Postprint: Water Resources Carrying Capacity Study in the Tarim River Basin Based on System Dynamics Model

Authors: Liu Xia

Date: 2021-10-10T00:00:00+00:00

Abstract

Quantitative assessment of water resource carrying capacity is a critical prerequisite for ensuring sustainable utilization of water resources in arid regions. Selecting the Tarim River Basin—the largest inland arid region basin in China—as the study area, this study constructs a system dynamics model that integrates its unique geographical environment and characteristics of water supply and demand. Based on data from field research, statistical yearbooks, and water resources bulletins, and constrained by water resource red lines, the historical status and future trends of water resource carrying capacity in the Tarim River Basin were quantitatively assessed and predicted. Results demonstrate that during the historical period (2008–2016), water resources in the Tarim River Basin and its affiliated prefectures (states) exhibited a state of mild overload, which will further intensify in the future (2017–2030). Under the current policy context, achieving a sustainable state of water resources in this region by 2030 necessitates expanding the scale of agricultural water-saving facilities construction and vigorously developing agricultural water-saving irrigation technologies, striving to attain an irrigation water quota below 5.70$\times103$m3 \cdot hm - 2andreduceagriculturalirrigationareatobelow$2.60×$106 hm2 by 2030. Simultaneously, agricultural water conservation and industrial transformation should be two key directions requiring focused consideration for future socio-economic development in this region.

Full Text

Study on Water Resource Carrying Capacity of the Tarim River Basin Based on a System Dynamics Model

LIU Xia[1], ZHANG Man[2], XU Jianhua[3], GUO Ying[1], DUAN Weili[4], SHEN Yanjun[1]

[1]Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences; Hebei Key Laboratory of Water-Saving Agriculture, Shijiazhuang 050021, Hebei, China
[2]College of Resources & Environmental Science, Hebei Normal University, Shijiazhuang 050024, Hebei, China
[3]School of Geographic Sciences, East China Normal University, Shanghai 200062, China
[4]State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China

Abstract: Quantitative assessment of water resource carrying capacity is a critical prerequisite for ensuring sustainable water utilization in arid regions. This study selected the Tarim River Basin, the largest inland arid basin in China, as the research area. Considering its unique geographical environment and water supply-demand characteristics, we constructed a system dynamics model. Based on field investigations, statistical yearbooks, and water resources bulletins, and constrained by water resource redlines, we quantitatively evaluated and predicted the historical status and future trends of water resource carrying capacity in the Tarim River Basin. Results show that during the historical period, water resources in the Tarim River Basin and its prefectures (states) exhibited mild overload conditions, with the most severe overload in Kizilsu Kirghiz Autonomous Prefecture. Agricultural water consumption is the primary cause of water resource overload. Future predictions indicate that if current development trends continue, water resource overload conditions will gradually worsen. To achieve a sustainable state by 2030, the basin must expand agricultural water-saving infrastructure and vigorously develop water-saving irrigation technologies, striving to reduce the irrigation water quota to below 5.70$\times10^{3}$ $m^3 \cdot hm^{-2}$ and decrease agricultural irrigation area to below 2.60$\times10^{6}$ hm^2. Simultaneously, agricultural water conservation and industrial transformation should be key considerations for future socio-economic development in the region.

Keywords: water resource carrying capacity; system dynamics model; arid region; water-saving agriculture; Tarim River Basin

1. Introduction

Water resource carrying capacity assessment is a critical issue in research on sustainable development and utilization of water resources in arid regions. Numerous studies on water resource carrying capacity exist in China, yet a complete theoretical system has not been formed, and definitions vary among experts. Current definitions fall into two categories: (1) Maximum water supply capacity—the maximum amount of water that can be supplied to industry, agriculture, domestic use, and ecological conservation under certain socio-economic conditions, representing the maximum exploitable water resources that can be continuously utilized without causing environmental degradation; and (2) Maximum supportable socio-economic scale—the maximum capacity of regional water resources to support socio-economic development under specific historical development stages, socio-economic development levels, and sustainable development principles while maintaining ecological balance. This "capacity" is typically characterized by population size and economic scale indicators. Compared to the maximum exploitable capacity theory, the maximum support capacity theory incorporates feedback relationships between water resource systems and socio-economic systems, gaining wider application.

