Postprint: SD-based Study on Water Resources Supply-Demand Balance Schemes for Bayannur City

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Abstract

With socioeconomic development, the contradiction between water supply and demand has become increasingly prominent in a growing number of cities, and exploring urban water supply-demand balance to achieve sustainable economic development has become a critical issue in contemporary urban development planning. Based on the current status of local social development, four water supply-demand balance scenarios were designed using the system dynamics method: steady-state equilibrium, economic growth, efficient utilization, and comprehensive coordination, to analyze the water supply-demand situation in Bayannur City from 2016 to 2035. Simulation results indicate that: (1) If Bayannur City adopts the steady-state equilibrium and economic growth scenarios, it is expected to face the risk of water supply being unable to meet demand during 2018–2027. (2) However, adopting the efficient utilization and comprehensive coordination scenarios can effectively ameliorate this situation. (3) The comprehensive coordination scenario not only benefits local economic development, but also effectively reduces water demand in agriculture, secondary industry, and tertiary industry, greatly alleviating water supply-demand pressure, and can serve as a preferred option for future water resource development and utilization in the region.

Full Text

Preamble

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Water Resources Supply and Demand Balance Scheme of Bayannur City Based on SD Model

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Abstract: With socioeconomic development, the contradiction between urban water supply and demand has become increasingly prominent. Exploring urban water resources supply-demand balance to achieve sustainable economic development has emerged as a critical issue in urban planning. Based on local social development conditions, four water resource supply-demand balance schemes were designed using system dynamics: steady-state equilibrium, economic growth, efficient utilization, and comprehensive coordination. The water resources supply-demand situation in Bayannur City from 2016 to 2035 was analyzed. Simulation results indicate: (1) If Bayannur City adopts the steady-state equilibrium or economic growth schemes, it will face the risk of water supply failing to meet demand during 2018–2027. (2) The efficient utilization and comprehensive coordination schemes can effectively improve this situation. (3) The comprehensive coordination scheme not only promotes local economic development but also effectively reduces water demand in agriculture, secondary industry, and tertiary industry, greatly alleviating water supply-demand pressure. This scheme can serve as the optimal approach for future water resource development and utilization.

Keywords: system dynamics; water supply and demand; water balance; Bayannur City

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1 Study Area Overview

Bayannur City is located in western Inner Mongolia Autonomous Region, China (40°13 -42°28 N, 105°12 -109°53 E), with a total area of approximately 6.51×10^{4} km^2. Situated in a temperate continental monsoon climate zone, the city features four distinct seasons with an average annual temperature of 7°C. The region enjoys abundant sunlight and high heat storage, but experiences dry conditions with low rainfall and high evaporation, with average annual precipitation of only 188 mm. By the end of 2022, the city faced severe soil erosion, affecting 46,770.56 km^2. The population reached 1,084.55$\times10^{4}$ people with an urbanization rate of 60.89%. The gross domestic product was 151.76$\times10^{9}$ yuan, representing a year-on-year increase of 8.1% at comparable prices.

Bayannur City possesses complex geological structures and variable total water resources. According to statistical data, the city’ s average annual water resources during 2016-2022 totaled 55.504$\times10^{8}$ m^{3}, comprising surface water (20.928$\times10^{8}$ m^{3}) and groundwater (47.135$\times10^{8}$ m^{3}), with double-counted water volume of 53.458$\times10^{8}$ m^{3}. However, per capita water availability is only 600 m^{3}, approximately 27% of the national average. Bayannur’ s water resources face severe structural shortages, challenging sustainable utilization. To ensure long-term supply-demand balance, this study employs Vensim software to construct a system dynamics model tailored to Bayannur’ s water resources conditions. Scenario analysis is then applied to examine potential water resource issues during socioeconomic development, providing systematic evaluation of supply-demand balance under various scenarios. This research holds significant importance for achieving coordinated and sustainable development of Bayannur’ s economy and water resources.

2 Model Construction

2.1 Model Boundary Determination

The system dynamics model encompasses the entire Bayannur City region, with a simulation timeframe of 2016–2035. The year 2016 serves as the baseline year, 2016–2022 as the data collection period, and 2023–2035 as the forecast period. The year 2020, being closest to the current situation, was selected for historical validation.

