

Integrated Assessment of Water Resources Potential in the North China Region: *Developmental Trends and Challenges*

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Abstract: Potential assessment of water resources development (PAWRD) is very important for regional water management, water allocation, water transfer, and economic planning, especially for today's China, which is under a rapid economic growth, a continued expansion of population, and an increasingly deteriorating eco-environment. In this work, the southern part of Haihe River (SPHR) is selected as the representative area of the North China Region for a case study based on considerations such as available data, geographic characteristics, administrative boundaries, and the state of water shortage. A growth pattern of regional water resources development is presented. A fuzzy assessment model is established and applied to determine the growth stage, an indicator for water resources development potential. Seven assessment factors, selected based on the conditions of supply, demand, and use efficiency of water subjected to the regional physical, social, and economic settings, include irrigation rate of arable land, exploitation rate of water resources, the water-saving level, a water supply and demand modulus, the water supply per capita, and the ratio of eco-environmental water use. These factors are integrated into the fuzzy assessment model, which is shown to be capable and effective for potential assessment. The assessment results demonstrate the potential of water resources development is little in SPHR and are substantiated by the necessity of the middle route of the South-North Water Transfer (SNWT) in the long run. It is also suggested at present that promoting water saving and strengthening water demand controls would be the most feasible and effective solution to mitigate water shortage stress of SPHR before the SNWT scheme is implemented. PAWRD provides a scientific tool for water-demand management and water-saving improvement, as well as a necessary basis for decision-making for economy planning and water transfer design.

Keywords: integrated fuzzy assessment model, potential of water resources development, middle route of South-North Water Transfer, North China Region

Introduction

Potential Assessment of Water Resources Development (PAWRD) is very important for regional water management, water allocation, water transfer, and economic planning (Liu and He, 1996), especially for today's China, which is under a rapid economic growth, a continued expansion of population, and an increasingly deteriorating eco-environment.

The North China Region (NCR), as the political, economic, and cultural center of China, has been suffering the

crisis of water shortage since 1970s. Under rapid economic growth and lasting population expansion, the crisis of water shortage has become more and more serious. Eco-environmental problems, owing to water shortage and over-exploitation, have also become increasingly pressing (Liu and Yu, 2001).

The middle route of South-North Water Transfer (SNWT) schemes, which intends to transfer water from Yangtze River northwards to NCR (Figure 1), is accepted as the most feasible solution to the water shortage problem of NCR in the long run (Liu, 1998; Zhang, 1999; Zuo et al., 1983). Some questions must be answered prior to

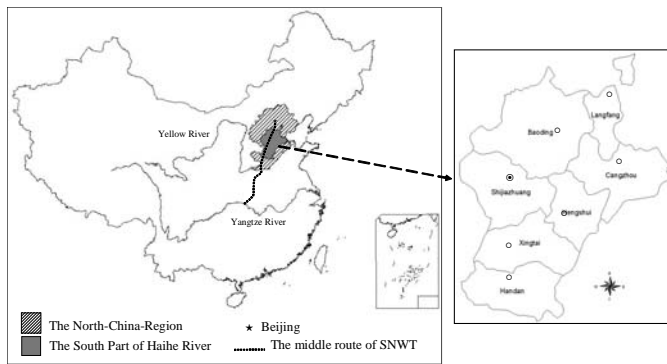


Figure 1. Geographic location and administrative boundaries of the study area

whatever economic development plans or SNWT schemes are laid out, such as what is the potential of water resources development of NCR? and what is the most challenging task to resolve the water shortage problem for NCR, intensifying water exploitation, strengthening water saving, or transferring water from far Yangtze River?

Providing scientific information relevant to policy makers and water resources managers is an important reason for potential assessment of regional water resources development. The primary purpose of this study is to assess the potential of water resources development in NCR using an integrated fuzzy assessment model in order to deliver the necessary information to aid decision-making on economy planning and the South-North Water Transfer. The objectives are: 1) to put forward a general growth pattern of regional water resources development; 2) to develop an integrated fuzzy assessment model to identify the stage that is the indicator for regional water resources development potential (factors that can reflect the state of water supply and demand, the status of water resources exploitation, and water use efficiency, were well integrated in this model); and 3) to present synoptic strategies for water shortage based on the assessment result.

In this work, the southern part of Haihe River is selected as the representative area of the North China Region for case study based on the considerations such as available data, geographic characteristics, administrative boundaries, and state of water shortage. The calendar year 1994 is singled out from its respective decade as a representation owing to the fact its meteorological data, such as rainfall record, spatiotemporal distributions, and seasonal temperature variations, were close to that of the average of the decade.

