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Assessing water renewal of the northern coastal zone in China using a variable fuzzy pattern recognition model

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ABSTRACT

An integrated indexes system for assessing water renewal of the northern coastal zone is developed; and rough sets theory is used to eliminate the redundancy in the indexes system. Then a variable fuzzy pattern recognition model is selected to evaluate the state of water renewal, which involves fuzzy information and interval numbers of classification standard values for evaluation. The indexes system and evaluation model are illustrated in water renewal evaluation of Dalian City. The results of the recent ten years show that natural renewal is much lower than social renewal. The evaluation result of the planning year implies that measures including increasing efficiency of water consumption, increasing use of reclaimed water amounts, desalinated water and seawater, and use of trans-basin water work are effective for improving social renewal; furthermore, water use of trans-basin work is the most sensitive factor influencing social renewal, and other measures including use of reclaimed water, water-saving of urban living, use of seawater for industry, water-saving of agriculture and water-saving of industry are in sequence of sensitivity.

Key words | northern coastal zone, rough sets theory, single factor sensitivity analysis, variable fuzzy pattern recognition model, water renewal

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NOTATION

Variable fuzzy sets

$\underset{\sim}{A}$ and $\underset{\sim}{A}^c$	two fuzzy concepts of attractability and repellency
$\mu_{\underset{\sim}{A}}(u)$ and $\mu_{\underset{\sim}{A}^c}(u)$	relative membership degree of attractability and that of repellency
$D_{\underset{\sim}{A}}(u)$	relative difference degree of u to $\underset{\sim}{A}$
$\underset{\sim}{V}$	variable fuzzy sets
A_+, A_- and A_0	attracting (as priority) sets, repelling (as priority) sets and qualitative change boundary of $\underset{\sim}{V}$

Indexes filter

h	evaluation level of water renewal
x_i	characteristic value for index i
y_i	discrete value for index i
I_l	information table for cellular system l in the unit floor
D_{I_l}	discernibility matrix for information table l
CORE_{I_l}	core set of attributes for information table l
${}_lF$	disjunctive normal form for information table l

Variable fuzzy pattern recognition model for assessing water renewal

w_i^4	normalized weight value for index i in the index floor
μ_{ih}^4	relative membership degree for index i belonging to level h in the index floor
μ_{lh}^3	synthetic relative membership degree (SRMD) for cellular system l belonging to level h in the unit floor

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w_l^3	normalized weight value for cellular system l in the unit floor
μ_{1h}^2	SRMD for cellular system of natural renewal belonging to level h in the sub-target floor
w_1^2	normalized weight value for cellular system of natural renewal in the sub-target floor
μ_{2h}^2	SRMD for cellular system of social renewal belonging to level h in the sub-target floor
w_2^2	normalized weight value for cellular system of social renewal in the sub-target floor
μ_h^1	SRMD for cellular system of water renewal belonging to level h in the target floor
H	level characteristic value on water renewal
${}_1H$	level characteristic value on natural renewal
${}_2H$	level characteristic value on social renewal

INTRODUCTION

Water is a type of renewable resource, and renewal is its fundamental attribute. Postel *et al.* (1996) proposed that the renewable volume was the annual volume of freshwater via the natural hydrological cycle. Usually, an index such as renewal time or renewal rate is used to evaluate the state of water renewal, and this has been discussed by many researchers (You 2000; Hoppema *et al.* 2001; Le Gal La Salle *et al.* 2001; Masson 2002; Yang *et al.* 2002; Xia *et al.* 2003; Andrejev *et al.* 2004; Yan *et al.* 2005).

In recent decades, numerous man-made water cycle measures including water saving, disposal and reclamation of wastewater, use of desalinated seawater, direct use of seawater and use of rainwater have been taken to gain more volume of water, and these make water resources renewable, in a way. As a result, not only the volume of freshwater via the natural hydrological cycle but also that via man-made water cycles should be considered as the volume of water renewal (Yang *et al.* 2005). Zeng *et al.* (2001) defined water renewal affected by the natural hydrological cycle as the natural renewal of water, and called water renewal affected by man-made water cycles as the social renewal of water. This definition indicates that multiple factors impose obvious influences on water renewal; consequently, it is difficult for us to assess water renewal by using a single index, and an integrated indexes system involving multiple indexes is required. Yang *et al.* (2005) developed the integrated indexes system to assess water renewal of the Yellow River basin, and the evaluation models including the genetic projection pursuit method (Yang *et al.* 2004*a*), multi-objective decision-making ideal interval method (Yang *et al.* 2004*b*), matter element model (Yang *et al.* 2004*c*), technique for order preference by similarity to the ideal solution (Li & Yang 2005) and variable fuzzy sets theory (Chen & Li 2006) were applied.

The northern coastal zone is one of the areas suffering serious water scarcity in China, and water scarcity has brought serious threats and great loss to life and the national economy. The assessment of water renewal of this area has been urgently called for, but little research has been reported. This paper aims to ascertain the state of water renewal of the northern coastal zone, find the central factors limiting renewal and propose measures for improving its water renewal. The specific objectives are: (1) to construct the integrated indexes system for assessing the water renewal of the northern coastal zone from the viewpoint of the natural hydrological cycle and the man-made water cycle; (2) to apply rough sets theory (Pawlak 1997; Walczak & Massart 1999) to eliminate the redundancy in the preliminary indexes system; (3) to apply the variable fuzzy pattern recognition model (Chen 2005) to gain the state of water renewal; and (4) to make a case study of Dalian City, which involves the renewal assessment of the current year (1998–2007) and the planning year 2020, and propose measures of improving renewal of the area.

