Dynamic Simulation of the Kubuqi Desert Socio-Economic System and Its Applications Postprint

Authors: Lu Fangyuan

Date: 2022-09-26T00:00:00+00:00

Abstract

Based on the integration of water resources and socioeconomic data for the Kubuqi Desert region from 1999–2019, a system dynamics model was employed to simulate the water resources-socioeconomic-ecological system of the Kubuqi Desert, analyzing the spatiotemporal variation characteristics of socioeconomic development and water utilization in the Kubuqi Desert from 1999–2019. Simultaneously, a multi-scenario parameter regulation model was established to comprehensively simulate changes in total water demand in the region under the influence of different parameters. The results indicate: (1) Under the scenario of no additional interventions (conventional development pattern), total water demand will reach 11.90$\times10^{8}$ m^3 by 2035, exceeding the total water supply capacity of the region and resulting in an overloaded state. (2) After regulation through different parameter schemes, maintaining the region' s planting area unchanged and current irrigation methods unchanged, water demand is 9.76$\times10^{8}$ m^3; with drip irrigation coverage reaching over 50% (S3), the region will be in a sustainable state, and water demand decreases to 7.80$\times10^{8}$ m^3, alleviating the water supply-demand contradiction in the desert. It is recommended that in the process of ecological restoration in the Kubuqi Desert, emphasis should be placed on promoting water-saving drip irrigation, rationally utilizing local water resources, and pursuing sustainable ecological development.

Full Text

Dynamic Simulation and Application of the Socio-Economic System in the Kubuqi Desert

LU Fangyuan[1,2], JIA Debin[1,2], GAO Ruizhong[1,2], SU Wenxu[1,2], ZHAO Hang[1,2], YANG Li' na[1,2]

[1]School of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot 010018, Inner Mongolia, China
[2]Key Laboratory of Water Resources Protection and Utilization of Inner Mongolia Autonomous Region, Hohhot 010010, Inner Mongolia, China

Abstract

Based on integrated water resources and socio-economic data for the Kubuqi Desert region from 1999 to 2019, this study employs a system dynamics model to simulate the water resource-ecosystem-society system and analyze spatiotemporal variation characteristics of socio-economic development and water consumption in the Kubuqi Desert from 2000 to 2035. A multi-scenario parameter regulation model was established to comprehensively simulate changes in total water demand under different parameter influences. The results indicate that: (1) Under a conventional development scenario without additional measures, total water demand in 2035 will reach 11.90×10^{8} m^3, exceeding the regional water supply and indicating an overloaded state. (2) After adjusting parameters through different schemes while maintaining constant planting area and current irrigation methods, water demand is 9.76×10^{8} m^3. (3) When drip irrigation penetration exceeds 50% (S3), the region enters a sustainable state, with water demand decreasing to 7.80×10^{8} m^3, which alleviates the water supply-demand contradiction. The study recommends prioritizing the promotion of water-saving drip irrigation, rational utilization of local water resources, and sustainable ecological development during ecological restoration of the Kubuqi Desert.

Keywords: water resources carrying capacity; system dynamics; desert; arid area; Kubuqi Desert

Introduction

Desertification represents one of the greatest challenges in global ecological security governance, causing severe ecological impacts and significant socio-economic consequences. As a typical and particularly damaging form of desertification, sandy desertification has attracted increasing attention in recent years. Proper coordination of various aspects of desertification control is therefore critical. The Yellow River basin serves as an important ecological protection belt and economic development zone in China, where ecological protection and high-quality development have become national strategic priorities, though the region remains ecologically fragile. This study focuses on the Kubuqi Desert as a typical ecologically fragile desertification area, using system dynamics modeling to analyze spatiotemporal characteristics of socio-economic water use and dynamically simulate water resources carrying status under different parameter scenarios, providing strong support for ecological improvement and sustainable socio-economic development in the Kubuqi Desert.

