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RESEARCH ARTICLE

Quantitative Evaluation of Sustainable Development and Eco-Environmental Carrying Capacity in Water-Deficient Regions: A Case Study in the Haihe River Basin, China

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Abstract

Quantitative assessment of development sustainability could be a challenge to regional management and planning, especially for areas facing great risks of water shortage. Surface-water decline and groundwater over-pumping have caused serious environmental problems and limited economic development in many regions all around the world. In this paper, a framework for quantitatively evaluating development sustainability was established with water-related eco-environmental carrying capacity (EECC) as the core measure. As a case study, the developed approach was applied to data of the Haihe River Basin, China, during 1998 through 2007. The overall sustainable development degree (SDD) is determined to be 0.39, suggesting that this rate of development is not sustainable. Results of scenario analysis revealed that overshoot, or resource over-exploitation, of the Basin's EECC is about 20% for both population and economy. Based on conditions in the study area in 2007, in order to achieve sustainable development, i.e., SDD>0.70 in this study, the EECC could support a population of 108 million and gross domestic product (GDP) of 2.72 trillion CNY. The newly developed approach in quantifying eco-environmental carrying capacity is anticipated to facilitate sustainable development oriented resource management in water-deficient areas.

Key words: eco-environmental carrying capacity, development scenario, Haihe River Basin, sustainable development, water resources

INTRODUCTION

The Limits to Growth, a book published in 1972 (Meadows 1972), predicted that the world would exceed its human carrying capacity, resulting in a sudden and uncontrollable decline in population and industrial capacity, unless the current trajectory of population and industrial growth was decreased. Based on thirty years of additional data and refinements in computer modeling, the follow-up publication in 2004, *Limits to Growth: The 30-Year Update*, concluded that the world had already achieved a state of unsafe overloading (Meadows *et al.* 2004).

The concept of carrying capacity originates from the field of ecology (Park and Burgess 1921). It is conventionally defined as the maximum population size of a given species that an area can support without re-

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ducing its ability for the same species in the future. In the human context, it is sometimes defined as the maximum "load" (as product of population and per capita impact) that can safely and persistently be imposed on the environment by people (Food and Agricultural Organization of the United Nations 1985). Carrying capacity is an essential component of sustainable development theory, which relates eco-environmental integrity to socio-economic development in situations with limited resource and increased environmental pollutions. The definition of sustainable development by the Brundtland Commission is "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Rees and Smith 1987; UN 1987). Sustainable development is a pattern of resource use that aims to meet the needs of human being while to preserve the environment. It takes the consideration of both the carrying capacity of natural systems and the social challenges in humanity.

Since the concept of carrying capacity was introduced into the field of human ecology in the population theory of Thomas Malthus, many people have studied different aspects of this concept (Seidl and Tisdell 1999). For example, Wetzel and Wetzel (1995) discussed the economic carrying capacity of the entire Earth. Harris and Kennedy (1999) analyzed the carrying capacity of agriculture at both global and regional scales. Pimentel *et al.* (1994, 1998) advanced a population-resource equation to identify the optimum population under the limited natural resources. Xia and Shao (2008) developed a physically based model of soil water carrying capacity for vegetation. However, most of these studies did not consider the relationships and interactions among input variables.

The water-related eco-environmental carrying capacity (EECC) has been introduced to represent the capacity of the macro eco-environment system, including water resources and water quality which serve as indicators for a regulating services (Zhu *et al.* 2005). EECC is usually expressed at population and economic scale, with the latter usually indicated by the gross domestic product (GDP). EECC determines the sustainable development rate and scale of the socio-economy of a given region. According to our previous study (Zhu *et al.* 2010), EECC is defined as the maximum population and GDP that can be sustained in a particular region based on available water and other resources.

In this study, the quantitative assessments for social, economic, and eco-environmental developments were incorporated into the EECC calculation based on the regional water balance. The resultant EECC reflected the dependence of sustainable development on the water availability, especially for areas facing severe water crisis such as the Haihe River Basin (HRB) of China. The specific objectives of this study were: (1) to develop an index system for evaluating the sustainability of the development; (2) to establish the method and framework for quantitative analysis of EECC; and (3) to conduct a scenario analysis to determine sustainable population and economic scales based on current circumstances. The developed approaches were applied in the HRB during 1998-2007 to assess the regional development and the associated EECC. The concept of sustainable development was emerged at the United Nations Conference on the Human Environment, Stockholm, 1972. The concept is usually presented as the intersection between society, economy and environment. Although each entity can be viewed and assessed separately, it is essential to quantify all three aspects together. In the developing stage of a region, the economy is often given the priority in policies and the environment is often viewed as apart from humans. However, the society, the economy, and the environment are interconnected. The presented results in this study can provide information for policy makers to fully understand that the integration of these aspects leading to sustainable development.

RESULTS

Evaluation of the sustainable development in the Haihe River Basin

Social development Table 1 lists the resultant scores of the input data and indicators in evaluating the sustainable development associated with social-economic-ecological environment in the HRB. From the social viewpoint alone, the development in the Basin has been in a good condition, as measured by per capita GDP, per capita water use, and drinking water quality classes. The total population increased by 10.6% for the study period, from 0.122 billion in 1998 to 0.135 billion in 2007 (Table 2), while GDP steadily increased by 254%, from 0.96 trillion CNY in 1998 to 3.4 trillion CNY in 2007. For per capita GDP, there was a 219% increase, from 7 900 CNY in 1998 to 25 200 CNY in 2007 (Table 2). Scores of per capita GDP increased more than 3-fold, from 0.28 in 1998 to 0.94 in 2007.