VARIABLE FUZZY PATTERN RECOGNITION MODEL

Suppose $\underset{\sim}{A}$ and $\underset{\sim}{A}^c$ are two fuzzy concepts of attractability and repellency, respectively. To any element u in universe U, $u \in U$, let $\mu_{\underset{\sim}{A}}(u)$ and $\mu_{\underset{\sim}{A}^c}(u)$ denote the relative membership degree of attractability and that of repellency, respectively, and the expressions $\mu_{\underset{\sim}{A}}(u) + \mu_{\underset{\sim}{A}^c}(u) = 1$,

$\mu_{\underset{\sim}{A}}(u) \in [0,1]$, $\mu_{\underset{\sim}{A}^c}(u) \in [0,1]$ are satisfied. Let

$$D_{\underset{\sim}{A}}(u) = \mu_{\underset{\sim}{A}}(u) - \mu_{\underset{\sim}{A}^c}(u) \tag{1}$$

where $D_{\underset{\sim}{A}}(u)$ is defined as the relative difference degree of u to $\underset{\sim}{A}$. Mapping

$$\begin{aligned} &D_{\underset{\sim}{A}}(u): D \rightarrow [-1,1] \\ &\quad u| \rightarrow D_{\underset{\sim}{A}}(u) \end{aligned} \tag{2}$$

is defined as the relative difference function of u to $\underset{\sim}{A}$. Let

$$\begin{cases} \underset{\sim}{V} = \{(u,D)|D_{\underset{\sim}{A}}(u) = \mu_{\underset{\sim}{A}}(u) - \mu_{\underset{\sim}{A}^c}(u),\ D \in [-1,1]\} \\ A_+ = \{u|u \in U,\ 0 < D_{\underset{\sim}{A}}(u) \le 1\} \\ A_- = \{u|u \in U,\ -1 \le D_{\underset{\sim}{A}}(u) < 0\} \\ A_0 = \{u|u \in U,\ D_{\underset{\sim}{A}}(u) = 0\} \end{cases} \tag{3}$$

where $\underset{\sim}{V}$ is called the variable fuzzy sets, A_+, A_- and A_0 are called attracting (as priority) sets, repelling (as priority) sets and qualitative change boundary of $\underset{\sim}{V}$, respectively.

Suppose that there are m indexes denoting the evaluated sample. Let the matrix of the characteristic values of indexes be expressed as

$$X = (x_i),\ i = 1,2,\ \ldots,m \tag{4}$$

where x_i is the characteristic value of the ith index.

Let the matrix of classification standard values be

$$S_{ab} = ([a_{ih}, b_{ih}]),\ i = 1,2,\ \ldots,m;\ h = 1,2,\ \ldots,c \tag{5}$$

where $[a_{ih}, b_{ih}]$ is the interval numbers of the classification standard value of the ith index in the hth level, and c is the total number of levels.

After the matrix S_{ab} is determined, the bound matrix $S_{cd} = ([c_{ih},\ d_{ih}])$ is gained according to the definition of variable fuzzy sets, and the point value matrix $M = (m_{ih})$ is ascertained according to the actual problem or selected as the midpoint value of the interval $[a_{ih}, b_{ih}]$. Then the relative membership degree $\mu_{\underset{\sim}{A}}(x)_{ih}$ of the ith index belonging to the hth level can be elicited by using Formulae (6), (7) or (8):

$$\mu_{\underset{\sim}{A}}(x)_{ih} = \begin{cases} 0.5 + 0.5[(x_i - a_{ih})/(M_{ih} - a_{ih})]^{\beta}, & x_i \in [a_{ih}, M_{ih}] \\ 0.5 - 0.5[(x_i - a_{ih})/(c_{ih} - a_{ih})]^{\beta}, & x_i \in [c_{ih}, a_{ih}] \end{cases} \tag{6}$$

$$\mu_{\underset{\sim}{A}}(x)_{ih} = \begin{cases} 0.5 + 0.5[(x_i - b_{ih})/(M_{ih} - b_{ih})]^{\beta}, & x_i \in [M_{ih}, b_{ih}] \\ 0.5 - 0.5[(x_i - b_{ih})/(d_{ih} - b_{ih})]^{\beta}, & x_i \in [b_{ih}, d_{ih}] \end{cases} \tag{7}$$

$$\mu_{\underset{\sim}{A}}(x)_{ih} = 0, \quad x_i \notin [c_{ih}, d_{ih}] \tag{8}$$

where β is a non-negative coefficient and is usually taken as $\beta = 1$.

The synthetic relative membership degree (SRMD) $u_h^{'}$ of the evaluated sample belonging to the hth level is

$$u_h^{'} = \left[1 + \left(\frac{\sum_{i=1}^{m}[w_i(1 - \mu_{\underset{\sim}{A}}(x)_{ih})]^p}{\sum_{i=1}^{m}(w_i \mu_{\underset{\sim}{A}}(x)_{ih})^p}\right)^{\alpha/p}\right]^{-1} \tag{9}$$

where w_i is the normalized weight value of the ith index, while α and p are variable coefficients.