General Growth Pattern of Regional Water Resources Development

Water resources systems are dynamic with the interactions between human activities and the natural environment. The development intensity of water resources is usually increased along with the increase of social demand,

economic growth, and technological improvement. However, the increase cannot be infinite (Gao and Liu, 1997). Restricted by natural conditions, the socioeconomic state, and technological advancements, regional water resources development generally follows a growth pattern subject to damping factors, which could be approximately expressed with LOGISTIC model

$$\frac{dW_t}{dt} = R_t \cdot W_{t0} \cdot \left(1 - \frac{W_t}{Q_{max}}\right) \quad (1)$$

where W_t is the total volume of water resources development in t period; W_{t0} is the initial value of water resources development; R_t is the growth rate of water resources development in t period; and Q_{max} is the limit of regional water resources development. Described by graphical mode, the general pattern of regional water resources development can be illustrated as following figure (Figure 2).

In Figure 2, the two inflexions t_1 and t_2 divided the curve into three segments of $V_1 \in (t_0, t_1)$, $V_2 \in (t_1, t_2)$ and $V_3 \in (t_2, \infty)$, which correspond with following three stages of water resources development.

- (1) The preliminary stage ($W_t \in V_1$). In this stage, water resources development is characterized by small scale and low intensity. "Demand decides supply" is the main feature of this stage. Water users could intake water at their will. No water-use conflicts exist between the upstream and the downstream users or the left-bank and the right-bank users. Water conservancy is usually engineered for single objective. The water-savings level is very low due to poor comprehensive management and high-water-consuming types of industries and agriculture. However, this stage has an advantage of huge potential for water resources development.
- (2) The transition stage ($W_t \in V_2$). In this stage, the scale of water resources development is continuously enlarged, and the intensity is increased along with the rapid economic growth, continued expansion of population, and the swift advancement of science and technology. The inconsistency of water supply and demand

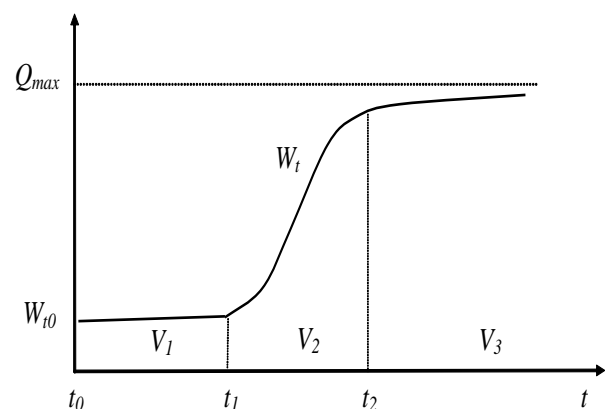


Figure 2. The general pattern of regional water resources development

tends to be increasingly strong. "Demand decides supply," the chief feature of the preliminary stage, gradually changes to "supply decides demand" of this stage. The water development mode transforms from extensive exploitation and single-aimed utilization of the preliminary stage into intensive exploitation and multi-goal comprehensive use in this stage. The economy changes from high water-consuming type to water-saving type. Water management changes from water-supply management to water-demand management. The water-savings level steadily rises with the advancement of water-saving technology and investment. The potential for water resources development is still large in this stage.

(3) The limit stage ($W_i \in V_j$). In this stage, water resources development is close to the limit of local water resources available. This stage is characterized by following features: "supply decides demand," a high level of water-saving, intensive development and comprehensive use of water resources, a water-saving economy, and a high social water-saving consciousness. The potential for water resources development is extremely limited. In this stage, the goal of zero growth or even the reduction of water demand should be achieved by controlling demand; otherwise water transferring from another watershed is necessary to alleviate the strong inconsistency between water supply and demand.

Integrated Fuzzy Assessment Model

The general pattern of regional water resources development indicates that assessing the potential of water resources development is approximately equivalent to identifying the stage at which the study area is presently. The identification process should consider not only the limit of local water resources development but also the intensity of water supply, water demand, and the present level of water-saving. The limit of local water resources development is defined as the maximum exploitation capacity of local water resources with the highest achievable water-use efficiency. Under the limit, water resources can maintain the natural cycle, renewal and reuse, without deteriorating the eco-environment (Xu, 1993). Therefore, PAWRD is a multi-variable assessment based on comprehensive analyses of different factors related to water supply, water demand, and water use. Due to the fact that these factors come from natural, social, and economic domains with different dimensions and are of great uncertainties within the scope of the aforementioned three stages, it is difficult for conventional regression, clustering, and optimization.

Fuzzy logic seems to offer a way to improve existing operation practices, which is relatively easy to explain and understand and more flexible than regression. The main concept in fuzzy logic is to simulate the operating system with both fuzzy logic programming and fixed rules. The key idea about fuzzy logic is that it allows for something to be partly this and partly that, rather than having to be ei-

ther all this or all that, and that the degree of 'belongingness' to a set or category can be described numerically by a membership number between 0 and 1. For a fuzzy problem, the fuzzy objective and constraints are characterized by their membership functions.

First introduced by Zadeh (1965), fuzzy set theory has been applied in various engineering applications to deal with imprecise information (Klir and Yuan, 1995). Recently, fuzzy regression, fuzzy clustering, fuzzy multi-objective programming, and fuzzy uncertainty have been applied in the field of hydrology and water resource in succession (Bardossy et al., 1990; Chen, 1995; Wu et al., 1997; Perret and Prasher, 1998; Yu and Yang, 2000; Chen et al., 2003). In this study, a fuzzy assessment model was established and applied to identify the growth stage of SPHR.