2.2 Model Structure

The Bayannur City water resources supply-demand balance model consists primarily of two main systems: water supply and water demand, each influenced by various subsystems (Fig. 1). The water supply system comprises five subsystems: groundwater supply, surface water supply, water storage engineering supply, urban reclaimed water supply, and secondary industry water reuse. Groundwater supply depends on groundwater resources and utilization rate; surface water supply depends on surface water resources and utilization rate; urban reclaimed water supply depends on sewage treatment rate and discharge volumes from urban domestic and secondary industry sources; secondary industry water reuse depends on water demand and reuse rate.

The water demand system comprises five subsystems: agricultural, ecological, domestic, secondary industry, and tertiary industry demands. Agricultural demand includes fishery, irrigation, and livestock components; ecological demand comprises change rate and change volume; domestic demand includes urban and rural residential components; secondary industry demand depends on output value and unit water consumption; tertiary industry demand depends on output value and unit water consumption. These variables interconnect quantitatively and qualitatively to form a complex integrated system (Fig. 2).

2.3 Data Sources and Model Equations

Data were obtained from the *Bayannur City Statistical Yearbook (2017–2023)*, *Bayannur City Water Resources Bulletin (2017–2022)*, *Inner Mongolia Autonomous Region Soil and Water Conservation Bulletin (2017–2022)*, *Bayannur City "14th Five-Year" Water Security Guarantee Plan*, *Bayannur City National Economic and Social Development 14th Five-Year Plan and 2035 Vision Outline*, *Bayannur City "14th Five-Year" Climate Change Response Plan*, *Bayannur City Wetland Protection Plan*, and *Inner Mongolia Autonomous Region Industry Water Quota (DB15/T 385-2020)*. Some variable values were derived from simple statistical calculations of multiple initial values.

Although the model involves numerous variables, their relationships are relatively clear and simple. Key variable equations are listed below:

1) **Water Resources Supply-Demand Ratio** = Water Resources Supply Volume / Water Resources Demand Volume
2) **Agricultural Water Demand** = Irrigation Water Demand + Fishery Water Demand + Livestock Water Demand
3) **Secondary Industry Water Demand** = Secondary Industry Output Value × Unit Secondary Industry Water Consumption
4) **Tertiary Industry Water Demand** = Tertiary Industry Output Value × Unit Tertiary Industry Water Consumption

2.4 Model Validation

Vensim' s built-in "Units Check" module enables rapid consistency verification. Since variable units are independent and the software cannot perform logical calculations with mismatched units, standardization was required first. When using the time implicit function (), an additional time unit "fraction/year" with a function value of 1 was added to resolve unit inconsistencies. After "Units Check" validation, all model units were unified.

Absolute Relative Error (ARE) testing validates consistency between simulation results and actual data. If ARE < 10%, results fall within the allowable error range, indicating close alignment between simulated and historical results. The ARE formula is:

$$ARE = \frac{|Y_t - Y_t'|}{Y_t} \times 100\%$$

where Y_t' is the simulated data for year t and Y_t is the historical data for year t.

The 2020–2022 simulation results for major variables show ARE values meeting requirements (Table 1), indicating the model adequately reflects reality and can be used for subsequent simulations.

Table 1 Summary of simulation results of main variables in Bayannur City from 2020 to 2022

Variable	2020	2021	2022	ARE (%)
Agricultural Water Demand	2.689×10^{8} m^3	2.572×10^{8} m^3	2.489×10^{8} m^3	3.76
Secondary Industry Water Demand	12.572×10^{8} m^3	12.489×10^{8} m^3	12.376×10^{8} m^3	2.01
Tertiary Industry Water Demand	8.045×10^{8} m^3	8.123×10^{8} m^3	8.208×10^{8} m^3	2.89

2.5 Sensitivity Analysis

Sensitivity analysis is an important tool in water resources management, helping understand and predict how variable changes affect the water supply-demand ratio, thereby identifying key influencing factors. During analysis, only one variable was adjusted at a time while others remained constant. Based on Bayannur' s characteristics, 11 variables were selected, all of which affect model results to varying degrees and can be used for subsequent scheme design.

The sensitivity formula is:

$$S_i = \frac{\Delta Y_i / Y_i}{\Delta X_i / X_i}$$

where S_i is the sensitivity of variable i, ΔY_i is the change in supply-demand ratio caused by variable i, Y_i is the baseline supply-demand ratio, ΔX_i is the change range of variable i, and X_i is the baseline value of variable i.

A positive sensitivity indicates that increasing the variable value raises the supply-demand ratio, while negative sensitivity indicates the opposite. Larger absolute sensitivity values indicate greater impact on the water supply-demand ratio. Results show that unit water consumption of secondary and tertiary industries has high sensitivity (91.5% and 74.9%, respectively). By 2035, unit secondary industry water consumption decreases to 9.44×10^{-4} m^3/yuan (a 91.5% reduction) and unit tertiary industry water consumption decreases to 0.681×10^{-4} m^3/yuan (a 74.9% reduction), significantly reducing industrial water demand and improving the supply-demand ratio.

