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Sustainability assessment of regional water resources under the DPSIR framework

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SUMMARY

Fresh water is a scarce and critical resource in both natural and socioeconomic systems. Increasing populations combined with an increasing demand for water resources have led to water shortages worldwide. Current water management strategies may not be sustainable, and comprehensive action should be taken to minimize the water budget deficit. Sustainable water resources management is essential because it ensures the integration of social, economic, and environmental issues into all stages of water resources management. This paper establishes the indicators to evaluate the sustainability of water utilization based on the Drive-Pressure-Status-Impact-Response (DPSIR) model. Based on the analytic hierarchy process (AHP) method, a comprehensive assessment of changes to the sustainability of the water resource system in the city of Bayannur was conducted using these indicators. The results indicate that there is an increase in the driving force of local water consumption due to changes in society, economic development, and the consumption structure of residents. The pressure on the water system increased, whereas the status of the water resources continued to decrease over the study period due to the increasing drive indicators. The local government adopted a series of response measures to relieve the decreasing water resources and alleviate the negative effects of the increasing driver in demand. The response measures improved the efficiency of water usage to a large extent, but the large-scale expansion in demands brought a rebounding effect, known as "Jevons paradox" At the same time, the increasing emissions of industrial and agriculture pollutants brought huge pressures to the regional water resources environment, which caused a decrease in the sustainability of regional water resources. Changing medium and short-term factors, such as regional economic pattern, technological levels, and water utilization practices, can contribute to the sustainable utilization of regional water resources.

1. Introduction

Fresh water is an increasingly critical issue at the forefront of global policy change, management and planning (Grafton and Hussey, 2011). The imbalance between water availability and water demand causes water scarcity, which has become one of the most pressing issues in the world (Peterson and Schoengold, 2008). Rapidly expanding demand combined with increased competition over limited water resources has led to water shortages worldwide. The situation may worsen due to population growth, global climate change, and water quality deterioration (Chartres and Varma, 2010; Emelko et al., 2011; Qu et al., 2013). According to the prediction, approximately 60% of the world's population will face blue water shortages, and 36% will face both green and blue water shortages by 2050 (Rockström et al., 2009). One of the major solutions to this global water crisis is improved management of this valuable natural resource (Oelkers et al., 2011). Improving the global management of water resources is one of the most crucial challenges of the 21st century (Jury and Vaux, 2005; Emelko et al., 2011). Policy for the protection of water resources requires a more holistic and integrated approach to transcend disciplinary boundaries, overcome fragmented governance, and create solutions through collaborative planning (Bowmer, 2011, 2014). Current water management practices are not sufficient to alleviate the global water crisis as the water "deficit" still continues to grow,

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and comprehensive action should be taken to minimize this water budget imbalance (Ayers, 2001; Wyatt et al., 2015). Meanwhile, mounting evidence shows that current water management and utilization practices are unsustainable (Gleick, 2010). Globally, water resources stakeholders are developing action plans and evolving toward the integration of participatory processes for decision-making (Faust et al., 2013). Water resource systems are based on water circulation and the ecology of a region and therefore maintain the ecological balance among the sustainable development of water resources, the hydrological cycle, and the support of social and economic development. An overview of sustainable water resource management is essential because it can integrate social, economic, and environmental aspects into all processes of water resource management (Juwana et al., 2010; Gleick, 2010). Sustainability assessments of regional water resources contribute to understanding the evolution of the water system and its influences, which contributes to achieving the sustainable management of water resources.

The DPSIR model originated from the Pressure-State-Response (PSR) framework, which was established by the Organization of Economic Cooperation and Development (OECD, 1993). The DPSIR framework evolved into the Driver, Pressure, State, Impact, and Response (DPSIR) model that more explicitly depicts how socioeconomic development impacts the environment (Kelble et al., 2013). Because the DPSIR model can capture the "cause–effect" relationships between the sectors of social, economic, and environmental systems, it has been widely applied to analyze the interacting processes of human-environmental systems (Gabrielsen and Bosch, 2003; Feld et al., 2010; Pinto et al., 2013; Hou et al., 2014). The DPSIR model describes a general chain which triggers environmental issues between the origin and the results. This chain indicates that societal, economic and population development act as drivers (D) on the environment, thus producing pressure (P) on it, which gives rise to a change in its status (S) and thus affects it. All of these effects then either urge humans to respond (R) to the environmental status (S), changing the complex systems which consists of society, economics and population, or directly act on environmental pressure (P), status (S) and influence (I). This model looks at the interaction between socioeconomic development and the environment, analyzing the overall system they comprise, and it is widely used in environmental systems to evaluate key indicators. This model also serves as a general framework for organizing information about the status of the environment (Westing, 1989; Elliott, 2002). The DPSIR framework contributes to the understanding of relationships between system "state" and "driver" factors while helping hydrologists, water managers, policy makers, and the public understand and manage different water systems more effectively and sustainably (Gleick and Palaniappan, 2010; Timmerman et al., 2011). Thus, the DPSIR framework is an effective approach used to explore the relationships between water resource systems and the socioeconomic system because it provides an organized method for analyzing the causes, consequences and responses to changes in water systems (Fernando et al., 2013; Zhou et al., 2014).