Integrated Fuzzy Assessment Model

Suppose two finite universes of discourse U and V:

$$U = \{U_1, U_2, \dots, U_n\} \quad (2)$$

$$V = \{V_1, V_2, \dots, V_n\} \quad (3)$$

where U represents assessment the factor set; and V represents the remark set. Then, integrated fuzzy assessment could be regarded as the following fuzzy conversion

$$B = A \bullet R \quad (4)$$

where A is a fuzzy subset of U; and B is a fuzzy subset of V, that is

$$A = (a_1, a_2, \dots, a_n), 0 \leq a_i \leq 1 \quad (5)$$

$$B = (b_1, b_2, \dots, b_m), 0 \leq b_j \leq 1 \quad (6)$$

where a_i is membership of U_i to A, which indicates the importance of uni-variant U_i compared to other assessment factors, and reflects the ability of U_i factor to classify the grades; b_j is membership of grade V_j to fuzzy subset B, which represents the results of fuzzy integrated assessment (Wang, 1984).

Judgment matrix R is:

$$R = \begin{pmatrix} r_{11} & r_{12} & \dots & r_{1m} \\ r_{21} & r_{22} & \dots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \dots & r_{nm} \end{pmatrix} \quad (7)$$

where r_{ij} is membership of U_i to V_j . Therefore, the i -th line of matrix R, $R_i = (r_{i1}, r_{i2}, \dots, r_{in})$, is the assessment result of single factor U_i .

Because $A = (a_1, a_2, \dots, a_n)$ represents the weights of assessment factors, $\sum_{i=1}^n a_i = 1$, and the fuzzy conversion $A \bullet R$ can be calculated as common matrix:

$$b_i = \min\{1, \sum_{i=1}^n a_i \cdot r_{ij}\} \tag{8}$$

Assessment Factors

Assessment factors should be able to reflect not only the state of water supply and demand, but also the exploitation condition and use efficiency. After thorough analyses of: the regional water resources system and various influencing factors; analyses of the regional differences of both natural renewability and development method of water resources; referring to the assessment system of “National Water Supply and Demand Analysis” (Hydrology Bureau, 1987) and other factors from the literature (Falkenmark and Lindh, 1976; Raskin et al., 1997; Arnell, 1999), these following factors were selected for integrated assessment:

- 1) U_1 : Irrigation rate of arable land (area of irrigation land/area of arable land);
- 2) U_2 : Exploitation rate of water resources (water supply/water resources amount);
- 3) U_3 : Water-saving level (overall water-saving index);
- 4) U_4 : Water supply modulus (water supply/area of land);
- 5) U_5 : Water demand modulus (water demand/land area);
- 6) U_6 : Water supply per capita (water supply/population);
- 7) U_7 : Ratio of eco-environmental water use (eco-environmental water use/water supply).

In order to quantitatively reflect the degree of influence the above indices have over the potential of regional water resources development, V_1 , V_2 , and V_3 , the three stages of water resources development, are applied as evaluation criterion of three grades and scored at a scale from 0 to 1 as $a_1=0.95$, $a_2=0.5$, $a_3=0.05$, the higher the value of a_j , the larger the potential of water resources development. The final integrated assessment value is calculated by the following formula

$$\alpha^{1/2} \frac{\sum_{j=1}^3 b_j^k \cdot \alpha_j}{\sum_{j=1}^3 b_j^k} \tag{9}$$

generally, $k=1$.

Assessment Matrix R

As known from above analysis, assessment factor set $U = \{U_1, U_2, \dots, U_n\}$ corresponds with remark set $V = \{V_1, V_2, \dots, V_n\}$, and the element r_{ij} of judgment matrix R is a membership function indicating the membership of U_i to grade V_j . Values of r_{ij} could be inferred by comparing the actual values of assessment factors with the classification values of assessment indices. In order to eliminate possible grade discrepancy of those assessment values with small differences, membership function should be smoothed out between the grades, which could be carried out by the fuzzy algorithm: let membership of midpoint of

grade V_2 (intermediate interval) receive a score of 1 and each of the two marginal points receive a score of 0.5, then linear functions could be constructed from midpoint to two ends. For the other two intervals V_1 and V_3 , make membership to these two grades V_1 and V_3 increase with the distance to the two marginal points from initial value 0.5 of these two marginal points. Based on this assumption and the definition of membership function (Chen, 1989; 1994; 1995), membership function to the three classification grades could be described by the following formula:

