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Analysis of Temporal and Spatial Differences in Eco-environmental Carrying Capacity Related to Water in the Haihe River Basins, China

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Abstract With overly-rapid socio-economic development and population increases, water abstraction for agricultural, industrial and municipal use increases rapidly, while the water left for ecological maintenance decreases greatly. At the same time, large amounts of polluted water are discharged into rivers because purification plants are inadequate or not built in time, causing serious eco-environmental problems in the Haihe river basins which make regional development unsustainable. Estimating eco-environmental carrying capacity related to water is a key to curbing overuse of water and resolving eco-environmental problems. Because of different trends in water resources development and resultant eco-environmental problems in different sub-basins of the Haihe river, there are different water-related eco-environmental carrying capacities (EECCs) in these sub-basins. Time-series and multi-objective optimization methods are used to determine the EECC in various eco-environmental regions of the Haihe river basins, China. The results show that the entirety of the

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Haihe river basins will not reach a stable, sustainable state until about 2033, through gradual amelioration of eco-environmental problems. The various eco-regions of the sub-basins will need different lengths of time to reach their own stable states because of different available water resources, eco-environmental problems and social and economic development.

Keywords Multi-objective optimization method · Time-series · EECC · Haihe river basins

1 Introduction

The Haihe river basin holds special importance for China' political and economic functions because the capital, Beijing, is located there, as well as the third-largest city, Tianjin, and other large and medium-sized municipalities. Since the People's Republic of China was founded, society and economy have developed perhaps too rapidly in this region, and population has increased sharply. This has led to substantial abstraction of water from the river system for agricultural, industrial and municipal uses, leaving a meager and shrinking share for in-stream flow and ecological maintenance of the riparian system. Moreover, returns of polluted water from industry and inadequate sewage treatment facilities have exacerbated ecological degradation. Environmental protection has not kept pace with economic development. Looming shortages of water and serious eco-environmental problems now threaten continued growth and sustainable use of the region.

Eco-environmental restoration is demanded by government in the Haihe river basins. To augment local water resources, water will be diverted into the Haihe river basin by the South-to-North Water Transfer Project. From 2010 on, 79.9×10^8 m^3/year of water will be diverted into the Haihe river basins from the Yangtse river by an eastern route, and from 2030 on, a total of 108.4×10^8 m^3/year will be diverted into the Haihe from the Yangtse by the eastern route and an added middle route. Based on the South-to-North Water Transfer Project, a program of eco-environmental restoration in the Haihe river basins will be carried out by the Haihe Water Conservancy Committee, State Water Conservancy Ministry, in order to mitigate eco-environmental problems related to water. The study of carrying capacity of eco-environments in the Haihe river basins is an important part of the program. Based on the South-to-North Water Transfer Project functioning as planned, and on assumptions about future socioeconomic development, this study is intended to answer: (1) What is the status quo of sub-basin eco-environments related to water; (2) How many years are needed for the Haihe river basins to reach a critical sustainable state of environment-society-economy; and (3) What is the largest population that can be carried by the river basins when they reach their critical sustainable state.

EECC is defined as the largest population and economic scale (usually expressed as gross domestic product, GDP) that can be sustained in a particular region, over a specified time, under a certain environmental protection standard and social welfare level, when the eco-environments, society and economy of the region reach a critical acceptable state by using the local (or diverted from outside) water and other resources available. In the context of the Haihe river basins, EECC is put forward as a basis for finding a way to resolve the eco-environmental problems related to water. It is the capacity of the eco-environmental system (water resources, soil resources and ecological services such as water quality restoration) to support a society-economy system restrained by a certain technology level, welfare level and environmental quality standards. The carrying capacity is expressed by population and GDP.

