

Cloud model-based analysis of regional sustainable water resource utilization schemes

Fu Qiang^{1,2,3*}, Meng Fanxiang¹, Li Tianxiao¹, Liu Dong^{1,2,3}, Gong Fanli¹,
Amgad Osman¹, Li Yutong¹

(1. School of Water Conservancy and Civil Engineering, Northeast Agricultural University, Harbin 150030, China;

2. Heilongjiang Provincial Collaborative Innovation Center of Grain Production Capacity Improvement, Northeast Agricultural University, Harbin 150030, China; 3. Key Laboratory of High Efficiency Utilization of Agricultural Water Resource of Ministry of Agriculture,

Northeast Agricultural University, Harbin 150030, China)

Abstract: Given the adverse effects of current water shortages, low utilization and imbalance between the supply and demand, and other status quo problems relating to social economic development, the construction industry and agriculture, a cloud model was applied to a water resource system using five sustainable water resource utilization schemes for Kiamusze, Heilongjiang Province, as an example. This research changes the qualitative description of the concept language into a quantitative analysis of an evaluation indicator. A cloud model-based analytical method for regional sustainable water resource utilization schemes was proposed, and the sustainable grades of the water resources were calculated. The research results showed that, in addition to the natural continuation of such schemes, the development trends of four new schemes achieved the sustainable utilization of water resources, and thus, the sustainable water resource utilization was optimized. However, when the open-source, throttle, comprehensive and coordination schemes were subjected to the optimum applicability analysis, based on the limiting factors in different periods, resource availability and long-term development, decision-making regarding the best solution in different periods better ensures sustainable development in Kiamusze. The research results provide a significant theoretical basis for the formulation of scientific and reasonable sustainable water resource utilization strategies in Kiamusze.

Keywords: cloud model, regional water resources, sustainable utilization, normal cloud, scheme analysis

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1 Introduction

With rapid economic development, the demand for water resources has increased in Kiamusze, and thus, the imbalance between the supply and demand is becoming increasingly severe. In addition, water shortages,

pollution, low utilization, and other problems have also been exposed. These risks will threaten regional sustainable development in the future. Analyzing sustainable water resource utilization schemes will not only improve the efficiency of the optimum allocation of the water resources but also facilitate the development of

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Biographies: **Meng Fanxiang**, Master, Engineer, Research interests: system analysis of agricultural water and soil resources, Email: mengfanxiang100@163.com; **Li Tianxiao**, Master, Engineer, Research interests: system analysis of agricultural water and soil resources, Email: litianxiao@neau.edu.cn; **Liu Dong**, PhD, Professor, Research interests: system analysis of agricultural water and soil resources, Email: Liu72dong@126.com; **Gong Fanli**, Master, Engineer, Research interests: system analysis of agricultural water and soil resources, Email: gongfanli1118@163.com; **Amgad Osman**,

Postgraduate, Research interests: system analysis of agricultural water and soil resources, Email: amjed.osman@yahoo.com; **Li Yutong**, undergraduate, Research interests: system analysis of agricultural water and soil resources, Email: 15546530408@163.com.

***Corresponding author: Fu Qiang**, PhD, Professor, Research interests: system analysis of agricultural water and soil resources. Address: School of Water Conservancy and Civil Engineering, Northeast Agricultural University, Harbin 150030, China. Tel: +86-451-55190209, Email: fuqiang0629@126.com, fuqiang@neau.edu.cn.

scientific and rational sustainable water resource utilization management strategies for Kiamusze, ultimately, and the achievement of regional sustainable development.

