Water security evaluation based on comprehensive index in Jing-Jin-Ji district, China
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ABSTRACT

China has long faced the problem of uneven distribution of water resources in time and space. The state of water security is therefore a key factor in regional development. The Jing-Jin-Ji district in China, which includes Beijing, Tianjin and Hebei Province, faced severe water security problems. Therefore, to improve the management of water resources, water security should be properly evaluated. This study established a comprehensive evaluation index system for evaluation. Furthermore, it analyzed the impacts of the South-to-North Water Transfer Project (SNWTP), which fully reflects the impact of human activities on the spatial distribution of water resources and is an innovation. The results showed that the state of water security in the Jing-Jin-Ji district generally had an increasing trend, and the score of the overall evaluation was increased by 65.8%. The Middle Route of the SNWTP had played a major role in water security in resources criterion, which increased by 28.53% in 2015 and 13.64% in 2016. With social development, the general state of water security in the district was improving. These findings could provide a scientific basis for regional water resources management.

Key words | AHP, comprehensive index method, water resources management, water security

HIGHLIGHTS

• In this study, a general multi-criteria water security evaluation index system was established.
• This study considered the impact of human activities on the spatial distribution of water resources.
• This study forecasts and evaluates future scenarios.

INTRODUCTION

Water resources are indispensable to social development, and water security is a key factor in national and regional development (Krysanova & White 2015). Water security has been studied since the 1970s, but its definition remains unclear (Jia et al. 2006). It could be defined according to the changes in human needs and the environment. Bakker (2012) defined water security as an acceptable level of water-related risks to humans and ecosystems, coupled with the availability of water of sufficient quantity and quality to support livelihoods, national security, human health and ecosystem services. Wheater & Gober (2015) said water security has moved from a more narrow focus on quantity, quality, access and hazards to a more multi-criteria sustainability-based integrated systems perspective. Xia & Shi (2016) believes that water security refers to the quantity and quality of water resources needed for the survival and development of a country or region. Other researchers believe that it involves multiple criteria, such as society, economy and ecology (García et al. 2008; Hamouda et al. 2009; Song et al. 2011).
The Jing-Jin-Ji district is one of the most important urban agglomerations for the country’s development. However, the Haihe River Basin, in which the district is located, is one of the most water-deficient basins in China (Liu et al. 2010), and the per capita water resources are below the international water shortage limit of 1,000 m$^3$. Moreover, water pollution in the Jing-Jin-Ji district was relatively serious, water resources in some areas were entropic, and groundwater was over-exploited (Yan & Guo 2018). The water supply from the South-to-North Water Transfer Project (SNWTP) to the Jing-Jin-Ji district had alleviated the water shortage to a certain extent, but it remains far from being solved in the region. Effectively addressing water security issues in a changing environment has become an important issue in regional management (Thapa et al. 2018). Therefore, a reasonable evaluation of water security in the Jing-Jin-Ji district is of great significance for regional water security management.

Water security can be accessed via various methods. The Organization for Economic Co-operation and Development proposed the pressure–state–response (PSR) theory in 1990, which suggests that water security was highly correlated with human activities (Yao et al. 2019). Human activities impact on the environment, leading to changes in the state of the environment. Society, in turn, responds to these changes. Based on the PSR theory, researchers divided water security index systems into socioeconomic, water resource, ecological and technological indicators (Liu et al. 2014). Jiang & Yang (2015) used the entropy weight method to determine the weights of various indicators in a water security assessment index system and evaluated the water security situation in 47 countries in the Asia–Pacific region. Luan et al. (2015) evaluated the water cycle health of Handan City in Hebei Province based on a key performance indicator (KPI) assessment. Sahin presented a system dynamics model to evaluate water security in the south-east Queensland region in Australia (Sahin et al. 2015). Wheater & Gober (2015) discussed the multiple criteria of water security and encompassed many of the water security challenges of Saskatchewan River basin in western Canada. Thapa analysed the impact of human living habits and economic development on water safety in Kathmandu (Thapa et al. 2018). Allan indicated that water security had inherent economic, social and environmental complexity and evaluated water security under the climate change in Australia’s Murray-Darling Basin Plan (Allan et al. 2013). However, existing research usually focuses on only one aspect of water security, such as resources or environment. At the same time, most of this recent research did not analyze the impact of human activities on regional water security or predict the future development trend. This study aims to establish a multi-criteria evaluation system for water security, and analyse the impact of future social development and human activities on regional water security.

