Generalized Index of Regional Socio-economic Consumption Level of Water Resource

Zhiwei Qi, Changlai Xiao, Bo Zhang and Xiujuan Liang

ABSTRACT

Traditional indicators of water resource utilization degree and efficiency cannot show the stressed relationship between the level of water resource utilization and economic development level in a region. Therefore, this manuscript proposes a generalized index of socio-economic consumption level of water resources. The definition of the index is the ratio of water consumption change for GDP growth per unit, and the potential of water resources exploitation and utilization. The theoretical curve of this index has a rise period, a high value period, and a decline period, which correspond to the take-off period, bottleneck period and maturity period of the regional economic development, respectively. This index can help us find the turning point of water resources restricting economy. The indexes of each year are calculated respectively from 1994 to 2010 of Beijing and Hebei province of China as example. The result shows that both two provinces are in the transitional period from high value period to the decline period. This example shows the universality of Generalized Index of Regional Socio-economic Consumption Level of Water Resources. Setting a target Generalized Index of Regional Socio-economic Consumption Level of Water Resources is consistent with the sustainable development level of regional economy which could promote both regional economic development and water resources protection.

Key words | ecological water, water economics, water resource coerciveness, water resource redline, water resource utilization degree

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INTRODUCTION

Under the current economic situation in China, the economy is going through a period of high-speed development. Without external influence, the total water resource of a region is basically stable. The region's total water consumption will increase as its economy develops (Wu *et al.* 2014). Without an essential industrial restructuring, and effective engineering and non-engineering measures, the potential of the development and utilization of water resources will become smaller and smaller, and even negative. If the incessant rise of water consumption per unit Gross Domestic Product (GDP) drives the potential of water resources exploitation close to zero or even below zero, this would indicate that water resource stress has seriously harmed the sustainability of regional economic development.

Industrial restructuring has greatly improved water use efficiency. There would be considerable water saving benefit from industrial restructuring (Wu *et al.* 2014). Urbanization and industrial updating in developing countries would raise the cost of water use and increase the competition for water between non-agricultural users and irrigation water users (Jiang *et al.* 2014). Therefore, water use efficiency has become a major factor of water resource assessment (George *et al.* 2011).

Combined hydro-economic models are fundamental tools for assessing management and infrastructure strategies which improve the economic efficiency of water use in a context of competition over scarce water resources (Pulido-Velazquez *et al.* 2008). The water resource assessment model should

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take both eco-environmental and socio-economic benefits into consideration (Xuan *et al.* 2012).

However, the feedback effect of water resource changes on the economy and changes in the economy on the water system are often missing in practice (Brouwer & Hofkes 2008). Present researches of the relationship between water resources and the regional economic development mainly focus on the water resources allocation and economic output (Cai 2008; Guan & Hubacek 2008; Birol *et al.* 2010; Jia & Huang 2011; Xuan *et al.* 2012; Kragt 2013). Other similar studies are the pressure–state–response framework proposed by Meng (2008); and global water resource integrated with the social-economic-environmental system proposed by Davies & Simonovic (2011). So far, the index of relationship between the management of water resources and regional economic developing level has not been proposed.

In accordance with the toughest water management policies, the Three Red Lines of water management was presented by the Ministry of Water Resources of China (Tao *et al.* 2012), which is total quantity control, water use efficiency control, and reducing emissions control (Wang 2011; Chen 2012). However, if the relationship between the red line indicators and economic development could not be clarified, it would be difficult for administrators of local economy to implement the Three Red Lines.

It is difficult for traditional indicators like water resource utilization degree and efficiency to describe the relationship between the level of water resource utilization and economic development, and describe the stress that water resources exert on that water social and economic development in a region. So it is necessary to find a new indicator that takes into account both the condition of water resource utilization and social economic development. This manuscript presents a generalized index of socio-economic consumption level of water resource, with a view to determining the red line of regional water resource utilization through the description of the stress.