In 1992, the “International Conference of Water and Environment--Development Issues in the 21st Century” was held in Dublin, Ireland. The water resource system and the sustainable utilization research problems proposed by the conference aroused broad concern among scholars at home and abroad, and thus, sustainable water resource utilization research emerged^[1,2]. Subsequently, an increasing number of scholars began to conduct in-depth research investigating indicators for sustainable water resource utilization evaluation, evaluation principles and evaluation methods^[3-8], and a series of improved methods for sustainable water resource utilization evaluation were introduced, such as the fuzzy four-element connection coefficient, the quantum genetic algorithm, the set pair analysis, and the evaluation method combining analytic hierarchy process with projection pursuit^[9-12]. Most of these methods are employed for sustainable water resource utilization evaluations based on the relationship between the existing annual actual indicator quantification value and the sustainable estimation scale standard, thereby reflecting the development level of the current sustainable water resource utilization system. However, when the uncertainty of the quantitative description of the evaluation indicator and the evaluation result grading are analyzed by these traditional methods, the self-uncertainty of these descriptions and evaluation is not considered, resulting in an inaccurate evaluation of the results^[13]. For such common uncertainty in both the subjective and objective worlds, Li et al.^[14] first proposed the state space theory and the cloud and language atomic models in the 1990s. Subsequently, the cloud model^[15] was gradually improved and developed, and the exploratory qualitative-quantitative conversion^[16] was achieved and successfully applied in many research fields, such as the intensive land use situations relating to development and utilization, air quality assessment, ship traffic adaptability and water resource-carrying capacity evaluations^[17-23]. However, sustainable water resource

utilization analyses have rarely been reported. Therefore, this study will introduce the cloud model for the analysis of regional sustainable water resource utilization schemes, dynamically integrate fuzziness with randomness in the analysis process, and verify the rationality of the water resource schemes and sustainable utilization from the perspectives of persistence and feasibility, thereby evaluating the uncertainty of the regional sustainable water resource utilization. Then, the best scheme for regional sustainable water resource utilization in different periods of development will be screened, and policy guidance will be provided regarding the further development and utilization of the water resources in Kiamusze.

2 Materials and methods

2.1 Study area

Kiamusze is located in the northeast border of China in the heartland of the Sanjiang Plain where the Heilong River, the Wusuli River and the Songhua River converge (Figure 1). It is an important commodity grain producer and a key development zone in the Sanjiang Plain. Its total area is 32 704 km². It is an economic and cultural center and a traffic hub in the eastern region of Heilongjiang Province and has enormous potential for investment and development^[24].

Kiamusze's total water resources consist of three parts: surface water resources, groundwater resources and the Songhua River's transit water resources. For many years, the average surface water was 2.25×10^8 m³, the groundwater resources totaled 2.57×10^8 m³, and the water supply and demand ratio was 0.76. The groundwater development and utilization ratio reached 71.2%, and the surface water only 8.2%. In addition, a series of immeasurable losses, such as land subsidence, water inflow attenuation, and a suspended pump at a well site, occurred because of the overexploitation of groundwater resources. Thus, the low surface water development and utilization ratio, the overexploitation of groundwater, the imbalance between the water supply and demand, and other hidden dangers seriously threaten the sustainable utilization of water resources and socio-economically sustainable development in Kiamusze. However, the

cross-border water supply is $2.84 \times 10^8 \text{ m}^3$, whereas the development utilization rate is only 0.42%. Both the

cross-border water and surface water have substantial potential for development.