Common methods for determining weights include the binary comparison method, entropy weight method and analytic hierarchy process (AHP), (Hosseini-Moghari et al. 2017). Diamantopoulou & Voudouris (2008) selected the strengths, weaknesses, opportunities and threats (SWOT) to analyse groundwater resources in Zakynthos Island, which included four criteria and 19 indicators. Azarnivand selected the order of preference by similarity to ideal solution (TOPSIS) method to evaluate sustainable development in Iran, which include four criteria (Azarnivand et al. 2017). Kagalou selected the driving-pressure-state-impact-response (DPSIR) framework as a methodological tool for the case study of Kalamas River basin (NW Greece), which included five criteria (Kagalou et al. 2012). Azarnivand and Chitsaz selected the enhanced driving force pressure-state-impact-response (eDPSIR) sustainability framework to deal with water shortage in Yazd, an arid province of Iran, which included seven aspects of indicators (Azarnivand & Chitsaz 2015). Among these, the AHP was probably the most popular in group decision support, which is a multi-attribute utility theory method based on the cardinal preferences of elements contained in a given hierarchy of the decision problem (Srdjevic 2007). During the decision process, decision makers usually have different attitudes. Another difficulty was the inconsistency problem in subjective weighting (Harmancioglu & Yilmaz 2010). In order to avoid the interference of the above problems as much as possible, this study conducted multiple rounds of evaluation by decision makers, and finally made the results consistent. The weight sensitivity analysis method in the multi-criteria decision analysis (MCDA) model was used to verify the rationality of the weight.

This study aimed to establish a general multi-criteria system to evaluate regional water security and provide a
theoretical basis for regional management according to the results. However, it did not analyze the impact of climate change on regional water security, which needs to be explored in future study.

METHODS AND MATERIALS

Study area and data

The study area comprised the Jing-Jin-Ji district, which includes Beijing, Tianjin and Hebei Province. A map of the study area is shown in Figure 1 and information of the area is shown in Table 1.

This study used data on various criteria namely resources, society, economy, ecology and environment. Data on the social, economic and ecological criteria were derived from the official website of the National Bureau of Statistics of China. Data on the water resources, water supply volume of the SNWTP, and water environment status were obtained from the water resources bulletin of the corresponding years in each province or city. For analyses and calculations, relevant data were collected from 2006 to 2016 in the Jing-Jin-Ji district.

Roadmap of study

This study first constructed an evaluation index system applicable to the Jing-Jin-Ji district. A comprehensive index method was used to evaluate the multi-year water security situation. Simultaneously, this study analysed the impact of the SNWTP on water security in the Jing-Jin-Ji district. The grey prediction model (GM) model was used to predict the various indicators in the Jing-Jin-Ji district, and the degree of water security in 2020, 2035 and 2050 were finally calculated. The technical roadmap for this study is shown in Figure 2.

Method of water security evaluation

The comprehensive index method first determines the evaluation indicator system. On this basis, the actual value of each evaluation indicator was compared with the standard value, and the data were normalized to obtain a series of dimensionless numbers. Second, the weights of each evaluation indicator are given. Subsequently, the weighted calculation of the normalized dimensionless numbers of each indicator was carried out to obtain a comprehensive evaluation result.

Indicator system of water security evaluation and its accounting standards

The establishment of the water security indicator system for the Jing-Jin-Ji district followed the principles of scientific evaluation and operability. Scientific evaluation involves the reasonable selection of indicators and determination of their weights, and operability entails that the indicators are quantitatively described (Croke et al. 2006; Song et al. 2011). Wang & Jia (2016) believes that due to the strong influence of human activities, the dynamic conditions, circulation structure and characteristics of the water cycle in the Haihe River Basin have changed and are characterised by resource attenuation, environmental pollution, ecological degradation and supply–demand imbalances. Therefore, the evaluation of water security should be carried out from environmental and social perspectives. Based on previous studies (Jia et al. 2002; Feng & Huang 2008; Wang et al. 2009; Gao et al. 2012; Liu et al. 2017), this study constructed a water security evaluation index system, consisting of five criteria involving resource, social, economic, ecological and environmental, with a total of 16 evaluation indicators, suitable for the Jing-Jin-Ji district.