Irrigation water quota is also highly sensitive (sensitivity = 6.0). As Bayannur is an agriculture-dominated city where agricultural water demand accounts for 60.89% of total demand, reducing irrigation quotas substantially decreases agricultural water demand, thereby improving the supply-demand ratio. Other indicators show relatively low sensitivity (Table 2).

Table 2 Statistical table of variable sensitivity analysis results

Variable	Baseline Value	Change Range	Baseline Supply-Demand Ratio	Sensitivity
Secondary Industry Output Growth Rate	6.972%	0%–6.972%	1.089	0.045
Tertiary Industry Output Growth Rate	3.76$×10^{-4}$	-15.788%–0%	1.089	0.038
Unit Secondary Industry Water Consumption	$3 \cdot yuan^{-1}$	-2.816$×10^{-4}-0 [illegible] 1}$	-7.364$×10^{-5} [illegible] 1}$	-1–0 [illegible] {{3}·person^{-
Urban Domestic Water Quota	$3 \cdot person^{-1}$	-1–0	1.089	0.018
Large Livestock Water Quota	$3 \cdot head^{-1}$	-1.095–0	1.089	0.067
Small Livestock Water Quota	$3 \cdot head^{-1}$	-0.103–0	1.089	0.045
Irrigation Water Quota	2.01 $m^3 \cdot mu^{-1}$	-0.5–0	1.089	6.000

3 Scenario Analysis

3.1 Scenario Design

Considering Bayannur' s future socioeconomic development, four scenarios were selected: steady-state equilibrium, economic growth, efficient utilization, and comprehensive coordination. Based on the control variable principle, each scenario employs different variable settings tailored to Bayannur' s water supply-demand development conditions. Variable settings were determined through reference to statistical source documents and sensitivity analysis results (Table 2).

Scenario 1: Steady-State Equilibrium maintains current policies without adjusting any variable values.

Scenario 2: Economic Growth builds upon Scenario 1 by increasing secondary industry output growth rate by 6.972% annually and tertiary industry output growth rate by 3.76% annually before 2025, with other variables consistent with Scenario 1.

Scenario 3: Efficient Utilization builds upon Scenario 1 by reducing unit secondary industry water consumption by 2.816$\times10^{-4}$ m^3/yuan annually and unit tertiary industry water consumption by 7.364$\times10^{-5}$ m^3/yuan annually. In the demand system, urban domestic water quota decreases to 54.605 $m^3 \cdot person^{-1}$, rural domestic water quota to 20.805 $m^3 \cdot person^{-1}$, large livestock water quota to 100.095 $m^3 \cdot head^{-1}$, small livestock water quota to 1.907 $m^3 \cdot head^{-1}$, and irrigation water quota by 0.5 $m^3 \cdot mu^{-1}$, with other variables consistent with Scenario 1.

Scenario 4: Comprehensive Coordination integrates all variable adjustments from both Scenario 2 and Scenario 3 upon the steady-state equilibrium foundation, with unadjusted variables consistent with Scenario 1.

3.2 Scenario Analysis Results

Agricultural Water Demand: Simulation results show Scenarios 3 and 4 have significantly lower agricultural water demand than Scenario 1 (Fig. 3). In the peak demand year of 2027, Scenarios 3 and 4 save approximately 2.0$\times10^{8}$ m^3 compared to Scenario 1, and by 2035, they remain about 2.0$\times10^{8}$ m^3 lower. However, Scenario 2' s adjustment of secondary and tertiary industry growth rates has minimal impact on agricultural water demand, so its results closely match Scenario 1. In conclusion, rationally reducing livestock water quotas and irrigation water quotas can effectively decrease agricultural water demand pressure.

Secondary Industry Water Demand: Scenario 2' s secondary industry water demand exceeds Scenario 1 due to its 6.972% annual increase in secondary industry output growth rate, leading to higher output value and thus greater water demand while maintaining constant unit water consumption. On average, Scenario 2 increases secondary industry water demand by 4.8×10^{8} m^3. Scenario 3' s results are significantly lower than Scenario 1; by 2035, reducing unit secondary industry water consumption lowers demand by 12.376×10^{8} m^3 compared to Scenario 1, demonstrating that reducing unit water consumption effectively decreases secondary industry water demand.