The aim of this paper is to assess the sustainability of regional water resource systems. An indicator framework based on the DPSIR model and analytic hierarchy process (AHP) method are applied to synthesize the social and economic factors which may impact the sustainability of water resources and to understand the major cause-and-effect relationships in regional water systems.

2. Material and methods

2.1. Study area

Bayannur, located in the province of Inner Mongolia (105°12′–109°59′E, 40°13′–40°28′), is an area that faces serious water scarcity in Northwest China (Fig. 1). The annual precipitation is approximately 180 mm, and the annual average evaporation is more than 2000 mm. Bayannur City is composed of 7 counties with an area of 6.44×10^4 km^2 and a population of 1.67 million in 2010 (Bureau of Statistic in Bayannur, 2010). Bayannur is a major agricultural production region in Inner Mongolia, which has 0.70 million hectares of cultivated lands. Water diverted from the Yellow River is the major source for the study area, and the annual diversion of water from the Yellow River is approximately 5 Gm^3. Increased cultivated

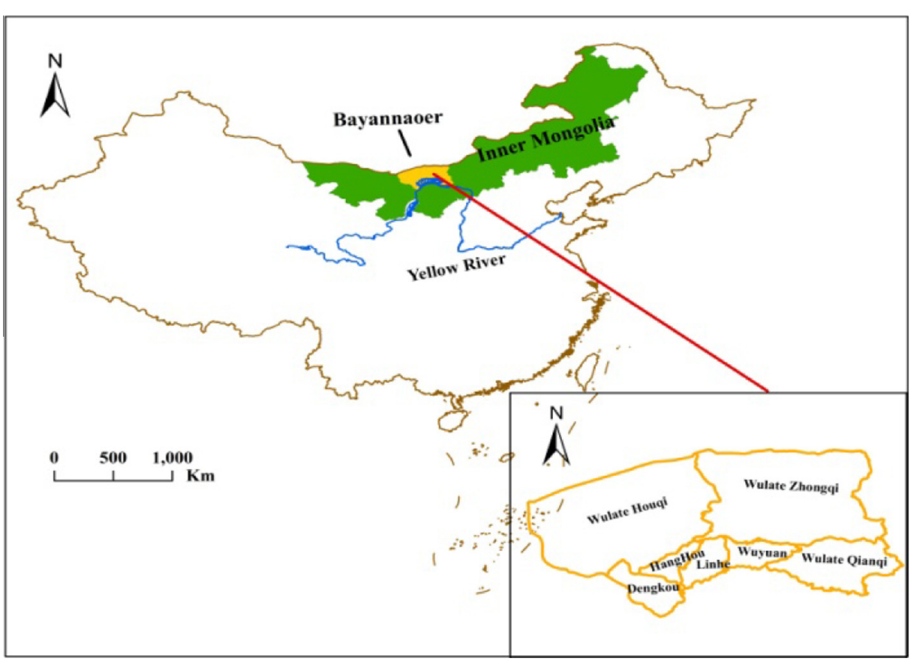

Fig. 1. Location of the study area.

acreage in recent years along with rapid urbanization and industrial expansion has resulted in greater competition between agriculture and other sectors for water resources. (Bureau of Statistics in Bayannur, 2010).

2.2. Data

The data used in this study mainly includes meteorological, socioeconomic, and water utilization data. Climatic data were obtained from the China Meteorological Data Sharing Services System (http://cdc.cma.gov.cn/home.do) (CMA, 2011). The socioeconomic data were taken from the "Inner Mongolia Statistical Yearbook" and "China agricultural statistics data" (MAC, 2000-2010; NBSC, 2000-2010). The hydrologic data were provided by the water authority in Bayannur (Water Authority in Bayannur, 2010).

2.3. Methods

2.3.1. Analytic hierarchy process (AHP) method

In this study, the analytic hierarchy process (AHP) is used to quantify the relative importance of the socioeconomic impacts on water resources sustainability. The AHP is an effective method for decision analysis and weighing factors based on multiple criteria to solve complicated problems (Saaty, 2008; Do et al., 2013). The AHP method provides a framework to handle decisions without making assumptions about the independence of higher-level elements from lower-level elements or about the independence of the elements within a level (Das and Chakraborty, 2011).