The AHP was used to empower various indicators and criteria, and the comprehensive index evaluation method was subsequently implemented to evaluate water security. The AHP is a decision analysis method proposed in the mid-1970s. This method is easy to operate and widely used (Lu et al. 2011; Wang et al. 2019). In determining the weights of various criteria and indicators in the indicator system, this study refers to other research (Jia et al. 2002; Feng & Huang 2008; Wang et al. 2009). This other research was used as the basis for determining the weights of the indicators that were considered to be suitable for this study.

Weight sensitivity analysis in the MCDA model can judge the accuracy of weight distribution of output results (Yang & Singh 1994). This model could reduce the uncertainty of index weight assignment. When conducting a sensitivity analysis, the main indicator, which had the largest weight, should be selected first. On this basis, the
weight of this indicator was changed at equal steps, and the changes of other weights were calculated (Chen et al. 2010). Finally, the calculation results were used to analyze the rationality of weight distribution. The results and analysis of the MCDA method are described later.

At the same time, suggestions from experts familiar with the study area were considered. The comprehensive index evaluation method first normalises the indicators to obtain a dimensionless value (Zhang et al. 2005). Subsequently, the weight of each indicator or criteria was used to calculate and obtain a comprehensive evaluation index. The specific indicators and their weights are shown in Table 2. In the column ‘Type’, ‘a’ means the bigger the better, ‘b’ means the smaller the better.
For security evaluation, it can be considered as a scoring process. We liken this process to an exam. Generally speaking, if you want to improve the score of exam, more effort should be put forward into it. Here, effort is the independent variable and the test result is the dependent variable. When the score is high (for example, close to the full mark), it is more difficult to improve the score, so more effort is required. Similarly, when the current level of the indicator is high, it is more difficult to improve the score in evaluation, and the slope of the function can reflect the relationship between the independent and the dependent variable. Therefore, this study hopes to choose a model whose slope decreases with increasing independent variables. Obviously, exponential and linear function models do not conform to this law.

The logarithmic function model and the power function model, whose power exponent is less than 1, conform to this law. However, there was uncertainty in the choice of power exponents. For example, when the power exponents were chosen to be 0.5 and 0.51, respectively, there was almost no difference in the calculation results of the model. Therefore, it was impossible to judge which power exponent had the better effect. The logarithmic function model did not have such a problem, and so this study chose the logarithmic function model.

The logarithmic function model, schematically depicted in Figure 3, had the following characteristics: first, the function had monotonicity, and each index has a worst and an optimal value. When the actual index is equal to or less than the worst value, the index score is 0, and when it was equal to or higher than the optimal value, the index score was 1. Second, the growth rate of the logarithmic function decreases with an increase in the independent variable value, which was in line with the law of social development. Third, with this model, the specific score could be obtained through the actual value of the indicator rather than the fuzzy definition (Zeng et al. 2004). In summary, the logarithmic model was reasonable and operable. The model function is as follows: \( y = a + b \times \ln(x) \), where \( a \) and \( b \) are parameters; each indicator required two sets of data to determine the parameters. In the calculation, two of the special values (optimal, qualified or worst values) could be used to determine the parameter value. For the special value, each indicator referred to international standards, policy documents and national statistical data. The evaluation result of each indicator or criterion was between 0 and 1. The water security status can then be divided into five levels: (0,0.2) is unsafe; (0.2,0.4) is less safe; (0.4,0.6) is critically safe; (0.6,0.8) is relatively safe; and (0.8,1) is safe. Classification results by this model are shown in Table 3.

After constructing a logarithmic model of each indicator, the raw value of each indicator can be used to obtain standardized results. When the raw value was greater than or equal to the best value (worst value), the normalized result is 1 (0). Therefore, the standardization results of all indicators are between 0 and 1. Using the standardized values of the indicators and their corresponding weights, the comprehensive results can be calculated.