The word "carrying capacity" was first put forward in ecology, to mean the largest number of a certain kind of living thing that can be carried by a regional ecological system (Odum 1972; Long and Jiang 2003). With human population increase, economic growth and technological advancement, the human appropriation of resources and environments becomes higher, and the phenomenon of over-use of resources occurs. Non-harmonious relationships among resources, environments, population and economy arise and can hamper sustainable development. The word "carrying capacity" no longer belongs only to ecology (e.g. Retzer and Reudenbach 2005; Downsa et al. 2008); it can be applied to economics, eco-economies, geography, environmental science or other sciences. Therefore, appeared environmental carrying capacity (Mcleod 1997; Tang et al. 1997; Guo et al. 2000; Liu et al. 2009), soils (Feng 1994; Li 1996), water resources (Wei and Zhang 1995; Xu et al. 1997; Jia et al. 1998, 2000; Xu 1999; Qu and Fan 2000; Li et al. 2000; Xu and Cheng 2000, 2002; Jiang et al. 2001; Cheng 2002; Liu et al. 2004; Feng and Huang 2008; Gong and Jin 2009), water-environmental carrying capacity (Guo et al. 1994; Wang 1996; Zen and Cheng 1997; Cui 1998; Jiang et al. 2001; Long and Jiang 2003; Zhao et al. 2005; Zhang and Zhao 2007; Weng et al. 2009), parks and wilderness (Manning and Lawson 2002; Lawson et al. 2003; Wang et al. 2007; Dong et al. 2008), and other synthetic carrying capacities (Arrow et al. 1995; Zhang et al. 2002; Zhang and Fang 2002; Simón et al. 2004; Zhu et al. 2005a, b; Zheng et al. 2007; Wang et al. 2008; Prato 2009). Except for the studies of Zhu et al. (2005a, b), among previous studies of carrying capacity related to water, water-related environmental problems refer only to water pollution, other environmental problems related to water, such as river de-watering, falling water tables, urban rivers and lakes drying, wet lands shrinking, sea outfall decreasing, erosion and soil loss, were not considered in combination (e.g. Xu et al. 1997; Xu 1999; Xu and Cheng 2000, 2002; Li et al. 2004). Previous carrying capacity studies have not investigated the time required for a river basin to reach a stable, sustainable state in the context of eco-environmental restoration processes, nor considered large-scale spatial and temporal variations in carrying capacity across a basin. In this paper, the stable-state points to a state as LI (the eco-environmental quality estimating index) is equal to 0.8 and at the same time, the maximum sustainable population is greater than actual population.

In this paper, the carrying capacity of seven Haihe river sub-basins is studied in the context of system theory, through multi-objective optimization and time-series analysis. The most frequently seen environmental problems related to water in the Haihe sub-basins are considered together (synthetically) in a water resources–environments–social-economy interactional model. The current status and future changes in the carrying capacity of eco-environments in the Haihe basins are examined. The time required for each sub-basin, and the Heihe basin as a whole, to reach a stable, sustainable state is calculated, and their maximum population and GDP in 2010, 2020, 2030 and 2040 are predicted. Lastly, whether or not the results are rational is analyzed.

2 Materials and Methods

2.1 General Situation of the Haihe River Basins

The Haihe river basins (Fig. 1) are located in northeastern China, at 35°–43° N and 122°–120° E, bordered by the Bo sea in the east, Liaoning Province in the northeast, the Inner Mongolia Autonomous Region in the northwest, Shandong Province in the

