Water resource management based on trade-off analysis of multi-dimensional critical regulation and control indicators
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ABSTRACT
Water resources exist in a large and complex system with multi-dimensional objectives. In this paper, the multi-dimensional nature of water resource systems was analyzed. Then, those indicators were used to set the regulation objective for each dimension and establish an indicator system for use in multi-dimensional critical regulation and control (MCRC). The case of Jiamusi was studied as an example: an MCRC water use model was established and the model was solved to derive Jiamusi’s initial water use plan in the target year of 2020. The relationships between the economic benefits produced by water consumption and the groundwater exploitation rate, agricultural water consumption, chemical oxygen demand, and ecological water consumption were analyzed based on this plan: the trade-off among indicators of various dimensions was analyzed to obtain the relationship curves between the regulation indicators of the economic dimension and those of the other dimensions (resource, social, environmental and ecological dimensions). Finally, multi-dimensional regulation was applied to the plan based on the relationship curves from the trade-off analysis, and the best water use plan for the target year was proposed. This study provided a strong basis for setting thresholds for the planning and management of water use in Jiamusi.

Key words | water resource system, multi-dimensional regulation indicator, multi-objective decision making, trade-off analysis, multi-dimensional critical regulation plan

INTRODUCTION
As the imbalanced supply and demand of water and the theory of sustainable development became more widely recognized (Terpstra 1999; Arnim & Kelli 2012), scholars began to take social security (Parviz and Saeed 2010), ecosystems (Bunch et al. 2011; Azzellino et al. 2015) and the coordinated development of the economy, society and the environment (Evan et al. 2011) into account when pursuing economic benefits and to study and regulate water use from multiple perspectives. Studies have found that more factors should be considered than currently are being considered in the current management of water resources, and the multi-objective nature of water resources has brought about the development of multi-dimensional critical regulation and control (MCRC) theory (Huang & Chang 2007).

The sustainable use of water essentially requires the coordination of multiple objectives for changes in one dimension which can cause responses in other dimensions. Meanwhile, the indicators of the objectives of different dimensions are difficult to quantify using the same measure (Gan et al. 2010). In this study, the MCRC water use model was applied to the water resource system in the city of Jiamusi of Heilongjiang Province in China. Then, the resources, society, environment and ecology can be represented by the economic value, so five indicators can be included in one dimension.
METHODS AND THE MCRC MODEL

MCRC indicators

The five dimensions of water resources systems are the dimensions of economy, resources, society, environment and ecosystem. The MCRC indicator system needs to be built by choosing indicators that best reflect the attributes of each dimension and are based on the respective dimensions’ regulatory criteria (Gan et al. 2013). The key indicators for each dimension are as follows: the economic benefit resulting from water consumption (denoted as G), the groundwater exploitation rate, the chemical oxygen demand (COD) released into the river and the ecological water consumption were used as the characteristic indicator of the economic, resource, environmental and ecological dimensions.

The per capita food availability is closely related to social stability and economic development in the social dimension. Agricultural irrigation is a key factor in food production with easily accessible values; thus, agricultural water consumption was used as the characteristic indicator of the social dimension.

Objective function of the MCRC model

Let the sample set of the study area (Jiamusi) be \( \{x_{ij} \mid i = 1, 2, \ldots, n; j = 1, 2, \ldots, m\} \), where, \( x_{ij} \) is the water supplied by the \( i \)th water source to the \( j \)th water-using sector (in \( 10^4 \) m\(^3\)); \( n \) and \( m \) are, respectively, the number of water sources and water-using sectors, and there are currently two water supply sources and four water-using sectors in Jiamusi, i.e., \( n = 2, m = 4 \). The value of \( i = 1 \) indicates surface water and \( i = 2 \) refers to groundwater; and \( j = 1, 2, 3, \) and \( 4 \) refers to, the domestic, agricultural, industrial and ecosystem water-using sectors, respectively.

The MCRC water use model is built according to the multi-dimensional regulatory requirements for water resource allocation optimization, as well as the ultimate objective of maximizing the overall benefits for the objectives of all five dimensions (economy, resources, society, environment and ecosystem):

\[
\text{max } F = \text{max } \{f_1(x), f_2(x), f_3(x), f_4(x), f_5(x)\} \tag{1}
\]

where \( F \) is the overall benefit; and \( f_1(x), f_2(x), f_3(x), f_4(x) \) and \( f_5(x) \) are the economic, resource, social, environmental and ecological objectives, respectively.