### Model of prediction for indicators

With the continuous socioeconomic development, the industrial structure underwent major changes. These changes, in turn, caused changes in the natural and social environments of the region, which ultimately affected regional water security. In this study, the GM was used to predict the indicators. The GM generates a data sequence with strong regularity by identifying the degree of the development trend between system factors, and then establishing a corresponding differential equation model to predict the future development trend (Tabaszewski & Cempel 2015; Javed & Liu 2018). The steps for GM are as follows:

With original series: \( x^{(0)} = (x^{(0)} (1), x^{(0)} (2), \ldots, x^{(0)} (n)) \), \( n \) stands for the number of data. Accumulate the original data to weaken the sequence volatility and

### Table 1  Information of study area

|                | Rainfall (mm) | Runoff (10^8 m³) | Evapotranspiration (mm) | Climate regime           |
|----------------|---------------|------------------|-------------------------|--------------------------|
| Beijing        | 552.9         | 9.25             | 1,699.8                 | Temperate monsoon climate |
| Tianjin        | 535.6         | 9.45             | 1,715.6                 | Warm temperate semi-humid continental monsoon climate |
| Hebei          | 503.3         | 60.06            | 1,703.7                 | Temperate continental monsoon climate |

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With original series: \( x^{(0)} = (x^{(0)} (1), x^{(0)} (2), \ldots, x^{(0)} (n)) \), \( n \) stands for the number of data. Accumulate the original data to weaken the sequence volatility and
randomness and obtain a new data sequence: 
\[ x^{(1)} = (x^{(1)}(1), x^{(1)}(2), \ldots, x^{(1)}(n)) \]
\( x^{(1)}(t) \) represents the accumulation of the previous data:
\[ x^{(1)}(t) = \sum_{k=1}^{t} x^{(0)}(k) \quad (t = 1, 2, 3, \ldots, n) \]  

Establish first-order linear differential equation:
\[ \frac{dx^{(1)}}{dt} + ax^{(1)} = u \]  

where \( a \) and \( u \) are the undetermined coefficients, \( x^{(1)}(t) \) can be calculated after calculating \( a \) and \( u \). In turn, the predicted
value \( x^{(0)} \) can be obtained. Calculate the average of the accumulated data, and generate \( B \) and constant term vector \( Y_n \), where \( T \) is the transpose of the vector:

\[
B = \begin{bmatrix}
0.5(x^{(1)}(1) + x^{(1)}(2)) \\
0.5(x^{(1)}(2) + x^{(1)}(3)) \\
0.5(x^{(1)}(n - 1) + x^{(1)}(n))
\end{bmatrix}
\]

\[
Y_n = (x^{(0)}(2), x^{(0)}(3), \ldots, x^{(0)}(n))^T
\]

Use parameters least squares to obtain parameters \( a \) and \( u \):

\[
\begin{pmatrix}
a \\
u
\end{pmatrix} = (B^T B)^{-1}B^T Y_n
\]

Substituting the result of Equation (3) into Equation (2) and solving it, the result is as follows:

\[
x^{(1)}_n(t + 1) = \left(x^{(0)}(1) - \frac{u}{a}\right)e^{-at} + \frac{u}{a}
\]

where \( x^{(1)}_n \) is for the accumulated value of the prediction, and the prediction result \( x^{(0)}_n \) is as follows:

\[
x^{(0)}_n(t + 1) = x^{(1)}_n(t + 1) - x^{(1)}_n(t)
\]

This study first verified the rationality of the GM. The model was established using the data of the district from 2006 to 2013 for a total of 8 years and verified by data from 2014 to 2016 for a total of 3 years. On this basis, the model is used to predict the future development of various indicators.

The exponential smoothing (ES) method is one of the moving average methods, characterized by giving different weights to past observations (Taylor 2005; Billah et al. 2006). The basic idea is that the predicted value is a weighted sum of previous observations. This article used the single ES and the second ES for calculation. The calculation formula of the single ES is as follows:

\[
y^{t+1'} = \alpha y^t + (1 - \alpha)y^t
\]
where \( y_{t+1} \) is the predicted value for period \( t + 1 \), \( \alpha \) is the smoothing index, \( y_t \) is the actual value for period \( t \), and \( y_t \) is the predicted value for period \( t \).

The calculation formula of the second ES is as follows:

\[
\hat{y}_{t+T} = a_t + b_t \times T \\
\begin{cases}
    a_t = 2S_t^{(1)} - S_t^{(2)} \\
    b_t = \frac{\alpha}{1 - \alpha} (S_t^{(1)} - S_t^{(2)})
\end{cases}
\]

\( S_t^{(2)} = \alpha S_t^{(1)} + (1 - \alpha) S_{t-1}^{(2)} \)   

\( S_t^{(2)} \) is the second ES value for period \( t \), \( S_t^{(1)} \) is the first ES value for period \( t \), and \( S_{t-1}^{(2)} \) is the second ES value for period \( t - 1 \).