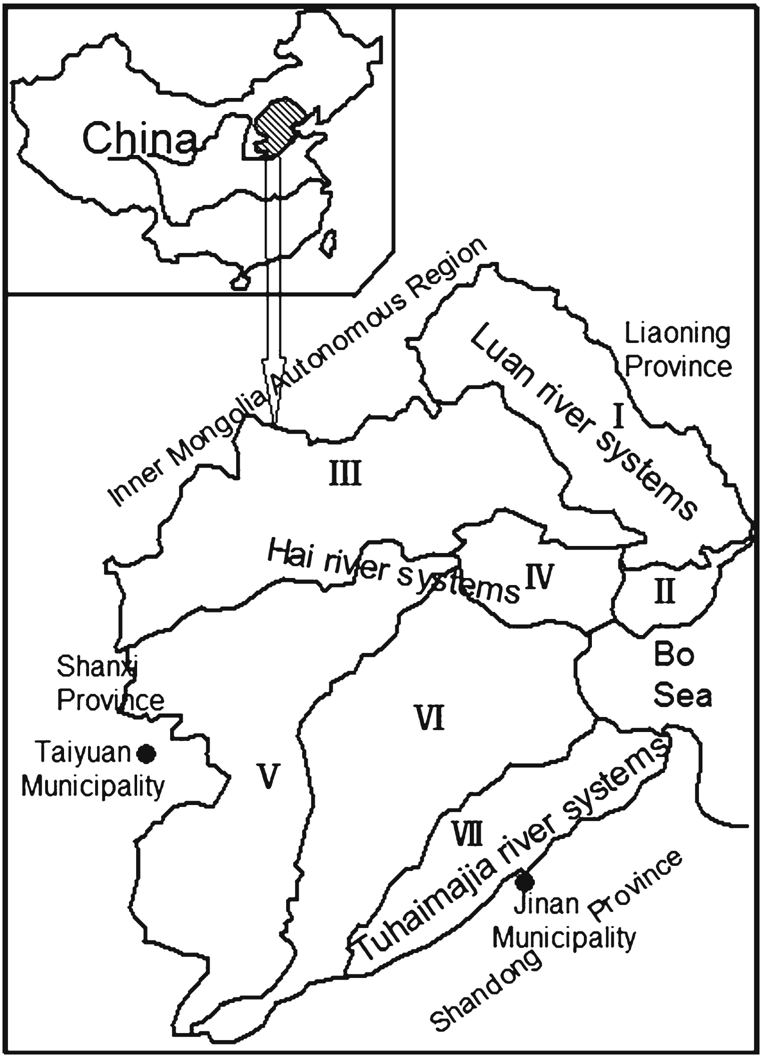

Fig. 1 Location of seven eco-environmental regions in the Haihe river basins. *I* Mountainous area of Luan river and eastern Hebei Province shoreward. *II* Plains area of Luan river and eastern Hebei Province shoreward. *III* Mountainous area of northern river systems of the Haihe. *IV* Plains area of northern river systems of the Haihe. *V* Mountainous area of southern river systems of the Haihe. *VI* Plains area of southern river systems of the Haihe. *VII* Plains area of the Tuhaimajia river

southeast, and Shanxi Province in the west. Included in this area are Beijing, Tianjin Municipality, most of Hebei Province, eastern Shanxi Province, northern parts of Henan and Shandong Provinces, a small part of the Inner Mongolia Autonomous Region and Liaoning Province. The total area is 318,000 km^2, of which hills and plateaus make up 189,000 km^2 or 60%, while lowland plains comprise 129,000 km^2 or 40% of the area. The Haihe basins lie in the temperate zone of semi-moist and semi-arid continental monsoon climate. Mean annual precipitation is 539 mm, mean annual free water surface evaporation is 1,100 mm, and mean annual land surface evaporation is 470 mm. In 1998 (latest figures available), the total population was 122 million, nearly 10% of the total population of China. Urban population was 33,650,000 according to the census register, and the rate of urbanization was 28%. The mean population density of upland regions was 384 persons per square kilometer, and 608 persons per square kilometer in the plains.

Within the Haihe river system are the Luan river, Hai river and Tuhaimajia river from north to south. The Haihe basin is divided into seven eco-environmental regions according to river system and topography (Fig. 1). In the seven eco-environmental regions, there are different eco-environmental problems related to water (Table 1). In mountainous regions, the primary problem is serious water and soil loss, while in plains regions most of the observed problems are present: water contaminants, perennial river segment shortening or river water drying, water table dropping down, wetlands shrinking, volume of sea outfall decreasing, etc.

2.2 Calculation of Eco-environmental Carrying Capacity

2.2.1 Model Description

The model includes objective functions and restraining conditions.

Objective Functions Our definition of EECC is the maximum population and GDP in a certain time period, when the eco-environmental quality and social economy levels are simultaneously maximized. Thus EECC is a multi-objective function.

Table 1 Main eco-environmental problems related to water in seven eco-environmental regions in the Haihe river basins

Region	Eco-environmental problems related to water
I	Water and soil loss, polluted water discharge
II	Groundwater over-extraction, water quality pollution, river channel shortening or river water drying and the volume of water reaching sea outfall decreasing
III	Water and soil loss, polluted water discharge
IV	Water quality pollution, groundwater over-extraction, river channel shortening or river water drying, wetlands shrinking and the volume of water reaching sea outfall decreasing
V	Water and soil loss, polluted water discharge
VI	Groundwater serious over-extraction, water quality pollution, wetlands shrinking, the volume of water reaching sea outfall decreasing and river channel shortening or river water drying
VII	Water quality pollution, wetlands shrinking, the volume of water reaching sea outfall decreasing, groundwater over-extraction, and river channel shortening or river water drying

During EECC calculation, in order to change the multi-objective function to single-objective, a synthetic index, ES, is developed, called the eco-environmental equality–social-economy level synthetic estimating index, which is expressed in Eqs. 1, 2, and 3:

$$ES(T) = EG(T)^{\beta_1} LI(T)^{\beta_2} \tag{1}$$

$$EG(T) = \prod_{i=1}^{m} U_i(T)^{a_i} \tag{2}$$

$$LI(T) = \prod_{j=1}^{n} H_j(T)^{b_j} \tag{3}$$

In Eqs. 1, 2, and 3, $ES(T)$ is the synthetic value of eco-environmental quality and social-economy level evaluated during the period T; and $EG(T)$ and $LI(T)$ express the value of the social-economy level and that of eco-environmental quality during the period T, respectively. $EG(T)$ is called the social-economy level estimating index and $LI(T)$ is called the social-economy level estimating index during the period. β_1 is the weight of the social economy level in $EG(T)$, and β_2 is the weight of eco-environmental quality in $EG(T)$. $U_i(T)$ expresses the subordination degree value of the social-economy level index i during the period T, $H_j(T)$ expresses the subordination degree value of the eco-environmental quality index j during the period T; m and n express the number of the social-economy level index and eco-environmental quality index, respectively; a_i is the weight of the social-economy level index i in $EG(T)$; b_j is the weight of the eco-environmental quality index j in $LI(T)$. All the weights are determined by stratification analysis (analytic hierarchy process), the specific determination is similar to the method used by Miao et al. (2006).

In year N, the objective function is expressed in Eq. 4:

$$BTI = Max \prod_{T=1}^{N} \left(ES(T)\right)^{\frac{1}{N}} \tag{4}$$

BTI is called the measuring index of sustainable development of the eco-environments–social-economy compound system.

In the Haihe river basins, the indexes of social-economy level, chosen by their importance in the social-economy system, are: per capita GDP, percentage of tertiary industry to GDP, urbanization ratio and per capita grain yield. The indexes of eco-environmental quality, chosen according to the main eco-environmental problems in the Haihe river basins, are: area ratio of water and soil loss, the discharge amount of chemical oxygen demand (COD), groundwater extraction coefficient, length ratio of perennial river segment shortening, area ratio of wet-lands, area ratio of urban rivers and lakes, and volume of water reaching sea outfall. The indexes of social-economy level are the same in the seven eco-environmental regions, but the indexes of eco-environmental quality are different in regions with different eco-environmental problems (Table 2).

Table 2 Eco-environmental indexes in seven eco-environmental regions

Region	Eco-environmental indexes expressing LI
I	Area ratio of water and soil loss, area ratio of urban river or lake and discharge amount of COD
II	Discharge amount of COD, groundwater extraction coefficient, length ratio of river channel shortening, area ratio of urban river or lake and volume of water reaching sea outfall
III	Discharge amount of COD, area ratio of water and soil loss and area ratio of urban river or lake
IV	Discharge amount of COD, groundwater extraction coefficient, length ratio of river channel shortening, area ratio of wetlands, area ratio of urban river or lake and volume of water reaching sea outfall
V	Discharge amount of COD, area ratio of water and soil loss and area ratio of urban river or lake
VI	Discharge amount of COD, groundwater extraction coefficient, length ratio of river channel shortening, area ratio of wetlands, area ratio of urban river or lake and volume of water reaching sea outfall
VII	Discharge amount of COD, groundwater extraction coefficient, length ratio of river channel shortening, area ratio of wetlands, area ratio of urban river or lake and volume of water reaching sea outfall

Constraints

1. Interactional relationship among the water resources–eco-environments–social economy compound system

   The model of the water–eco-environments–social economy compound system interactional relationship includes a water budget sub-model, social economy–water relationship sub-model, environments–water relationship sub-model and society–economy prediction sub-model. The model is indispensable and it connects the other indexes in the calculating model of carrying capacity functions with water. Thus by optimization we can obtain the maximum sustainable population and GDP under the conditions of available water consumption. The result is a benefit to decision-makers.

   (a) Water budget sub-model. It is expressed by Eq. 5

   $$P + W_{\text{in}} = R + E + W_{\text{out}} + \Delta W$$

   $$\frac{\Delta W}{\Delta t} = P + W_{\text{in}} - \left(W_{\text{prod}} + W_{\text{life}} + W_{\text{eco}}\right) - W_{\text{out}} \tag{5}$$

   Where, P, R, E is the precipitation, runoff and evporation, respectively; ΔW is the change of water storage in the studied region, positive as increasing; t is the time; W_{in} is the water volume running into or diverted into the studied region; W_{out} is the water volume running out of the studied region; W_{prod} is the water volume used by production including Industry and Agriculture; W_{life} is the water volume used by life and W_{eco} is the water volume used by eco-environments.

   (b) Social economy-water relationship sub-model. It is expressed by the functions between social economy indexes and various water volumes in water budget sub-model. The social economy indexes used are domestic product of Industry and Agriculture; GDP; crop yield and population, respectively

(c) Environments–water relationship sub-model. It is expressed by the functions between environmental indexes related to water and the corresponding ecological water usage. The environmental indexes related to water are area ratio of water and soil loss, groundwater extraction coefficient, length ratio of perennial river segment shortening, area ratio of wet-lands, area ratio of urban rivers and lakes, and the discharge amount of chemical oxygen demand (COD), respectively. The corresponding ecological water usages are ecological water usage for water and soil conservation, the supplied water volume for groundwater, the ecological water usage by river, the ecological water usage by urban rivers and lakes.