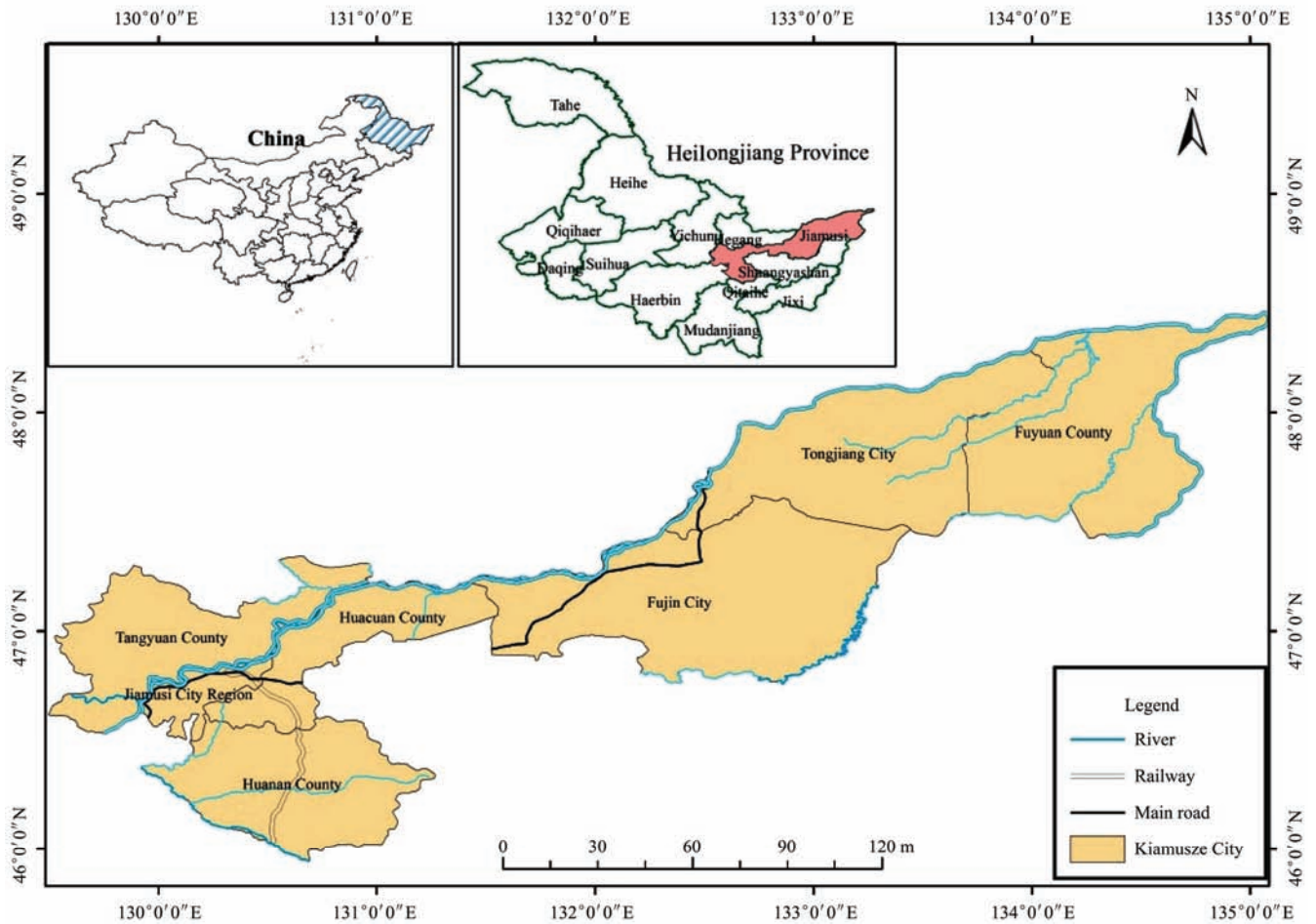


Figure 1 Geographic location of Kiamusze

2.2 Cloud model theory

2.2.1 Clouds and their numerical characteristics in an indicator system

(1) Clouds and cloud drops

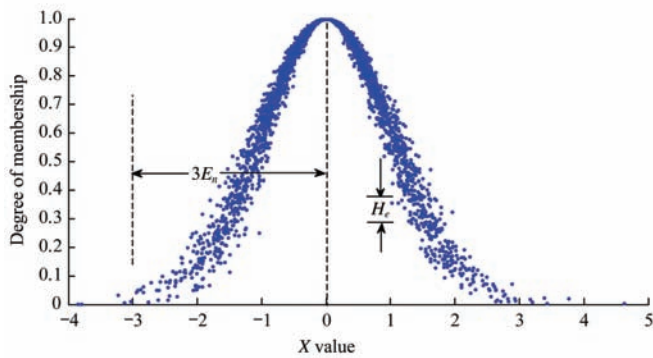
The indicator system is defined as a cloud space, in which a unit cloud is related to the evaluation indicator system via the indicator grading standard, which corresponds to a domain of discourse C that can be represented by a precise numerical quantity with an appropriate qualitative concept Q . Moreover, the actual specific indicator x is the cloud drop that is dropped in the qualitative concept Q of its attribution indicator system; thus, we have a stable random number $\mu_{(x)} \in [0, 1]$, which is called the degree of certainty of x to Q . The distribution of x on C is called the cloud. The cloud is composed of many cloud drops, and the indicator system is thus composed of many indicator factors. The overall shape of the cloud reflects the important features of the

qualitative concept of the evaluation indicator. The indicator value quantitatively describes the qualitative concept, and the process of generating each cloud drop maps the uncertainty relationship between the qualitative concept and the quantitative description^[25].