### RESULTS

#### Analysis of water security changes and driving forces

Using the MCDA method, select degree of utilisation of surface water \( (x_{13}) \) as the main indicator, and \( \pm 1\% \) as the step size, change the weight of this indicator and calculate the changes of other indicators. For calculation methods, please refer to the reference (Ganji et al. 2016). On this basis, the change in results was analyzed when the weights were changed. The specific results are shown in Table 4. When the weight of the main indicator was changed within \( \pm 20\% \), the results did not show significant changes. It can be seen that the determination of the index weight was reasonable.

#### Table 3 | Grading threshold for water security evaluation indicators

| Index number | Unsafe \([0,0.2)\) | Less safe \([0.2,0.4)\) | Critically safe \([0.4,0.6)\) | Relatively safe \([0.6,0.8)\) | Safe \([0.8,1]\) |
|--------------|----------------|-----------------|-----------------|-----------------|-----------------|
| \( x_{11} \) | <371           | [371,1,063)     | [1,063,2,100)   | [2,100,3,513)   | >3,513          |
| \( x_{12} \) | >144           | [144,97)        | [97,60)         | [60,31)         | <31             |
| \( x_{13} \) | >83            | [83,60)         | [60,40)         | [40,24)         | <24             |
| \( x_{21} \) | >1,087         | [1,087,760)     | [760,491)       | [491,281)       | <281            |
| \( x_{22} \) | <31            | [31,44)         | [44,60)         | [60,78)         | >78             |
| \( x_{23} \) | <78            | [78,107)        | [107,140)       | [140,178)       | >178            |
| \( x_{31} \) | >349           | [349,176)       | [176,63)        | [63,6)          | <6              |
| \( x_{32} \) | <0.87          | [0.87,1.74)     | [1.74,2.9)      | [2.9,4.35)      | >4.3            |
| \( x_{33} \) | >50            | [50,33)         | [33,20)         | [20,10)         | <10             |
| \( x_{34} \) | >82            | [82,71)         | [71,60)         | [60,50)         | <50             |
| \( x_{41} \) | <1.1           | [1.1,1.9)       | [1.9,3)         | [3,4.3)         | >4.3            |
| \( x_{42} \) | <7             | [7,18)          | [18,35)         | [35,57)         | >57             |
| \( x_{43} \) | <1.47          | [1.47,4.44)     | [4.44,9)        | [9,15.17)       | >15.17          |
| \( x_{51} \) | <90            | [90,93)         | [93,95)         | [95,97)         | >97             |
| \( x_{52} \) | <90            | [90,93)         | [93,95)         | [95,97)         | >97             |
| \( x_{53} \) | <19            | [19,34)         | [34,52)         | [52,74)         | >74             |

#### Table 4 | Evaluation results in the case of weight changes

| Year | Variation range of main indicator (%) |
|------|--------------------------------------|
|      | – 20% | – 10% | 0% | 10% | 20% |
| 2006 | 0.4447 | 0.4454 | 0.4462 | 0.4470 | 0.4478 |
| 2007 | 0.4644 | 0.4641 | 0.4639 | 0.4636 | 0.4634 |
| 2008 | 0.5613 | 0.5663 | 0.5713 | 0.5763 | 0.5813 |
| 2009 | 0.5311 | 0.5316 | 0.5321 | 0.5327 | 0.5332 |
| 2010 | 0.5742 | 0.5757 | 0.5773 | 0.5788 | 0.5804 |
| 2011 | 0.6005 | 0.6044 | 0.6082 | 0.6121 | 0.6160 |
| 2012 | 0.6917 | 0.7031 | 0.7146 | 0.7260 | 0.7375 |
| 2013 | 0.6073 | 0.6114 | 0.6155 | 0.6197 | 0.6238 |
| 2014 | 0.5835 | 0.5812 | 0.5789 | 0.5767 | 0.5744 |
| 2015 | 0.6242 | 0.6216 | 0.6189 | 0.6163 | 0.6137 |
| 2016 | 0.7091 | 0.7134 | 0.7176 | 0.7219 | 0.7262 |
Using the actual values of the indicators and their corresponding weights, the changes in the multi-year index of each criterion in the Jing-Jin-Ji district were calculated (Figure 4). For the district, the scores of the four criteria, namely resources, economy, ecology and environment, increased, whereas that of the social criterion decreased. This phenomenon also occurred when Beijing, Tianjin and Hebei Province were evaluated separately. The variation range of each indicator (2006–2016) is shown in Table 5.