Formula (9) is called the variable fuzzy pattern recognition model, and four groups of parameters $\alpha = 1$, $p = 1$, $\alpha = 1$, $p = 2$, $\alpha = 2$, $p = 1$ and $\alpha = 2$, $p = 2$ can be taken.

Finally, the level characteristic value H of the sample can be expressed as

$$H = \sum_{h=1}^{c} u_h \cdot h \tag{10}$$

where u_h is the normalized synthetic relative membership degree.

INTEGRATED INDEXES SYSTEM FOR ASSESSING WATER RENEWAL

Preliminary selection of indexes

It is well known that constructing a scientific and reasonable indexes system is the first step to perform an evaluation. The integrated indexes system for assessing water renewal of the northern coastal area is constructed based on the following principles:

(1) The general principles of constructing the indexes system, which includes systematization and hierarchy, comprehensiveness and representative, feasibility and operability, etc.
(2) The feature of water renewal of the northern coastal area. For example, the lower natural renewal of water caused by the lower rainfall, quicker runoff yield, soil and water losses, and serious seawater intrusion, etc, and the higher social renewal of water caused by the higher efficiency of water use, use of reclaimed water, seawater and trans-basin water.
(3) The basic ideas of developing the indexes system proposed by Yang *et al.* (2005).

Here, 8 indexes are selected to representing the natural renewal of water and 20 indexes are selected to representing the social renewal of water. The integrated indexes system is shown in Table 1.

Indexes filter

Due to our imperfect knowledge, some redundancy exists in the preliminary selected indexes, which perhaps disturbs

Table 1 | Integrated indexes system for assessing water renewal of the northern coastal zone

Target floor	Sub-target floor	Unit floor	Index floor
Water renewal of northern coastal zone	Natural renewal of water	Natural feature	Annual rainfall E_1
			Runoff yield in per unit area E_2
			Percentage of forest coverage E_3
		Environ-mental feature	Ratio between seawater intrusion area and total land area E_4
			Rate between controlling area and total area of water and soil losses E_5
			Rate between the depredated area and total land area E_6
			Percentage of urban greening area coverage E_7
			Rate of drinking water quality reaching standard E_8
		Water use efficiency	Water consumption of per urban resident E_9
			Water consumption of per suburban resident E_{10}
			Water consumption of per unit production value of industry E_{11}
			Rate between recycling water amount and total water use for industry E_{12}
			Water consumption of per unit area of farmland E_{13}
			Ratio between water-saving irrigation area and total irrigation area E_{14}
			Water consumption of per unit GDP E_{15}
	Social renewal of water	Water utilization feature	Rate of utilization of surface water E_{16}
			Rate of utilization of groundwater E_{17}
			Rate of wastewater disposal E_{18}
			Ratio between reclaimed water and total amount of treated wastewater E_{19}
			Ratio between desalinated seawater and total water supplies E_{20}
			Ratio between seawater using and total industrial water consumption E_{21}
			Total amount of reclaimed water, desalinated seawater and seawater E_{22}
			Total amount of trans-basin work water supply E_{23}
		Socio-economic feature	GDP per people E_{24}
			Annual growth rate of GDP E_{25}
			Annual natural growth rate of population E_{26}
			Ratio between environmental protection investment and GDP E_{27}
			Rate between urban population and total population E_{28}

the correct and concise decision-making. Thus, it is essential to eliminate the redundancy. Rough sets theory is a methodology which has demonstrated its usefulness in the context of various cognitive science processes, and its algorithm of the reduction of attributes provides an efficient tool in eliminating the redundant attributes from the decision table, finding all possible minimal subsets of attributes and ensuring the same quality of classification as the whole set (Pawlak 1997; Walczak & Massart 1999). The algorithm used to determine the possible minimal subsets of the indexes is indicated as follows.

Let the state of water renewal be classified into five levels, with $h = 1$ for extremely high level, $h = 2$ for high level, $h = 3$ for medium level, $h = 4$ for low level and $h = 5$ for extremely low level. The matrix of standard values' classification is expressed as $S_{ab} = ([a_{ih}, b_{ih}])$, $i = 1,2, \ldots ,28$; $h = 1,2, \ldots ,5$.

Step 1. Elicit the discrete value $y_i = \{y|1,2,3,4,5\}$, $i = 1,2, \ldots ,28$.

Step 2. Construct the information table I_l, $l = 1,2 \ldots ,5$ for the five cellular systems in the unit floor. For example, since indexes E_1, E_2 and E_3 belong to the cellular system of natural features, then the information table I_1 is determined based on the affiliation.

Step 3. Ascertain the discernibility matrix D_{I_l}, $l = 1,2, \ldots ,5$ and its core set of attributes CORE_{I_l}.