To assessment factors U_1, U_2, U_3, U_4, U_5 their membership functions of three classification grades are

$$\mu_{V_1}(U_i) = \begin{cases} 0.5(1 + \frac{k_1 - U_i}{k_2 - U_i}), & U_i < k_1 \\ 0.5(1 - \frac{U_i - k_1}{k_2 - k_1}), & k_1 \leq U_i < k_2 \\ 0, & U_i \geq k_2 \end{cases} \tag{10}$$

$$\mu_{V_2}(U_i) = \begin{cases} 0.5(1 - \frac{k_1 - U_i}{k_2 - U_i}), & U_i < k_1 \\ 0.5(1 + \frac{U_i - k_1}{k_2 - k_1}), & k_1 \leq U_i < k_2 \\ 0.5(1 + \frac{k_3 - U_i}{k_3 - k_2}), & k_2 \leq U_i < k_3 \\ 0.5(1 - \frac{U_i - k_3}{U_i - k_2}), & k_3 \leq U_i \end{cases} \tag{11}$$

$$\mu_{V_3}(U_i) = \begin{cases} 0.5(1 + \frac{U_i - k_2}{U_i - k_2}), & k_3 \leq U_i \\ 0.5(1 - \frac{k_3 - U_i}{k_3 - k_2}), & k_2 \leq U_i < k_3 \\ 0, & U_i \leq k_2 \end{cases} \tag{12}$$

To assessment factors U_6 and U_7 :

$$\mu_{U_6}(U_i) = \begin{cases} 0.5(1 + \frac{U_i - k_1}{U_i - k_2}), & k_2 \leq U_i \\ 0.5(1 - \frac{k_1 - U_i}{k_1 - k_2}), & k_2 \leq U_i < k_1 \\ 0, & U_i \leq k_2 \end{cases} \tag{13}$$

$$\mu_{U_7}(U_i) = \begin{cases} 0.5(1 - \frac{U_i - k_1}{U_i - k_2}), & U_i < k_1 \\ 0.5(1 + \frac{U_i - k_1}{k_2 - k_1}), & k_2 \leq U_i < k_1 \\ 0.5(1 + \frac{k_3 - U_i}{k_3 - k_2}), & k_3 \leq U_i < k_2 \\ 0.5(1 - \frac{U_i - k_3}{U_i - k_2}), & U_i \leq k_3 \end{cases} \tag{14}$$

$$\mu_{U_5}(U_i) = \begin{cases} 0.5(1 + \frac{U_i - k_2}{U_i - k_2}), & U_i < k_3 \\ 0.5(1 - \frac{k_3 - U_i}{k_3 - k_2}), & k_3 \leq U_i < k_2 \\ 0, & k_2 \leq U_i \end{cases} \tag{15}$$

where k_1 is the critical value between grade V_1 and V_2 , k_2 is the midpoint value of grade V_2 , and $k_2 = (\frac{k_1 + k_3}{2})$, k_3 is the critical value between grade V_2 and Grade V_3 .

Case Study

Characteristics of the Study Area

Location

The southern part of the Haihe River (SPHR) lies at the center of the North China Region between 113°27' to 117°48'E and 36°05' to 40°05'N, with an area of 89,942 km². Administratively, it consists of three large cities of Shijiazhuang (SJZ), Baoding (BD) and Handan (HD), three medium cities of Langfang (LF), Xingtai (XT), and Cangzhou (CZ), and one district of Hengshui (HS) (Figure 1). Owing to its convenient transportation, abundant mineral resources, and favorable meteorological conditions, SPHR is the most important industrial and agricultural region for Hebei Province.

Physiography

Mountainous areas, accounting for 29.3 percent of the whole area, stretches from north to south like a belt along the west of SPHR. Plains, accounting for 70.7 percent, are spread from piedmonts along the Taihang Mountains eastward to the coast of Bohai Sea. Four river nets, Yongding, Daqing, Ziya, and the Nanyun, traverse the plain area and flow into the Bohai Sea.

SPHR is characterized by the continental-monsoon-type of sub-humid warm-temperate climate (Zhao, 1986). This climate features great daily, seasonal, and annual variations in temperatures, as well as moderate but highly concentrated precipitation. Due to the variations in latitude and altitude, the mean annual air temperature is 0-11.5°; the frost free period is 180 to 220 days; the number of hours of sunshine is 2,450 to 2,780; precipitation is 500 to 600mm; evaporation from water surface is 1,000 to 1,400mm and from land surface it is 450 to 550mm; and runoff depth is 50 to 300mm. The basic vegetation type is the summer green deciduous broad-leaved forest, which corresponds to the continental monsoon climate with a cold and dry winter and a warm and wet summer. Zonal soils are represented by brown forest soils and drab soils. Brown forest soils are mainly distributed in the humid coastal region, while drab soils are extensively distributed in piedmont plains and foothills. From piedmonts along the Taihang

Mountains foot-slope eastward to the coastal plain, climatic, hydrogeologic, and geomorphologic conditions change in succession.

Socioeconomic Conditions

According to statistical data, the population in 1994 in SPHR was 46.6 million: 40.4 million resided in the agricultural areas and 6.2 million in the urban areas. The average population density was 518/km², which is 4.3 times of the average of China at the same time. There were 4.50x10⁷ hectares of farmland, more than 70 percent of those were irrigated. The main grain crops were winter wheat and summer maize. Industries were resource intensive, including metallurgy, machinery, textile, architecture, and foodstuff production. Heavy industry outweighs light industry, contributing nearly 60 percent of the value of total industrial production. Detail is shown in Table 1.