(d) Sociey–economy prediction sub-model. The sub-model is used to predict the state of social-economic development for the studied region in the future. It is expressed by

$$P_t = P_{t-1}\,(1 + k_P) \tag{6}$$

$$GDP_t = GDP_{t-1}\,(1 + k_{GDP}) \tag{7}$$

Where, P_t, GDP_t, are the population and GDP in the Year t, respectively. P_{t-1}, are the population and GDP in the Year t − 1, respectively. k_p, k_{GDP} are the increasing rate of population and GDP, respectively.

2. Water resources constraint

The water resources constraint is expressed in the following:

$$\begin{aligned} W_{usable} &\geq W_{ind.} + W_{agr.} + W_{eco} + W_{lif.} \\ W_{usable} &= W_{surface} + W_{ground} + W_{sea-\inf low} + W_{cleaned\ polluted-water} \\ &\quad + W_{brackish} + W_{de-salinated} \end{aligned} \tag{8}$$

where W_{usable} is the total usable water volume of the studied region during the calculated period, which includes surface water ($W_{surface}$), groundwater (W_{ground}), sea inflow ($W_{sea-\inf low}$), cleaned polluted water ($W_{cleaned\ polluted-water}$), brackish water ($W_{brackish}$) and de-salinated water ($W_{de-salinated}$). $W_{ind.}$ is the water volume to be used by industry; $W_{agr.}$ is the water volume to be used by agriculture; $W_{eco.}$ is the water volume to be used for ecological maintenance (water and soil conservation, groundwater recharge, wetlands and perennial flow preservation, urban river or lake ecology and for sea outfall ecology); $W_{lif.}$ is the water volume to be used for human life, municipal consumption.

3. The constraint of environments related to water

Polluted water discharge is expressed as:

$$PW_{ind.} + PW_{lif.} \leq B \tag{9}$$

where $PW_{ind.}$ is waste water from industry, and $PW_{lif.}$ is polluted municipal water. B is the polluted water volume permitted to discharge during the calculated time, including the volume of polluted water that can be cleaned and the runoff self-purification capacity of the Haihe river basins.

Each of the different types of pollutants present in the Haihe river system must be considered over the calculated period. Here COD (chemical oxygen demand) in water is taken as an example:

$$COD_{ind.} + COD_{lif.} \leq B_1 \tag{10}$$

$COD_{ind.}$ and $COD_{lif.}$ are the amounts of COD in waste water from industry and in polluted water from human use, respectively. B_1 is the COD amount permitted to discharge during the calculated time, including the amount that can be cleaned and the runoff self-purification capacity of the Haihe river basins.

A groundwater exploitation coefficient and length ratio of perennial river segment shortening are included as:

$$C_k \leq A_k \quad (K = 3, 4) \tag{11}$$

If $k = 3$, then C_3 and A_3 are the actual groundwater exploitation coefficient and the maximum sustainable coefficient (Table 3), respectively. If $k = 4$, C_4 and A_4 are the actual length ratio of perennial river segment shortening and the maximum permitted, respectively. First- to third-order rivers are considered.

The area ratio of wetlands, area ratio of urban rivers and lakes, and volume of water reaching sea outfall are included:

$$C_k \geq A_k \quad (K = 5, 6, 7) \tag{12}$$

If $k = 5$, C_5 and A_5 are the area ratio of actual wetlands and the minimum demanded in the Haihe river basins, respectively. If $k = 6$, C_6 and A_6 are the

Table 3 The input parameters for the carrying capacity calculation scheme

Parameter	The status value	The programmed value	
	1998	2010	2030
Usable water resources (10^8 m^3)		503.80	537.00
Actual water abstraction(10^8 m^3)	432.30		
Water volume from South-to-North Water Transfer Project(10^8 m^3)*		79.90	108.40
Sewage treatment ratio (%)	13.00	45.00	60.00
Urbanization ratio (%)	27.60	27.60	46.30
Percentage of tertiary industry to GDP (%)	33.00	33.00	46.00
COD discharge amount(10^4 t)	128.10	$\leq B_1$	
Waste water discharge amount (10^4 m^3)	60.30	$\leq B$	
Polluted water discharge ratio from life (%)	16.7	16.7	16.7
Waste water discharge ratio from industry (%)	56.7	51.0	45.3
Per capita grain yield (kg/person)[a]	438	≥350	≥300
Per capita GDP (Yuan/person)	7,922	17,963	42,941
Water-used quota in agriculture (m^3/10^4Yuan)	2,377	2,140	1,902
Water-used quota in industry (m^3/10^4Yuan)	143.7	71.9	50.3
Minimum ecological water requirement(10^8 m^3)	121.3		