Drinking water in the HRB was of “high” or “very high” quality, indicated by the score of 0.75 or higher (Table 1), despite more than 60% polluted rivers in the region. However, due to the increased population and reduced precipitation, the amount of available water per capita decreased during the study period. Scores of per capita water use declined from 0.62 in 1998 to 0.4 in 2007. During the period of 1998 to 2007, the indicator measuring social development (SDL) was generally stable with a slight increase for recent years (Table 1). The per capita water use is less than 300 m^3 yr^{-1}, while that for the United States is 1 550 m^3 yr^{-1} and the worldwide average is 506 m^3 yr^{-1} (Food and Agricultural Organization of the United Nations 2011). Per capita water use in this region was obviously the bottleneck which limits social development. Therefore, one strategy to improve the quality of social development in this region would be to effectively raise average water use amount, by simultaneously increasing water resources while controlling population increase.

Economic development From the economic viewpoint, the development in the HRB has been improving, indicated by a substantial increase in the degree of economic development (EDL) from 0.12 to 0.70 (Table 1). Water use per unit GDP decreased from 441 $m^3/10^4$ CNY in 1998 to 113 $m^3/10^4$ CNY in 2007. Based on the critical values listed in Table 3, the water use efficiency increased from the category of “very poor” condition in 1998, to “moderate” in 2003, and to “good” in 2007. Irrigation water use per ha was 4 320 m^3 in 1998 and 249 m^3 in 2007, with a steady decrease. The wastewater discharge per unit of GDP also decreased steadily from 58.4 ton/10^4 CNY (categorized as the “very poor” condition) in 1998 to 14 ton/10^4 CNY (“good” condition) in 2007. During

Table 1 Assessment results on the sustainable development in the Haihe River Basin

Item	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Average
Per capita GDP	0.28	0.30	0.32	0.35	0.41	0.45	0.56	0.74	0.84	0.94	0.52
Per capita water use	0.62	0.61	0.53	0.5	0.51	0.41	0.36	0.41	0.45	0.40	0.48
Drinking water quality class	0.75	0.75	0.75	0.75	0.75	0.78	0.78	0.75	0.75	0.75	0.76
Social development level (SDL)	0.53	0.53	0.51	0.51	0.54	0.52	0.54	0.61	0.67	0.68	0.56
Water use per unit GDP	0	0	0	0	0	0.06	0.25	0.48	0.56	0.67	0.20
Irrigation water per ha	2.25	2.25	7.35	8.40	6.90	9.75	11.4	10.95	8.70	9.60	7.80
Waste water discharge per unit GDP	0.26	0.30	0.36	0.40	0.46	0.5	0.61	0.72	0.73	0.80	0.51
Economic development level (EDL)	0.12	0.13	0.25	0.29	0.27	0.37	0.51	0.62	0.61	0.70	0.39
Modulus of exploited groundwater	0.65	0	0.30	0	0	0.68	0.65	0.33	0	0.30	0.29
Water discharge to sea	0.62	0	0	0	0	0.3	0.08	0.1	0.13	0.18	0.14
River water quality class	0.38	0.4	0.33	0.40	0.40	0.38	0.4	0.38	0.35	0.35	0.38
Eco-environmental quality (EQ)	0.55	0.12	0.20	0.12	0.12	0.45	0.37	0.26	0.15	0.27	0.26
Sustainable development degree (SDD)	0.33	0.23	0.32	0.28	0.28	0.45	0.47	0.46	0.42	0.50	0.39

Table 2 Input data for assessing the eco-environmental carrying capacity in the Haihe River Basin

Item	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Population (million)	122.0	125.2	128.5	130.1	131.1	131.7	132.7	133.7	134.5	135.2
GDP (trillion CNY)	0.96	1.05	1.14	1.29	1.51	1.68	2.04	2.64	3.02	3.40
Per capita GDP (thousand CNY)	7.9	8.4	8.9	9.9	11.5	12.7	15.4	19.7	22.5	25.2
Per capita water use (m^3)	348	345	312	301	305	286	277	285	292	284
Drinking water quality class	1.9	2.0	2.0	1.9	1.8	1.8	1.8	1.9	1.9	1.9
Water use per unit GDP ($m^3/10^4$ CNY)	441	408	350	303	265	225	180	144	130	113
Irrigation water per ha (m^3 ha^{-1})	4 320	4 320	3 915	3 825	3 945	3 720	3 570	3 630	3 810	3 735
Waste water discharge per unit GDP (ton/10^4 CNY)	58.4	53.6	47.5	41.8	35.5	30.5	23.5	17.0	16.0	14.0
Modulus of exploited groundwater	1.04	1.55	1.18	1.53	1.85	1.03	1.04	1.17	1.33	1.18
Water discharge to sea (billion m^3)	4.4	0.45	0.41	0.08	0.18	2.18	1.30	2.48	0.50	1.71
River water quality class (dimensionless)	4.5	4.4	4.7	4.4	4.4	4.5	4.4	4.5	4.6	4.6

the study period, the water use per unit GDP decreased 76%. During the similar period of 1990 to 2005, the economic productivity of water changed from 5.5 to US$8.45, indicating a 35% decrease of per GDP water use (PACINST 2009). However, due to the increase in GDP, the reduction of wastewater release was only about 15%. The strategies to improve the quality of economic development in this region should focus on developing and applying techniques of water conservation and clean production. This strategy has been adapted in many developed countries such as Israel and USA (SWSME 1999; U.S. Agency for International Development 2012).

Eco-environmental quality The quality of the environmental ecosystem was relatively poor. Groundwater overdraft has been a serious problem. The long-term average of groundwater exploitation modulus was 1.29, and the average amount of groundwater in the HRB was about 1.1 trillion m^3. During the drought years of 1999, 2001, and 2002, the modulus exceeded 1.5, meaning that groundwater use was 1.5 times of the local capacity of groundwater recharge. The quality of surface water did not change much with an averaging score of 0.38. Therefore, the strategies recommended to improve ecological environmental quality would include: strictly controlling groundwater over-pumping, increasing the amount of water in the watershed, and reducing river system pollution. In California, USA, State Water Resources Control Board is in charge of enforcing the laws and policies to regulate the groundwater over pumping, water transfers and water quality controls. These regulations have been proved to be necessary to protect surface and ground waters in California (Moran *et al.* 2005).