Water Resources

The total amount of water resource is 1.37x10¹⁰ m³: surface water is 6.98x10⁹ m³, and ground water is 8.50x10⁹ m³ (Gao, 1998). The per capita water resource of SPHR is 294.2 m³, less than one-seventh of the average of China; and the per hectare water resource of SPHR is 3043.1 m³, less than one-ninth of the average of China (Liu and Chen, 2001). Water resources in SPHR are characterized by five features:

- 1) Great seasonal fluctuation (Liu and Wei, 1989) where 60 to 70 percent of the total precipitation occurs in summer and only 5 to 10 percent in winter. Consequently, the surface water runoff is concentrated in the same period.
- 2) High exploitation intensity. Exploitation rate is already very high: 40 percent for surface water resources, 131 percent for groundwater resources, and 99 percent for the total amount of SPHR. Therefore, potential for further exploitation is extremely limited (Table 2).
- 3) Relatively higher level of water saving as compared to the average of Hebei province in 1994 (Table 3, Appendix I: Calculation method of water-saving index).
- 4) Severe over-exploitation of groundwater (Table 2) and

Table 1. Social-economic data of SPHR in 1994

	SJZ	BD	HD	LF	XT	CZ	HS	SPHR
Population (10 ⁴)	835.7	1,012.1	788.1	357.5	627.9	633.1	402.3	4,656.7
1.City	178.2	101.8	111.8	59.8	61.4	76.1	28.3	617.4
2.Country	657.5	910.3	676.3	297.7	566.5	557.0	374.0	4,039.3
Land (km ²)	14,027	22,112	12,047	6,429	12,456	14,056	8,815	89,942
1.Mountain	7,334	10,968	4,529	48	3,507	0	0	26,386
2.Plain	6,693	11,144	7,518	6,381	8,949	14,056	8,815	63,556
Farmland (10 ³ ha)	595.1	808.2	676.1	317.4	680.4	786.1	584.7	4,502.0
1.Irrigation land	524.0	667.4	493.7	236.2	450.9	402.9	367.8	3,169.9
2.Dry land	71.1	140.8	182.4	108.2	229.5	383.2	216.9	1,332.1
Output (10 ⁸ RMB)*	468.3	264.6	257.6	152.9	186.1	181.7	129.9	1,641.0
1.Industry	382.0	197.7	210.7	121.5	143.8	140.9	99.3	1,295.5
2.Agriculture	86.3	66.9	46.9	31.4	42.3	40.8	30.6	345.2

* Converted into the price of 1980.

Table 2. Water resources exploitation rate of SPHE in 1994

	<i>SJZ</i>	<i>BD</i>	<i>HD</i>	<i>LF</i>	<i>XT</i>	<i>CZ</i>	<i>HS</i>	<i>SPHR</i>
Exploitation rate of surface water resources (%)	0.52	0.24	0.76	0.46	0.40	0.21	0.37	0.40
1.Surface water resources (10 ⁸ m ³)	14.46	24.49	9.54	3.53	7.84	7.98	1.95	69.78
2.Surface water supply (10 ⁸ m ³)	7.48	5.82	7.26	1.64	3.17	1.70	0.72	27.79
Exploitation rate of groundwater resources (%)	187	115	128	75	156	97	145	131
1.Groundwater resources (10 ⁸ m ³)	17.10	22.15	9.48	9.87	9.40	10.09	6.86	84.95
2.Groundwater supply (10 ⁸ m ³)	31.96	35.54	12.11	7.36	14.65	9.76	9.92	111.30
Water resources exploitation rate of SPHE (%)	153	80	109	73	106	59	115	99

Table 3. Assessment result of water-saving level of SPHE in 1994

	<i>SJZ</i>	<i>BD</i>	<i>HD</i>	<i>LF</i>	<i>XT</i>	<i>CZ</i>	<i>HS</i>	<i>SPHR</i>
Overall water-saving index	0.93	1.12	1.11	1.39	1.10	1.27	1.29	1.11
1. Industry water-saving index	1.08	0.69	0.69	2.14	0.84	1.37	1.77	0.95
2. Agriculture water-saving index	0.92	1.19	1.29	1.22	1.13	1.25	1.27	1.15
3. Domestic water-saving index	0.82	1.08	1.04	2.13	0.78	1.31	1.21	0.98

Table 4. Water supply, demand and shortage of SPHE in 1994

	<i>SJZ</i>	<i>BD</i>	<i>HD</i>	<i>LF</i>	<i>XT</i>	<i>CZ</i>	<i>HS</i>	<i>SPHR</i>
Water supply (10 ⁸ m ³)	39.44	31.36	19.37	9.00	17.82	11.62	10.64	139.09
Water demand (10 ⁸ m ³)	39.45	32.56	22.47	9.40	19.08	13.91	13.53	150.40
Water shortage (10 ⁸ m ³)	0.01	1.2	3.1	0.4	1.26	2.29	2.89	11.31

eco-environmental problems, such as land subsidence, sea water intrusion, and water quality degradation.