(2) Numerical characteristics of the cloud

The numerical characteristics are represented based on expectation (E_x), entropy (E_n), and hyper entropy (H_e), and their distribution features^[14] are shown in Figure 2. Combined with the evaluation indicator system, E_x is the point that best represents the qualitative evaluation indicator concept in the sample data, and the peak value is the most representative water resource evaluation indicator value. Moreover, E_n represents the random measurement of the importance of the indicator concept, i.e., the measurement that can be accepted by the qualitative concept in the domain of the discourse space of the elevation indicator grading standard. It reflects

the dispersion degree of the specific indicator value and its range (based on the distribution characteristics of the normal cloud and the cloud drops that contribute to the qualitative concept, which mainly fall in $[E_x-3E_n, E_x+3E_n]$). The evaluation indicator value in $[E_x-3E_n, E_x+3E_n]$ is denser, indicating that this section is more important in the water resource evaluation indicator concept. Furthermore, H_e measures the uncertainty to the entropy and reflects the cohesion of the evaluation indicator value in the overall space of the number field; higher hyper entropy correlates with a greater dispersion degree of the evaluation indicator value. Additionally, the greater the randomness of the degree of the membership is, the thicker the cloud is, and vice versa^[17].



Note: $E_x=0, E_n=1, H_e=0.1$ and $n=3000$.

Figure 2 Digital characteristics of the cloud model

2.2.2 Cloud generator

The cloud generator is divided into a forward cloud generator and a backward cloud generator^[25]. The forward cloud generator is mapped from a qualitative to a quantitative space to produce a cloud drop according to the numerical characteristics (E_x, E_n, H_e) , which is a basic cloud algorithm used to realize and obtain quantitative information from the qualitative expression of the concept language. The backward cloud generator is converted from quantitative to qualitative because the qualitative concept expressed by a cloud feature digit according to the specific quantitative value^[17]. Their working principles are shown in Figure 3.

2.2.3 Modeling steps for water resource sustainable utilization based on the cloud model

According to the aforementioned theories, the specific evaluation steps of the cloud model are as follows (see Figure 4):