Water resources carrying capacity is a crucial indicator for assessing regional water resource status. Correct evaluation is both a prerequisite for rational water allocation and a necessary condition for sustainable water resource utilization. Early research methods for water resources carrying capacity tended toward static approaches, such as Analytic Hierarchy Process and fuzzy evaluation methods, which often overlooked relationships within the water resource system itself. Subsequent research gradually incorporated dynamic methods like system dynamics and scenario planning, providing more comprehensive consideration of water resources carrying capacity within the overall system. The advantage of system dynamics lies in its ability to analyze multi-level, nonlinear, complex system problems. As water resources carrying capacity involves numerous influencing factors including socio-economics, water resources, and ecological environment, it requires research methods capable of handling multiple complex issues. System dynamics has become an important method for dynamic prediction research on water resources carrying capacity. However, when using system dynamics models to simulate water resources carrying capacity, focusing only on water supply-demand relationships may neglect impacts from socio-economic development and population variables. Therefore, recent studies have gradually considered interactions between socio-economics, ecological environment, food-energy systems, and the water resource system.

1.1 Study Area Overview

The Kubuqi Desert (39°30 28 ~40°41 28 N, 107°18 54 ~111°30 46 E) is located on the northern edge of the Ordos Plateau south of the Yellow River, with a total length of approximately 400 km, width of 30–80 km, and total area of about 1.39$×10^{4}$ km^2. The region encompasses three banners: Hanggin, Jungar, and Dalad, primarily cultivating corn, sunflower, and wheat. The three banners' industrial structure adjusted from 9.5:53:37.5 to 36.8:39.7:23.4, with a GDP of 29.94$×10^{8}$ yuan. The region has an average annual precipitation of 200–400 mm (approximately 659.17$×10^{8}$ m^3) and average annual evaporation of 2162 mm, with unevenly distributed precipitation decreasing from northwest to southeast. Total water resources are scarce, with agricultural water demand dominating the regional water use structure. Due to insufficient water resources support and excessive development, the Kubuqi Desert has experienced lake shrinkage and oasis land desertification, making it a key area for studying complex water resources carrying conditions. Limited by data availability, this study covers only the administrative regions of the Kubuqi Desert [Figure 1: see original paper].

1.2 Data Sources

The water resources carrying status simulation model comprises variables from population, economic, water resource, and water pollution discharge subsystems, providing comprehensive understanding of regional water resources and socio-ecological development. The key to constructing this simulation model lies in establishing connections among subsystems to reveal evolution patterns of carrying status from a mechanistic perspective. Data include socio-economic and meteorological-hydrological data from 1999 to 2019. All statistics are compiled at the banner level, with sources including the *Ordos Statistical Yearbook*, *Ordos Water Resources Bulletin*, *National Second Pollution Source Census Domestic Source Pollution Generation and Discharge Coefficient Handbook*, *14th Five-Year Plan for National Economic and Social Development of Inner Mongolia Autonomous Region and 2035 Long-Range Objectives Outline*, *Inner Mongolia Autonomous Region Water Use Quota*, and *Ordos City Master Plan (2011-2035)*.

1.3 Methods

1.3.1 Key Driver Indicator Identification

Pearson correlation analysis and principal component analysis were used for key indicator identification. Pearson correlation analysis discriminates relationships between two variables, where values of 0.4–0.7 indicate close relationships, and values above 0.7 indicate very close relationships. Principal component analysis reduces dimensionality through orthogonal transformation to examine correlations among multiple variables.

1.3.2 System Dynamics Simulation Model

System dynamics operates by mastering feedback relationships among system indicators to conduct dynamic and holistic system analysis. This study used system dynamics to construct a water resources carrying status simulation model for each banner within the Kubuqi Desert region, then spatially coupled these banner-level models through integrated modeling to construct a regional carrying status simulation model for the entire Kubuqi Desert.

The Kubuqi Desert water supply system consists of three components: surface water supply, groundwater supply, and reclaimed water supply (wastewater reuse), where surface water includes reservoir storage and diverted water. The social water cycle process in the study area is illustrated in [Figure 2: see original paper]. The water resources carrying status simulation model comprises population, economic, water resources, and water pollution discharge subsystems. The model includes 5 state variables, 42 auxiliary variables, 9 rate variables, and 16 constants, with main parameters and equations shown in .