- 5) Serious water shortage (Table 4). In 1994, it was 859 million m³, equivalent to 6 percent of the water demand. In dry years, the water shortage rate is usually more than 20 percent.

Water shortage becomes a bottleneck constraint factor for sustainable growth of economy, eco-environment protection, and social development in SPHR. In the middle route of SNWT scheme, SPHR is an important part of water-import region.

Model Application

After thorough analyses of the physiographical features, natural resources conditions, socioeconomic state, and the status of water supply and demand in SPHR, the values of classification grades V_i and the critical points k_j were determined (Tables 5 and 6). In Table 5, the assessment index U_3 , water-saving level, was indicated by overall water-saving index of SPHR, which is determined according to the average water-saving level of Hebei Province. For example, 0.6 is identified as the critical value between V_1 and V_2 , and 2.0 between V_2 and V_3 , which means the overall water-saving index of 0.6 or 2.0 could be regarded as the boundary points between the preliminary stage and the transition stage or the transition stage and the limit stage according to the average water-saving level of Hebei province in 1994. It is known from Table 3 that the overall water-saving index of SPHR is 1.11 and LF has the highest water-saving level among the sub-areas with an index of 1.39. In fact, in developed countries

such as Japan, USA, England, the Netherlands, Sweden, Germany, and France, the overall water-saving indices are approximately within the range of 1.5 to 2.5 in 1994 after preliminary estimation. Therefore, taking the overall water-saving index of 2.0 as the starting point of the limit stage is not a low criterion for water-saving level of SPHR.

Based on the statistical data of land use, socioeconomic state and the status of water exploitation and use (Tables 1 to 4), values of assessment factors U_i were obtained (Table 7). Substituting these values of k_j and U_i from Table 6 and Table 7 into equations (10)-(15) to calculate r_{ij} , the membership of

Table 5. Classification grade values of V_i

<i>Index</i>	<i>Unit</i>	V_1	V_2	V_3
U_1	%	<30	30-70	>70
U_2	%	<40	40-80	>80
U_3		<0.6	0.6-2.0	>2.0
U_4	10 ⁴ m ³ /km ²	<5	5-15	>15
U_5	10 ⁴ m ³ /km ²	<5	5-15	>15
U_6	m ³ /capita	>2000	1,000-2,000	<1000
U_7	‰	>5	5-2	<2
α_j		0.95	0.50	0.05

Table 6. Values of the critical points k_j

<i>Index</i>	<i>Unit</i>	k_1	k_2	k_3
U_1	%	30	50	70
U_2	%	40	60	80
U_3		0.6	1.3	2.0
U_4	10 ⁴ m ³ /km ²	5	10	15
U_5	10 ⁴ m ³ /km ²	5	10	15
U_6	m ³ /capita	2,000	1,500	1,000
U_7	‰	5	3.5	2

Table 7. Values of assessment factors U_i

Index	Unit	SJZ	BD	HD	LF	XT	CZ	HS	SPHR
U_1	%	88.1	82.6	73.0	70.9	66.3	51.3	62.9	70.4
U_2	%	153	80	109	73	106	59	115	99
U_3		0.93	1.12	1.11	1.39	1.10	1.27	1.29	1.11
U_4	$10^4\text{m}^3/\text{km}^2$	27.3	12.9	16.0	12.6	15.3	8.0	12.1	15.0
U_5	$10^4\text{m}^3/\text{km}^2$	27.8	14.7	18.7	14.6	15.3	9.9	15.3	16.7
U_6	m^3/capita	458.2	281.7	245.3	226.9	304.3	177.9	264.5	290.4
U_7	‰	2.0	3.0	2.0	3.0	2.0	3.0	2.0	2.5

^aEco-environmental water use mainly includes irrigation for garden, lawn and water use for cleaning, forestation etc.. Due to the lack of statistical data, U_7 of some sub-areas of SPHR were determined based on concerned eco-environmental protection plans as well as the status of water supply and demand.

assessment factors U_i to grade V_j , where, r_{i1} equals $\mu_{V_1}(U_i)$, r_{i2} equals $\mu_{V_2}(U_i)$, and r_{i3} equals $\mu_{V_3}(U_i)$ then assessment matrix R were obtained (Table 8).

Considering the degree of influence of different assessment factors to the potential of water resources development, taking their interactions, repetitions and overlaps into account, and using ‘‘Assessment Criterion of National Water Resources’’ (Hydrology Bureau, 1987) as reference, weights of assessment factors were assigned as

$$A = (a_1, a_2, a_3, a_4, a_5, a_6, a_7) \\ = (0.15, 0.20, 0.20, 0.10, 0.10, 0.15, 0.10)$$