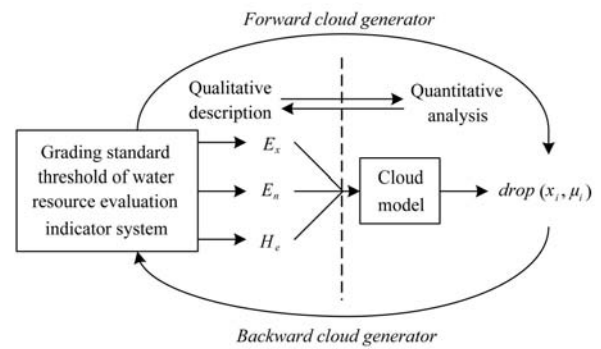


Figure 3 Schematic diagram of the forward (backward) cloud generator

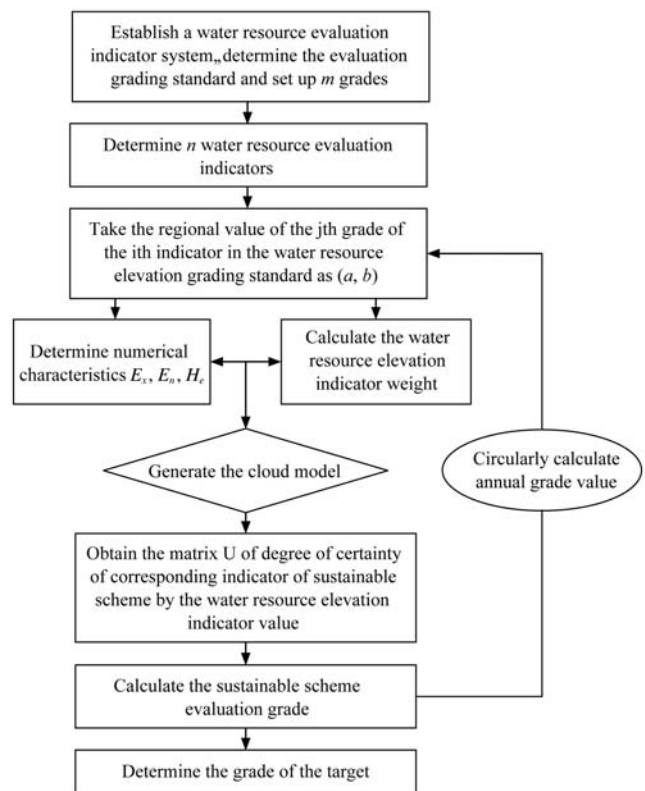


Figure 4 Flow chart of cloud model-based sustainable water resource utilization scheme evaluation

Step 1: Determining the cloud parameters in the water resource system

Determine 3 numerical characteristics of the cloud model according to the established water resource evaluation index and its standard:

$$\begin{cases} E_x = (a + b) / 2 \\ E_n = |a - b| / 6 \\ H_e = k \end{cases} \quad (1)$$

where, a and b represent the boundary values of the evaluation indicators in the attributed zone, and k is a constant that is regulated according to the fuzzy indicator threshold of the variable (in this study, H_e is taken as 0.1).

Step 2: Determining the water resource evaluation

indicator weight

Because the impact of each evaluation indicator on the sustainable water resource utilization is different, its indicator weight also differs. In this study, the actual value of the evaluation indicator and the grading standard value (the larger value of the same indicator grading boundary) are used to calculate the weight vector of the evaluation indicator, where $N=\{x_1, x_2, \dots, x_n\}$ is assumed to be $W=\{\omega_1, \omega_2, \dots, \omega_n\}$. Then,

$$\omega_i = \frac{\gamma_i}{\sum_{i=1}^n \gamma_i} \tag{2}$$

$$\gamma_i = \frac{\frac{1}{q} \sum_{j=1}^q c_i}{\frac{1}{m} \sum_{i=1}^m p_{im}} \tag{3}$$

where, n is the number of evaluation indicators, m is the grade number of the evaluation indicator, q is the evaluation year, ω_i is the weight of the evaluation indicator x_i , c_i is the indicator value of x_i , p_{im} is the grade m standard value of x_i , and γ_i is the average ratio of the sum of the average indicator value of the q -year evaluation indicators and the evaluation indicator p_{im} . In this study, $n=13$, $m=5$ and $q=23$ (2008-2030).

Step 3: Generating the matrix of the degree of certainty using the forward cloud generator

Take E_n and H_e calculated in step 1 as the expectation and variance, respectively, to generate the normality random number $E'_n = NORM(E_n, H_e^2)$. Then, generate another normal random number $x_i = NORM(E_x, E'^2_n)$ using E_x as the expected number and E'^2_n as the variance. This study utilized 23-year simulation data of 13 sustainable water resource utilization evaluation indicators in Kiamusze for c_i in the system, and the degree of certainty of the corresponding indicator was calculated using the following formula:

$$\mu_i = e^{-\frac{(c_i - E_x)^2}{2E'^2_n}} \tag{4}$$

The matrix of the degree of certainty of each evaluation indicator can be obtained as follows:

$$U = \mu_{n \times m} = \begin{pmatrix} \mu_{11} & \mu_{12} & \dots & \mu_{1m} \\ \mu_{21} & \mu_{22} & \dots & \mu_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ \mu_{n1} & \mu_{n1} & \dots & \mu_{nm} \end{pmatrix}, n = 1, 2, \dots, 13;$$

$$m = 1, 2, \dots, 5.$$

Step 4: Calculating the sustainable water resource utilization scheme evaluation grading value

$$\begin{cases} q_i = \sum_{i=1}^n w_i \times \mu_{nm} \\ Q^* = \sum_{j=1}^m j \times q_j / \sum_{j=1}^m q_j \end{cases} \tag{5}$$

where, Q^* is the scheme evaluation grading value.