*Data points to the water volume from South-to-North Water Transfer project included in the total usable water volume

[a] The programmed values of per capita grain yield in 2010, 2030 is given on the low side, because of the thought that the Haihe river basins have the special regional locations, which lie in Capital Cycle and Beijing, Tianjing and Tangshan Economic Regions, and their grains need not to be autarkic, can be supplied by trade and other ways

area ratio of urban rivers and lakes and the minimum demanded. If $k = 7$, C_7 and A_7 are the volume of water reaching sea outfall and the minimum permissible.

4. Social-economy constraints
   The primary social-economy constraint is per capita GDP:

$$GDP_{rj} \geq A_{GDP_{rj}} \tag{13}$$

   where GDP_{rj} and $A_{GDP_{rj}}$ are per capita GDP and the minimum regional per capita GDP, respectively.
   Also included is per capita grain yield:

$$G \geq A_{grain} \tag{14}$$

   where G and A_{grain} are per capita grain yield and the minimum regional per capita grain stock (kg) required for sustenance.
5. Sustainable development constraint
   The sustainable development constraint is stated as:

$$ES\left(T\right) \geq ES\left(T-1\right) \tag{15}$$

   Because the course described by the model will affect the later course after period T, this does not accord with the essential nature of dynamic programming in operations analysis (no after-effect).

2.2.2 Analysis of Maximum Eco-environmental Loading

In the Haihe river basins, whether or not the social-economy system is sustainably carried by the eco-environmental system is decided by an eco-environmental quality estimating index LI and predicted human population, including natural increase and migration (Report of Water Resources Layout in Haihe River Basins, Haihe Water Conservancy Committee, State Water Conservancy Ministry, 2000). By definition, when $LI \geq 0.8$ and the maximum sustainable population is greater than actual population, the social-economy system can be carried by the eco-environmental system. LI is a combination of various eco-environmental quality indexes, and $LI = 0.8$ is the minimum value of the compound index endured by man.

2.2.3 Calculation Scheme and Material Source

The calculation scheme contains the assumptions that the South-to-North Water Transfer Project functions as planned, and that local society and economy develop in a usual style, as determined by the report on the program of water resources in the Haihe river basins (Haihe Water Conservancy Committee, State Water Conservancy Ministry, 2000). The input parameters for the carrying capacity calculation scheme are shown in Table 3. The baseline year for calculations is 1998. The materials needed are those on water and soil resources, eco-environments and the economy, except the programmed values of sewage treatment ratio and percentage of tertiary industry to GDP; other materials are from the report of water resources programme in Haihe river basins (Haihe Water Conservancy Committee, State Water Conservancy Ministry, 2000) and the Statistical Yearbook of Peking Municipality, Tianjin Municipality, Hebei, Shanxi, Shandong, Henan Province and the Inner Mongolia Autonomous Region (1998–2003). The programmed value of sewage treatment ratio is determined by the proportion of capital investment for environmental

Table 4 The status quo (1998) of eco-environments and social-economy in the Haihe river basin

Region	LI	EG	BTI	Sewage treatment ratio (%)
I	0.03	0.78	0.16	3.50
II	0.14	0.90	0.35	25.00
III	0.17	0.90	0.39	49.00
IV	0.15	0.95	0.38	54.80
V	0.14	0.80	0.33	3.20
VI	0.08	0.90	0.27	5.00
VII	0.09	0.77	0.27	15.00

EG The measuring index of social-economic level, *BTI* the measuring index of sustainable development of eco-environments–social-economy compound system

protection in GDP, and that of percentage of tertiary industry to GDP is determined by the corresponding industrial structure relationship theory on various economic development phases developed by H. Qiannule, the famous USA economist, and revised by the development centre of the State Council in 2001, according to conditions in China.

2.2.4 Calculation Process of the Carrying Capacity

The calculation process of the carrying capacity are the following: Firsty, the total usable water is distributed in a ratio of 1998, the initial year of the calculation, to be the water volume used by production including Industry and Agriculture, the water volume used by life and the water volume used by eco-environments; secondly, BTI is calculated by running the carrying capacity model under various kinds of constraints; thirdly, the results are outputted. The specific contents is seen in the paper of Zhu et al. (2005b).