The main steps involved in the AHP method are as follows:

Step 1: Determination of an evaluation index system. This step is to establish an index system and identify the indices. "m" indices are assumed to be in the index system. The index system can be expressed as follows (Feng et al., 2014):

$$I = \{i_1, i_2, \ldots\ldots, i_m\} \tag{1}$$

The selection of an index should consider the processes of water resources and the natural characteristics of the study area. Additionally, social, economic and policy factors regarding the subsequent use of the water resources should also be considered (Feng et al., 2014). Hence, the second layer of the index system related to the social and economic factors was divided into five groups according to their impacts on regional water resources: Driver, Pressure, State, Impact and Response. The third layer of the index system explains the component of the each index in the second layer, such as GDP, Per Capita GDP, total population, crop sown area, etc.

Step 2: Construct an evaluation matrix. An n-criteria evaluation matrix A in which every element a_{ij} $(i, j = 1, 2, \ldots, n)$ is the quotient/ratio of the preference values attached to the criteria as shown in the following matrix (Gao and Hailu, 2013):

$$A = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1i} & \cdots & a_{1j} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2i} & \cdots & a_{2j} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{i1} & a_{i2} & \cdots & 1 & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{j1} & a_{j2} & \cdots & a_{ji} & \cdots & 1 & \cdots & a_{jn} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{ni} & \cdots & a_{nj} & \cdots & 1 \end{pmatrix} = (a_{ij})_{n \times n} \tag{2}$$

where a_{ij} is governed by the following rules (Gao and Hailu, 2013):

$$a_{ij} > 0;\ a_{ij} = 1/a_{ji};\ a_{ii} = 1 \tag{3}$$

Step 3: Derive criteria weights.

The consistency index (CI) is used to determine whether and to what extent decisions violate the transitivity rule. The CI was calculated as follows (Saaty, 2006; Feng et al., 2014):

$$CI = (\lambda_{\max} - n)/(n - 1) \tag{4}$$

where $\lambda_{\max}$ is the largest eigenvalue of matrix a, n is the order of matrix A, and $\lambda_{\max}$ was calculated as follows (Yu et al., 2011; Feng et al., 2014):

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(Aw)_i}{w_i} \tag{5}$$

The weight of an index was calculated using the importance scales in the second and third layers. For this process, the square-root method was used as follows (Feng et al., 2014; Saaty, 2006):

$$m_i = \prod_{j=1}^{n} a_{ij}, \quad i = 1, 2, \ldots, n \tag{6}$$

$$\overline{w}_i = \sqrt[n]{m_i}, \quad i = 1, 2, \ldots, n \tag{7}$$

$$w_i = \overline{w}_i \bigg/ \sum_{k=1}^{n} \overline{w}_k \tag{8}$$

2.3.2. Logistic curve of water resource utilization level

Water shortage is one of the main constraints to regional socioeconomic development. There is a limit on regional technology levels as well as the quantity and quality of water resources. Thus, water utilization has an upper limit which leads to an increasing damping factor model of regional water resources. The speed of system development decreased under the limited resource conditions, and the relative developing speed is a decreasing linear function related to the system development state (Zeng and Gu, 2000). This relationship can be described by the following logistic curve in which S represents the water resource utilization level, t is the development and evolution time, and C is the upper limit of water resource system utilization. The Logistic curve can be divided into four stages: $(0, t_1)$ initial stage, (t_1, t_0) growth stage, (t_0, t_2) mature period and $(t_2, +\infty)$ degenerating stage. In stage 1, the regional water resource utilization levels are at the initial stage with a slow development speed; in stage 2, they have a faster development speed; in stage 3, the development level decelerates relatively but maintains a high development speed; in stage 4, the development speed of the system decreases and approaches zero (Fig. 2). The Logistic-increasing process of the water resource utilization level is a combined effect of both promoting and hindering factors in the water resource system. In the initial stage, there is only a small impact by the damping factor, and water resource utilization levels develop at a fast speed. Over time, there is an increase in the scale of water resource utilization, and the room for development as well as the water supply decreases. Finally, development of the system was increasingly blocked in the end, and the rate of change approaches zero (Wang, 2000; Feng et al., 2006).