Step 5: Repeating steps 1-4 to calculate the sustainable water resource utilization scheme evaluation grading value.

3 Results and analysis

3.1 The sustainable water resource utilization schemes

Based on the inherent characteristics of the water resources in Kiamusze, different measures can be dynamically regulated, such as the surface water development and utilization rate, the groundwater development and utilization rate, the cross-border water supply and the industrial and agricultural production water saving, through sustainable water resource utilization schemes. Thus, five sustainable water resource utilization schemes were developed: natural continuation, open source, throttle, comprehensive and coordination. The natural continuation scheme follows the level of the status quo level year (2008) and is not subject to any adjustment measures. The open-source scheme considers the improvement of the water resource supply as a principle, i.e., taking the improvement of the surface water supply capability and the vigorous development of the cross-border water supply as the main measures. The throttle scheme takes the reduction of the water demand and industrial and agricultural production water-savings as the main design principles. The comprehensive scheme combines the open-source scheme with the throttle scheme. The coordination scheme adjusts the cross-border water supply, the groundwater development and utilization ratio, the industrial and agricultural production water-savings and the other measures of the comprehensive scheme. The specific regulation magnitude is used to dynamically regulate the indicative sensibility parameters from 2008 to 2030 via a system dynamics method year by year to achieve a balance between the supply and demand for regional

water resources. Table 1 shows the primary regulation measures of the five schemes.

Table 1 Main regulation measures for different sustainable water resource utilization schemes

| Program | Surface water development and utilization rate | Cross-border water supply | Groundwater development and utilization rate | Industrial and agricultural production water saving |
|-----------------------------|--|---------------------------|--|---|
| Natural continuation scheme | ☆ | ☆ | ☆ | ☆ |
| Open-source scheme | ★↑ | ★↑ | ☆ | ☆ |
| Throttle scheme | ☆ | ☆ | ★↓ | ★↑ |
| Comprehensive scheme | ★↑ | ★↑ | ★↓ | ★↑ |
| Coordination scheme | ★ _{com} ↓ | ★ _{com} ↓ | ★ _{com} ↓ | ★ _{com} ↓ |

Note: ☆ represents the measure that follows the natural continuation condition without regulation; ★ indicates that the relative measure is under dynamic regulation based on the natural continuation scheme; ★_{com} indicates that relative measure is under dynamic regulation based on the comprehensive scheme; ↑/↓, represent increase/invariant/drop respectively.

3.2 Establishment of a sustainable water resource utilization evaluation indicator system

A sustainable water resource utilization evaluation indicator system is the basis for the establishment of an evaluation model and is the primary objective of analyzing sustainable water resource utilization schemes^[26]. Based on the fundamental principles of the regional policy, the systematic objectivity and the overall operability and combined with the influencing factors, such as the balance between water supply and demand, the agricultural production capacity, the national economic level, and the water resource development and

utilization degree, a sustainable water resource utilization evaluation indicator system was established in Kiamusze.

Another important task in sustainable water resource utilization analysis is the grading of the elevation indicator system. The generality of and differences in the indicator among the grading zones are indicated by judging the grade of the indicator. Thus, this study combines the water resource development and utilization characteristics in Kiamusze and screens the targeted indicator factors to establish five standard grades for sustainable water resource utilization evaluation in Kiamusze to achieve sustainable regional development^[27] (Table 2). Grade I indicates that the sustainable water resource utilization prospect is good and that the balance between the water supply and demand is sufficient to support the coordinated development of a complex system of population-economy-resources-environment. Grade III indicates that the sustainable water resource utilization prospect is average and that the water resource supply and demand can support sustainable regional development. Grade V indicates that the sustainable water resource utilization prospect is poor and that the imbalance between the water supply and demand is large, that it will seriously limit industrial and agricultural production and socio-economic development, and that maintaining sustainable utilization will be difficult. Grades II and IV are intermediate grades. As different control measures and development and utilization patterns occur, grade II and grade IV shift towards the other three grades.