PRINCIPLE OF DEFINITION

The framework of regional generalized index of socio-economic consumption level of water resource could be defined as the ratio of water consumption changes for GDP growth per unit, and the potential of water resources exploitation and utilization. The stress has a threshold, which means the red line of water resource management. If it exceeds the threshold, the economic development would be restricted, then some measures must be taken to reduce the stress. The index is not only a concept in water science and ecology, but also one in water economics and regional science.

From the perspective of social and economic development, the index is not only an indicator of water quantity, quality and water intaking, supplying, consumption, and drainage, but also an indicator of the process management of water demand and consumption. As the implementer of this indicator the governor needs to reconsider how to allocate water resources from the perspective of regional economic development instead of the sole consideration of quantity. Thereby, the stress exerted by water resources on regional economic and social sustainable development would be reduced. Based on these, this manuscript proposes the formula discussed below as the index of generalized socio-economic level of water resources.

In this manuscript, we use the ratio of water resources utilization efficiency and water resources development and utilization potential as a basis to measure the pressure of water resources in economic growth. The water consumption per unit of GDP growth is an indicator of water use efficiency, and the smaller the consumption indicates the higher water use efficiency. The potential of water resources development and utilization shows the degree of water resources shortage, and the smaller the potential, and the more severe water resources shortage. The higher water consumption per unit of GDP growth and the smaller the potential of water resources development and utilization, the greater the water resources stress on regional economic development. As a result, the ratio of water resources utilization efficiency and water resources development could be used as the definition framework of the generalized index of regional socio-economic consumption level of water resource.

FORMULA

In order to avoid the denominator being zero, the exponent form of these two items is introduced. So the generalized index of socio-economic consumption level of water resources is expressed as follows:

$$C = \frac{EXP(0.1 \times W)}{EXP(\alpha)} \tag{1}$$

where C is generalized index of socio-economic consumption level of water resources; W is water consumption per unit of GDP growth; α is potential of water resources development and utilization; W is an indicator for water use efficiency.

Replacing high-water-consumption industries with low-water-consumption industries through industrial upgrading makes the allocation of water resources in different industry more reasonable, so that water use efficiency would be improved.

α refers to the ratio of unexploited water resources to total available water resources under certain economic, technical and environmental constraints.

Theoretical curve

Expend formula 1, and then theoretical curve of the index C is available. Suppose R is the regional average amount of water resource for years; α_1, α_2 are two consecutive years of potential of water resources development and utilization; r_1, r_2 are two consecutive years of exploited amount of water resources; G_1, G_2 are two consecutive years of GDP. Then W could be expressed as follows:

$$W = \frac{r_2 - r_1}{G_2 - G_1} = \frac{R(1-\alpha_2) - R(1-\alpha_1)}{G_2 - G_1} = \frac{R(\alpha_1 - \alpha_2)}{G_2 - G_1} \tag{2}$$

The introduction of the differential form, W, can be expressed as:

$$W = \frac{R(-d\alpha)}{dG} = -R\frac{\frac{d\alpha}{dt}}{\frac{dG}{dt}} \tag{3}$$

Regional water resources are affected by the social and economic development stages, which can be divided into three stages in terms of time: the first stage is to experience extensive economy (low water use efficiency), the second stage is to experience bottleneck or transitional growth economy (economic development is restricted by available water resources, and the development and utilization potential of water resources declines or even declines), and the third stage is a negative value. The three stages are intensive economy (in the later stage of industrialization, the efficient utilization of water resources is realized). The potential of water resources development and utilization went through a process from large to small and from small to large, and it is similar to the cosine curve. Therefore, the calculation formula of coefficient α can be assumed as follows:

$$\alpha = 0.8\cos(0.12t + 0.5) \tag{4}$$

Then the potential of water resources development and utilization has transformed into a function of time.