Step 4. Modify the elements containing CORE_{I_l} in the discernibility matrix D_{I_l}, $l = 1,2, \ldots ,5$ as zeroes, and then use the elements $d_i, d_i \neq 0, d_i \in D_{I_l}$ to construct the disjunctive normal form ${}_lF_i$, $l = 1,2, \ldots ,5$ as (11):

$${}_lF_i = \vee d_i, \forall l \tag{11}$$

Step 5. Gain the conjunctive normal form ${}_lF'$, $l = 1,2, \ldots ,5$ by using (12):

$${}_lF' = \wedge_l F_i, \forall l \tag{12}$$

Step 6. Gain the disjunctive normal form ${}_lF$, $l = 1,2, \ldots ,5$ by using (13) and all possible minimal subsets of the indexes are determined. Then we can select the satisfying subsets of indexes according to the actual evaluation issue:

$${}_lF = \vee_l F', \forall l \tag{13}$$

VARIABLE FUZZY PATTERN RECOGNITION MODEL FOR ASSESSING WATER RENEWAL

The evaluation model should be selected according to the feature of the evaluation problem. The state of water renewal is fuzzy (Chen & Li 2006), and the classification standard values for evaluation are usually interval numbers. Therefore, the variable fuzzy pattern recognition model is suitable for such an evaluation issue. In order to present the algorithm briefly, we suppose that there are still m indexes by using rough sets theory to eliminate the redundancy, and the algorithm of the variable fuzzy pattern recognition model used to evaluate water renewal is illustrated as follows.

Step 1. Elicit the relative membership degree μ^4_{ih}, $i = 1,2, \ldots ,28$; $h = 1,2, \ldots ,5$ by using Formulae (6), (7) or (8).

Step 2. Determine the weight value w^4_i, $i = 1,2, \ldots ,28$ by using the Analytic Hierarchy Process (AHP) approach (Saaty 1980).

Step 3. Determine a local SRMD $u^{3'}_{1h}$ for the cellular system of natural features by inputting the parameters $\alpha = 1$, $p = 1$, the values (w^4_1, w^4_2, w^4_3) and $(\mu^4_{1h}, \mu^4_{2h}, \mu^4_{3h})$ into Formula (9); similarly, ascertain the local values of SRMD $u^{3''}_{1h}, u^{3'''}_{1h}$ and $u^{3''''}_{1h}$ by using the parameters $\alpha = 1$, $p = 2$, $\alpha = 2$, $p = 1$ and $\alpha = 2$, $p = 2$, respectively. Normalize the values $u^{3'}_{1h}$, $u^{3''}_{1h}$, $u^{3'''}_{1h}$ and $u^{3''''}_{1h}$, and then the SRMD for natural features $u^3_{1h} = (u^{3'}_{1h} + u^{3''}_{1h} + u^{3'''}_{1h} + u^{3''''}_{1h})/4$ is determined. Similarly, we determine the values of SRMD u^3_{2h}, u^3_{3h}, u^3_{4h} and u^3_{5h} for four other cellular systems in the unit floor.

Step 4. Determine the weight value w^3_l, $l = 1,2, \ldots ,5$ in the unit floor by using the AHP approach.

Step 5. Elicit four local values of SRMD for natural renewal by inputting the four groups of parameters, (w^3_1, w^3_2) and (u^3_{1h}, u^3_{2h}) into Formula (9), normalize the four values and the SRMD for natural renewal is $u^2_{1h} = (u^{2'}_{1h} + u^{2''}_{1h} + u^{2'''}_{1h} + u^{2''''}_{1h})/4$. Similarly, we can determine the SRMD for social renewal u^2_{2h} by using four groups of parameters, the values (w^3_3, w^3_4, w^3_5) and $(u^3_{3h}, u^3_{4h}, u^3_{5h})$.

Step 6. Determine the weight values w^2_1 and w^2_2 by using the AHP approach, respectively.

Step 7. Elicit four local values of SRMD for water renewal by inputting the four groups of parameters, (w_1^2, w_2^2) and (u_{1h}^2, u_{2h}^2) into Formula (9), normalize the four values and the SRMD for water renewal is $u_h^1 = (u_h^{1'} + u_h^{1''} + u_h^{1'''} + u_h^{1''''})/4$.

Step 8. Input the value u_h^1 into Formula (10), and then the level characteristic value on water renewal H is determined. Similarly, we can obtain the level characteristic value on natural renewal ${}_1H$ and the level characteristic value on social renewal ${}_2H$ by inputting the values u_{1h}^2 and u_{2h}^2 into Formula (10), respectively.

The flowchart of the variable fuzzy pattern recognition model for assessing water renewal of the northern coastal zone is shown in Figure 1.

CASE STUDY

Research area

The research area, Dalian City, is in Liaoning Province of northeastern China, and is located between 120°58′E and 123°31′E and between 38°43′N and 40°10′N. Dalian City, with the water consumption of 575 m^3 per person, is one of the coastal zones suffering serious water shortage. Here, the state of water renewal, natural and social renewal of water between the years 1998 and 2007 are evaluated; then the measures for improving renewal are analyzed; finally we perform the evaluation on social renewal for the planning year 2020 to verify the efficiency of the proposed measures.

Data acquisition

The data of five level classification standard values for the 28 indexes are shown in Table 2, in which the data of indexes E_4, E_{17}, E_{19}, E_{20}, E_{21}, E_{22}, E_{23}, E_{27} and E_{28} are ascertained based on the actuality of Tianjin, Qingdao and Dalian in the northern coastal areas; and the data of the rest of the indexes are from Yang *et al.* (2005).

The data on the characteristic values of the 28 indexes in Dalian City (shown in Table 3) are mainly from the *Bulletin of Water Resources of Dalian City* and the *Bulletin of Socioeconomic Development of Dalian City*.