2.3.3. Water footprint accounting

Water footprint was selected to reflect the water consumption and pollution in this study. And it is calculated according to the framework provided by Hoekstra et al. (2011). For the blue water

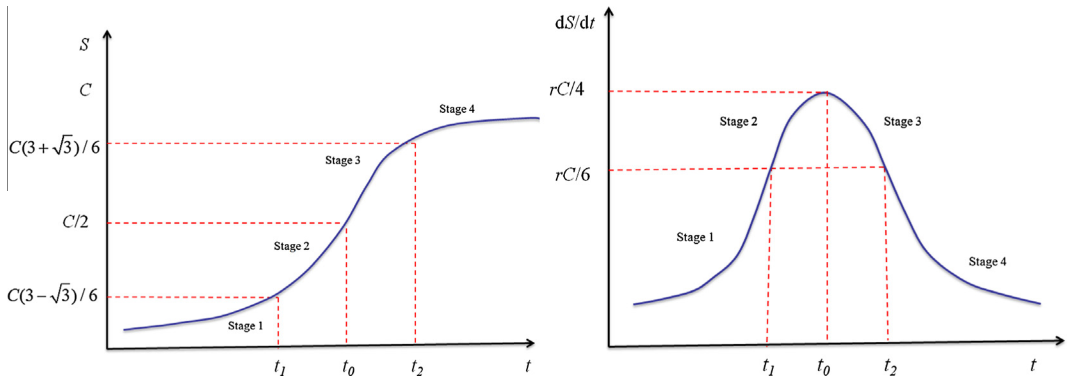

Fig. 2. The curve of the resource utilization level and its variation rate (revised from Feng et al. (2006)).

footprint, this study used a modified method that takes into account the water consumption during the water transfer process referred to Sun et al. (2013). The green water footprint of the crop was calculated according to the evapotranspiration of water supplied from the precipitation during the crop growing period. The gray water footprint refers to the volume of water that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards, and the calculation process of gray water footprint can refer to Hoekstra et al. (2011).

3. Results

3.1. DPSIR framework in Bayannur

The evaluation framework set up in the city of Bayannur is based on the DPSIR model (Fig. 3). The driver index reflects the effects of changes in society, the economy, population increases, and infrastructure on sustainable water resource development and utilization. The driver that affect water resources in this research include indices such as GDP, acceleration of GDP, population, the Engel Coefficient, and crop sown area. The Engel coefficient can be used for a reflection of the living standard of a country (or region). As the Engel coefficient increases, the country (region) is by nature poorer; conversely, a low Engel coefficient indicates a higher standard of living.

The pressure index reflects the factors which cause changes in the water system and act on the water resource system, and it is caused by the influence of the driver. Similarly to the driver indices, pressure indices are external forces which affect the changes in the water resource system. The difference between them, however, is that driver affects the development of water resource systems implicitly, whereas pressures act explicitly. This study considers the pressures to be the need for water resources due to social and economic development, and therefore the pressure index refers to the need for water resources and is the index that impacts water quality. It includes the total water usage, the ratio of the water usage among each sector, the annual average potential evapotranspiration, and the chemical fertilizer usage per unit area.

The state index refers to the state of the water system under the pressure of the driver and describes the physical characteristics of the water system. This article considers the index for the state of the water system as the capability of the water system to satisfy demand, the quantity of available water resources, the exploitation ratio of the water resources, the average water use per capita, the total irrigation per unit area, the water footprint of agriculture products, the water consumption per unit of economic output, and the quantity of wastewater discharge.

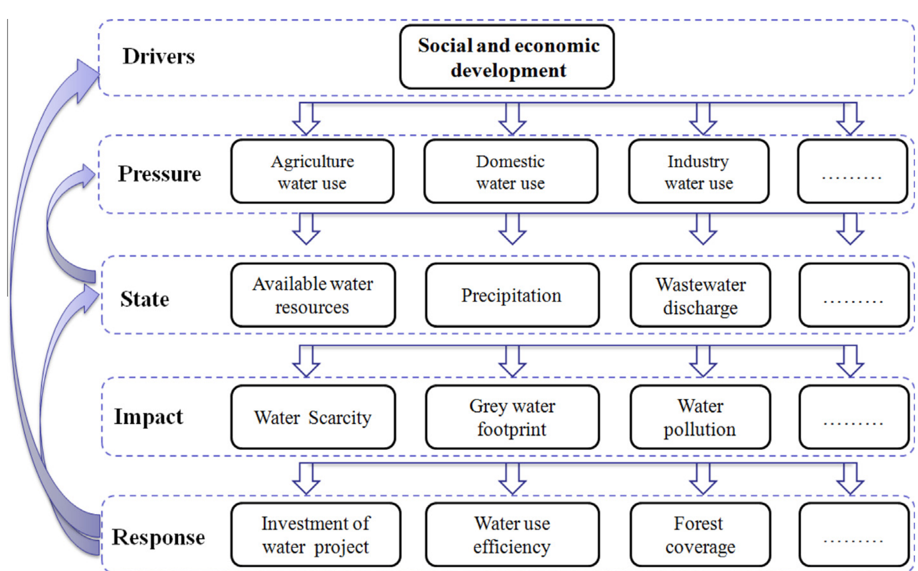

Fig. 3. Framework of DPSIR in the study area.

