.13
The Huai River	0.71	0.00	0.28	0.06	0.94	0.00	0.95	0.05
The Yangtze River	0.13	0.04	0.83	1.00	0.00	0.00	0.90	0.10
The Pearl River	0.30	0.00	0.70	0.03	0.97	0.00	0.17	0.83
RSE	0.60	0.01	0.39	0.16	0.74	0.10	0.15	0.85
RSW	0.22	0.59	0.19	0.00	1.00	0.00	0.27	0.73
IRNW	0.58	0.32	0.09	0.00	0.02	0.98	0.88	0.12

Table 6. Dominated indicators for different type of basin

Type	***Basin***	***Dominate indicators (weighting)***
pressure-dominated	The Pearl River	natural population increase ratio (0.42)
	RSE	Farming fertilizer use (0.33)
State-dominated	The Songhua River	Percentage of I-III river length (0.87)
	The Hai River	Percentage of I-III river length (0.18)
	The Yellow River	Percentage of I-III river length (0.5)
	The Huai River	Eutrophication percentage of lake and reservoir(0.33)
	The Yangtze River	Underground funnel area ratio (0.87)
	IRNW	Area ratio of Soil Erosion (0.35)
Response-dominated	The Liao River	Sewage and rainfall reuse rate (0.37)
	RSW	Environmental Pollution Treatment Investment (0.7)

4. Conclusions

To assess the Water related Ecological Security (WES) in the ten basins of China, a Pressure-State-Response (PSR) model with indicators of society, economy, water resources, water environment and ecology was constructed. Based on the datum of 2003 to 2012, the entropy method was used to determine the weighting of each indicator. Afterwards the WESI of each basin in every year was calculated. Based on these results, the temporal and spatial distribution of WES was analyzed to identify the ecologically safer basins and the basins ecologically at risk. By using the weighting analysis, dominant factors that significantly threaten eco-security were determined. Results show that,

(1) The basin of Inland Rivers in the Northwest (IRNW) and the basin of Rivers in the Southwest (RSW) are the most ecologically threatened regions in China. In the IRNW basin, the WES is mostly affected by the factors of water consumption ratio and soil erosion area ratio; while in the RSW basin the natural population increase ratio and the investment percent of GDP in environmental pollution treatment influence the WESI greatly.

(2) Most WES indices (WESIs) in the ten basins of China show an increasing trend except for that in the basin of Rivers in Southeast (RSE). The WESI in RSE reveals an apparent decreasing trend due to the reduction of the investment ratio of environmental pollution treatment.

(3) According to the dominant factors of WESI, the basins are divided into pressure-dominated ones with the Pearl River and RSE; the state-dominated ones with the Songhua River, the Hai River, the Yellow River, the Huai River, the Yangtze River, and IRNW; and the response-dominated ones with the Liao River and the RSW.

All these results would provide valuable information to the decision-makers for the eco-environment and water resources management. However, for the limitation of historical data, there exist some uncertainties in the results. The choice of model is always a compromise between accuracy and costs. Therefore, long-term data on the whole water ecosystem is important in the future.

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