Therefore, final fuzzy integrated assessment values of SPHR and its sub-areas could be calculated. For example, the final result of SPHR is

$$B = A \bullet R = (a_1, a_2, a_3, a_4, a_5, a_6, a_7) \bullet \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ \dots & \dots & \dots \\ r_{71} & r_{72} & r_{73} \end{pmatrix}$$

$$= (0.15, 0.20, 0.20, 0.10, 0.10, 0.15, 0.10) \bullet \begin{pmatrix} 0.000 & 0.490 & 0.510 \\ 0.000 & 0.256 & 0.744 \\ 0.136 & 0.864 & 0.000 \\ 0.000 & 0.500 & 0.500 \\ 0.000 & 0.373 & 0.627 \\ 0.000 & 0.207 & 0.793 \\ 0.000 & 0.667 & 0.333 \end{pmatrix}$$

$$= (0.027, 0.483, 0.490)$$

Consequently, the final fuzzy integrated assessment value of SPHR is

$$\alpha = \frac{\sum_{j=1}^3 b_j^k \cdot \alpha_j}{\sum_{j=1}^3 b_j^k} = (\alpha_1, \alpha_2, \alpha_3) \bullet (b_1, b_2, b_3)^T \\ = (0.95, 0.50, 0.05) \bullet (0.027, 0.483, 0.490)^T \\ = 0.292$$

Table 8. Calculation results of assessment matrix R of SPHR

	SJZ			BD			HD			LF		
	V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3
U_1	0.000	0.262	0.738	0.000	0.307	0.693	0.000	0.435	0.565	0.000	0.478	0.522
U_2	0.000	0.108	0.892	0.000	0.500	0.500	0.000	0.204	0.796	0.000	0.675	0.325
U_3	0.264	0.736	0.000	0.129	0.871	0.000	0.136	0.864	0.000	0.000	0.936	0.064
U_4	0.000	0.145	0.855	0.000	0.710	0.290	0.000	0.417	0.583	0.000	0.662	0.338
U_5	0.000	0.140	0.860	0.000	0.530	0.470	0.000	0.287	0.713	0.000	0.537	0.463
U_6	0.000	0.240	0.760	0.000	0.205	0.795	0.000	0.199	0.801	0.000	0.196	0.804
U_7	0.000	0.500	0.500	0.000	0.833	0.167	0.000	0.500	0.500	0.000	0.833	0.167
	XT			CZ			HS			SPHR		
	V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3
U_1	0.000	0.592	0.408	0.000	0.967	0.033	0.000	0.667	0.323	0.000	0.490	0.510
U_2	0.000	0.217	0.783	0.025	0.975	0.000	0.000	0.182	0.818	0.000	0.256	0.744
U_3	0.142	0.858	0.000	0.021	0.979	0.000	0.007	0.993	0.000	0.136	0.864	0.000
U_4	0.000	0.472	0.528	0.200	0.800	0.00	0.000	0.790	0.210	0.000	0.500	0.500
U_5	0.000	0.472	0.528	0.010	0.990	0.00	0.000	0.472	0.528	0.000	0.373	0.627
U_6	0.000	0.209	0.791	0.000	0.189	0.811	0.000	0.202	0.798	0.000	0.207	0.793
U_7	0.000	0.500	0.500	0.000	0.833	0.167	0.000	0.500	0.500	0.000	0.667	0.333

Table 9. The final fuzzy integrated assessment values of SPHE

$\mu_{V_i}(\text{regions})$	V_1	V_2	V_3	Total score
SJZ	0.053	0.323	0.625	0.243
BD	0.026	0.558	0.416	0.324
HD	0.027	0.429	0.544	0.268
LF	0.00	0.626	0.374	0.332
XT	0.028	0.480	0.492	0.291
CZ	0.030	0.827	0.143	0.449
HS	0.003	0.542	0.456	0.296
SPHR	0.027	0.483	0.490	0.292

In the same way, the final fuzzy integrated assessment values of the sub-areas are also obtained (Table 9).

Results Analysis

In Table 9, $\mu_{V_3}(\text{SPHR})$ is 0.490, greater than $\mu_{V_2}(\text{SPHR})$ and $\mu_{V_1}(\text{SPHR})$. Comparing the memberships of SPHR to V_1 , V_2 and V_3 shows that in the overall growth path of water resources development, SPHR has already entered the limit stage. Namely, the potential of water resources development is little in SPHR. However, $\mu_{V_2}(\text{SPHR})$ is 0.483, slightly smaller than $\mu_{V_3}(\text{SPHR})$, and $\mu_{V_1}(\text{SPHR})$ is 0.027. That is to say, although SPHR has entered the limit stage, it still bears some features of transition stage or even preliminary stage, such as low water use efficiency and poor overall management. In other words, SPHR has not completely converted from water-supply management to water-demand control and water-saving management although it has already entered the limit stage.

Table 9 has also demonstrated that among the seven sub-areas, SJZ, HD, and XT have been in the limit stage of water resources development, while BD, LF, CZ, and HS are still in the transition stage. SJZ shows the most notable features of the limit stage with a membership of 0.625; however, it has retained the most relatively evident features of the preliminary stage with a membership of 0.053. The sub-area that bears the most remarkable features of the transition stage is CZ with a membership of 0.827. In terms of integrated assessment value, SPHR has very small potential of water resources development with the score 0.292, which substantiates the necessity of the middle route of SNWT scheme in the long run. CZ ranks on top with a score of 0.449, in contrast to SJZ in the worst situation with a score of 0.243. The sub-areas could be ranked by magnitudes of integrated assessment value in descending order as CZ, LF, BD, HS, XT, HD, and SJZ. Correspondingly, it is in the same order for potential of water resources development as the integrated assessment value.