As the results show, situations of each criterion changed during 2006–2016. For the resource criterion, the SNWTP provided water resources for the district, and the degree of utilisation of groundwater and surface water showed a downward trend, which led to higher scoring when evaluating. For the social criterion, because the region’s population was concentrated, population density showed an upward trend, which led to lower scoring when evaluating. For the economic criterion, the water use ratio of irrigation and water consumption per 10,000 yuan declined, which led to higher scoring when evaluating. For the ecological and environmental criteria, all indicators showed an upward trend, which led to higher scoring when evaluating. In summary, four criteria had higher scores when evaluating, which led to higher water security states from 2006 to 2016.

The multi-year changes for water security in the Jing-Jin-Ji district were generally increased (Figure 5). Water security in the district scored 0.38 in 2006 and was in a less safe state. In 2016, the score was 0.63, which indicated a relatively safe state. As can be seen in Figure 5, the spatial distribution of water security in Jing-Jin-Ji district was not balanced. For years 2006–2016, the status of water security in Beijing was high, follow by Hebei Province and, lastly, Tianjin. Although the overall status had a rising trend, this spatial pattern did not change much. Take 2016, for example, in relation to the resources and environmental criteria Tianjin had the lowest score due to the overexploitation of groundwater and lower compliance rate for water quality. For the social criterion, due to the population aggregation, Beijing had the lowest score. For the economic and ecological criteria, Hebei was the lowest due to its lower economic volume and lower rate in ecological water use. Due to the high weights for resources and environmental criteria, the status of water security in Tianjin was low.

**Contribution of the SNWTP to water security**

One of the important factors affecting water security is human activities, and the construction of some major projects could change the existing state of water security. The Middle Route of the SNWTP had supplied water to the Jing-Jin-Ji district since 2014, which had alleviated pressure on water supply in this region to some extent. The main contribution of the project was to secure urban water supply, which greatly reduced the utilisation of surface water and groundwater and protected water resources from being overexploited.

The impact of the Middle Route of the SNWTP on the resource criterion is shown in Figure 6 (Situation 1...
Figure 5 | Changes in water security states in Jing-Jin-Ji district from 2006 to 2016.

Figure 6 | Impact of the SNWTP on scores of resource criterion.
represents not considering the project; Situation 2 represents considering the project), and the impact on the overall score of water security is shown in Figure 7. Figure 6 shows that the Middle Route of the SNWTP had a great impact on the resources criterion, especially in Beijing and Tianjin. The score in 2015 increased by 181.04% in Beijing and 103.03% in Tianjin, and in 2016 it increased by 58.62% and 157.86% in these cities, respectively. The overall score of Beijing increased by 18.14% in 2015 and 11.93% in 2016, whereas for Tianjin it increased by 6.98% in 2015 and 14.90% in 2016.

Analysis of impact of social development on water security

This study verifies the rationality of using GM to predict indicators. First, use the data from 2006 to 2013 as input conditions to build a GM and then use it to predict the value of 2014–2016. The predicted value was compared with the actual, and the relative error was calculated to verify the rationality of the prediction using GM. This study established a GM model for each indicator. The $R^2$ of each indicator model is shown in Table 6. It can be seen that there are nine indicators with an $R^2$ value greater than 0.8, accounting for 56%, and four indicators less than 0.5, accounting for 25%. On the whole, the model worked well.

The single ES method and the second ES method were used for calculation in this study, and errors were calculated under different smoothing exponents. The results are shown in Table 7. The errors for the GM were small, and the deviation has a tendency to decline with the extension of the prediction time. Therefore, it can be considered that GM was more reasonable for prediction.
The predicted years were 2020, 2035 and 2050. According to the forecasted results of the various indicators, the results of water security prediction for each criterion of Jing-Jin-Ji district are shown in Figure 8. The prediction of the overall water security is shown in Figure 9. The range of change between the forecasted results for 2050 and the actual for 2015 are shown in Table 8.

