Assessment and Prediction of Water Resource Vulnerability in the Kekeya Project Area Under Multiple Future Scenarios (Postprint)

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Abstract

To objectively and scientifically evaluate and manage water resource vulnerability in the Kekeya ecological engineering area of Xinjiang, a water resource vulnerability assessment index system was constructed based on natural, anthropogenic, and socio-economic dimensions. Four development scenarios were established: current development pattern, economy-oriented pattern, resource-saving pattern, and green coordination pattern. The comprehensive fuzzy evaluation method, entropy weight method, and system dynamics model were employed to assess and predict regional water resource vulnerability. The results demonstrate that: (1) The overall water resource vulnerability score in the study area from 2010-2020 was 0.466, indicating moderate vulnerability. (2) Water resource vulnerability under all four development scenarios exhibits an upward trend, with projected vulnerability values of 0.512, 0.574, 0.549, and 0.511 by 2035, respectively. This indicates that water supply-demand issues in the region will become increasingly severe in the future, with the resource-saving pattern proving most effective for alleviating water supply-demand imbalance. This study explores the changing characteristics of water resources before and after the implementation of the Kekeya Project, analyzes future water resource vulnerability variation patterns through different development scenarios, provides theoretical references for the implementation of afforestation projects in arid regions, and holds practical significance for local sustainable water resource development.

Full Text

Assessment and Prediction of Water Resource Vulnerability in the Kekeya Project Area Under Future Multi-Scenario Models

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Abstract

To objectively and scientifically evaluate and manage water resource vulnerability in the Kekeya ecological project area of Xinjiang, this study constructed a water resource vulnerability evaluation index system based on natural, anthropogenic, and socio-economic factors. Four development scenarios were established: status-quo development, economy-oriented, resource-conservation, and green-coordination. The study applied integrated fuzzy evaluation, entropy weight method, and system dynamics models to assess and predict regional water resource vulnerability. Results indicate that: (1) Under the four scenarios, water resource vulnerability values showed an upward trend, reaching [MATH_0] by [MATH_1]. The overall vulnerability score for the study area during [MATH_2] was [MATH_3], indicating that water supply-demand contradictions are becoming increasingly severe. The resource-conservation scenario proved most effective in alleviating water supply-demand imbalances. This research explores water resource change characteristics before and after Kekeya project implementation, provides analysis of future water resource vulnerability patterns under different development scenarios, offers theoretical reference for afforestation projects in arid regions, and holds practical significance for local sustainable water resource development.

Keywords: water resource vulnerability; system dynamics model; fuzzy comprehensive evaluation; Kekeya area

Introduction

Water resources constitute crucial material foundations for human survival while simultaneously being influenced by human activities in terms of both quantity and quality [?]. With rapid societal development and accelerating urbanization, water scarcity and pollution have become critical constraints on sustainable development [?], causing transformations in water resource systems [?]. Water resource vulnerability serves as an important indicator for measuring changes in water resource systems, and its scientific and comprehensive evaluation promotes efficient water utilization and coordinated urban development [?].

Early research on water resource vulnerability primarily focused on groundwater vulnerability before gradually extending to entire water resource systems [?].

The concept originated in [?], with subsequent research by numerous experts enriching the study of water environments. Research content mainly includes establishing evaluation index systems [?], analyzing interactions among water resource system components [?], and conducting evaluations [?]. For instance, Ning Like et al. [?] applied water resource vulnerability indices to study the Tarim River Basin, while Cao Lijuan et al. [?] used principal component analysis to evaluate water resource vulnerability in Gansu Province. Gao Ya et al. [?] applied system dynamics models to evaluate water resources in Jiangsu Province. These methods exhibit diversity in both approach and model selection, but most provide only static analysis and cannot comprehensively reflect interrelationships and constraints among various elements.

System dynamics methodology, characterized by multiple variables and ability to reflect nonlinear, high-order causal feedback relationships [?], can more comprehensively reveal relationships between current conditions and historical status while designing different scenarios to predict and simulate future development trends of various factors. This enables selection of optimal scenarios and factor designs for better regulation of water resource vulnerability in study areas.

The Kekeya ecological project in Aksu Prefecture, Xinjiang, represents an important ecological restoration initiative aimed at improving local ecological conditions, reducing wind-sand disasters, and promoting sustainable development. Since implementation, the project has yielded significant ecological, social, and economic benefits, serving as a model for desertification control through ecological engineering. However, located in an extremely arid inland region of northwest China, the project relies entirely on artificial irrigation for ecological construction. With further socio-economic development, water resource shortages have become increasingly prominent [?]. While the Kekeya afforestation project has played crucial roles in local climate regulation and wind-sand protection, current research on its impacts remains limited to windbreak and sand fixation functions and ecological service values, with scarce attention to water resource vulnerability in the Kekeya region. This study applies fuzzy comprehensive evaluation and system dynamics models to assess and predict water resources in the Kekeya area, aiming to provide insights for green and sustainable water resource development and references for the next phase of the Kekeya afforestation project.