This means that the potential of water resources development and utilization has gone from positive to negative, then from a negative to positive process again, over 50 years of economic development. Assuming the average growth rate of GDP per year is a, then the GDP curve changing over time could be written as follows:

$$G = G_0(1+a)^{t-1} \tag{5}$$

$$\frac{d\alpha}{dt} = -0.8 \times 0.12\sin(0.12t + 0.5) \tag{6}$$

$$\frac{dG}{dt} = G_0(1+a)^{t-1} \cdot \ln(1+a) \tag{7}$$

Convert Equations (6) and (7) into Equation (3):

$$W = \frac{0.8 \times 0.12\sin(0.12t + 0.5)}{(1+a)^{t-1}\ln(1+a)} \tag{8}$$

So the theory curve expression of C is:

$$C = EXP\left(\frac{0.1 \times 0.8 \times 0.12\sin(0.12t + 0.5)}{(1+a)^{t-1}\ln(1+a)} - 0.8\cos(0.12t + 0.5)\right) \tag{9}$$

In this formula, the independent variables only include the average annual GDP growth rate and t (year). Setting the average growth rate of GDP per year at $a = 5\%$, then the theoretical curve of generalized index of regional of social economic water consumption level based on the cosine function to simulate the relationship of economic growth and water resource could be obtained.

Obviously the cosine function could not simulate all the real processes of the relationship of economic development and water resource, but it could generally reflect the dialectic relationship of the water resource and economic development. According to the empirical relationship of economic development and water resource, a more ideal curve could be painted as shown in Figure 1(b) in the light of Figure 1(a). Through the ideal curve, the index has experienced three periods:

Segment A, the up period refers to regional economic take-off stage. The economic development is in proportion to the exploitation of water resources with low water-use efficiency and the extensive economic mode. The degree of water resource development and utilization is increasing rapidly without restriction. If it goes beyond the red line, the index would quickly reach a threshold of water resource development and cross the red line, that means production and living water use will squeeze ecological water use.

Segment B, the high-value period refers to the bottleneck stage of economic development. The sustainability of economic development is constrained by water resources. The potential of water resources development turns negative. At inflection point P, regional economic begins to transform from high water consumption to low water consumption. At inflection point Q, the economic center of gravity has further shifted from the primary- and the secondary-based industry to the tertiary- and the quaternary-based industry. With the water reuse system, the energy conservation and the emission reduction, water-use efficiency has been improved significantly. The potential of water resources development and utilization begins to recover.