The Tarim River Basin is located in southern Xinjiang, bordered by the Tianshan Mountains to the north, the Kunlun Mountains to the south, and the Pamir Plateau to the west. With low precipitation and high evaporation, it is a typical arid region where water resources have long been the primary constraint on local socio-economic development. The basin is also a core area of China' s "Belt and Road" initiative and a hub connecting eastern China with Central, South, and West Asia. As modern socio-economic development progresses, water shortages have become increasingly prominent, emerging as a decisive factor constraining local development. Additionally, the basin' s unique "mountain-oasis-desert" landscape pattern exacerbates contradictions between climate change-induced water shortages and social development. Therefore, assessing water resource carrying capacity and predicting future trends under the dual influences of economic development and climate change is crucial for achieving coordinated and sustainable basin development.

Methods for assessing water resource carrying capacity remain a hot topic in this field, broadly categorized into three types: (1) empirical estimation methods, (2) indicator system evaluation methods, and (3) complex system analysis methods. Previous studies on Tarim River Basin water resource carrying capacity have focused on empirical estimation and indicator system evaluation, with no reported applications of complex system analysis methods. System dynamics, a component of complex system analysis, has been increasingly applied to water resource carrying capacity research in recent years, demonstrating good applicability for basin-scale assessments. This study establishes a system dynamics model for the Tarim River Basin with simple structure and statistical data support to quantitatively evaluate historical water resource carrying capacity and predict future trends based on current socio-economic development trajectories, providing scientific support for sustainable development.

2. Methods

2.1 Data Sources

Data were primarily obtained from the *Xinjiang Statistical Yearbook* (2009-2017) and the *Xinjiang Water Resources Bulletin* (2008-2016). The *Water Resources Bulletin* provided data on total water consumption, primary industry water use, secondary industry water use, tertiary industry water use, agricultural irrigation water use, non-irrigation water use, domestic water use, and ecological water use for Bayingolin Mongol Autonomous Prefecture (Bayingolin), Kizilsu Kirghiz Autonomous Prefecture (Kizilsu), Aksu Prefecture, Kashgar Prefecture, and Hotan Prefecture, with units of 10^8 m^3. The *Statistical Yearbook* provided data on primary industry GDP (10^4 yuan), agricultural irrigation area (10^3 hm^2), irrigation water quota ($m^3 \cdot hm^{-2}$), and population (persons). These data were used to determine model parameters and for model validation.

2.2 Model Construction

To assess water resource carrying capacity and analyze temporal trends, we constructed a system dynamics model for the Tarim River Basin. Based on hierarchical relationships, the model was divided into several sub-modules, each comprising single or multiple variables and equations, with inter-module connections established through hierarchical or causal relationships to describe complex real-world changes.

The model comprises three main modules: population, economy, and water resources. The framework is illustrated in [Figure 1: see original paper].

Population Module: Described by first-order dynamic equations for population growth rate and population size:

$$c(t) = c(t-1) \times (1+p)$$

where c represents population (persons), t represents time step (year), and p represents population growth rate (persons $\cdot$ person^{-1} $\cdot$ year^{-1}).

Economic Module: Composed of first-order dynamic equations for agricultural irrigation water use and secondary/tertiary industry GDP. Agricultural irrigation area, secondary industry GDP, and tertiary industry GDP are equation variables, while secondary industry GDP growth rate and tertiary industry GDP growth rate are parameters:

$$g(t) = x(t) \times q$$

$$y(t) = y(t-1) \times (1+r_2)$$

$$z(t) = z(t-1) \times (1+r_3)$$

where g represents irrigation water use (10^8 m^3), x represents agricultural irrigation area (10^3 hm^2), q represents irrigation water quota (m^3 · hm^{-2}), y represents secondary industry GDP (10^4 yuan), r_2 represents secondary industry GDP growth rate, z represents tertiary industry GDP (10^4 yuan), and r_3 represents tertiary industry GDP growth rate.