1.3.3 Data and Parameter Processing

Main parameters in the model were determined through conventional mathematical statistical methods, with some parameters referencing Ordos region values. Key equations include: - Population growth = INTEG(population growth rate × population initial value) - Industrial water use = INTEG(industrial output growth × unit industrial output water consumption / 1000) - Planting water use = INTEG(irrigation area growth × per-mu irrigation quota / 1000)

Total water use and domestic, industrial, and agricultural water consumption for each banner from 1999 to 2019 were combined with population, industrial output value, and irrigation area to calculate residential water use quotas, industrial water use per 10,000 yuan output value, and per-mu irrigation water use. Calculated residential water use quotas are approximately 85-95 $\mathrm{L} \cdot \mathrm{d}^{-1}$ per person, with minimal variation among banners. The domestic water system incorporates population growth rate and urbanization rate to ensure reasonable calculation of domestic water consumption. Industrial water use per 10,000 yuan of added value was calculated from the ratio of industrial water use to industrial output value, distinguishing industrial output growth rates and unit industrial output water consumption among banners. The wastewater centralized treatment rate is 65%-95%, with industrial and domestic sewage discharge coefficients referencing handbook and historical data at 40%-60%.

2.1 Socio-Economic Development Analysis in the Kubuqi Desert

From 1999 to 2019, the population of the Kubuqi Desert region showed a continuous upward trend, increasing from 72.03×10^{4} to 84.56×10^{4} people. Jungar, Hanggin, and Dalad banners account for 39.1%, 43.9%, and 17.0% of the Kubuqi Desert population, respectively. The region is predominantly rural, with rural population proportions in each banner exceeding 75%-85%. The second and third industries showed gradual growth, with the secondary industry in Dalad and Jungar banners growing fastest, while Hanggin banner showed consistent growth rates in both secondary and tertiary industries.

2.2 Water Resources Status Analysis in the Kubuqi Desert

From 1999 to 2019, water supply in the Kubuqi Desert region was 8.50×10^{8} m^3, while actual demand reached 9.18×10^{8} m^3, creating a water deficit of 0.68×10^{8} m^3 and highlighting prominent water supply-demand conflicts. Agricultural irrigation primarily relies on groundwater, accounting for 73.67% of total water use. To alleviate drought conditions, an ecological water diversion project was implemented in 2014, diverting Yellow River floodwater during ice-jam periods into low-lying areas on the northern edge of the Kubuqi Desert. This continuous annual diversion has created numerous lake wetlands, forming a water ecological management zone that alleviates water limitations on vegetation growth and greatly improves the northern edge environment. While this diversion relieves flood pressure on the Yellow River and transforms flood hazards into benefits, water scarcity remains a critical issue for desert management. After implementing the water ecological comprehensive management project, cumulative water diversion reached 2.94×10^{8} m^3.

Due to intensified ecological restoration and water-saving construction, agricultural water use efficiency has improved significantly, with the farmland irrigation water utilization coefficient increasing from 0.4 to 0.65. However, high-efficiency water-saving technology penetration remains low, dominated by canal water-saving with room for improvement. From 1999 to 2019, crop planting structure changed, with corn and sunflower becoming main crops. Planting area in Jungar banner decreased from 30.07$×10^{4}$ mu to 19.49$×10^{4}$ mu in 2005 due to local government policies returning farmland to forest and grassland, then gradually recovered after 2010. Dalad and Hanggin banners showed similar trends.

Pearson correlation analysis, grey correlation analysis, and principal component analysis identified key water use impact indicators. Results show that within available water indicators, surface water resources most significantly affect available water volume, while among load indicators, agricultural water use and its driving factors have the greatest impact on water consumption [Figure 3: see original paper].

3.1 Current Water Resources System Simulation in the Kubuqi Desert

3.1.1 Model Validation

System dynamics model validation aims to determine whether the model accurately and reasonably reflects system characteristics and changes. Historical validation compares simulation results with actual data to verify model effectiveness. When relative error between simulated and actual data is within acceptable limits, the model is considered valid. Due to numerous variables, selected validation indicators include agricultural population, industrial water use, effective irrigation area, forestry-animal husbandry-fishery-livestock water demand, and total water consumption. Validation results [Figure 4: see original paper] show that while Dalad banner' s forestry-animal husbandry-fishery-livestock water demand shows relatively larger absolute relative error, most points remain within acceptable bounds, with other variables' absolute relative errors below 10% and most below 5%. Overall, model fitting errors are within allowable ranges, indicating good model performance.