RESULTS AND ANALYSIS

Indexes selection

After the data of five level classification standard values and characteristic values for 28 indexes are acquired, the algorithm of rough sets theory can be carried out and the results of the reduction of attributes are listed in Table 4. As to the cellular system of water utilization features, since the amount of reclaimed water is much greater than the amount of desalinated water, index E_{19} is more important than E_{20}, so the set $\{E_6, E_{17}, E_{18}, E_{19}, E_{21}, E_{22}\}$ is as the reduced set.

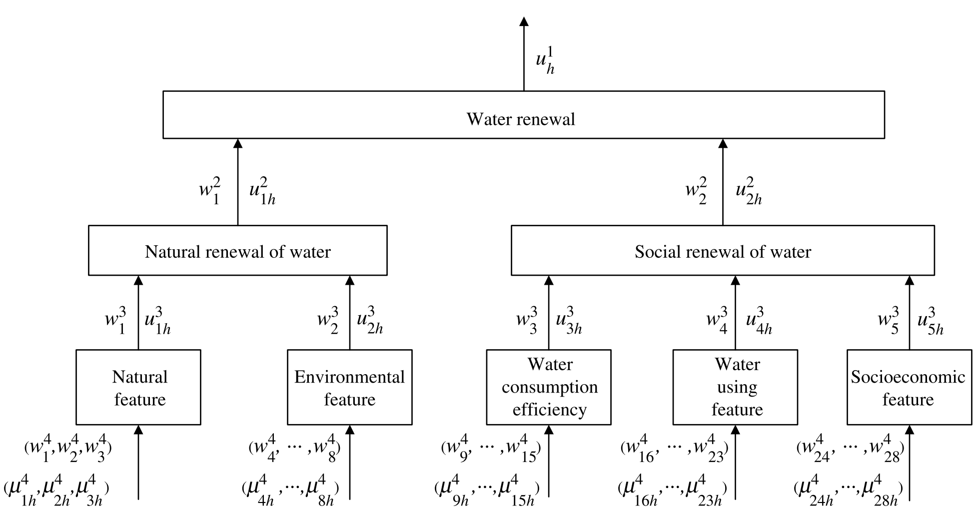

Figure 1 | Flowchart of the variable fuzzy recognition model for assessing water renewal of northern coastal zone.

Table 2 | Classification standard values of indexes for assessing water renewal of northern coastal zone

Indexes	Standard values $h=1$	$h=2$	$h=3$	$h=4$	$h=5$
E_1 (mm)	>1,500	1,000–1,500	600–1,000	100–600	<100
E_2 (10^4 m^3/km^2)	>85	45–85	20–45	5–20	<5
E_3 (%)	>60	40–60	20–40	10–20	<10
E_4 (%)	<1	1–3	3–6	6–10	>10
E_5 (%)	>80	60–80	40–60	20–40	<20
E_6 (%)	<0.01	0.01–0.02	0.02–0.05	0.05–0.1	>0.1
E_7 (%)	>40	30–40	20–30	10–20	<10
E_8 (%)	>90	85–90	80–85	75–80	<75
E_9 (m^3)	<69	69–77	77–84	84–146	>146
E_{10} (m^3)	<18	18–26	26–33	33–40	>40
E_{11} (m^3)	<15	15–50	50–100	100–300	>300
E_{12} (%)	>90	70–90	50–70	30–50	<30
E_{13} (%)	>82	67–82	52–67	37–52	<37
E_{14} (10^4 m^3)	<0.55	0.55–0.60	0.60–0.85	0.85–1.10	>1.10
E_{15} (m^3)	<74	74–194	194–314	314–434	>434
E_{16} (%)	<5	5–10	10–20	20–40	>40
E_{17} (%)	<10	10–20	20–40	40–60	>60
E_{18} (%)	>80	60–80	40–60	20–40	<20
E_{19} (%)	>50	30–50	20–30	10–20	<10
E_{20} (%)	>20	10–20	5–10	1–5	<1
E_{21} (%)	>80	60–80	40–60	20–40	<20
E_{22} (10^8 m^3)	>5	2–5	1–2	0.5–1	<0.5
E_{23} (10^8 m^3)	>4	2–4	1–2	0.5–1	<0.5
E_{24} (10^4RMB)	>7.74	2.5–7.74	0.66–2.5	0.3–0.66	<0.3
E_{25} (%)	>8.25	7.75–8.25	7.25–7.75	6.75–7.25	<6.75
E_{26} (‰)	<1	1–2	2–5	5–10	>10
E_{27}	>1.7	1.2–1.7	0.7–1.2	0.2–0.7	<0.2
E_{28} (%)	<20	20–40	40–60	60–70	>70

In particular, although Dalian City has no use of the water of trans-basin work in the recent ten years, the index E_{23} needs to be kept for the sake of comparing the state of social renewal in the planning year with that of current years. Therefore, 22 indexes are selected for evaluating the water renewal of Dalian City in total.

Determination of weight values

The normalized weight values $w_i^4, i = 1, 2, \ldots, 22$ for the 22 quantitative indexes in the index floor are (0.649, 0.279, 0.072), (0.522, 0.190, 0.190, 0.097), (0.474, 0.036, 0.132, 0.270, 0.087), (0.122, 0.122, 0.160, 0.161, 0.161, 0.161, 0.113) and (0.637, 0.105, 0.258), respectively.

The normalized weight values $w_l^3, i = 1, 2, \ldots, 5$ for the five qualitative indexes (cellular systems) in the unit floor are (0.650, 0.350) and (0.300, 0.300, 0.400), respectively.