The prediction results in Table 7 and scoring results in Figure 8 showed that with continuous social development, the scores of the resource, economy, ecology and environment criteria in the Jing-Jin-Ji district generally had an upward trend. However, the score of social criterion had a downward trend. For the resource criterion, the utilisation of groundwater and surface water gradually decreased, which caused a gradual increase in the score of resource criterion. For the economic criterion, the continuous adjustment in the industrial structure caused the water use ratio of irrigation and water consumption per 10,000 yuan to decline to varying degrees, which led to an increase in score of the economic criterion. For the ecological criterion, the vegetation area per capita and water use ratio of ecology increased significantly, which caused an increase in score of the criterion. Furthermore, the compliance rate of surface water quality increased significantly. The processing rates of city sewage and domestic garbage also increased to varying degrees, and this had contributed to the increased score. For the social criterion, water consumption per capita did not change much, and population density increased greatly. These two factors caused the social criterion scores to decrease. Although the urbanisation rate increased notably, the weight of this indicator was low; and it therefore had little effect on the results.

The overall water security score of the Jing-Jin-Ji district had a gradual upward trend (Figure 8), and the score for 2050 was predicted to be 0.792, which indicated a relatively safe state and was close to the upper threshold, that is, close to the safe state. The average score of the Jing-Jin-Ji district from 2006 to 2016 was 0.511, which was at a critically safe state. The predicted value for 2050 was 0.281 points higher than the average for many years. The improvement of groundwater and surface water gradually decreased, which caused a gradual increase in the score of resource criterion. For the economic criterion, the continuous adjustment in the industrial structure caused the water use ratio of irrigation and water consumption per 10,000 yuan to decline to varying degrees, which led to an increase in score of the economic criterion. For the ecological criterion, the vegetation area per capita and water use ratio of ecology increased significantly, which caused an increase in score of the criterion. Furthermore, the compliance rate of surface water quality increased significantly. The processing rates of city sewage and domestic garbage also increased to varying degrees, and this had contributed to the increased score. For the social criterion, water consumption per capita did not change much, and population density increased greatly. These two factors caused the social criterion scores to decrease. Although the urbanisation rate increased notably, the weight of this indicator was low; and it therefore had little effect on the results.
in overall security was due to the fact that in the evaluation index system, the scores of all criteria had an increasing trend, except for the social criterion.

**DISCUSSION**

In this study, a general multi-criteria water security evaluation index system was constructed, and the comprehensive index method was used to evaluate the regional water security. This method was easy to operate and the key point is to determine the evaluation index suitable for the study area and its weight reasonably. However, there were still some uncertainties in the process.

**Rationality and uncertainty in selection of evaluation indicators**

In the establishment of the index system, this study drew on the ideas and methods of the PSR theory and KPI evaluation model. For the PSR theory, in the process of constructing the indicator system, the indicators were divided into three criteria, namely water demand pressure, water resource status and human response. This study summarised the ideas of relevant studies on the construction of an index system. Dickson et al. (2016) attributed water security evaluation indicators to six criteria, and Norman (Norman et al. 2013) established a water security evaluation index system including criteria for water quality and quantity. Nie et al. (2018) incorporated...
sustainability indicators into the water security indicator framework, which included four criteria Shao et al. (2012) also established a water sustainability assessment model with four criteria, and Jensen (Jensen & Wu 2018) established an urban water sustainability assessment model with four criteria. These studies fully considered various factors affecting regional water security, but some were not quantitatively described. Combined with the specific characteristics of China and the methods of Chinese researchers (Luan et al. 2016; Cao & Zhang 2017; Zhong & Liu 2018), the establishment of the indicator system in this study considered various aspects affecting water security, and the selected indicators were quantitatively described. The specific data of the indicators were obtained through relevant channels and had a certain degree of versatility.

However, it should be noted that this study had limitations in the selection of indicators. The water cycle has social attributes, and human consciousness and behaviours therefore impacts on the state of water security. But generally speaking, subjective factors cannot be quantitatively described, and thus cannot be applied to the actual calculation, which could restrict the integrity of the indicator system to a certain extent.

Uncertainty analysis of the modeling process

There were uncertainties in the modelling processes for evaluation and prediction in this study. Such uncertainties would affect the results to a certain extent. Three aspects of uncertainties are discussed in this section.

Uncertainty of weights: when determining the weights for various indicators, AHP was used for weight distribution in this study. Although the MCDA method was used to analyse the rationality of the weights, AHP still had certain subjectivity. The weight may have a certain relationship with subjective cognition. Even experienced experts would inevitably have differences in determining weights. Calculation results of the model would be affected by this kind of difference to a certain extent.