3.1.2 Socio-Economic Water Resources System Structure

Through system structure analysis, internal positive and negative feedback relationships among key variables were identified to establish regional causal feedback diagrams. The system dynamics model for socio-economic water use in the Kubuqi Desert administrative region includes domestic, industrial, agricultural, water supply, and pollution discharge subsystems. Based on banner-level carrying status flow diagrams, the regional socio-economic water use system model [Figure 5: see original paper] was constructed to ensure completeness and rationality. The model incorporates diverted water into the water supply system and uses water shortage coefficients to reflect regional water scarcity. Key driving indicators for water resources carrying status are shown in .

3.1.3 Carrying Status Prediction Under Conventional Development Mode

Conventional development mode maintains all initial variable parameters in the water resources carrying capacity model without change, following current development trends to analyze water resources carrying capacity changes. Simulation results show that under conventional development, Dalad, Jungar, and Hanggin banners will all be in overload status by 2035 (water shortage index > 0.2). In 2020, Jungar banner was in a critical carrying state, while Hanggin banner’ s carrying status was slightly better than Dalad banner’ s, primarily because the Yellow River diversion project utilizes Hanggin banner’ s unique terrain to divert ice-jam floodwater.

Predicted trend curves [Figure 6: see original paper] clearly show that industrial water demand, farmland irrigation water demand, and forestry-animal husbandry-fishery-livestock water demand all exhibit continuous growth trends, with irrigation water demand growth rate exceeding other indicators. Total water demand shows an upward trend while water supply remains constant, highlighting prominent supply-demand contradictions under conventional development mode. If current trends continue, water resources carrying capacity will remain in an overloaded state.

3.2 Scenario Design and Simulation

3.2.1 Regulation Scenario Design

Domestic water demand parameter regulation references the *Inner Mongolia Autonomous Region Industry Water Use Quota*, setting urban and rural per capita domestic water demand quotas at 150 $L \cdot d^{-1}$ and 101.73 $L \cdot d^{-1}$, respectively, by 2035. Given that water use in the Kubuqi Desert region is dominated by farmland irrigation, primarily affected by irrigation area, irrigation method, and per-mu irrigation quota, agricultural water use efficiency management should be strengthened to improve irrigation guarantee rates and reduce water waste.

According to the *Ordos City National Economic and Social Development 14th Five-Year Plan Outline* and *Ordos City Government Work Report*, population will grow to 101.73$×10^{4}$ by 2035, with GDP increasing by 20.3%. Simulation results show that industrial and domestic water demands exhibit continuous growth trends, making water efficiency improvements and high-efficiency water-saving measures essential for reducing growth rates. As agriculture is the primary water use sector, enhanced water efficiency management is critical for alleviating regional water stress.

3.2.2 Different Scenario Simulation Results

Four scenarios (S1–S4) were designed based on policy documents, assuming constant crop planting area across the three banners while varying irrigation methods and drip irrigation penetration rates (drip irrigation uses 50% of sprinkler irrigation water) .

Simulation results [Figure 7: see original paper] show: - **S1 (Baseline):** Maintaining current irrigation methods yields a 2035 water demand of 9.76$\times10^{8}$ m^3, indicating severe water supply-demand imbalance. - **S2–S4:** With drip irrigation penetration rates of 30%, 50%, and 70%, total water demands are 8.73$\times10^{8}$ m^3, 7.80$\times10^{8}$ m^3, and 6.87$\times10^{8}$ m^3, respectively.

When drip irrigation penetration exceeds 50% (S3), water demand falls below supply, achieving a sustainable state. Results demonstrate that higher drip irrigation penetration leads to lower irrigation water demand and consequently lower total socio-economic water demand. Promoting drip irrigation in Dalad banner, which has large crop planting areas, yields significant water savings—saving 3.38$\times10^{8}$ m^3 under 70% drip irrigation penetration.

In summary, while measures like returning farmland to forest remain environmental priorities, relying solely on water-saving effectiveness is insufficient. Future research should focus on high-efficiency water resource utilization and integrated water-energy-food management systems.

4 Conclusion

Based on system dynamics simulation of the current water resources system and future scenarios, key findings include:

1. During 1999–2019, socio-economic water demand grew substantially (increasing by 73.67%), with agricultural water use and its driving indicators significantly affecting regional available water volume. Agricultural water proportion gradually decreased, while domestic and industrial water proportions increased.