Degree of sustainable development Fig. 1 shows the evaluation results of sustainable development and its contributing components as social, economic, and eco-environmental indicators. The sustainable development degrees in the HRB were relatively low, ranging from 0.33 in 1998 to 0.50 in 2007, indicating a situation of unsustainable development across all years. However, it is noteworthy that the score has increased in later years of the study period, ranging from 0.45 in 2003 to 0.50 in 2007. The observed increase in SDD was mainly attributed to the improvements in the quality of social and economic development (Table 1). The indicator of eco-environmental quality (EQ) remained the limiting variable for the sustainable development in the region. EQ values fluctuated from 0.12 to 0.55 during the study period, and were highly correlated with the variations of the average annual rainfall. For example, the drought years of 2001, 2002, and 2006 each had relatively poor EQ values.

Scenario analysis of EECC in the Haihe River Basin

Table 4 lists the 16 development scenarios with population and GDP pairs as input data, and the corresponding SDD results. Of these 16 datasets, scenario D3 with relative changes of -20% for both population and GDP yielded an EECC with SDD=0.71, which is higher than the selected threshold value of SDD*=0.70. This suggested that the population and economic scale of 2007 in the HRB exceeded the predicted EECC by 20%. In other words, sustainable development could be established with a population of 108 million and GDP of 2.72 trillion CNY based on the water resources available in

Table 3 The index system and grades for development quality evaluation of "society, economy and eco-environment" system in the Haihe River Basin

Evaluation index system		Category criteria for quality levels				
		I (very high)	II (high)	III (moderate)	IV (poor)	V (very poor)
Social development level	Per capita GDP (thousand CNY)	27	20	14	7	5
	Per capita water use (m^3)	600	400	300	260	200
	Drinking water quality class (dimensionless)	1	2	2.3	2.7	3
Economic development level	Water use per unit GDP ($m^3/10^4$ CNY)	60	100	140	180	240
	Irrigation water per ha (m^3 ha^{-1})	3000	3 600	3900	4200	4500
	Waste water discharge per unit GDP (ton/10^4 CNY)	10	15	30	60	100
Eco-environmental quality	Modulus of exploited groundwater	0.8	1.0	1.1	1.2	1.3
	Water discharge to sea (billion m^3)	10	6	3	2	1
	River water quality class	2	3	4	5	6

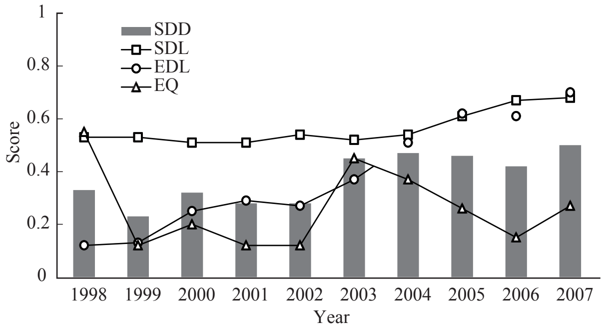

Fig. 1 Assessment results on the sustainable development in the Haihe River Basin.

Table 4 The scenario analysis of the eco-environmental carrying capacity in the Haihe River Basin

Scenario	Population change (%)	GDP change (%)	SDD in 2007
A0	0	0	0.50
A1	-10	0	0.35
A2	-15	0	0.39
A3	-20	0	0.41
B0	0	-10	0.43
B1	-10	-10	0.46
B2	-15	-10	0.48
B3	-20	-10	0.50
C0	0	-15	0.48
C1	-10	-15	0.50
C2	-15	-15	0.51
C3	-20	-15	0.53
D0	0	-20	0.51
D1	-10	-20	0.52
D2	-15	-20	0.53
D3	-20	-20	0.71

2007. This recommended GDP was comparable to the historical record of 2.64 trillion CNY in 2005.

To assess the EECC for the future, the impacts of water diversion and climate change should also be incorporated in analyzing sustainable development. To remedy the water crisis in the HRB, China aims to construct the "South-to-North Water Diversion Project" (SNWDP), which will funnel 44.8 billion m^3 of water annually from the southern river Basins to the northern China. The annual total water diverted to the North China Plain (mainly in the HRB) would be 27.8 billion m^3, comparable to total annual groundwater consumption in this area. In addition, the precipitation in the HRB is expected to increase in the near future according to the intergovernmental panel on climate change (IPCC) models (Meehl *et al*. 2007). The projected water diversion and climate change are favorable to achieving sustainable development while bringing prosperity to the HRB, China. However, it's also worthy to note that both the proposed water diversion and projected climate change are associated with great uncertainty. For example, the planed water diversion of the central route in the SNWDP has been based on a period which was wetter than the last two decades. This could lead to ecological problems in the headwater source areas (Liu *et al*. 2012). In addition, the observed precipitation has been decreasing in the North China Plan in the past decades, inconsistent to the projected climate data (Wang *et al.* 2011). The precipitation trends in the future may have significant impacts on China's strategies for improving the adaptive capacity especially for the agricultural sector.

DISCUSSION

Sustainable development

The dramatic increase of GDP indicated that living standards in the HRB also greatly increased. However, the per capita water supply was reduced due to the decreased rainfall and increased population. Lower SDD values were observed for early years of the study period. For example, the SDD of 1998 was determined to be 0.33, consistent to the range of 0.16-0.39 derived for various subBasins of the study area in the previous study (Zhu *et al.* 2010). The reduced water use limited further development. In addition, the degraded water quality certainly affects drinking water quality. In the extreme drought years, degraded water quality may lead to the instability of the society.