The normalized weight values for the two qualitative indexes (cellular systems) in the sub-target floor are $w_1^2 = 0.595$ and $w_2^2 = 0.405$, respectively.

Table 3 | Characteristic values of indexes for assessing water renewal of Dalian City

	Characteristic values									
Indexes	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
E_1	830.00	387.00	459.00	605.50	405.30	561.70	750.30	681.70	594.40	788.60
E_2	23.10	7.90	5.10	17.81	5.05	9.89	22.05	32.62	17.60	24.40
E_3	38.00	38.20	38.20	38.20	38.20	38.20	38.20	41.50	41.50	42.99
E_4	2.78	3.02	3.14	3.23	3.23	3.22	3.77	3.72	3.98	6.81
E_5	31.12	36.47	40.00	44.02	48.60	56.49	60.22	63.96	67.12	69.60
E_6	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.05	0.05	0.05
E_7	39.40	40.00	40.50	41.00	41.50	41.80	42.40	42.80	42.80	43.30
E_8	100.00	100.00	100.00	100.00	71.43	73.81	100.00	100.00	100.00	100.00
E_9	85.32	79.15	100.01	73.00	76.29	87.24	105.12	110.60	85.40	81.80
E_{10}	30.15	28.63	27.39	27.74	27.01	31.39	33.95	24.82	25.60	32.90
E_{11}	50.77	45.50	36.15	37.52	36.38	54.00	36.00	34.00	26.00	22.00
E_{12}	81.60	82.10	87.00	89.00	85.30	83.00	84.00	84.20	84.30	84.40
E_{13}	0.64	0.67	0.55	0.71	0.57	0.47	0.41	0.64	0.63	0.65
E_{14}	2.09	15.41	23.20	32.68	38.60	41.77	45.20	47.33	51.20	53.42
E_{15}	130.60	116.25	105.00	75.00	66.00	54.00	46.00	51.00	45.00	39.00
E_{16}	24.49	25.02	26.74	33.75	130.07	56.98	26.47	23.68	40.58	30.51
E_{17}	36.92	33.36	26.56	41.32	80.91	65.79	41.45	27.07	44.40	50.78
E_{18}	23.10	28.95	30.24	34.33	35.70	42.00	44.44	53.00	71.00	90.40
E_{19}	0.00	0.00	10.00	10.00	10.00	15.00	25.86	30.00	30.50	32.00
E_{20}	0.03	0.03	0.07	0.10	0.20	0.30	1.60	3.10	2.50	2.10
E_{21}	19.89	20.10	30.05	26.10	23.84	27.77	28.22	25.83	20.93	20.67
E_{22}	0.38	0.39	0.51	0.51	0.54	0.56	0.69	0.82	0.87	0.88
E_{23}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E_{24}	1.71	1.84	2.03	2.23	2.53	2.92	3.49	3.82	4.26	5.16
E_{25}	10.00	11.10	11.80	11.80	14.10	15.20	16.20	14.20	16.50	17.50
E_{26}	1.11	1.05	1.08	1.19	1.16	−0.54	0.68	0.40	−0.04	1.65
E_{27}	2.16	2.57	2.33	2.05	2.16	2.05	2.03	2.04	1.99	1.90
E_{28}	48.90	49.46	49.90	50.50	51.60	53.60	55.60	56.20	57.50	58.30

Determination of level characteristic values of the current years

Here, the variable fuzzy recognition model for assessing the first sample (the year 1998) is illustrated. Since the indexes E_1, E_2 and E_3 belong to the cellular system of natural feature, according to Table 2 and Chen (2005), the matrix of classification of standard values S_{ab}, bound matrix S_{cd} and point value matrix M are listed as follows:

$$S_{ab} = \begin{bmatrix} [1500,3000] & [1000,1500] & [600,1000] & [100,600] & [0,100] \\ [85,100] & [45,85] & [20,45] & [5,20] & [0,5] \\ [60,100] & [40,60] & [20,40] & [10,20] & [0,10] \end{bmatrix}$$

$$S_{cd} = \begin{bmatrix} [1000,3000] & [600,1500] & [100,1500] & [0,1000] & [0,600] \\ [45,100] & [20,100] & [5,85] & [0,45] & [0,20] \\ [40,100] & [20,100] & [5,85] & [0,45] & [0,20] \end{bmatrix}$$

$$M = \begin{bmatrix} 2250 & 1250 & 800 & 350 & 50 \\ 92.5 & 65 & 32.5 & 12.5 & 2.5 \\ 80 & 50 & 30 & 15 & 5 \end{bmatrix}$$

Then the relative membership degree $(\mu_{ih}^4)_{3\times5}$ is determined as

$$(\mu_{ih}^4)_{3\times5} = \begin{bmatrix} 0 & 0.288 & 0.925 & 0.213 & 0 \\ 0 & 0.202 & 0.904 & 0.298 & 0 \\ 0 & 0.450 & 0.600 & 0.050 & 0 \end{bmatrix}, i = 1,2,3$$