Considering the status of water supply and demand in Jiamusi, the regulatory objectives of the five-dimensional system, including economic \((f_1(x))\), resource \((f_2(x))\), social \((f_3(x))\), environmental \((f_4(x))\) and ecological \((f_5(x))\) dimensions, are as follows:

\[
\begin{align*}
  f_1(x) &= \sum_{j=1}^{n} \sum_{i=1}^{n} gd p_i x_{ij} \\
  f_2(x) &= \left( \sum_{i=1}^{m} x_{2i} \right) / gw_0 \\
  f_3(x) &= D_2 - \sum_{i=1}^{n} x_{i2} \\
  f_4(x) &= \sum_{j=1}^{n} 0.01d_j p_j \left( \sum_{i=1}^{n} x_{ij} \right) \\
  f_5(x) &= \sum_{i=1}^{n} x_{i4}/S_4
\end{align*}
\tag{2}
\]

where \( gd p_i \) is the volumetric water output coefficient of the \( j \)th water-using sector, namely the ratio between the total output of the \( j \)th water-using sector and the water consumption of that sector in yuan/m\(^3\). \( gw_0 \) is the amount of groundwater available for the target year (2020). \( D_2 \) is the agricultural water demand in the target year. \( d_j \) is the COD per unit wastewater from the \( j \)th water-using sector in mg/L; \( p_j \) is the sewage discharge coefficient of the \( j \)th water-using sector; and \( S_4 \) is the ecological water demand for the target year.

Constraints

The constraints include water supply, water demand and non-negative variables.

(1) Water supply constraint. The total water supply to all water-using sectors from the \( i \)th water source should not exceed the amount of water available, that is

\[
\sum_{j=1}^{m} x_{ij} \leq W_i \quad (i = 1:n) \tag{3}
\]

where \( W_i \) is the amount of water available from the \( i \)th water source.
(2) Water demand constraint. The amount of water obtained by the \( j \)th water-using sector from all water sources should be between the upper and lower limits of the water demand of the user, namely

\[
D_{j \text{min}} \leq \sum_{i=1}^{I} x_{ij} \leq D_{j \text{max}} \quad (j = 1:m)
\]  

where \( D_{j \text{max}} \) and \( D_{j \text{min}} \) are the upper limit and lower limit of the water demand of the \( j \)th water-using sector, in \( 10^4 \) m\(^3\).

(3) Non-negativity constraint for variables: the variables cannot be negative

\[
x_{ij} \geq 0 \quad (i = 1:n; \ j = 1:m)
\]  

Solving the model

In our study, the model was solved using the function 'fgoalattain' (Su et al. 2004; Lei 2009; Shang et al. 2013) function. It is a function included in the toolbox of the Matlab mathematical software and a target approximation method based on multi-objective decision-making techniques (Andrew et al. 2008; Han et al. 2008; Dong et al. 2013). Then, the target values of economic, resource, social, environmental and ecological dimensions were 829.65 \( \times \) 10\(^8\) yuan, 90.53\%, 0, 27129 m\(^3\), 100\%, respectively. The domestic, agricultural, industrial and ecological water-using sectors supplied by the surface water were 3242, 25337, 68297, and 2 (in \( 10^4 \) m\(^3\)), respectively, and those supplied by the groundwater were 976, 4069, 11830 and 610 (in \( 10^4 \) m\(^3\)), respectively.

Data show that the groundwater exploitation rate of the resource dimension in this plan was 90.53\%. Even though this value does not exceed the allowed level of exploitation, adopting this rate in long-term practice will affect the sustainable use of groundwater (Jiang 2011). Therefore, the plan needed to be adjusted.