Economically, the total revenue generated from the watershed exceeded 3.4 trillion CNY. There was an increase for every economic measure. Comparing the values in 2007 to 1998, water use per ten thousand CNY GDP declined by 74%, irrigation water use per ha declined to 13%, wastewater per ten thousand CNY GDP declined by 76%. The economic values in the watershed illustrated fast development. Ecologically, however, the fast economic development did not improve the environment, but further degraded it. Although the use of water saving technologies has increased, total water use did not evidently decrease due to GDP over development. The current pace of economic development is only achieved by groundwater overdraft and the exploitation of water use for ecological environment. This is especially true in drought years. In the last ten years, wastewater per ten thousand CNY GDP discharge decreased by 76%. However, the total reduction of wastewater discharge was only 15% in the watershed. Because of a time lag and longer term accumulation of pollutants, the watershed is still heavily polluted. It is predicted that the length of the polluted rivers will continue to increase. The improvement of the environment in the HRB can be a long process.

EECC overshoot and management implications

The integrated measures of social, economic, and ecological environment indicate an unbalanced system in the HRB. It is obvious that the recent economic growth was achieved through the sacrifice of the environment. Natural ecosystems are the foundation for sustainable economic development. If the resources are over exploited, they become the limiting factors for further economic development. The development trend in the HRB over the past ten years shows that the quality of ecological environment was associated with the fluctuation of rainfall patterns. For example, the low quality of ecological environment appeared to be associated with the draught years of 1999, 2001, 2002, and 2006 when annual rainfall was less than 440 mm. Therefore, local environmental conditions were heavily affected by the climatic changes in the region.

Based on the data for the past ten years in the HRB, the region's eco-environmental quality has been severely degraded, indicating a state of overshoot. This means that there is a lack of balance between several components: the extent of the development and population density under the current economic and technological levels, the resources, and the eco-environment. The exploitation and overuse of water resources led to heavy degradation of the environment. If these problems cannot be solved, the HRB will face huge challenges and water resource crises in the future.

Chinese government is also paying more attention to ecological restoration and environmental pollution prevention. The conservation of water use and production technologies is gradually improving. In addition to the implementation of water-saving technology, water diversion from outside of the HRB is considered as an important measure to mitigate the current water crisis. These factors are favorable to achieving sustainable development while bringing prosperity to the HRB.

CONCLUSION

A computational framework was developed to quantitatively evaluate regional development and estimate the eco-environmental carrying capacity based on available water resources. This approach incorporated the analyses of water balance and the eco-environmental quality into the assessment of sustainable development. The concept of EECC incorporated major elements in evaluating the quality of social, economic, and eco-environmental development, and provided guidance for decision making in sustainable development. By linking with Basin-scale water balance, the newly developed framework in this study extended traditional single-indicator based approaches for EECC estimation. A case study was conducted in the HRB of China where the eco-environmental system has been seriously degraded by rapid economic growth and water crises during the past decade.

The fast growth of per capita GDP and the decrease in per capita water use were observed during 1998-2007 in the study area. Therefore, the quality of social development was only slightly increased from 0.53 to 0.68. For the economic development, significant increases were observed for all individual variables of water use per unit GDP, wastewater discharge per unit GDP, and irrigation water use per unit farmland. Consequently, the quality of economic development was increased from 0.12 to 0.70 during 1998 through 2007. Eco-environmental quality was found to be sensitive to annual precipitation, and associated with a general decreasing trend for the study period. With the exception of the wet years of 1998 and 2003, scores of eco-environmental quality were lower than 0.40. The results showed that the increases in total GDP and per capita GDP in the HRB might be associated with over-exploitation of natural resources and sacrifice of eco-environmental quality.

Based on the conditions in 2007, the overall sustainable development degree was 0.39, suggesting a status of unsustainable development. Scenario analyses were conducted to estimate the appropriate EECC to bring the SDD to 0.70, the threshold used in this study indicating sustainable development. The results indicated that the overloading of the Basin's EECC was about 20% in 2007. In theory, sustainability could be achieved with a population of 108 million and GDP of 2.72 trillion CNY under available water resources of 2007. The demonstrated approach and analysis in this study can provide useful information for sustainable development oriented resource management in the HRB and other water-deficient areas.

MATERIALS AND METHODS

The degree of development and EECC

Based on the definition of this study, the EECC could be determined under sustainable conditions. In the previous studies (Xia and Zuo 2001; Zhu *et al.* 2010), we evaluated the development sustainability based on economic development and eco-environmental quality. In this study, a separate indicator of social development (SDL) is introduced, and the degree of sustainable development at time T, SDD(T), (calculated at yearly time interval) is quantitatively estimated as,

$$SDD(T) = SDL(T)^{\beta_1} EDL(T)^{\beta_2} EQ(T)^{\beta_3} \quad (1)$$

Where *SDL* is an indicator of social development level, *EDL* is an indicator of economic development level, *EQ* is an indicator of eco-environmental quality (Table 5), and *β*'s are the weights of corresponding variables. The return-to-unit weights (*β*'s) reflect the relative importance of social, economic, and eco-environment development in a given study area and period. Eq. (1) is designed by following the format of the Cobb-Douglas function, and the exponent for any input term represents the productivity elasticity of the input. In this study, we first determine the weights by an analytical hierarchy process (AHP). This approach is a structured technique for organizing and analyzing complex decisions (Saaty 2008), and has been widely used for eco-environmental quality evaluation (Stahl *et al.* 2002; Li *et al.* 2007b; Ying *et al.* 2007; Akhgari *et al.* 2011). Expert opinions from local professionals were incorporated in the AHP.

The values of the three indicators in eq. (1) are in the range of [0, 1], and the approaches for calculating them are described in the next section. The SDD, also within [0, 1], could be considered as a synthetic index to measure the degree of development in a given year. For the descriptive classification of SDD, a threshold value (SDD*) is required for a specific region of study. If SDD⩾SDD*, we conclude that the evaluated system is sustainable. The relationship between the EECC and SDD can be expressed as,

$$EECC = \max(\text{popolution}, \text{GDP}), \text{ given SDD} \geqslant \text{SDD*} \quad (2)$$

Water balance and the indicators SDL, EDL, and EQ calculation

Linked by water, the components of society, economy, and eco-environment were integrated into a single system in this study (Fig. 2). Water balance is first analyzed based on the water supply and water demand. Specifically, the following steps are followed in the final water balance calculation.