Table 2 Grading standards of the sustainable water resource utilization evaluation indicators in Kiamusze

| Indicator | I | II | III | IV | V |
|---|---------------|----------------|--------------------|------------------|---------------|
| Water resources per capita/m ³ per capita | 10 000-12 000 | 1700-10 000 | 1000-1700 | 500-1000 | 0-500 |
| Groundwater development level/% | 0-20 | 20-40 | 40-70 | 70-90 | 90-100 |
| Water supply modulus/×10000 m ³ ·km ² | 30-40 | 15-30 | 5-15 | 2-5 | 0-2 |
| Natural population growth/‰ | 0 | 0-2 | 2-15 | 15-20 | 20-25 |
| Primary industry share of GDP/% | 0-3 | 3-12 | 12-15 | 15-30 | 30-95 |
| Irrigation volume/% | 60-80 | 50-60 | 30-50 | 10-30 | 0-10 |
| Industrial share of GDP/% | 30-95 | 25-30 | 20-25 | 10-20 | 0-10 |
| Water supply and demand ratio | 1 | 0.95-1; 1-1.05 | 0.8-0.95; 1.05-1.2 | 0.6-0.8; 1.2-1.4 | <0.6; >1.4 |
| Surface water development and utilization level/% | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 |
| Reclaimed water reuse rate/% | 60-80 | 30-60 | 15-30 | 5-15 | 0-5 |
| Irrigation water capacity per unit area/m ³ ·hm ² | 0-5500 | 5500-6000 | 6000-8500 | 8500-11 000 | 11 000-15 000 |
| Water rate of ecological environment/% | 5-7 | 3-5 | 2-3 | 1-2 | 0-1 |
| Cross-border water supply/×10 000 m ³ | 400-100 | 20-40 | 10-20 | 1-10 | 0-1 |

3.3 Application of the cloud model

According to the 13 established sustainable water resource utilization indicators and the dynamic simulation data of each indicator from 2008 to 2030^[28], the sustainable water resource utilization scheme in Kiamusze

was optimized and evaluated using the cloud model. The sustainable utilization grading values of the five schemes for each year were calculated, and their development trends were analyzed to identify the best scheme for sustainable development in the region (see Figure 5).

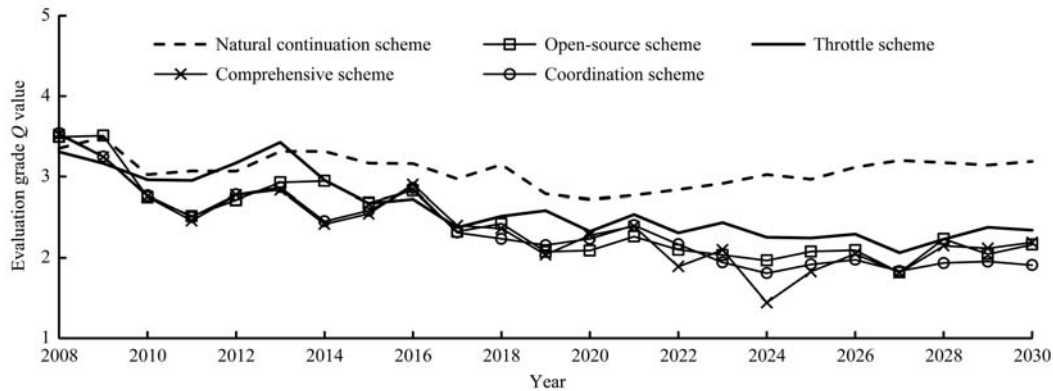


Figure 5 Sustainable water resource utilization scheme grade trends

Figure 5 shows that, in addition to the natural continuation scheme, the other four schemes generally develop from grade III (“the basic sustainable state”) to grade II (“the sustainable transitional state”), indicating that the overall design adopted for the regional water resource system essentially reflected the development trend of the sustainable water resource utilization in Kiamusze. However, because the schemes consider different regulation measures, the amplitude of the variation of the scheme grade values also varies. The specific analysis results are as follows:

(1) The evaluation grade value of the natural continuation scheme in 2008 is 3.352, and it will remain 3.188 until 2030. Grade III persists for a long period, and thus, the sustainable utilization prospect is average. The water resource supply can support regional development, and thus, it corresponds to the basic sustainable state relative to the ideal development trend of sustainable water resource utilization. This is because the status quo continuation scheme is designed based on the state in 2008 without appropriately adjusting and managing the water resource system, leading to no significant increase in the sustainable water resource utilization capacity.