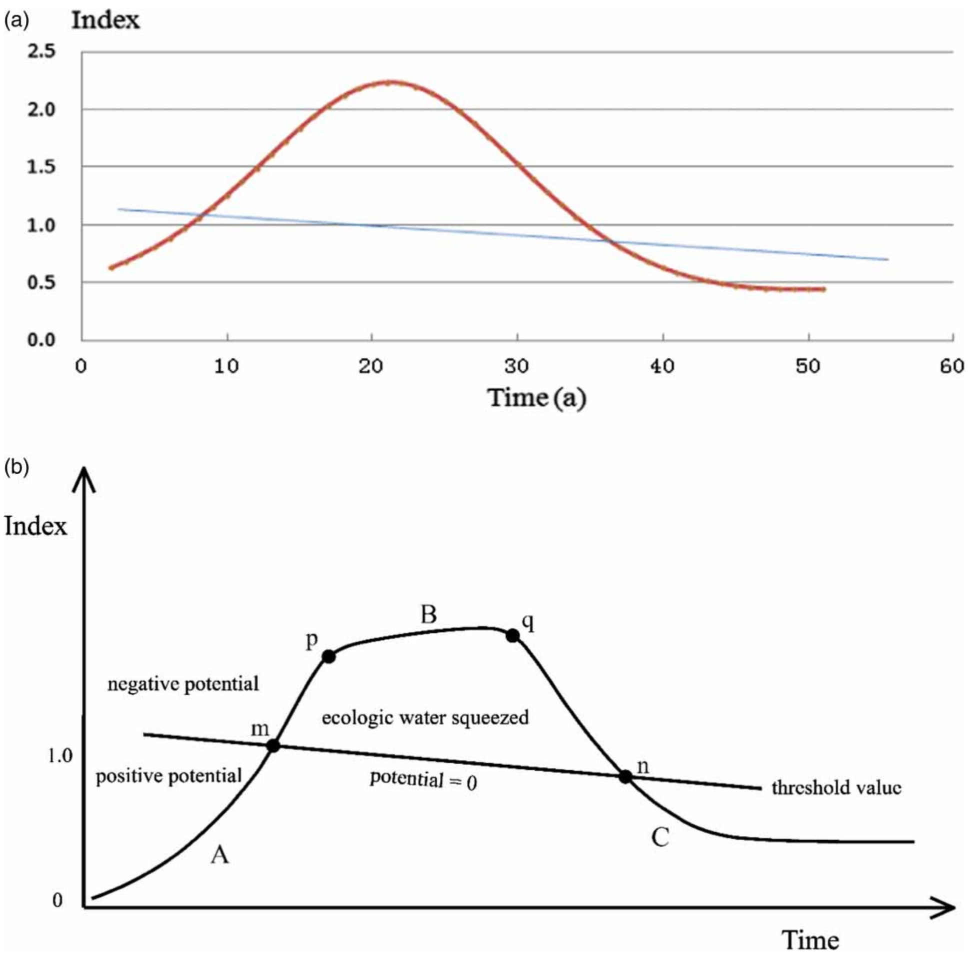

Figure 1 | Curve of generalized index socio-economic consumption level of water resource based on the empirical relationship of economic development and water resource.

Segment C, the down period refers to the maturity stage of economic development. Tertiary- and quaternary industry-based economy in the post-industrial stage achieves the efficient use of water resources. Production and living water use no longer squeezes ecological water use. The potential of water resources development and utilization has been improved continually.

If production and living water use squeezes ecological water use, then $\alpha = 0$ or $\alpha < 0$, and the sustainability of economic development is constrained by water resources. When putting $\alpha = 0$ into the theoretical formula, then the index $C =$ 1.15 or 0.81 respectively. So, if the generalized index socio-economic consumption level of water resources is chosen as the red line indicator, the threshold should be set near 1.0.

CASE STUDIES

Using Beijing and Hebei Province of China as examples, the following data were collected: average amount of annual surface water, groundwater resources, and the repeated amount of surface water and groundwater, the amount of water supply, water reuse, as well as annual GDP data from 1994 to 2010. Then the average amount of annual water resources, base flow, and potential of water resources development and utilization, water consumption per unit of GDP growth were calculated. Among them:

$$\text{water resource utilization} = \text{water supply} - \text{water reuse}$$

$$\begin{aligned}\text{utilizable water resources} \\ &= \text{average amount of annual water resources} \\ &\quad - \text{minimum ecological water demand}\end{aligned}$$

Minimum ecological water demand is substituted by annual base flow. It is relatively conservative and reasonable, and consistent with the minimum ecological water demand in Beijing. For example, the minimum ecological water demand in Beijing is 580 million m^3/a, and the annual base flow of Beijing is 570 million m^3/a. Similarly, the minimum ecological water demand in Hebei province is 3.48 billion m^3/a, and the annual base flow of Hebei province is 4.0 billion m^3/a. The value is relatively conservative and reasonable as the other regions do not have minimum ecological water demand calculations.

According to the results above, the curve of annual water resource amount, water resource utilization amount are shown in Figures 2 and 3, the potential of water resources development and utilization is shown in Figure 4, annual GDP in Figure 5, and water consumption per unit of GDP growth in Figure 6, in Beijing and Hebei province from 1995 to 2010. The curve of generalized index socio-economic consumption level of water resource in Beijing and Hebei province from 1995 to 2010 is shown in Figure 7.