2.2.5 Results of Carrying Capacity Calculation

Results obtained from the carrying capacity model are presented in Tables 4, 5 and 6. Table 4 shows the current status of eco-environments and social-economy in the Haihe river basins. Table 5 shows the time to reach a stable state for seven sub-regions and for the whole Haihe river basin. Table 6 shows the population in 1998, 2010, 2020 and 2030 of the seven regions.

Table 5 Time to reach a stable state for seven sub-regions and for the whole Haihe river basin

Region	Time to reach stable state	Number of years to reach stable state from 2004
I	2037	34
II	2035	32
III	2035	32
IV	2031	28
V	2040	37
VI	2039	36
VII	2025	22
Whole river basin	2033	30

Table 6 Population in 1998, 2010, 2020 and 2030 of the seven regions (104 persons)

Region	1998		2010		2020		2030	
	Actual	Maximum	Predicted	Max.	Predicted	Max.	Predicted	Max.
I	582	546	635	664	654	669	702	687
II	438	418	477	538	492	565	527	573
III	1,095	1,058	1,196	1,255	1,232	1,312	1,306	1,340
IV	1,395	1,365	1,615	1,491	1,664	1,549	1,760	1,674
V	1,924	1,733	2,104	1,842	2,168	1,946	2,367	2,037
VI	5,129	5,132	5,727	5,686	5,901	5,874	6,408	5,970
VII	1,649	1,666	1,801	1,699	1,856	1,805	1,998	2,036

3 Results and Analysis of their Rationality

(1) Currently, all seven studied eco-environmental regions in the Haihe river basin are in an over-loaded state. The causes are different in each region. The causes of region I being in an over-loaded state are: lower social-economy development level; insufficient investment in environmental protection, particularly sewage treatment; emphasis on agricultural and industrial production at the expense of water and soil conservation; and lack of available water for urban rivers and lakes. The causes of region II being in an eco-environmentally over-loaded state are: groundwater over-extraction leaving insufficient water for ecological maintenance, with perennial river segment shortening and sea outfall volume decreasing; and inadequate sewage treatment leading to excessive polluted water discharge and water quality deterioration. The causes of overloading in region III are: socio-economic development occupying the ecological water supply and arable soils; and large discharges of polluted water lacking treatment. The causes of region IV being over-loaded are: excessive water usage for economic development, with not enough water supplied to ecology; groundwater over-extraction; river de-watering; wetlands shrinking; sea outfall decreasing; and low sewage treatment rates leading to polluted water discharge. Causes of overloading in region V are: large polluted water discharge due to inadequate treatment rate; social-economy water usage preempting ecological maintenance; and decreasing area of urban rivers and lakes. Causes of region VI being over-loaded are: water resources shortage; excessive economic water usage at the expense of ecological maintenance; serious groundwater over-extraction; water pollution; shrinking wetlands; river de-watering; and sea outfall decreasing. The causes of overloading in region VII are: insufficient treatment, large polluted water discharges and decreasing water quality; and perennial river segment shortening or river de-watering.

(2) In the case that eco-environments are perfected gradually, available water supplies are increased by the South-to-North Water Transfer Project and the local society and economy develop in a usual manner, the Haihe river basin as a whole will not reach a sustainable stable state until about 2033, but the various eco-environmental regions will need different lengths of time to reach their own stable states because of differing available water resources, eco-environmental problems and social and economic development, as described below.

(a) Among the seven eco-environmental regions of the Haihe river basins, the plains area of the Tuhaimajia river is the first to reach its sustainable state, and the mountainous area of the south sub-basins of the Haihe is the last. The plains area of the Tuhaimajia is primarily agricultural, and it has relatively mild eco-environmental problems of low sewage treatment rates causing pollution, and some wetlands disappearance and river de-watering due to abstraction of surface water for agriculture. Water pollution can be mitigated by improving sewage treatment technology and ubiquity. Water resources here are the most sufficient among the seven regions, and its river de-watering and wetlands disappearance can be relatively quickly restored by technical level improvements and industrial structure regulation.

The mountainous area of the south river systems of the Haihe suffers from diversion of water for use in other regions, and the per capita water used is only 260 m^3, far lower than the critical per capita water requirement of 305 m^3 in the Heihe river basins. Most of the available water not diverted is used in the human economy and very little is left for ecological maintenance, creating serious eco-environmental problems. Groundwater extraction and COD discharge are greatest in the three mountainous regions, and their sewage treatment ratio is smallest. Socio-economic development is slowed, and the amount of available water is not expected to increase in the future.