(1) Analysis of raw data on water amounts used by industry, agriculture, residents, and eco-environmental protection, and total use;

(2) Estimation of total water supply based on local water resources and water diversion from outside of the watershed;

(3) Calculation of overall water balance based on total water supply and demand.

The indicators for development evaluation, i.e., SDL, EDL, EQ, are determined based on statistical results derived from basic datasets, including population, GDP, water resources, and water quality measures. The development of social system was evaluated by factors related to life quality

Table 5 Data required in the quantification of eco-environmental carrying capacity

Indicator	Variable	Data needed
Social development level (SDL)	Per capita GDP	Population; GDP
	Per capita water-use	Population; domestic water use
	Quality class of drinking water	Drinking water quality
Economic development level (EDL)	Water-use per unit GDP	Productive water use; GDP
	Irrigation water per unit farmland	Agricultural water use; cultivated area
	Wastewater discharge per unit GDP	Wastewater discharge; GDP
Eco-environmental quality (EQ)	Groundwater exploitation modulus	Groundwater consumption and recharge
	Water outflow	Total water resource; water use
	Quality class of surface water	Surface water quality

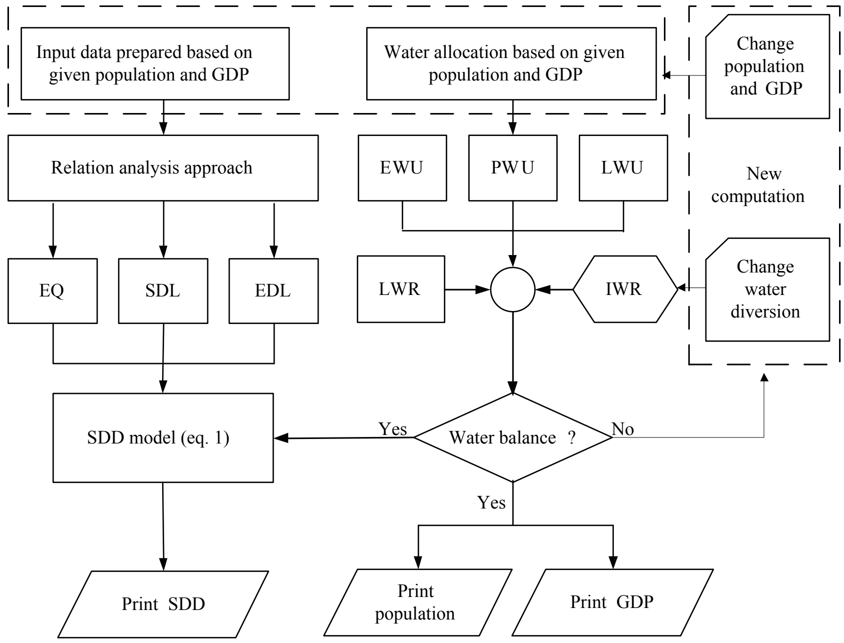

Fig. 2 The flow chart of development evaluation and EECC quantification. EQ, indicator of eco-environment quality; SDL, indicator of social development level; EDL, indicator of economic development level; SDD, sustainable development degree; EWU, eco-environmental water use (including water stored in impoundments and released for environmental purposes); PWU, productive water use; LWU, domestic water use; LWR, local water resource; IWR, imported water resource; and GDP, gross domestic product.

and per capita resources, such as per capita GDP, per capita water resources and environmental conditions. Based on literature review, various factors are used in quantifying the social development. The corresponding index system should be developed based on the operable and quantitative factors which characterize the study areas. Similarly, factors to evaluate the development of economic system should reflect economic structure and product efficiency, such as GDP per unit use of water, emissions per unit GDP, and fraction of tertiary industry. For eco-environmental system, its quality was assessed by selected factors reflecting ecological and environmental quality including forest coverage, wetland coverage, water volume discharge to sea, and in-stream water quality. A set of category criteria was developed to normalize the input variables into values ranging from 0-1. The relation analysis approach developed in our previous study was utilized to construct these indices (Xia 1996; Xia and Wang 2001).

The quantification of EECC is an iterative process involving adjusting population and GDP for simultaneously satisfying the requirements of water balance and sustainable development (i.e., SDD>SDD*) (Fig. 2). To simplify the computing process, we were using a "trial and error" method in this study to estimate the EECC. Actual values of population and GDP in the evaluated years were relatively changed to generate scenarios with input datasets of paired population and GDP values (Fig. 2). Requirements of water balance and sustainable development might be satisfied in multiple scenarios, among which the scenario with maximum population and GDP was reported as EECC.

Site description for case study

The HRB (35°-43°N, 112°-120°E) is an area of 318 200 km^2 located in the northern China (Fig. 3). It discharges into the Bohai Sea, neighboring with the Yellow River on the south, and the Mongolia Plateau on the north. The mountain and plateau region accounts for 60% of the total area, while the plain accounts for 40% of the total area. Characterized by hot, wet summers and cold, dry winters, the HRB belongs to the semi-humid climate in the monsoon region of the East Asia warm temperate zone (Edmonds 1998; Domagalski *et al.* 2001). From 1998-2007, the mean annual precipitation in the study area was 477 mm. There has been a general decreasing trend of precipitation in the HRB, with the average of 568 mm during 1951-1979 dropping to an average of 504 during 1980-2008 (Wang *et al.* 2011).