(2) The evaluation grade values of the open-source scheme and the throttle scheme from 2008 to 2030 developed from 3.493 and 3.308 to 2.163 and 2.343, respectively. The sustainable water resource utilization grade, which shifted from grade III to grade II, was

realized by implementing different control measures. However, analyzing the grade trend lines of both of these schemes revealed that the sustainable utilization of the open-source scheme will be lower than that of the throttle scheme after 2017; namely, the sustainable utilization capacity of the former is higher, and the open-source scheme is a better choice than the throttle scheme. Therefore, considering the status quo of the water resources in Kiamusze, when the objective factors constrain the development of water resources and the system does not control the surface water and groundwater simultaneous, instead, and only improves the water supply or reduces the water demand, the open-source scheme should be selected as the best solution for sustainable water resource utilization in Kiamusze. This is because the throttle scheme produced a trend that will result in severe damage, such as land subsidence, water inflow attenuation, and a suspended pump at a well site, because of the overexploitation of the groundwater resources at the present stage. Therefore, it is cannot recover in a short time, and independently considering the reduction in the groundwater supply is inferior to increasing the surface water supply and the cross-border water supply capacities. As a result, the sustainable utilization of the throttle scheme will be lower than that of the open-source scheme in the short term. Thus, the control measure of the open-source scheme “to improve the surface water supply capacity and endeavor

to develop cross-border water supply” will become the main basis for the efficient, stable and sustainable development of water resources in Kiamusze in the future.

(3) The elevation grade values of the comprehensive and coordination schemes will be 2.190 and 1.908, respectively, until 2030. The grade trend lines of both generally indicate stronger sustainable utilization ability. However, the trend of the comprehensive scheme fluctuates greatly, its sustainable utilization will be higher than that of the coordination scheme from 2019 to 2025, and its elevation grade value will reach 1.442 in 2024; however, after 2026, a slight upward trend will occur, and the evaluation grade value will be significantly higher than that of the coordinated scheme. This finding shows that increasing the water supply and reducing water demand as much as possible in combination with the open-source scheme and the throttle scheme when the regional water resources are extremely abundant might be beneficial for the regional water resources system. However, given the restriction of the economy, sociality, ecology, and many other factors, if the water resource system in Kiamusze does not consistently increase the water supply and reduce the water demand as much as possible, a decrease in the sustainable water resource utilization capacity caused by wasted resources, unsustainable economic development and other factors will occur; the mentioned benefits will only be achieved by regulating the surface water and the groundwater supply capacity as much as possible. The overall trend of the coordination scheme is more stable. From 2008 to 2030, the sustainable water resource utilization capacity will gradually increase and be converted from the basic sustainable utilization state to the sustainable utilization state. Regarding the long-term benefits, the coordination scheme is more conducive to the sustainable utilization of the water resources and sustainable development in Kiamusze.

4 Conclusions

In this study, the cloud model was applied to analyze sustainable water resource utilization schemes. The results obtained for 23-year sustainable water resource grade values of 13 evaluation indicators of the water resource system in Kiamusze are as follows:

When there are more regional water resource limiting factors and full measures cannot be regulated, the development of the open-source scheme will support the sustainable utilization of water resources;

When regional water resources are extremely abundant, even when maximum exploitation of the resources occurs, coordinated social, economic and ecological development will not be limited, and the comprehensive scheme is the best scheme to ensure the sustainable utilization of the water resources in Kiamusze.

In the long term, when the development of the regional water resources is subject to certain restrictions and the maximum exploitation of the water resources cannot be supported, the implementation of the coordination scheme is more conducive to achieving the sustained, stable and coordinated development of the water resources in Kiamusze. These results have important theoretical and practical significance for guiding the further rational development and utilization of the water resources in Kiamusze.

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