MODEL APPLICATION AND RESULTS ANALYSIS

Trade-off analysis of MCRC indicators

The above-mentioned plan was identified as the initial water use plan (plan0) for Jiamusi in the target year (2020). Furthermore, the impact of changes in the indicator of one dimension on the economic benefit of the economic dimension (G) was studied using G as the reference variable to analyze the benefit relationships among the indicators of these five dimensions, and to carry out trade-off analysis on MCRC indicators. Trade-off analysis can convert the benefits in the resource, social, environmental and ecological dimensions into economic benefits and provide support for MCRC results by using the benefit relationship curves to screen for irrational plans.

The MCRC trade-off analysis was conducted based on plan0.

(1) The impact of the resource dimension on the economic dimension was analyzed by maintaining constant values for the target values and related parameters of the social, environmental and ecological dimensions same. Fifteen groundwater exploitation rates were selected within a suitable range and used as the adjusted characteristic indicators of the resource dimension, defined as plan-r1–plan-r15 (plan-r1 = 50, r2 = 55, r3 = 65, r4 = 77, r5 = 79, r6 = 81, r7 = 83, r8 = 85, r9 = 87, r10 = 89, r11 = 90, r12 = 91, r13 = 92, r14 = 93, r15 = 95). When the resources change, the corresponding economic dimension values would change with it. According to the relationship and Equation (2), we can depict the curve, as shown in Figure 1.

Using this analogy, Figures 2 and 3 can be achieved.

Most of the water used in Jiamusi is from groundwater, while the level of surface water utilization is relatively low. Figure 1 shows that G increased when the groundwater exploitation rate was increased. However, when the
Groundwater exploitation rate is greater than 90%, increasing the groundwater exploitation will no longer produce any economic benefits. Therefore, the groundwater exploitation rate should not be greater than 90%.

(2) The impact of the social dimension on the economic dimension was analyzed in a similar way. Fifteen agricultural water consumption values were selected and defined as plan-s1–plan-s15 (plan-s1 = 2.1, s2 = 2.2, s3 = 2.3, s4 = 2.4, s5 = 2.5, s6 = 2.55, s7 = 2.6, s8 = 2.65, s9 = 2.7, s10 = 2.75, s11 = 2.8, s12 = 2.85, s13 = 2.9, s14 = 2.94, s15 = 3). Together with Equation (2), the impacts of regulated agricultural water consumption on G were analyzed (Figure 2).

The agricultural water use in Jiamusi is mainly for agricultural irrigation. As shown in Figure 2, the increase in agricultural water use led directly to economic growth, and the growth was almost linear. Therefore, the agricultural water demand in Jiamusi should be met.

(3) The impact of the environmental dimension on the economic dimension was analyzed in a similar way. Fifteen COD values to be released into rivers were selected and defined as plan-e1–plan-e15 (plan-e1 = 2.3, e2 = 2.4, e3 = 2.5, e4 = 2.6, e5 = 2.65, e6 = 2.69, e7 = 2.71, e8 = 2.73, e9 = 2.75, e10 = 2.77, e11 = 2.79, e12 = 2.8, e13 = 2.82, e14 = 2.85, e15 = 2.87). Together with Equation (2), the impacts of the COD released into rivers on G were analyzed (Figure 3).

As shown in Figure 3, when the COD released into rivers was greater than 27,900 m³, G decreased with increasing COD. The higher the quantity of COD released, the worse the water quality became. When water quality reaches the threshold value (27,900 m³), the water quality cannot meet the requirement of the total water users, therefore the G decreases. Therefore, the COD released into rivers should be controlled to be less than 27,900 m³.

(4) The impact of the ecological dimension on the economic dimension was analyzed in a similar way. Fifteen ecological water consumption values were selected and defined as plan-ec1–plan-ec15 (plan-ec1 = 200, ec2 = 250, ec3 = 300, ec4 = 340, ec5 = 380, ec6 = 420, ec7 = 460, ec8 = 500, ec9 = 530, ec10 = 570, ec11 = 600, ec12 = 612, ec13 = 640, ec14 = 670, ec15 = 700). Together with Equation (2), the impacts of ecological water consumption on G were analyzed (Figure 4).

As shown in Figure 4, when the ecological water consumption was greater than 6 million m³, as the ecological water consumption increased, ecological water use started to compete with agricultural and industrial water uses;
thus, when the water supply is insufficient, meeting the ecological water demand will lead to reductions in agricultural and industrial water uses and the consequent decrease of G. Therefore, the ecological water consumption should be controlled to be less than 6 million m³.