The mean local total water resources were 25.3 billion m^3, which consisted of surface water of 11.5 billion m^3 and groundwater of 13.8 billion m^3. Groundwater in the HRB includes "shallow" aquifer and "deep" aquifer which are hydraulically connected. Since the 1960s, ever-increasing exploitation has caused significant and continuing depletion of groundwater in the area. The maximum depths to water exceeded 65 and 110 m in the shallow and deep aquifers, respectively (National Research Council 2012). The

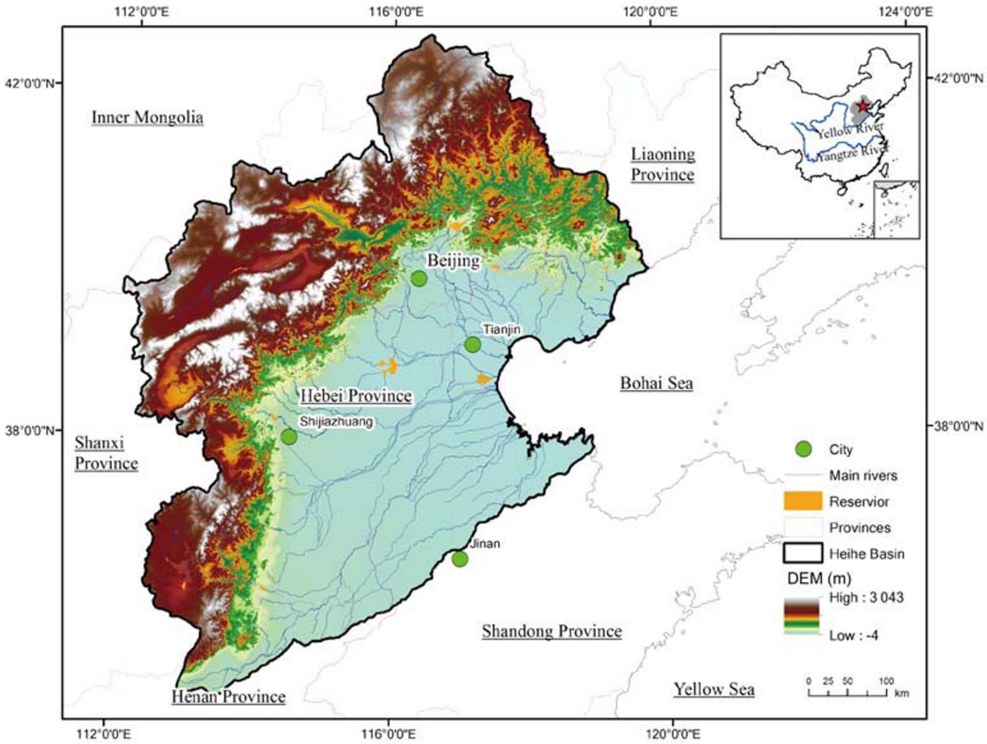

Fig. 3 The study area: Haihe River Basin of China.

consumption of groundwater for the 10-yr study period (1998-2007), 94.2 billion m^3, exceeded that of the prior 41-yr period (1958-1998) by 89.6 billion m^3.

The Basin includes Beijing and other metropolitan areas, and is recognized as the political, economic and cultural center of China. In 2007, the total population in the Basin was 0.135 billion, accounting for 10.2% of the total population of China. The Basin-wide GDP was 3.4 trillion CNY, or 13.5% of the nationwide GDP. Per capita GDP in the Basin was 25 200 CNY, which is higher than the national average. With the rapid growth of population and economic development, the HRB is one of the areas suffering severe water shortages and environmental pollution. The per capita water resources are less than 300 m^3 per year, 1/7 of the national average and 1/24 of the world average (Domagalski *et al.* 2001; Xia *et al.* 2006). Insufficient surface water and groundwater over-exploitation have resulted in eco-environmental degradation in this region (Li *et al.* 2007a). Therefore, determining EECC is very crucial to the planning for sustainable development of the economy, society and eco-environment in this region.

Input data and development scenarios

Required data for EECC calculation in the HRB, including data for hydrology, meteorology, eco-environment, society, and economy during 1998-2007, were retrieved from the Water Resources Bulletin published by the China Ministry of Water Resources (Chinese Ministry of Water Resources 2009). Illustrated in Table 6 are annual averages of precipitation, surface water, ground water, total water, water discharge to sea, and reservoir storage over the Basin. Water balance is summarized in Table 7 and water quality and pollution discharge are shown in Table 8. Data for social and economic development in Table 2 includes per capita GDP, per capita water resources, water use per unit GDP, and irrigation water per ha. The GDP values for different years were adjusted to the constant prices of 1998, i.e., the first studied year, to allow meaningful comparisons over time.

Each component (SDL, EDL, and EQ) of the regional sustainable development were assumed to have similar importance for the HRB. Therefore, all weights (β's) in eq. (1) were set as 1/3 based on analytic hierarchy process (Appendix). This implied equal importance of social development, economic development, and eco-environmental quality on the overall sustainability. The same weighting factors were used in our pervious study for the assessment of water resources carrying capacity in urbanizing area in the HRB (Zhang *et al.* 2007).

The quantification of EECC was demonstrated for 2007, the last year of the study period. The development scenarios were constructed by changing the population and GDP data for 2007 by 0, -10, -15, and -20%. The region-specific threshold of SDD (SDD*) was set as 0.7. In our previous study, a threshold of 0.8 was used for this study area when

Table 6 The water resources in the Haihe River Basin

Year	Precipitation (mm)	Surface water (billion m^3)	Groundwater (billion m^3)	Total water resource (billion m^3)	Water discharge to sea (billion m^3)	Reservoir storage (billion m^3)
1998	551	19.27	25.30	35.46	4.40	9.17
1999	385	9.20	17.23	19.38	0.45	7.02
2000	490	12.52	22.20	26.87	0.41	7.06
2001	416	8.97	17.46	20.01	0.08	6.34
2002	400	6.32	14.63	15.81	0.18	5.03
2003	582	13.08	25.29	32.02	2.18	6.11
2004	538	13.79	23.80	29.98	1.30	7.05
2005	487	12.19	21.55	26.75	2.48	7.85
2006	438	9.62	18.91	21.98	0.50	6.98
2007	483	10.18	21.19	24.79	1.71	6.72