2. Under conventional development mode simulation through 2035, the study area' s water resources carrying capacity will be in an overloaded state, with total water demand reaching 11.90$\times10^{8}$ m^3. By 2035, Dalad and Hanggin banners will be overloaded (water shortage index > 0.2), while Jungar banner will be in a critical carrying state.

3. According to scenario predictions (S2–S4), when drip irrigation penetration is controlled above 50%, the region achieves a sustainable state with water demand of 7.80$\times10^{8}$ m^3. This demonstrates that controlling water demand increase in the Kubuqi Desert depends primarily on reducing agricultural water use through enhanced agricultural water-saving measures, thereby achieving sustainable socio-economic development and effectively alleviating the desert water resources crisis.

References

[1] Wang Rui. Evaluation of ecological benefit of combating desertification in east edge of Hobq Desert [J]. Bulletin of Soil and Water Conservation, 2018,

38(5): 174-179, 188.

[2] Wang Rui, Yang Guojing. Coupling analysis of eco-economic system for ecological management in the Hobq Desert[J]. Arid Land Geography, 2020, 43(5): 1391-1400.

[3] Yu Fawen, Fang Lan. Issues regarding the ecological protection and high quality development of Yellow River basin[J]. China Soft Science, 2020(6): 85-95.

[4] Huang Changshuo, Geng Leihua, Yan Bing, et al. Dynamic prediction and regulation of water resource carrying capacity: A case study on the Yellow River basin[J]. Advances in Water Science, 2021, 32(1): 59-67.

[5] Shi Yafeng, Qu Yaoguang. The Carrying Capacity of Water Resources and Its Reasonable Use of Urumqi River [M]. Beijing: Science Press, 1992: 94-111.

[6] Lyu Yihe, Fu Wei, Li Ting, et al. Progress and prospects of research on integrated carrying capacity of regional resources and environment[J]. Progress in Geography, 2018, 37(1): 130-138.

[7] Zhu Wei, Zhou Hongfei, Li Lanhai, et al. Evaluation on carrying capacity of agricultural water and land resources and identification of affecting factors in Kazakhstan[J]. Arid Zone Research, 2020, 37(1): 254-263.

[8] Liu Shuang, Bai Jie, Luo Geping, et al. Analysis and prediction of socio-economic water use in the Aral Sea Basin[J]. Acta Geographica Sinica, 2021, 76(5): 1257-1273.

[9] Jin Juliang, Dong Tao, Li Jianqiang, et al. Water resources carrying capacity evaluation method under different carrying standards[J]. Advances in Water Science, 2018, 29(1): 31-39.

[10] Wang Jianhua, Jiang Dachuan, Xiao Weihua, et al. Assessment method of water resources carrying capacity based on dynamic trial calculation and feedback: A case study on the Yihe River (Linyi section) [J]. Journal of Hydraulic Engineering, 2016, 47(6): 724-732.

[11] Feng Zhiming, Bo Yansong, Yang Yanzhao, Yan Huimin, et al. A review of resources and environment carrying capacity research since the 20th Century: From theory to practice[J]. Resources Science, 2017, 39(3): 379-395.

[12] Tian Jing, Guo Shenglian, Deng Lele, et al. Adaptive optimal allocation of water resources response to future water availability and water demand in the Han River basin, China[J]. Scientific Reports, 2021, 11(1): 7879.

[13] Qu Xiuqi, Liu Miao, Li Chunlin, et al. Evaluation and prediction of the comprehensive carrying capacity in the Bohai Ring region[J]. Chinese Journal of Soil Science, 2020, 51(3): 552-560.

[14] Guo Weihong, Huang Junchang, Zhang Erchao. Simulation study of water resource carrying capacity in Henan Province based on SD model[J]. Journal of

Henan Agricultural University, 2020, 54(4): 689-697.

[15] Zhai Chenyang, Wang Shengyun. Spatio-temporal difference evolution and scenario simulation of multi-dimensional well-being in Poyang Lake area based on system dynamics[J]. Acta Ecologica Sinica, 2021, 41(8): 2954-2967.

[16] Liu Kun. Quantitative analysis based on the carrying capacity of resources and environment in Yulin City[J]. West Leather, 2020, 42(2): 88-90.