Table 4 | Results of reduction of indexes

Cellular system	Core set of indexes	Reduced sets of indexes	Redundant indexes
Natural feature	$\{E_1, E_2, E_3\}$	$\{E_1, E_2, E_3\}$	–
Environmental feature	$\{E_4, E_5, E_6, E_8\}$	$\{E_4, E_5, E_6, E_8\}$	E_7
Water consumption efficiency	$\{E_9, E_{10}, E_{11}, E_{13}, E_{14}\}$	$\{E_9, E_{10}, E_{11}, E_{13}, E_{14}\}$	E_{12}, E_{15}
Water utilization feature	$\{E_{16}, E_{17}, E_{18}, E_{21}, E_{22}\}$	$\{E_{16}, E_{17}, E_{18}, E_{19}, E_{21}, E_{22}\}$ or $\{E_{16}, E_{17}, E_{18}, E_{20}, E_{21}, E_{22}\}$	E_{20}, E_{23}
Socioeconomic feature	$\{E_{24}, E_{26}, E_{27}\}$	$\{E_{24}, E_{26}, E_{27}\}$	E_{25}, E_{28}

Then by using the value $(\mu^4_{ih})_{3\times5}$ and the weight vector (0.649, 0.279, 0.072), the SRMD for natural features $(u^3_{1h})_{1\times5} = (0.001\ 0.151\ 0.735\ 0.113\ 0.001)$ is determined. Analogously, the relative membership degree $(\mu^4_{ih})_{4\times5}$ for indexes E_4, E_5, E_6 and E_8 is gained as

$$(\mu^4_{ih})_{4\times5} = \begin{bmatrix} 0.055 & 0.610 & 0.445 & 0 & 0 \\ 0 & 0 & 0.278 & 0.944 & 0.222 \\ 0 & 0.003 & 0.507 & 0.497 & 0 \\ 0.500 & 0 & 0 & 0 & 0 \end{bmatrix}, i = 4,5,6,8$$

Then by using the value $(\mu^4_{ih})_{4\times5}$ and the weight vector (0.522, 0.190, 0.190, 0.097), the SRMD for the environmental feature $(u^3_{2h})_{1\times5} = (0.040\ 0.358\ 0.377\ 0.199\ 0.025)$ is gained. Also by inputting the weight vector (0.650, 0.350), the SRMD for natural renewal $(u^2_{1h})_{1\times5} = (0.022\ 0.126\ 0.680\ 0.146\ 0.026)$ is elicited; and then the level characteristic value on natural renewal of the first sample ${}_1H_1 = 2.928$ is elicited.

Similarly, we elicit the SRMD for social renewal $(u^2_{2h})_{1\times5} = (0.087\ 0.143\ 0.489\ 0.155\ 0.127)$ and the level characteristic value on social renewal ${}_2H_1 = 3.276$.

Finally, using the weight vector (0.595, 0.405) and the values $(u^2_{1h})_{1\times5}$ and $(u^2_{2h})_{1\times5}$, the SRMD for water renewal $(u^1_h)_{1\times5} = (0.027\ 0.080\ 0.762\ 0.093\ 0.038)$ is ascertained and then the level characteristic value on water renewal of the first sample $H_1 = 3.042$ is ascertained. Similarly, the level characteristic values on renewal, natural and social renewal of water for the other nine samples can be ascertained (shown in Table 5).

Since $h = 1$ represents the extremely high level of water renewal, so the smaller level characteristic value denotes the higher level of renewal. Thus, from Table 5 we know that the states on renewal of the recent ten years are the years 2007 > 2005 > 2004 > 1998 > 2006 > 2001 > 2000 > 1999 > 2003 > 2002; the states on natural renewal are 1998 > 2004 > 2005 > 2007 > 2001 > 2006 > 2000 > 1999 > 2003 > 2002; and the states on social renewal are 2007 > 2006 > 2002 > 2005 > 2004 > 2003 > 1999 > 2000 > 1998 > 2001.

In addition, Table 5 shows that the average value of level characteristic on natural renewal is ${}_1\bar{H} = 3.272$, and the average value of level characteristic on social renewal is ${}_2\bar{H} = 2.949$. The value $|({}_2\bar{H} - {}_1\bar{H})/{}_1\bar{H} \times 100\%| = 9.88\%$ illustrates that social renewal is apparently superior to natural renewal, and it also implies that the relative low natural renewal is the leading factor of limiting renewal in Dalian City. However, its special geographical feature leads to weaker natural renewal, which is difficult to regulate by human beings. Consequently, only the measures of the man-made water cycles can be carried out to improve renewal of the zone, which includes further raising the

Table 5 | Results of assessing water renewal of Dalian City between the years 1998 and 2007

Level characteristic values	Samples 1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Average values
H	3.042	3.377	3.371	3.272	3.404	3.382	2.973	2.942	3.073	2.930	3.177
${}_1H$	2.928	3.481	3.382	3.266	3.683	3.468	3.025	3.028	3.318	3.140	3.272
${}_2H$	3.276	3.128	3.204	3.278	2.746	3.038	2.837	2.759	2.632	2.588	2.949

Table 6 | Characteristic values of indexes representing social renewal of the planning year 2020

	Indexes														
	E_9 (m^3)	E_{10} (m^3)	E_{11} (m^3)	E_{13} (10^4 m^3)	E_{14} (%)	E_{16} (%)	E_{17} (%)	E_{18} (%)	E_{19} (%)	E_{21} (%)	E_{22} (10^8 m^3)	E_{23} (10^8 m^3)	E_{24} (10^4 RMB)	E_{26} (‰)	E_{27}
Values	105.67	29.31	16.7	0.30	87.87	34.41	27.05	96	37	20.25	5.09	2.7	12.34	0.8	1.9

efficiency of water consumption, improving the utilization rate of reclaimed water, desalinated water and seawater, and water use of Dahuofang trans-basin work.