Uncertainty in model selection: the reasons for choosing a logarithmic model were described earlier and it was clearly stated that the power exponential model can also be used as one of the alternative models. Since the most suitable power exponent value was difficult to find, the model had not been applied in this study. However, it should be pointed out that this did not mean the effect of the power exponential model was worse than that of the logarithmic model. The research on this part of the uncertain factors will also be developed in the future.

Uncertainty of prediction results: GM was used to predict the indicator, and the prediction results of single ES and second ES were compared. The results showed that GM had a better prediction effect. However, it can be seen from Table 5 that when modelling, some indicators have low $R^2$. Improving the accuracy of prediction is also one of the key points for future research.

Impact of changing environment on water security and adaptation countermeasures

With continuous social development and accelerating urbanisation, the natural and social environments of the Jing-Jin-Ji district have undergone major changes, which have different impacts on water security in the district.

First, with water supplied from the Middle Route of the SNWTP to the Jing-Jin-Ji district, the water resources per capita have increased. Second, with economic development and the continuous adjustment of the industrial structure, the water consumption per 10,000 yuan have decreased significantly, and the irrigation water use ratio has continually declined, whereas the industrial water use ratio has fluctuated. Third, as cities gradually focus on the development of ecological civilisations, the ecological water use ratio has also increased. Changes in these factors have led to increased regional water security. However, the population density of the district has also increased and the high urbanisation in Beijing and Tianjin has increased pressure on the water supply, causing a decrease in water security.

Faced with the double-sided impact of a changing environment on regional water security, the most stringent water resource management system should continue to be enacted to control water resource development and utilisation, improve water use efficiency, control pollutant emissions and improve water security in terms of resources and the economy, ecology and environment. In light of co-ordinated development in the Jing-Jin-Ji district, the spatial distribution of population should be effectively adjusted to
reduce the population density in Beijing and Tianjin to improve regional water security.

The limitations of this study and future directions for research

There were still some limitations in this study. First of all, in the analysis of the impact of human activities on regional water security, subjective factors such as awareness of water-saving was not considered, which would have changed the results of regional water security evaluation. This study did not consider subjective factors because they were difficult to quantify, which was one of the limitations of this study. Second, the impact of policy changes was not considered when predicting the future development trend of regional water security. The macro-control of national policies (such as adjusting the spatial distribution of population distribution, etc.) has a great impact on regional water security.

Based on these limitations, future research may include the following two directions. First, the subjective factors should be added in the evaluation index system of regional water security, and need to explore indicators suitable for quantitative characterization of human activities. Second, different development scenarios could be assumed to simulate the development trend of regional water security under the influence of different policy conditions.

CONCLUSIONS

A multi-criteria water security evaluation method was provided, which was universal. In this study, the water security assessment was divided into several criteria, and each of them contained different numbers of indicators. For other regions, the types of indicators were changed according to their local characteristics. At the same time, evaluation criteria were changed according to regional characteristics and policies. Therefore, the evaluation method provided in this study had certain universality and can be extended appropriately. The conclusions are as follows:

(1) The state of water security in the Jing-Jin-Ji district was generally on the rise from 2006 to 2016. However, social criterion showed a declined trend, which needs improving via planning for balanced development.

(2) The SNWTP has played an important role in ensuring water security in the Jing-Jin-Ji district, especially in the resources criterion. The project contributed to ensuring regional water security, and it also reflects the impact of human activities on resource allocation and water security.

(3) GM can be used to make good predictions for indicators. The state of water security in the Jing-Jin-Ji district is likely to increase with on-going social development, except social criterion. Thus, on the basis of maintaining good development trends in other criterion, the development plan for the social criterion should be adjusted.

With the prediction of the water security indicators, this study considered the impact of social development on regional water security. However, social development and human activities are likely to change the water cycle pattern and in turn, affect regional water security. This study did not consider this issue, which needs further research.

ACKNOWLEDGEMENTS

This study was supported by the National Key Research and Development Program of China (2016YFC0401401), the Chinese National Natural Science Foundation (No. 51739011 and No. 51879274), and the Research Fund of the State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (No. 2017ZY02).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 21 March 2020; accepted in revised form 10 July 2020. Available online 24 July 2020.