‘Impact’ refers to the changes in the water system caused by the driver and pressure and includes the quality and quantity of water. The impact on the water system due of socioeconomic driver, pressure, and state are indicated by the following index: the available blue water resources, the blue water footprint, the scarcity level of the water resource, the discharge of COD (Chemical Oxygen Demand), the gray water footprint, the pollution level of the water resource and the salinity of the groundwater.

‘Response’ refers to the different measures adopted during the process of development and utilization of the water resource to guarantee higher efficiency and sustainability of local water resources system. The response measures in this article include the following: investment in water conservation projects, increasing the irrigation water use efficiency and the wastewater processing ratio, decreasing range of water consumption per ten thousand GDP, decreasing range of the comprehensive crop water footprint, the increasing range of the ecological water utilization and forest coverage rate.

3.2. Weight of the indicators in the DPSIR framework

When analytically processed, the weight of each driver index results in the following hierarchy (Table 1): GDP, the annual increasing rate of GDP, GDP per capita, and so forth. This indicates that the main drivers causing changes to the water system are regional economic development (represented by GDP and its increasing level), crop sown area, and changes in consumption demands.

The weight ranking of the pressure index shows that the main pressure on the water system is the large overall water usage, the need for water by crops and the usage of chemical fertilizers. The weight ranking of the state indicators shows that the main indicator for the state of a regional water system is the quantity of regional water resources, the exploitation rate of water resources, the water footprint of crops and the quantity of wastewater discharge. For the impact index, the scarcity of the water resources, the quantity of available blue water, and the pollutant levels in the water resources are the main indicators reflecting the effects that socioeconomic development has on local water resources.

The weight ranking of the response indicators is as follows: the ratio of water conservation investment to GDP, the decline in the comprehensive crop water footprint, the irrigation water use efficiency, and so forth. Therefore, to face the increasing pressure with a decrease in the state of water resources, the main local response was to improve the water efficiency in industry and agriculture and to increase the ratio of wastewater treatment.

Table 1
Principal components of the indicators of each DPSIR sector and their interpretations.[a]

	Indicators	Units	Weight ranking
Driver	GDP	10^8 Yuan	1
	GDP annual rate of change	%	2
	Per capita GDP	Yuan/capita	3
	Total population	Persons	4
	Crop sown area	ha	5
	Population change	%	6
	Engel coefficient	%	7
Pressure	Total water use	10^9 m^3	1
	Potential evapotranspiration	mm	2
	Agriculture water usage ratio	%	3
	Chemical fertilizer use per unit area	kg/ha	4
	Per capita grain occupancy	kg/capita	5
	Industrial water use ratio	%	6
	Domestic water usage ratio	%	7
State	Total water resources	10^9 m^3	1
	Exploitation ratio of the water resources	%	2
	Per capita water use	m^3/capita	3
	Precipitation	mm	4
	Quantity of wastewater discharge	ton	5
	Water footprint of the crop	m^3/kg	6
	Irrigation water usage per unit area	m^3/ha	6
	Water usage per unit of economic output	m^3/ (10^4 Yuan)	7
Impact	Scarcity level of water resource	%	1
	Quantity of available blue water	10^9 m^3	2
	Blue water footprint	10^9 m^3	3
	Pollution level of water resource	%	4
	Gray water footprint	10^9 m^3	5
	Degree of mineralization of groundwater	g/L	6
	Effluent of COD	t	7
Response	Ratio of water conservation investment to GDP	%	1
	Change in comprehensive crop water footprint	%	2
	Irrigation water use efficiency	%	3
	Change in water consumption per ten thousand Yuan of GDP	%	4
	Wastewater treatment ratio	%	5
	Change in ecological water utilization	%	6
	Forest coverage rate	%	7

Note: The factor loadings with higher ranking indicate stronger correlations of the components with the associated variables.
[a] Source: China Meteorological Data-Sharing Service System, Inner Mongolia Statistical Yearbook, Water Resources Bulletin in Bayannur.

3.3. Sustainability assessment of the water resource system in Bayannur

The quantification and analysis of the 5 comprehensive indexes in the DPSIR are based on the weight of each indicator, which includes the annual change during the research period. The driver index of water use in the research area increased overall because of an expansion in agricultural and industrial production, an increase in living standards of the residents, and an increase in the area of cultivated land. This indicates an increase in driver for the local water consumption because of social and economic development and a change in residential consumption. The pressure on local water systems increased during the study period because of the increase in the driver indicators. The local water resource system faced pressure from both demand and water pollution due to the increasing water use in agriculture and industry in addition to the increasing application of chemical fertilizers and pesticides during agricultural production (Fig. 4).