It is shown from the curves of the two provinces that the index of Beijing and Hebei province are both in the adjustment period from segment B to segment C. This means that both of these two provinces have undergone a declining period of water resources restricting economic development. The curves of the two provinces are consistent with the theoretical curve in the reduced part. Among them, the decline in Beijing is greater than that in Hebei (Figure 8).

The threshold of generalized index of socio-economic consumption level of water resource is around 1.0. If it is above 1.0, then ecological water was squeezed; and if it is <1.0, then the status is healthy. Beijing's index has

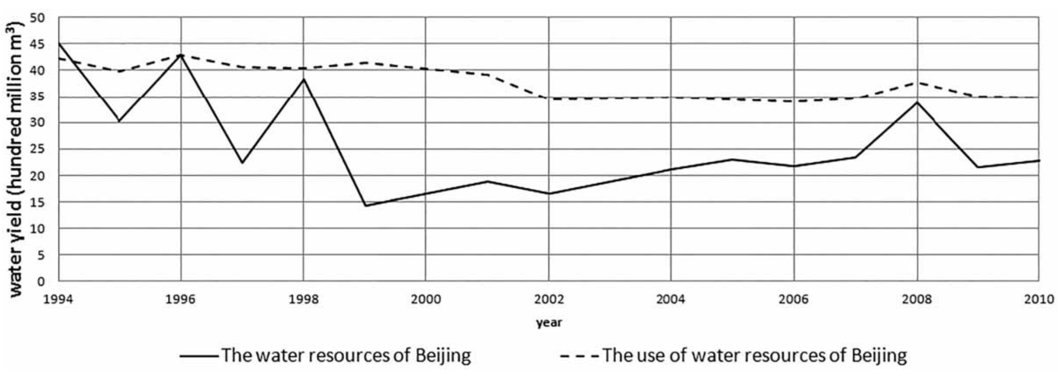

Figure 2 | The amount of exploitable and exploited water resource in Beijing from 1994 to 2010.

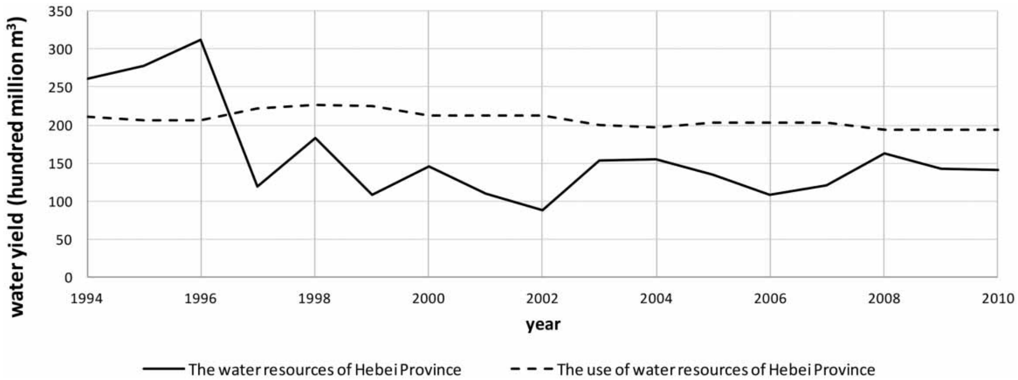

Figure 3 | The quantity of exploitable and exploited in Hebei province from 1994 to 2010.