Table 8 gives the memberships of seven assessment factors to the three stages of SPHR and all sub-areas in detail, which helps to find out the problems in water resources exploitation, management, and use efficiency. For example, memberships of U_3 (water-saving level) to V_i show that the most serious problem of SPHR is the poor state of water saving. Similarly, memberships of U_2 (ex-

ploitation rate of water resources) to V_i indicate that water exploitation potential is extremely little for SPHR. Apparently, at present, strengthening water demand control, improving water management, and promoting water savings would be the most feasible and effective solution to mitigate water shortage stress of SPHR before the South-North Water Transfer scheme comes true.

Summary and Discussion

Regional water resources systems are dynamic and complicated systems under the interactions between natural environments and human activities (Gao, 1998). The potential assessment, or carrying capacity evaluation, of regional water resources is certainly a difficult task, which involves many natural, physical, economic, human, and social factors. How to rationally integrate these factors selected from various domains with different dimensions is a difficult problem puzzling assessment workers for quite a long time. In this study, a general growth pattern of regional water resources development is proposed, and an integrated fuzzy assessment model is used to identify the stage that is the indicator for regional water resources development potential. Seven assessment factors are well integrated in the fuzzy assessment model. Comparing the assessment result to the actual status of SPHR, the model has been shown to be capable and effective for assessing the potential of regional water resources development.

Seven factors are selected for assessment in view of the physical, geographical, and socioeconomic conditions of the study area. In general, assessment factors are different when the study area is changed. For instance, for those regions of humid southern China, where rainfall is plentiful, water shortage is often produced by wastewater pollution, which makes abundant water resources out of use. Consequently, water quality or wastewater disposal rate should be selected as one of assessment factors. For coastal regions, seawater use should be taken into account. For desert regions, oasis area and ecological water use should be emphasized. Since a relative index is often more comparable and rational for potential assessment than an absolute index, all of the seven assessment indices in this paper are relative indices. With regard to the numerical values of the indices, such as the classification grades V_i (Table 5) or the critical points k_j (Table 6), they should be conformed to some accepted criteria. For example, the accepted criterion for rational exploitation rate of surface water resources is 40 percent, and for groundwater it is 100 percent. Conformed to this criterion, exploitation rates of water resources (U_2) were determined as less than 40 percent, 40 to 80 percent, and greater than 80 percent for V_1 , V_2 , and V_3 , respectively.

The middle route of SNWT scheme is feasible or at least not dependent upon so many natural, social, economic, and ecological factors. However, the potential of water resources development of NCR itself is one of the most

important factors. It is difficult to rationalize such an act that transfers water from far with enormous socio-economic and ecological costs for a region still with a huge potential of water resources development. This study cannot answer the question whether or not SNWT scheme is feasible, but to some extent, it can answer the question whether or not it is necessary.

Appendix I: Calculation method of water-saving index

1. Industry water-saving index

$$E_{i,1} = \frac{\sum_{j=1}^n \Delta V_{i,j} \cdot S_j}{W_i} \quad (A1)$$

where $E_{i,1}$ is industrial water-saving index of sub-area i ; W_i is actual water consumption for industry; $V_{i,j}$ is increment value of industry j ; S_j is the reference value of water consumption amount for per unit increment value, in this study, the average value of Hebei Province is taken as the reference; and n is the number of industries in i sub-areas.

2. Agriculture water-saving index

$$E_{i,2} = \frac{\sum_{j=1}^n O_{i,j} \cdot S_j \cdot \alpha_{i,j}}{W_i} \quad (A2)$$

where $E_{i,2}$ is agricultural water-saving index of sub-area i ; $O_{i,j}$ is the yield of crop j ; S_j is the reference value of water consumption amount per unit output, which, in this study, is taken to be the average value of Hebei Province; $\alpha_{i,j}$ is the modified coefficient of climatic factors, which strongly influences irrigation quota; and W_i is actual water consumption for agriculture in sub-area i .

3. Domestic water-saving index

$$E_{i,3} = \frac{S_i}{Q_i} \quad (A3)$$

where $E_{i,3}$ is domestic water-saving index of sub-area i ; Q_i is actual water consumption per capita; S_i is the reference value of water consumption amount per capita, which is determined by the actual conditions of sub-area i , such as the location in river basin, city size, and climate condition.

4. Overall water-saving index

Overall water-saving index is calculated based on water-saving indices of the above three sectors, the formula is

$$E_i = \sum_{j=1}^m \beta_{i,j} \cdot E_{i,j} \quad (A4)$$

where E_i is overall water-saving index of sub-area i ; $b_{i,j}$ is structural coefficient of sector j ; defined as the proportion of water consumption for sector j ; and m is the number of sectors.

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