1. Materials and Methods

1.1 Study Area Overview

The Kekeya ecological project area [Figure 1: see original paper] is located on the alluvial terraces in the northeast of Aksu City and Wensu County, Xinjiang, covering approximately 1152.48 km^2. The original topography featured crisscrossing gullies with higher elevation in the north and lower in the south (1071-1450 m). Due to special geographical location and geological conditions, the region suffers from severe soil salinization, poor soil quality, and sparse vegetation. The terrace climate is arid, with a multi-year average temperature of 10.2°C, precipitation of 85.7 mm, and evaporation of 1706.0 mm.

1.2 Data Sources

Required data primarily include meteorological data, water resource data, and socio-economic data. Precipitation data were obtained from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn) with 0.1 mm units and 0.0083333° spatial resolution at monthly temporal resolution. Evaporation data came from observations at Aksu and Wensu stations; since the Kekeya project area lies at the boundary between these two counties, averages of both stations were used. Runoff and water resource data were sourced from the *Aksu Prefecture Water Resources Bulletin*, while socio-economic data came from the *Aksu Statistical Yearbook*, *Aksu National Economic and Social Development Statistical Bulletin (2010-2020)*, and the *Aksu Prefecture National Economic and Social Development 14th Five-Year Plan and 2035 Long-term Goals Outline* at annual time scales. Missing data for some years were interpolated using interpolation methods.

1.3 Methodology

1.3.1 Evaluation Index System Construction Based on actual geographical conditions, socio-economic development status, and understanding of water resource vulnerability concepts and connotations, this study categorized influencing factors into three major groups—natural, anthropogenic, and socio-economic factors [?]—selecting [MATH_4] indicators to construct the Kekeya water resource vulnerability evaluation index system (Table).

1.3.2 Evaluation Index Weight Determination Entropy method and CRITIC method were combined to determine weights, improving result authenticity and accuracy. Specific calculation methods follow literature [?], with final weights obtained by averaging results from both methods.

1.3.3 Fuzzy Comprehensive Evaluation Method Fuzzy evaluation serves as a scientific method for comprehensive evaluation problems [?], transforming indicators into several grades and calculating membership degrees to obtain comprehensive water resource vulnerability scores. Referencing *Surface Water Environmental Quality Standards* [?] and considering the lack of unified grading standards for water resource vulnerability evaluation, this study divided indicator values into [MATH_5] grades using equal intervals between maximum and minimum values as grading criteria (Table). For the [MATH_6] evaluation indicators, [MATH_7] vulnerability grades were assigned values of [MATH_8]. The comprehensive index is calculated as:

$$C = \sum_{i=1}^{n} b_i \cdot v_i$$

where C represents water resource vulnerability value, b_i denotes the mean of each indicator within corresponding vulnerability grades, and v_i represents grade values. Detailed calculations follow literature [**?**].

1.3.4 System Dynamics Model (SD Model) System dynamics originated from systems theory [**?**], most notably capable of handling higher-order, more complex, nonlinear, multiple feedback, and complex time-varying system problems. Consequently, SD models have been early applied to dynamic prediction of water resource vulnerability [**?**]. This study' s SD model workflow for Kekeya water resource vulnerability is illustrated in Figure [Figure 2: see original paper]. Model validation primarily uses 2010-2020 historical data, with relative error absolute value (ARE) calculated as:

$$ARE = \frac{|\hat{Y}_t - Y_t|}{Y_t} \times 100\%$$

where $\hat{Y}_t$ represents simulated data, Y_t represents historical data, and t denotes year.

2. Results

2.1 Comprehensive Water Resource Vulnerability Assessment

Entropy and CRITIC methods calculated indicator weights for the study area' s water resource vulnerability (Table). Subsystem weights from high to low were: socio-economic vulnerability ([MATH_9]), natural vulnerability ([MATH_{10}]), and anthropogenic vulnerability ([MATH_{11}]). For individual indicators, forest coverage rate (X_2) had the highest combined weight of [MATH_{12}], indicating its fluctuation significantly impacts vulnerability index, while per capita domestic water consumption (X_8) had the lowest weight of [MATH_{13}], suggesting minimal impact on regional water resource vulnerability.

Water resource vulnerability assessment results for different Kekeya project implementation stages (1980-2020) show that vulnerability remained in the moderate range (Figure [Figure 3: see original paper]). In 1980 (pre-project implementation), the comprehensive vulnerability index was [MATH_{14}], classified as moderate vulnerability. During 1980-1990, vulnerability showed an upward trend, with the maximum value of [MATH_{15}] in 1985 and minimum of [MATH_{16}] in 1980, averaging [MATH_{17}], indicating increasingly severe water supply-demand contradictions.