The state of water resources in the research area indicates a decreasing trend under the driver and increasing pressure on water resources with a state of 0.71 in 2000 and 0.36 in 2010 (Fig. 4). Social and economic development demands an increasing water supply, and increasing living standards lead to a higher per-capita water use. Simultaneously, the state of the local water resource system exhibited a decrease due to the increase in wastewater discharge from both industrial and residential sources. For example, the local wastewater effluent increased from 282,600 thousand tons in 2000 to 814,500 thousand tons in 2010 with a rate of increase of 188.22%.

Driver and pressure have a significant influence on water resource systems. The impact indicators of the water system increased overall during the study period. Among these indicators, the regional blue water footprint, which reflects regional water consumption, increased. In addition to the increasing regional water use, social and economic development had a significant influence on the environmentally sustainable development of the water system. For example, the COD effluent increased from

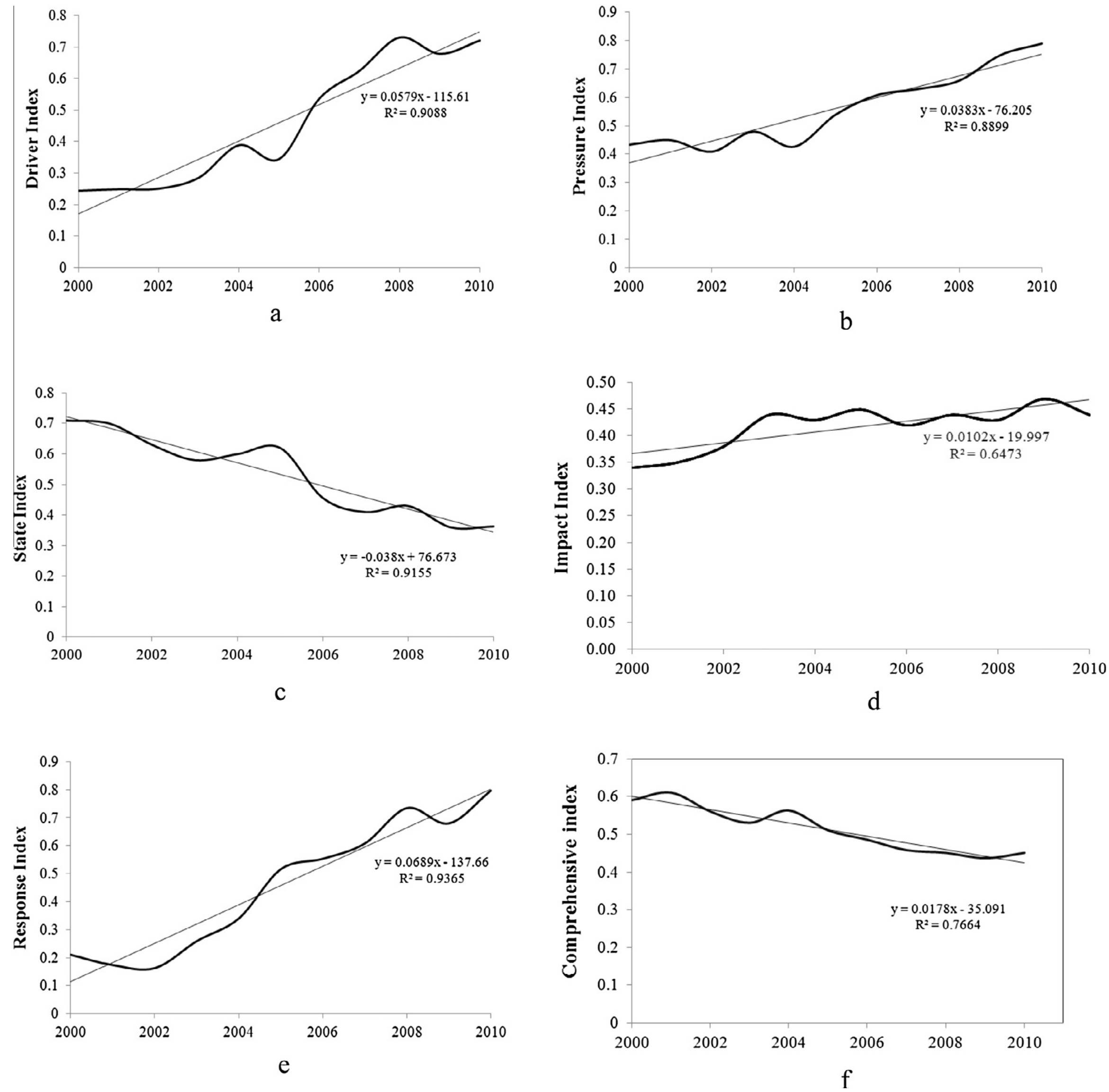

Fig. 4. Interannual variation of the DPSIR index (a) interannual variation of driver index; (b) interannual variation of pressure index; (c) interannual variation of state index; (d) interannual variation of impact index; (e) interannual variation of response index; (f) interannual variation of comprehensive index.