Determination of level characteristic value of the planning year and sensitivity analysis

In order to discuss the efficiency of the man-made water cycle measures above for improving social renewal, evaluation of the planning year 2020 is performed. The characteristic values of indexes representing social renewal of the planning year 2020 are shown in Table 6, which are mainly from the *Planning Report of Water Affair Development of Dalian City* and the *Report of Water Resources Allocation and Water Right Research of Dalian City*.

Using the approaches proposed in this paper, we can obtain the level characteristic value on social renewal ${}_2H_{2020} = 2.566$. The value $|({}_2H_{2020} - {}_2\bar{H})/{}_2\bar{H} \times 100\%| = 12.99\%$ implies that, compared with the current state, the state of social renewal of the planning year has improved obviously, and the measures of the man-made water cycle are feasible and effective.

Moreover, in order to ascertain the sensitivity factors influencing social renewal, single factor sensitivity analysis is performed in the following part. We regard the value of the index E_{23} (0.27 billion m^3) as the basis, let the total water amounts change in the interval $[-0.027, +0.027]$, and set two scenarios: (1) to increase the water amount by 0.027 billion m^3 and (2) to decrease the water amount by 0.027 billion m^3. For example, let the water consumption of urban living decrease by 0.027 billion m^3, then the value of the index E_9 decreases from 105.67 m^3 to 100.87 m^3; if we only make the value of E_9 changeable and keep the other values of indexes invariable, then the level characteristic value on social renewal of 2.541 is obtained. Let the water consumption of urban living increase by 0.027 billion m^3, then the value of the index E_9 increases from 105.67 m^3 to 110.47 m^3, then the level characteristic value on social renewal of 2.590 is achieved. The corresponding sensitivity coefficient is

$$|((2.541 - 2.566)/2.566 \times 100\% - (2.590 - 2.566)/2.566 \times 100\%)/(-10\%) - 10\%| = 0.095$$

Similarly, the sensitivity coefficients of indexes E_{11}, E_{13}, E_{19}, E_{21} and E_{23} are achieved (shown in Table 7).

Table 7 implies that the water use of trans-basin work imposes the most significant influence on social renewal, and other measures in sequence are the use of reclaimed water, the water-saving of urban living, the use of seawater for industry, the water-saving of agriculture, and the water-saving of industry.

Table 7 | Results of sensitive analysis on the measures of influencing social renewal of Dalian City

	Indexes					
	E_9 (m^3)	E_{11} (m^3)	E_{13} (10^4 m^3)	E_{19} (%)	E_{21} (%)	E_{23} (10^8 m^3)
Scenario 1						
Characteristic values	100.87	15.87	0.28	40.87	25.26	2.97
H^2	2.541	2.563	2.561	2.547	2.582	2.523
Scenario 2						
Characteristic values	110.47	17.53	0.32	32.24	15.23	2.43
H^2	2.590	2.567	2.571	2.599	2.595	2.611
Sensitive coefficients	0.095	0.008	0.019	0.101	0.088	0.172

By using these results, water resources agencies can shape efficient water resource planning and tackle the serious water shortage of the area. The variable fuzzy recognition model provides the tool for finding not only the state of water renewal but also the state of natural as well as social renewal of water. This study is the first to propose an integrated indexes system for the northern coastal zone, and to apply the variable fuzzy recognition model to ascertain comprehensive information on the state of renewal.

CONCLUSIONS

A framework for water renewal evaluation of the northern coastal zone is presented, which involves construction of an integrated indexes system and selection of a suitable evaluation model. The following conclusions are drawn:

(1) The integrated system developed with 28 indexes has effectively represented the factors influencing water renewal of the northern coastal zone. Also, by using rough sets theory to eliminate redundancy, a more sound indexes system has been determined.

(2) By using the variable fuzzy pattern recognition model, not only the state of water renewal, but also the state of natural and social renewal of water are ascertained; this could also provide decision-makers with more comprehensive and useful information. Furthermore, owing to the use of multiple parameters in the evaluation model, more creditable results are gained.

(3) By applying the indexes system and evaluation model to the case study of Dalian City, the conclusions are listed as follows:

(a) Out of the recent ten years, the year 2007, with the level characteristic value on renewal of 3.042, has the best state of water renewal, and the year 2002 is the worst. As to the state of natural renewal, the years 1998 and 2002 are the best and worst ones, respectively. Considering the state of social renewal, the best is the year 2007, and the worst is 2001. Also the relative low natural renewal is the leading factor of limiting renewal of Dalian City.

(b) Compared with the current average level characteristic value of social renewal, the value of the planning year 2020 has decreased by 12.99%; this illustrates that the measures including further increasing efficiency of water consumption, the increasing use of reclaimed water amounts, desalinated water and seawater, and the water use of Dahuofang trans-basin work are feasible and efficient for improving social renewal of the area.

(c) The results of single factor sensitivity analysis show that the water use of trans-basin work imposes the most significant influence on social renewal, and the measures including use of reclaimed water, the water-saving of urban living, the use of seawater for industry, the water-saving of agriculture and the water-saving of industry are in sequence.

The case study indicates that the approach proposed in this paper can solve the evaluation of problems of the renewability of water effectively and efficiently.

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