Table 7 The water supply and water use in the Haihe River Basin

Item	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Total water supply (billion m^3)	42.40	43.15	40.06	39.17	39.98	37.70	36.8	38.05	39.28	38.45
Surface water (%)	25.2	25.3	24.1	20.2	20.4	20.6	20.6	22.6	22.4	22.3
Ground water (%)	61.8	62.0	65.6	68.4	67.6	69.3	67.1	66.5	64.1	65.0
Imported water (%)	12.7	12.4	10.0	11.1	11.6	9.6	11.5	9.8	11.8	11.2
Other water supply (%)	0.3	0.3	0.3	0.3	0.4	0.5	0.8	1.1	1.7	1.5
Total water use (billion m^3)	42.38	42.78	39.83	39.17	39.98	37.7	36.8	37.98	39.27	38.45
Agricultural water use (%)	72.5	72.0	70.0	71.0	71.6	69.5	69.6	69.5	70.0	70.1
Industrial water use (%)	15.9	16.0	17.0	15.8	15.5	15.8	15.4	14.9	14.5	13.5
Domestic water use (%)	11.6	12.0	13.0	13.2	12.9	14.2	14.3	14.6	14.4	14.7
Eco-environmental water use (%)	0	0	0	0	0	0.5	0.7	1.0	1.1	1.7

Table 8 The water quality and waste water discharge in the Haihe River Basin

Year	Assessed stream length (km)	Total wastewater discharge (billion ton)	% stream length by water quality class					
			I	II	III	IV	V	Lower than V
1998	9 951	5.61	0.6	13.6	20.8	10.0	8.4	46.6
1999	9 229	5.62	0.2	16.2	19.3	9.8	8.4	46.1
2000	11 278	5.40	0.2	15.8	18.9	4.6	4.7	55.8
2001	10 076	5.40	0.7	15.3	23.3	7.9	6.7	46.1
2002	7 151	5.36	3.2	14.3	23.1	4.5	6.2	48.7
2003	7 918	5.11	3.1	17.3	18.2	6.1	2.8	52.5
2004	11 670	4.80	2.6	16.2	22.2	4.6	3.4	51.0
2005	11 808	4.49	1.8	20.8	17.6	3.7	2.5	53.6
2006	11 641	4.83	1.4	15.8	13.4	8.1	6.8	54.6
2007	11 819	4.75	1.2	14.1	12.0	12.4	2.9	57.4

only economic and eco-environmental development levels were incorporated into the SDD calculation (Xia and Zuo 2001). Therefore, it is reasonable to have a slightly lower threshold with the inclusion of one more indicator of social development (SDL) in this study.

Index system for normalizing input variables

The developed index system normalized the input variables into numerical values in the range of 0-1. Critical values were used to categorize each input variable into 5 quality levels with numerical scores, i.e., category I "very high" with score of 1.0, II "high" (0.75), III "moderate" (0.5), IV "poor" (0.25), or V "very poor" (0.0). For the actual value of the input variable, linear interpolation was applied to specify its score, based on the two nearest critical values. For the HRB, critical values were developed based on existing relevant national environmental standards, conventional international practice and consultation of experts in various relevant studies. The index system is summarized in Table 3. The input variables were normalized based on linear interpolation between two adjacent critical values,

$$y=\frac{yc_j\text{-}yc_i}{xc_j\text{-}xc_i}(x\text{-}xc_i)+i \quad (3)$$

Where y is normalized value of the input x, xc and yc are the critical value of x and the corresponding normalized value, respectively, and i and j are two adjacent categories enclosing the value of x. For example, the per capital GDP of 7.9 thousand CNY in 1998 (Table 2) can be normalized to 0.28, based on the critical values of 7 (category IV, poor) and 14 (category III, moderate) thousand CNY (Table 3). The implementation of sustainable development is dependent on the harmonious relationships among society, economy, and ecosystem. The key for the evaluation of development sustainability is to discover those relationships under the limiting factor of water resources. Although literature provides useful assessment methods for development evaluations (Park and Burgess 1921; Pimentel *et al.* 1998; Domagalski *et al.* 2001), this index system including the aspects of social and economic development as well as environmental quality will be especially useful to quantify development sustainability. More details in developing the index system are provided in the Appendix.

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Appendix associated with this pvaper can be available on http://www.ChinaAgriSci.com/V2/En/appendix.htm

References

Akhgari P A, Kamalan H, Monavari M. 2011. Utilizing AHP method in rating of highlighted environment parameters in most used renewable energies in electricity production. *Enropean Journal of Scientific Research*, **60**, 182-188.

Chinese Ministry of Water Resources. 2009. Water Resources Bulletin. [2012-5-10]. http://www.mwr.gov.cn/zwzc/hygb/szygb/ (in Chinese)

Domagalski J L, Zhou X, Lin C, Zhi D, Fan L, Xu K, Lv Y, Luo Y, Liu S, Liu D, *et al.* 2001. *Comparative Water-Quality Assessment of the Hai He River Basin in the People's Republic of China and Three Similar Basins in the United States*. [2012-5-10]. http://pubs.usgs.gov/pp/pp1647/

Edmonds R L. 1998. Geography and natural resources. In: Hook B, ed., *Beijing and Tianjin*, *Towards a Millennial Megalopolis*. Oxford University Press, Hong Kong. **4**, 56-103.

Food and Agricultural Organization of the United Nations. 1985. Carrying Capacity Assessment with a Pilot Study of Kenya: Population-Resources-Environment-Development: A Resource Accounting Methodology for Exploring National Options for ustainable Development. Rome, Italy.

Food and Agricultural Organization of the United Nations. 2011. AQUASTAT online database. [2012-5-10]. http://www.fao.org/nr/water/aquastat/main/index.stm

Harris J M, Kennedy S. 1999. Carrying capacity in agriculture: global and regional issues. *Ecological Economics*, **29**, 443-461.