The threshold value of the resources, society, environment and ecology which cause the economic benefits to decline can be calculated from Figures 1–4. Using Figures 1–4, the resource, society, environment and ecology parameters can be represented by the economic value.

MCRC plan analysis

The aforementioned retained plans were integrated to obtain 30 sets of feasible MCRC plans for the water resource system in Jiamusi. The benefits of the resource, social, environmental and ecological dimensions in the aforementioned 30 sets of plans were converted into economic benefits, and the overall benefits were calculated and sorted (Table 1).

First, the comparison among P1, P5 and P11: increasing the groundwater exploitation rate led to increased groundwater supply; thus, the amount of water available for agricultural and industrial use increased under the premise that the domestic water demand and ecological water demand were fully met, resulting in significantly improved economic benefits; comparison of P2, P4 and P8: increasing the COD released into rivers could reduce the cost of sewage treatment and slightly increase the economic benefits; finally, the comparison between P9 and P10 or P13 and P14: given the same total water supply, reducing the ecological water consumption in the ecological dimension was equivalent to increasing the agricultural and industrial water consumption, and thus the economic benefit increased slightly.

The results in Table 1 show that P30 yielded the greatest overall benefit, followed by P29. Comparison of P29 and P50: the values of the resource, social and environment dimensions were the same in both plans; only the value of the ecological dimension was different. The ecological water consumption in P29 was set to be 612 m³ and met the ecological water demand in 2020. However, in P50, the ecological water use did not meet the ecological water demand. Integrating these comparisons, although the overall benefits of P50 were slightly greater than those of P29, these immediate economic benefits come at the price of the ecosystem and environment and thus are opposed to the principle of sustainable development. Therefore, it is recommended to select the planned values of various dimensions in P29 as the target values for regulation in 2020.

The values in P29 were input to the MCRC water use model to derive the results of MCRC theory-based water resource regulation, and the results were used as the optimal MCRC water use plan for 2020, defined as plan-best. Then, the domestic, agricultural, industrial and ecological water-using sectors supplied by the surface water were 3181, 25630, 68064 and 2 (in 10⁴ m³), respectively, and the values supplied by the groundwater were 1037, 3776, 10221 and 610 (in 10⁴ m³), respectively.

Comparison of the initial MCRC plan and the best plan

The resource, social, environmental and ecological dimensions of plan0 and plan-best were converted into economic benefits and were 4315.98 (in 10⁸ yuan) and 4309.11 (in 10⁸ yuan), respectively.

MCRC was performed on plan0 to obtain plan-best. It is apparent that the COD released into rivers in this plan was slightly greater than that in plan0, even though the increase was very small (771 m³) and did not have a large impact on the environment of Jiamusi. However, the groundwater exploitation rate in plan-best was significantly reduced. Thus, plan-best was more conducive to the sustainable use of groundwater resource systems and the sustainable development of water resource systems while ensuring no large changes in the overall benefits or the economic benefits of the economic dimension and meeting the agricultural and ecological water demand.

CONCLUSIONS

(1) Through multi-dimensional analysis on the water resource system of Jiamusi, the MCRC system was established. This indicator system can more comprehensively reflect the characteristics of water systems in Jiamusi and provide a basis for building an MCRC model.

(2) An MCRC water use model was built and it can be applied in solving optimal multi-objective benefit.
Each subsystem of the model reflects the regulation objective of each dimension in MCRC, and the water use plan (plan0) to achieve the maximum overall target benefits in all five dimensions was calculated using multi-objective decision-making techniques.

(3) The relationships between the economic benefit and the groundwater exploitation rate, agricultural water consumption, COD released into rivers and ecological water consumption were analyzed, and the relationship curves were obtained.

(4) The value of resources, society, environment and ecology was represented by economic value, overcoming the problem that the same measurement between various indicators was difficult to quantify. Then, the method of scalar sum to measure comprehensive benefit of water scheme was adopted first. The more
the comprehensive benefit is, the better the scheme is. Finally, the best water use plan for 2020 was derived. According to this method, the sustainable development of water resources system can be guaranteed.

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