From 1990-2010, vulnerability values showed a declining trend, with the maximum of [MATH_{18}] in 1990 and minimum of [MATH_{19}] in 2005, averaging [MATH_{20}]. This decline indicates that Kekeya project implementation alleviated regional water supply-demand contradictions, demonstrating clear protective effects. During 2010-2020, vulnerability averaged [MATH_{21}], remaining moderately vulnerable with a slight upward trend, suggesting that although supply-demand contradictions intensified, they remained less severe than pre-project conditions. The maximum value occurred in 2020 ([MATH_{22}]), while the minimum was in 2010 ([MATH_{23}]).

2.2 SD Model Historical Validation

Using the relative error absolute value formula ([MATH_{24}]), ARE values were calculated for key variables affecting water resource vulnerability: permanent population, GDP, and water demand. All simulation errors remained within [MATH_{25}], indicating the system dynamics model effectively simulates regional water resource vulnerability without significant deviation from actual values, enabling future trend prediction.

2.3 Future Scenario Water Resource Vulnerability Simulation

Four scenarios were designed for analysis and prediction: status-quo development, economy-oriented, resource-conservation, and green-coordination (Table). All subsequent references to "four scenarios" follow this order.

Based on the water resource vulnerability model flowchart (Figure [Figure 2: see original paper]) and scenario descriptions, parameters were set for future development (Table). Under all four scenarios, total population shows annual linear growth, reaching [MATH_{26}] (status-quo), [MATH_{27}] (economy-oriented), [MATH_{28}] (resource-conservation), and [MATH_{29}] (green-coordination) by 2035. Industrial water proportion shows opposite trends, decreasing annually under all scenarios, with the most significant reduction under resource-conservation, followed by green-coordination and status-quo development.

Primary industry output values show exponential growth across all scenarios, reaching [MATH_{30}] (status-quo), [MATH_{31}] (economy-oriented), [MATH_{32}] (resource-conservation), and [MATH_{33}] (green-coordination) by 2035. Tertiary industry output values follow similar exponential patterns, reaching [MATH_{34}], [MATH_{35}], [MATH_{36}], and [MATH_{37}] respectively.

Water resource vulnerability under all four scenarios shows upward trends (Figure [Figure 6: see original paper]), with growth rates from fastest to slowest being: economy-oriented, green-coordination, status-quo, and resource-conservation. Under status-quo development, vulnerability fluctuates upward, transitioning from light to moderate vulnerability by 2035 with a score of [MATH_{38}], indicating increasing instability.

Under economy-oriented development, vulnerability shows more significant fluctuating upward trends, transitioning from moderate to severe vulnerability with an average of [MATH_{39}], suggesting this scenario exacerbates vulnerability compared to status-quo development. Under resource-conservation, vulnerability fluctuates upward from [MATH_{40}] to [MATH_{41}], with the slowest increase, demonstrating this scenario' s significant positive effect on reducing regional vulnerability.

Under green-coordination, vulnerability shows fluctuating upward trends second only to economy-oriented development, reaching maximum [MATH_{42}] and minimum [MATH_{43}] during the prediction period, with values rising from [MATH_{44}] to [MATH_{45}] (13.84% increase), potentially reaching severe vulnerability levels.

3. Discussion

Based on the constructed vulnerability evaluation index system, this study assessed water resources in the Kekeya project area, finding overall upward vulnerability trends consistent with Ning Like et al. [**?**]. Following Ling Hongbo et al. [**?**] and Lin Zhonghua et al. [**?**], current water resource vulnerability research primarily focuses on status-quo analysis with limited future prediction and simulation. System dynamics enables future water resource prediction through different scenario parameter settings, allowing better regulation of water supply-demand contradictions.

Forest coverage rate, with the highest weight, represents a crucial factor affecting water resource vulnerability. Understanding this key driver suggests that continued ecological project construction combined with optimized production technologies can prevent further water pollution. Regarding affected subsystems, water resource vulnerability primarily responds to the socio-economic subsystem, particularly related to water demands from domestic life and industrial production, requiring improved production methods, water-saving technology promotion, and public water conservation guidance.

However, unified standards for water resource vulnerability evaluation index systems remain lacking. This study determined relevant indicators based on local geographical conditions and socio-economic development backgrounds, though future research requires more refined indicator selection.

4. Conclusions

1) Regional water resource vulnerability results from multiple factor interactions. Subsystem weights affecting vulnerability from high to low are: socio-economic subsystem ([MATH_{46}]), natural vulnerability ([MATH_{47}]), and anthropogenic vulnerability ([MATH_{48}]). Among individual indicators, forest coverage rate has the highest weight while per capita domestic water consumption has the lowest.

2) Water resource vulnerability shows clear temporal variation patterns from 1980–2020. Fuzzy comprehensive evaluation reveals consistently moderate vulnerability (Level 3), which may transition to severe vulnerability under current trends.
3) All four scenarios show upward vulnerability trends, indicating deteriorating water resource conditions. The ascending order of growth rates is: resource-conservation, status-quo, green-coordination, and economy-oriented. The resource-conservation scenario demonstrates positive effects on mitigating vulnerability, suggesting future development should balance economic growth with ecological construction to achieve high-quality water resource development.

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