42,368 tons in 2000 to 52,300 tons in 2010 (a rate of 23.44%), and the gray water footprint increased from 3.06×10^9 m^3 in 2000 to 4.10×10^9 m^3 in 2010.

To face the driver of increasing demands on water resources because of social and economic development, local residents have adopted a series of measures to respond to and alleviate the increasing pressure on water resources (and the decreasing state of the water system). The measures include increases in water conservation investments, improving water use efficiency in production and the ratio of wastewater treatment, and so forth. The local response indicator increased overall because of these measures with 0.21 in 2000 and 0.79 in 2010 (Fig. 4).

There is an overall decrease in regional water resource system sustainability because of the influence of indicators along with driver, pressure, state, and response. Although the response measures improved the water use efficiency during the regional industrial and agricultural production process, the scale expansion brought an increase in resource consumption. At the same time, great pressure was brought to the regional water resource system environment by the increasing pollutant effluent from industry and agriculture, which led to the decrease in regional water resource system sustainability.

4. Discussion

Social and economic conditions combined with the environment and water systems to form a regional socioeconomic-environmental water system. The subsystems act and interact independently with each other to form an organic whole. Loucks (1997) proposed the definition of a Sustainable Water Resource System (SWRS) in 1997 and indicated that a sustainable water resource system should not only maintain the environmental subsystems but also satisfy the needs of the social and economic conditions. A sustainable regional water resource system should pay attention to the sustainability of water resources, society, the economy, and the environment (Feng et al., 2006). Sustainable water resource systems are complex, inter-coupled systems centered arounds water resources and connecting the social, economic, and environmental subsystems together. These subsystems interact and will continue to develop and evolve over time (Fig. 5). This is achieved through water conservation projects and technological measures for water resource exploitation, utilization, projection, and reasonable allocation and control. The ecological environment is the platform for the whole system and provides the physical basis for water circulation and human activity (Feng et al., 2006). On the contrary, a deterioration of the environmental system would degenerate the water resources system, thus blocking further social and economic development. The social and economic systems are the most active factors in the water resource system, and they will have impacts on environment and water resource system (Feng et al., 2006; Fitzhugh and Richter, 2004).

The development of open systems is affected by both internal and external factors, which include promotion factors as well as hindering factors. Time periods can be used to decide the level of difficulty of changing a condition based on how long the increase occurred in the corresponding Logistic (Wang, 2000). The development condition can be divided into long-, medium- and short-term based on the time period. Based on the dominant theory from synergetic theory, long-term factors dominate short-term factors, and short-term factors can only adapt to long-term factors. The climatic condition, water system structure, and geological structure in the region are long-term factors in the regional water resource system; cultures, traditions, values, behaviors, and population structures are medium-term factors; and the economic structure, technology structure, and water resource utilization methods are short-term factors. It is difficult to change long-term factors, which inhibit the structure and function of regional water resource system. Humans can only realize the sustainable regional water resource utilization and development through adjusting medium-term factors (cultural traditions, behaviors, and so forth) and short-term factors (regional economic pattern, water resource utilization technology, and so forth).

The specific causal relationship in the DPSIR model provides a feasible method for quantitatively evaluating water resource sustainability levels, which can be used not only to find the critical factors that affect the sustainable utilization of water resources but also to shape the discussion around future strategies for utilization improvements (Juwana et al., 2010; Cao et al., 2012). This study analyzed the driver, pressure, state, impact, and response factors that influence the sustainability of the water resource system in the city of Bayannur from 2000 to 2010 using the DPSIR framework based on the internal correlation among water resources and socioeconomic. It can be seen from the results that potential influence will be brought to water resources because of

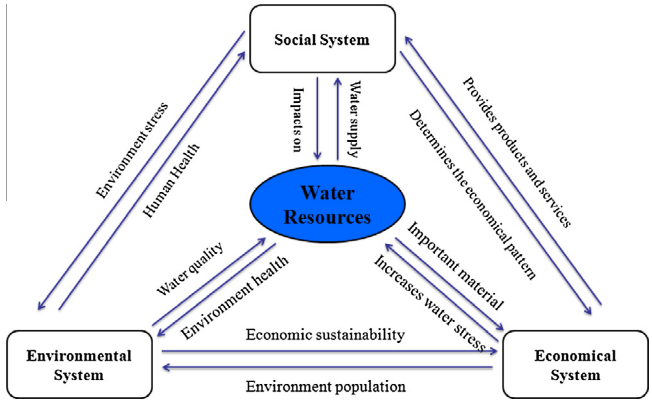

Fig. 5. Interaction and relationship of subsystems of water resource system (revised from Du et al. (2013)).