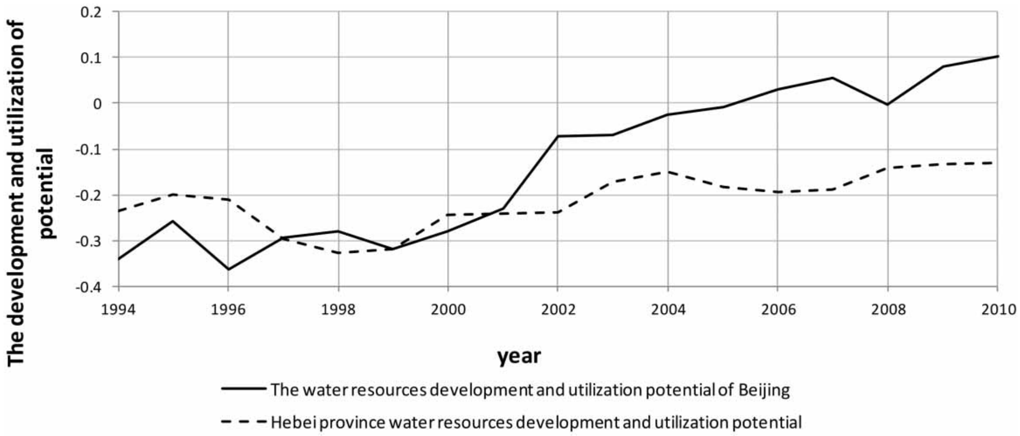

Figure 4 | The potential of water resources development and utilization in Beijing and Hebei from 1994 to 2010.

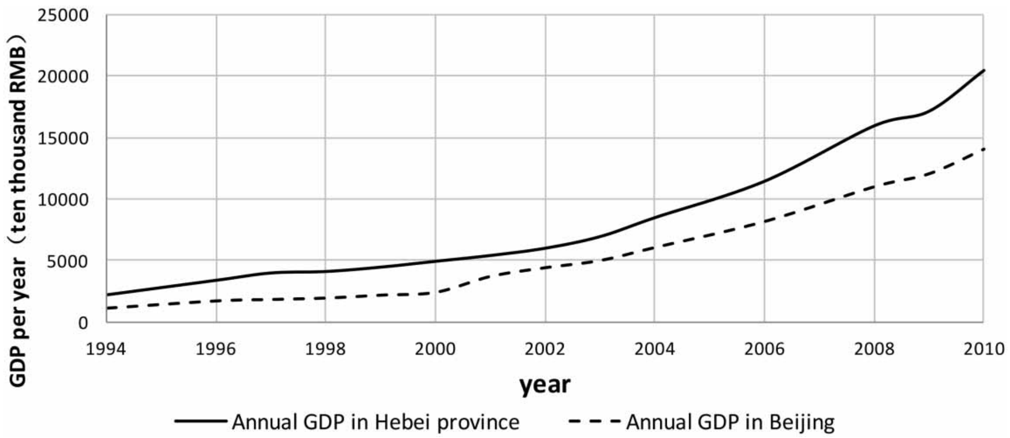

Figure 5 | GDP in Beijing and Hebei Province from1994 to 2010.

begun to be less than 1.0 and the potential of water resources development and utilization has begun to be positive from 2008. This benefited from Beijing's water reuse system which has gradually played a role in the