Notably, Scenario 4 falls below Scenario 1 before 2025 but exceeds it after 2030, as it combines both increased output growth and reduced unit water consumption. Specifically, before 2025, reducing unit water consumption lowers demand by an average of 11.2×10^{8} m^3, while increasing output raises demand by an average of 4.8×10^{8} m^3, resulting in net reduction. After 2030, the output increase effect (average $+12.5\times10^{8}$ m^3) surpasses the unit consumption reduction effect (average -11.2×10^{8} m^3), causing Scenario 4 to exceed Scenario 1. In summary, increasing secondary industry output growth raises output value but does not reduce water demand, whereas reducing unit water consumption effectively decreases secondary industry water demand.

Tertiary Industry Water Demand: Scenario 2 exceeds Scenario 1, Scenario 3 is generally lower than Scenario 1, and Scenario 4 is lower than Scenario 1 before 2025 but higher after 2030 (Fig. 5). In Scenario 2, increasing tertiary industry output growth rate raises output value, and with constant unit water consumption, increases water demand. In Scenario 3, reducing unit tertiary industry water consumption decreases demand while maintaining output value. Scenario 4 combines both adjustments. Before 2025, reducing unit consumption lowers demand by an average of 2.5×10^{8} m^3, while increasing output raises demand by an average of 1.8×10^{8} m^3, resulting in net reduction. After 2030, the output increase effect (average $+3.2\times10^{8}$ m^3) exceeds the unit consumption reduction effect (average -2.5×10^{8} m^3), causing Scenario 4 to surpass Scenario 1. In conclusion, increasing tertiary industry output growth and reducing output decline rate raises output value and increases water demand, while reducing unit water consumption decreases tertiary industry water demand.

Water Resources Supply-Demand Ratio: This ratio directly indicates water scarcity or surplus (Fig. 6). Scenario 1 shows ratios below 1 during 2018–2027, reaching a minimum of 0.89, indicating severe water scarcity challenges. Scenario 2' s adjustments have minimal impact, failing to resolve the 2018–2027 supply-demand gap, suggesting secondary and tertiary industry water demand are not key adjustment targets.

Scenario 3 maintains ratios above 1 throughout the simulation period. By reducing unit industrial water consumption, domestic water quotas, livestock water quotas, and irrigation water quotas, this scenario effectively alleviates water supply-demand conflicts. Scenario 4, integrating adjustments from Scenarios 2 and 3, achieves ratios above 1 across all years while promoting economic development. Therefore, improving industrial water use efficiency and reducing water quotas can effectively achieve high-efficiency urban water resource utilization. The comprehensive coordination approach of Scenario 4 serves as the optimal reference scheme for Bayannur' s water resources development from 2023 to 2035.

4 Discussion

This study combines Bayannur' s actual water resources development and utilization conditions to construct a system dynamics model. While the model includes numerous variables, other water resources data should be incorporated to improve completeness. Additionally, as simulation time extends, deviations between simulated and actual data will gradually emerge, requiring future model equation refitting and validation. The study only presents four scenarios, but other perspectives such as population growth, sewage treatment, and technological development could also be considered to adjust corresponding variables for water supply-demand balance analysis.

5 Conclusions

This study constructed a water resources supply-demand balance model for Bayannur City using system dynamics, designing four scenarios based on local development conditions and water resources utilization status. Main conclusions are:

1) If Bayannur City follows the steady-state equilibrium development model, it will face severe water shortage during 2018–2027, posing serious challenges to healthy socioeconomic development. Adjustments based on the economic growth model alone cannot resolve water supply-demand contradictions.

2) The efficient utilization development model focuses on comprehensively adjusting water quotas across sectors, including unit secondary and tertiary industry water consumption, domestic water quotas, livestock water quotas, and irrigation water quotas. This approach achieves water conservation and high-efficiency utilization, effectively solving water shortage problems.

3) The comprehensive coordination model integrates variable adjustment strategies from all three previous scenarios, promoting economic development while ensuring supply-demand ratios exceed 1.0. Rationally reducing livestock water quotas and irrigation water quotas effectively decreases agricultural water demand pressure. Increasing secondary industry output growth raises output value without reducing water demand, while reducing unit secondary industry water consumption decreases demand. Increasing tertiary industry output growth raises output value and increases water demand, while reducing unit tertiary industry water consumption decreases demand. Therefore, the comprehensive coordination model is considered the optimal scheme for local water resources development, providing a reference for future decision-making.

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Note: Figure translations are in progress. See original paper for figures.