the driver in population growth, increase in GDP, increase in crop sown area, and so forth. Pressure on the water system increased because of the increase in the driver factors. Increased pressure on water resource systems leads to a decrease in the sustainable state of the water resource system, therefore affecting the sustainability of the social, economic, and ecological environment systems related to the water resource system. To protect the sustainability of the regional water resource system, the government can adjust medium-term and short-term factors through a series of response measures. From the perspective of economy, the measures include changing the regional economic development structure, reducing the industrial scale involved in high water consumption and high pollution, and rising green taxes for the high water consumption industries. From the perspective of culture, measures include forming a water-saving dietary pattern, and implementing educational programs for water conservation in schools. From the perspective of technology, measures include improving water usage efficiency in industry and agriculture, and increasing the ratio of wastewater treatment (Perry et al., 2009; Sjah and Baldwin, 2014).

Although the response measures improved the water use efficiency during the regional industrial and agricultural production process, the scale expansion brought an increase in resource consumption. At times, the consumption even increased (rather than decreased) as a result of the efficiency increase. This specific case of the rebound effect is known as the "Jevons paradox" (Alcott, 2005; Peet, 2009). Some studies have also indicated that to mitigate water scarcity, water use efficiency increases are an essential but insufficient ingredient. According to the related research, the efficiency gains in water use will not be sufficient to offset the effects of the expansion in production scale (Perry et al., 2009; Hoekstra, 2013). The results of this study showed that the improvements in water use efficiency are not used to save water but to increase production scale. Therefore, the improvement of water use efficiency is a means to achieve a more sustainable use of water resources, but it also needs to be coupled with measures that constrain the continued growth of demand (Hoekstra, 2013; Sun et al., 2015).

The present study provides an effective approach for analyzing water resource system problems and their interrelationships with the socioeconomic system. Nevertheless, there are some limitations present in this study. The incompleteness and bias of the indicators selected, data unavailability, and data uncertainty will cause uncertainty of the results of the study. For instance, the present study uses the exploitation rate of water resources, which has the same meaning with water exploitation index (WEI), to reflect the effect of social and economic activity exerts on water resources. Traditionally the WEI has been defined as the annual total water abstraction as a percentage of available long-term freshwater resources. It has been calculated mainly on a national basis. Faergemann indicated that water exploitation index plus (WEI+) provides an indication of the pressure on the water resources of a certain territory as a consequence of water withdrawals, and WEI+ aims mainly at redefining the actual water exploitation, since it incorporates returns from water uses and effective management, tackling as well issues of temporal and spatial scaling. Hence, the WEI+ could be used as an index for the assessment of the regional water resources exploitation state (EEA, 2012). Additionally, there may be some temporal hysteresis effect between DPSIR sectors (Nelson et al., 2005; Hou et al., 2014). For instance, changes in a certain sector (e.g. State or Impact) are caused by other sectors (e.g. Driver or Pressure) that work over a certain amount of time. Therefore, further studies relative to temporal hysteresis effect between DPSIR sectors are required in order to obtain a more appropriate assessment of the interaction between DPSIR sectors.

5. Conclusions

The main challenge of future water resource management is planning holistically and considering socioeconomic development and the relationship of sustainable water resource systems while facing the daily shortage of water resources. To evaluate regional water resource sustainability, this study established an evaluation indicator system of water resource sustainability based on the DPSIR model and conducted an assessment on water resource sustainability in the city of Bayannur, China. The following conclusions can be drawn:

There is an overall increase in the driver of local water consumption due to changes in society, economic development and the consumption structure of residents. The pressure on the water system increased overall, whereas the status of the water resources continued to decrease over the study period due to the increasing driver indicators. The local government adopted a series of response measures to relieve the decreasing water resources and alleviate the negative effects of the increasing driver in demand.

Although the response measures improved the water use efficiency during the regional industrial and agricultural production processes, the expansion in production scale brought reverse effects that led to the increase in water resource consumption known as the "Jevons paradox." There is a decreasing trend of regional water resource system sustainability due to the combined influence of water consumption and pollution.

According to the logistic curve of water resource utilization level and synergetic theory, sustainable water resource utilization can be achieved by changing regional cultures, behaviors, economic patterns, technology, and water consumptions methods (medium- and short-term factors). The measures may include: changing the regional economic development structure, reducing the industrial scale involved in high water consumption and high pollution, rising green taxes for the high water consumption industries, forming a water-saving dietary pattern, improving water usage efficiency in industry and agriculture, and increasing the ratio of wastewater treatment.

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