[17] Cui Dan, Chen Xin, Zeng Weihua. Investigations on the medium-term early warning of water environmental carrying capacity: A case study of Kunming City[J]. China Environmental Science, 2018, 38(3): 1174-1184.

[18] Wei Shuai, Chen Zhihe, Liang Jianxi, et al. Analysis of water resource system characteristics and variation law for Zhongshan city based on system dynamics[J]. Resources Science, 2014, 36(6): 1158-1167.

[19] Qin Huanhuan, Lai Dongrong, Wan Wei. Analysis of water use structure variation and its influence factors for Jiangxi Province[J]. Jiangxi Hydraulic Science & Technology, 2018, 44(5): 324-329, 368.

[20] Jin Juliang, Shen Shixing, Cui Yi, et al. Dynamic evaluation of water resources carrying capacity in the Yellow River diversion irrigation district based on semipartial subtraction set pair potential[J]. Journal of Hydraulic Engineering, 2021, 52(5): 507-520.

[21] Wang Geng, Li You. Simulation of municipal solid waste resource recovery based on system dynamics model: The case of Dalian[J]. Journal of Environmental Engineering Technology, 2016, 6(5): 493-500.

[22] Yao Cuiyou, Chen Guojiao, Zhang Yang. Research on reconstruction path of urban ecosystem based on system dynamics: The case of Tianjin[J]. Acta Scientiae Circumstantiae, 2020, 40(5): 1921-1930.

[23] Lin Longzhen, Li Da, Lin Zhen. Evaluation of water resources carrying capacity in Kubuqi Desert Area based on entropy weight-TOPSIS model[J]. Journal of Central China Normal University (Natural Science Edition), 2020, 54(4): 640-648.

[24] Zhang Libing, Hu Ya’ nan, Jin Juliang, et al. Dynamic prediction of water resources carrying capacity of Chaohu Basin and system optimization regulation based on system dynamics simulation[J]. Lake Sciences, 2021, 33(1): 242-254.

[25] Li Jingwei, Zhang Wenli. Analysis of hydration rationality and water saving potential of surface coal mine[J]. Haihe Water Resources, 2016(1): 9-11.

[26] Liu Suying, Han Huiling. Simple analysis the model of water conservation in agriculture production at Bashang region[J]. South-to-North Water Transfers and Water Science & Technology, 2010, 8(2): 117-119, 123.

[27] Wu Weibin, Han Jinhui, Yang Tiantong, et al. Dynamic simulation of population carrying capacity of urban water resources based on two-factor model

of Changchun[J]. Journal of Zhengzhou University (Natural Science Edition), 2017, 49(4): 126-131.

[28] Peng Tao, Deng Hongwei, Lin Yun, et al. Assessment on water resources carrying capacity in Karst areas by using an innovative DPESBRM concept model and cloud model[J]. Science of the Total Environment, 2020, 767: 144353.

[29] Zhang Sijun, He Li, Wu Shuang, et al. Simulation and optimal allocation of agricultural water resources system in Xuanhua district[J]. Journal of Hubei University of Technology, 2020, 35(1): 29-32, 37.

[30] Zhang Zhijun, Chen Fulong, Long Aihua, et al. Assessment of water resource security in an arid area based on an extension cloud model: A case study of Shihezi District[J]. Arid Zone Research, 2020, 37(4): 847-856.

[31] Kang Yan, Yan Yating, Yang Bin. Simulation of water resource carrying capacity based on LMDI-SD model in green development irrigation areas[J]. Transactions of the Chinese Society of Agricultural Engineering, 2020, 36(19): 150-160.

[32] Wang Huan, Zai Meimei. Research on the evaluation model of multi-objective optimal allocation of water resources in Guizhou Province[J]. IOP Conference Series: Materials Science and Engineering, 2020, 914(1): 012018.

[33] Zhu Wenli, Zhang Libing, Wu Lulu, et al. Research on the dynamic prediction and regulation of quantitative and quality elements of water resources carrying capacity at county level based on system dynamics method[J]. China Rural Water and Hydropower, 2020(2): 16-22.

[34] Wang Bo, Duan Yuxi, Wang Weifeng, et al. Spatial and temporal variability of soil moisture content during vegetation succession in artificial sand-binding areas[J]. Arid Zone Research, 2020, 37(4): 881-889.

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