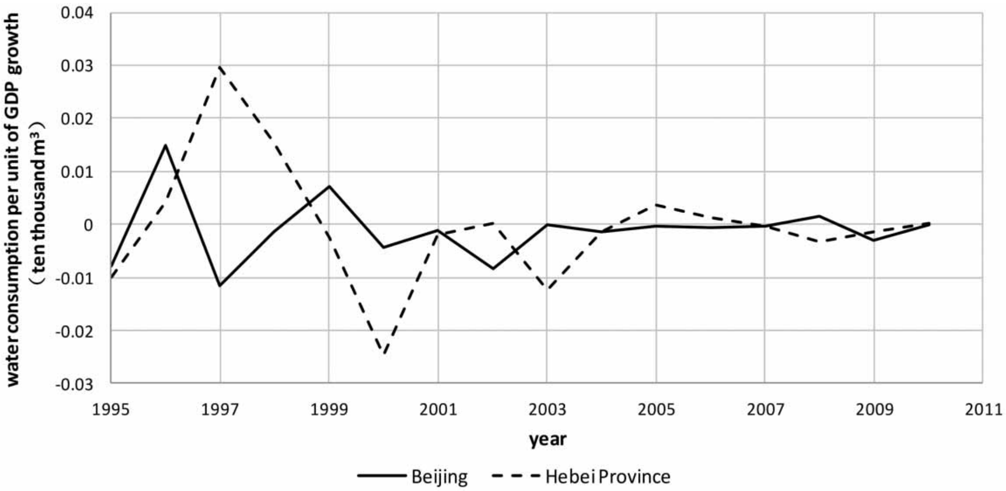

Figure 6 | Water consumption per unit of GDP growth in Beijing and Hebei province from 1995 to 2010.

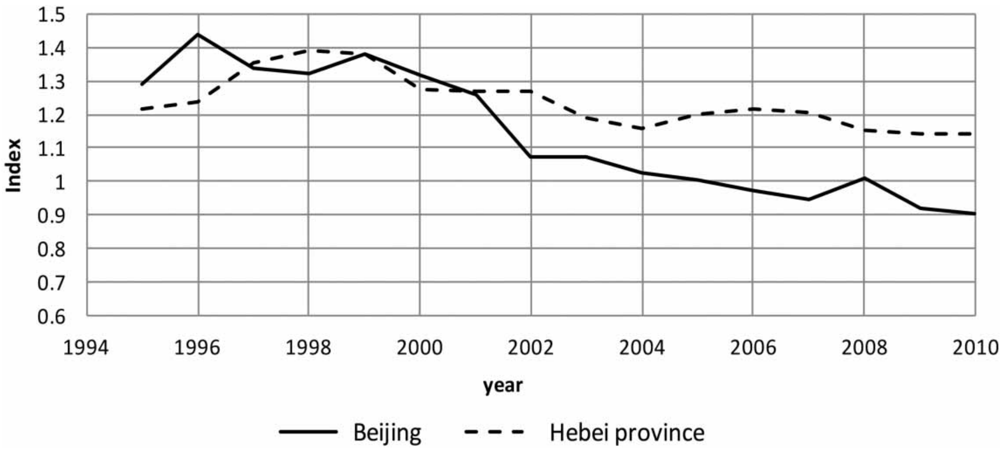

Figure 7 | Curves of generalized index socio-economic consumption level of water resource in Beijing and Hebei province from 1995 to 2010.

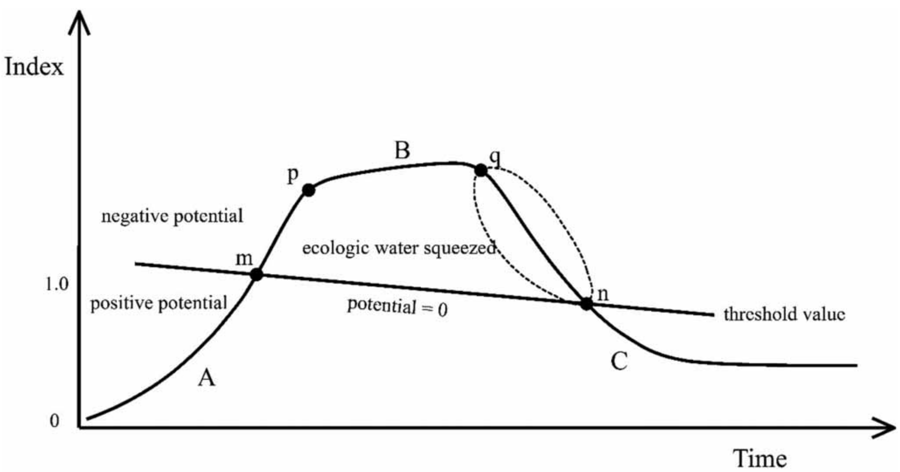

Figure 8 | The position of Beijing and Hebei province from 1995 to 2010 on the theoretical curve of generalized index socio-economic consumption level of water resource.

water supply system, so the amount of water reuse is increasing annually. The amount of water reuse in Beijing was 0 in 2000, but it had reached 680 million m^3 in 2010. Data in the water bulletin show that Beijing's water supply has been the same as the average annual water resource of 3.739 billion m^3.