Li C H, Yang Z F, Zheng X K, Li H H, Yu J S. 2007a. Integrated water resources and water environment management in Zhangweinan Canal SubBasin, China. *Environmental Informatics Archives*, **5**, 715-727.

Li Z W, Zeng G M, Zhang H, Yang B, Jiao S. 2007b. The integrated eco-environment assessment of the red soil hilly region based on GIS – A case study in Changsha City, China. *Ecological Modelling*, **202**, 540-546.

Liu X, Liu C, Luo Y, Zhang M, Xia J. 2012. Dramatic decrease in streamflow from the headwater source in the central route of China's water diversion project: climatic variation or human influence? *Journal of Geophysical Research* (Atmospheres), **117**, 27.

Meadows D H. 1972. *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*. Universe Books, New York, USA.

Meadows D H, Randers J, Meadows D L. 2004. *Limits to Growth: The 30-Year Update*. Chelsea Green, Vermont, USA.

Meehl G A, Stocker T F, Collins W D, Friedlingstein P, Gaye A T, Gregory J M, Kitoh A, Knutti R, Murphy J M, Noda A, *et al.* 2007. Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K B, Tignor M, Miller H L, eds., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Moran J E, Hudson G B, Eaton G F, Leif R. 2005. *California GAMA Program: Groundwater Ambient Monitoring and Assessment Results for the Sacramento Valley and Volcanic Provinces of Northern California*. Lawrence Livermore National Laboratory, Livermore, CA.

National Research Council. 2012. *Challenges and Opportunities in the Hydrologic Sciences.* The National Academies Press, Washington, D.C.

PACINST 2009. Fact sheet on water use in the United States. [2012-5-10]. http://www.pacinst.org/press_center/usgs/US%20Water%20Fact%20Sheet%202005.pdf

Park R F, Burgess E W. 1921. *An Introduction to the Science of Sociology*. Evergreen Review, Chicago, USA.

Pimentel D, Giampietro M, Bukkens S G F. 1998. An optimum population for North and Latin America. *Population and Environment*, **20**, 125-148.

Pimentel D, Harman R, Pacenza M, Pecarsky J, Pimentel M. 1994. Natural resources and an optimum human population. *Population and Environment*, **15**, 347-369.

Rees G, Smith C. 1987. *Economic Development*. Palgrave, Macmillan, UK.

Saaty T L. 2008. Decision making with the analytical hierarchy process. *International Journal of Services Sciences*, **1**, 83-98.

Seidl I, Tisdell C A. 1999. Carrying capacity reconsidered: from Malthus' population theory to cultural carrying capacity. *Ecological Economics*, **31**, 395-408.

Stahl C H, Cimorelli A J, Chow A H. 2002. A New approach to environmental decision analysis: multicriteria integrated resource assessment (MIRA). *Bulletin of Science*, *Technology & Society*, **22**, 443-459.

SWSME. 1999. *Water for the Future: The West Bank and Gaza Strip*, *Israel*, *and Jordan.* National Academy Press, Washington, D.C.

UN. 1987. Report of the world commission on environment and development: our common future. [2011-4-15]. http://www.un-documents.net/wced-ocf.htm

U.S. Agency for International Development. 2012. *Improving Water Productivity*.

Wang Z G, Luo Y Z, Liu C M, Xia J, Zhang M H. 2011. Spatial and temporal variations of precipitation in Haihe River Basin, China: six decades of measurements. *Hydrological Processes*, **25**, 2916-2923.

Wetzel K R, Wetzel J F. 1995. Sizing the earth: recognition of economic carrying capacity. *Ecological Economics*, **12**, 13-21.

Xia J. 1996. Study on multiple grade associated analysis methodology applied to water environmental quality assessment. *Journal of Ecological Research*, **10**, 1-8.

Xia J, Feng H L, Zhan C S, Niu C W. 2006. Determination of a reasonable percentage for ecological water-use in the haihe river Basin, China. *Pedosphere*, **16**, 33-42.

Xia J, Wang Z G. 2001. Eco-environment quality assessment: a quantifying method and case study in Ningxia, arid and semi-arid region in China. In: *Hydro-Ecology: Linking Hydrology and Aquatic Ecology*. Proceedings of Workshop 11W2 held at Birmingham, UK. July 1999. International Association of Hydrological Sciences publish, UK.

Xia J, Zuo Q T. 2001. Enlightenment on sustainable management of water resources from past practices in the bositeng lake Basin, Xinjiang, China. In: *Regional Management of Water Resources, Proceedings of a symposium field during the Sixth IAHS Scientific Assembly*. International Association of Hydrological Sciences Publication, Maastricht, The Netherlands.

Xia Y Q, Shao M A. 2008. Soil water carrying capacity for vegetation: a hydrologic and biogeochemical process model solution. *Ecological Modelling*, **214**, 112-124.

Ying X, Zeng G M, Chen G Q, Tang L, Wang K L, Huang D Y. 2007. Combining AHP with GIS in synthetic evaluation of eco-environment quality – a case study of Hunan Province, China. *Ecological Modelling*, **209**, 97-109.

Zhang Y Y, Xia J, Wang Z G, Chen X Y, Zuo Q T. 2007. Quantitative research on water resources carrying capacity of urbanizing area. In: *International Symposium on New Directions in Urban Water Management*. United Nations Educational, Scientific, and Cultural Organization, Paris, France.

Zhu Y H, Drake S, Lü H S, Xia J. 2010. Analysis of temporal and spatial differences in eco-environmental carrying capacity related to water in the haihe river Basins, China. *Water Resources Management*, **24**, 1089-1105.

Zhu Y H, Drake S, Xia J, Jia S F, Lu H S. 2005. The study of eco-environmental carrying capacity related to water: Haihe River Basins example. In: *Sustainable Water Management Solutions for Large Cities*. International Association of Hydrological Sciences Publication, **293**, 118-124.

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