(b) The number of years needed by mountainous regions to reach a stable state is greater than that of plains regions in the same river system. For example, the number of years needed for the mountainous area of the Luan river and eastern Hebei Province is greater than that of the plains in the same region. The reasons are that, at present, the eco-environmental quality and social-economy level are higher in the plains region, and predicted socio-economic development and technical level improvement in the plains will mitigate environmental problems. Moreover, in 2010 and 2030, the available water in the plains region will be increased by using desalted sea water available through more advanced technology. Similar factors are also at play in the mountainous area of the northern river systems of the Haihe, with a certain amount of available water increase in the plains region from the South-to-North Water Transfer Project, while only a small amount of additional water will be available in the mountainous region as input from the Yangtse river. In the southern river systems of the Haihe, a large increase in available water from the South-to-North Water Transfer Project will occur in the plains, but no increase will occur in the mountainous region.

(c) Time needed to reach a stable state in the mountainous area of the northern river systems of the Haihe is less than in the mountainous area of the Luan river and eastern Hebei Province, and a stable state will be reached earlier in the mountainous area of the Luan river and eastern Hebei Province than in the mountainous area of the southern river systems of the Haihe. The reasons for this are that present eco-environmental conditions are best and the economy's technical level in the mountainous area of the northern river systems of the Haihe is highest among the three mountainous regions, and in the future its technological level will improve most and its available water will be increased. The present eco-environmental state is poorer in mountainous areas of the Luan river and eastern Hebei Province than in mountainous areas of the southern river systems of the Haihe because of the greater area ratio of water and soil loss, caused by inadequate ecological water availability. However, its per-capita water resource is larger, its percentage of tertiary industry to GDP is higher and increasing faster, and its sewage treatment ratio and per-capita GDP are larger. Among the three mountainous regions, the present actual available water is least, and the rate of improvement in the social-economy level is slowest in the mountainous area of the southern river systems of the Haihe.

(d) The order in which stable states are reached successively among the three plains regions of the Haihe basin is: (IV) plains area of the northern river systems of the Haihe; (II) plains area of the Luan river and eastern Hebei Province; and (VI) plains area of the southern river systems of the Haihe. This is based on differences in their current eco-environmental state, level of socio-economic development, water treatment efforts, and available water resources. The current eco-environmental state of (IV) is highest, and of (VI) lowest; (VI) also has the lowest sewage treatment rate. Socio-economic level is highest in (IV) and lowest in (II) and(VI). Secondly, in the context of water resources, the present per capita available water in the three plains regions all exceed the critical value of 305 m^3, and future available water in the plains will be increased by desalted sea water and the South-to-North Water Transfer Project, so water resources are not the decisive factor influencing the time needed to reach a stable sustainable state in these regions. Lastly, the future development of socio-economic level and technical level is projected to be fastest in (IV), moderate in (II) and slowest in (VI).

4 Conclusions

(1) In this paper, a scientific and rational multi-objective optimization method was developed to calculate EECC of seven eco-environmental regions in the Haihe river basin.

(2) The number of years required to reach a sustainable eco-environmental stable state is mainly determined by socio-economic factors and by various eco-environmental factors. Among the latter, only discharge of COD is not relative to ecological water supply, so where ecological water supply is greater, the number of years to reach a stable state is fewer. The amount of COD discharged is relative to sewage treatment ratio and the amount of polluted water discharged by industry and agriculture, and these are determined by economic and technical level. So, where economic and technical development are greater, the amount of COD discharged is smaller, and it is easier to reach the stable state.

(3) It is in about 30 years that the eco-environments in the Haihe river basins will reach a sustainable stable state, but the time to reach this state differs among the

seven eco-environmental regions due to differences in available water, socio-economic development and current eco-environmental problems.

(4) Under the projected available water increase due to the South-to-North Water Transfer Project, the Haihe river basin will reach a stable state in 2033. The South-to-North Water Transfer Project has great practical significance for achieving eco-environmental restoration and sustainable development in the Haihe river basin.

(5) In this paper, in calculating W_{usable}, the surface water ($W_{surface}$), groundwater (W_{ground}) and other components are all treated as constants, mean annual values. In practice, the surface water and groundwater of a region are variables. So, further work is needed in which the EECC is calculated with surface water and groundwater treated as variables. The method used in the Haihe river basins could be applied to other river basins or other kinds of carrying capacity.

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