The index of Hebei province continues to decline too, mainly due to the upgrading of the industrial structure and water-saving irrigation technology. From 2000 to 2010 alone, the irrigation water consumption had declined to 1.4 billion m^3.

Although the indexes have been declining, the loss of groundwater has not been compensated, and the environmental geological problems caused by long-term overexploitation are still difficult to solve.

Case analysis shows that the generalized index of regional socio-economic consumption level of water resource and its threshold can describe the relationship of water resource and economic development in a region. It is an indicator to represent the coercion of water resource to social economic development.

DISCUSSION

A dynamic indictor of water consumption process management

How the index changes over the years shows how water resources are associated with economic development. The index sums up the restriction ability of water resources to economy in the past process and helps predict future trends. Under the conditions of reasonable GDP growth level and growth structure in the dynamic economic social development, using this index can help determine current and future stress of water resources scarcity, thus avoiding the unsustainable development of economy.

Maximizing the integrated value of water resources with a price-and-market mechanism

The smaller the potential of water resources development and utilization is, the higher the water price is. The potential of water resources development and utilization actually influences the water price. Water consumption per unit of GDP growth also implicates water price. So this index is actually the marginal cost of water resources. With an appropriate government policy and industrial upgrading through the price leverage, a higher efficiency of water utilization maximizes the regional integrated value of regional water resources.

Self-evaluation by local government

This indicator is not inconsistent with the regional economic development, and it aims to promote maximizing the integrated value of water resources. Setting red line indicators consistent with the regional economic sustainable development level can help activate the win–win effect of regional economic development and water resource environmental protection. It would be easily accepted by decision-makers at all levels as an indicator for evaluating and accessing regional economic and social development potentials. It has crossing regional comparability and historical comparability. The local government will be able to evaluate the history, current situation and future development of the stress degree of water resource on economic development. So it is a 'positive' red line indicator to promote local economic development.

General principle of water resource red line policy

The indicator not only accords with the Three Red Lines of water management policies of the Ministry of Water Resources of China, it also helps to facilitate and evaluate the implementation of the Three Red Line policies. It could reflect the effect of total quantity control policy; it could promote the demands of water use efficiency by considering water consumption per unit of output growth; it could promote emission reduction through improving water reuse and increasing recycling rates.

CONCLUSIONS

This paper defines the generalized index of socio-economic consumption level of water resources by the ratio of water consumption per unit of GDP growth and the potential of water resources development and utilization. The index describes the relationship between the development and utilization of water resources and economic development. The size of the index determines whether the socio-economic development is restricted by the current situation of water resources. The threshold of this index is the red line of water resources development and utilization. The up, high-value and down periods of the theoretical curve correspond to the regional economic take-off, bottleneck and maturity stages. This index is a dynamic indicator of water consumption management. It is easy to identify the inflection point of the red line, and to avoid the occurrence of unsustainable development of economy resulting from stress of water resources. This index is actually the marginal cost of water resource, and it could maximize the integrated value of water resources. This index could reflect the effect of total quantity control, water efficiency control and emission control, and it could be the facilitator and evaluator of implementation of the Three Red Lines policies.

It could bring a win–win situation for regional economic development water resources protection by setting a generalized index of socio-economic consumption level of water resources control target consistent with the level of regional economic development.

Taking Beijing and Hebei Province as examples, their indexes from 1994 to 2010 show that they are both in the adjustment phase from a high-value period to down period, which can be attributed to the improvement of water reuse system, upgrading of industrial structure and water-saving irrigation technology. The case study shows a generalized index of regional socio-economic consumption level of water resources which can describe the relationship between water resources development and utilization and economic development in a region. It is an indicator representing the stress of water resources on regional social economic development.

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