Water Resources Module: Comprises calculations for domestic water use, primary industry water use, secondary industry water use, tertiary industry water use, total water use, and water resource carrying coefficient:

$$w_{dom} = c \times w_{pc}$$
$$w_{pri} = g + f$$
$$w_{sec} = y \times w_{unit,2}$$
$$w_{ter} = z \times w_{unit,3}$$
$$w_{eco} = w_{eco}(t-1) \times (1 + r_{eco})$$
$$w_{total} = w_{dom} + w_{pri} + w_{sec} + w_{ter} + w_{eco}$$
$$\alpha = \frac{w_{total}}{w_{redline}}$$

where w_{dom} is domestic water use, w_{pc} is per capita water use (m^3 · person^{-1}), w_{pri} is primary industry water use, f is non-irrigation agricultural water use (10^8 m^3), w_{sec} is secondary industry water use, $w_{unit,2}$ is unit secondary industry GDP water use (m^3 · yuan^{-1}), w_{ter} is tertiary industry water use, $w_{unit,3}$ is unit tertiary industry GDP water use (m^3 · yuan^{-1}), w_{eco} is ecological water use, r_{eco} is ecological water use change rate, w_{total} is total water use, α is water resource carrying coefficient, and $w_{redline}$ is the water resource redline value (10^8 m^3).

According to field investigations, Xinjiang implements a water allocation policy of "determining demand based on supply." Therefore, this study uses the ratio of total water consumption to water resource redlines as the carrying coefficient to evaluate water resource carrying capacity. The coefficient is dimensionless: values <1 indicate sustainable capacity, while values >1 indicate overload. Water resource redlines for the Tarim River Basin and its regions are shown in .

2.3 Model Calibration

Model applicability requires consistency between simulated and actual values. Calibration involved comparing simulated total water use from the system dynamics model with actual values for the Tarim River Basin and its prefectures, using coefficient of determination (R^2) as the evaluation metric. Calibration results are shown in [Figure 2: see original paper]. All R^2 values exceed 0.9, indicating excellent parameter fit and strong model applicability for simulating the entire Tarim River Basin and its constituent prefectures (Bayingolin, Kizilsu, Aksu, Kashgar, Hotan).

3. Results and Analysis

3.1 Current Assessment of Water Resource Carrying Capacity

Mean water resource carrying coefficients and excess water volumes during the historical period (2008-2016) are presented in . Water resources in the Tarim River Basin and its prefectures exhibited mild overload conditions, with Kizilsu showing the most severe overload (carrying coefficient = 1.35), exceeding its water resource redline by 35%. Other regions exceeded redlines by approximately 10%, indicating relatively mild overload. Although Kizilsu' s overload degree was high, its excess water volume was low and not the main cause of basin-wide overload. Kizilsu' s severe overload primarily stems from its low water resource redline value (4.30$×10^{8}$ m^3), far below other regions. Kashgar, Bayingolin, Hotan, and Aksu showed relatively mild overload with carrying coefficients around 1.10, exceeding their maximum allowable water volumes by approximately 10%.

Agricultural water consumption is the primary cause of water resource overload in the Tarim River Basin. As shown in and , unit water use for primary industry is significantly higher than for secondary/tertiary industries and domestic use. In 2016, unit primary industry water use reached 5.06$×10^{3}$ m$^3 \cdot$ person^{-1}, while unit secondary and tertiary industry water use were 40.48 m$^3 \cdot$ person^{-1} and 37.68 m$^3 \cdot$ person^{-1}, respectively. Despite rapid growth in secondary and tertiary industry water use, their proportion of total water consumption remains small. Similarly, domestic water consumption is not a primary driver of overload. Therefore, large agricultural water consumption is the main cause of severe water resource overload, consistent with previous findings.

The Tarim River Basin' s industrial structure from 2008-2017 ([Figure 3: see original paper]) reveals that despite relatively backward economic foundations and low agricultural contribution to economic growth, rapid agricultural economic development has consumed substantial water resources, becoming the primary cause of overload. Therefore, controlling excessive population growth, promoting industrial transformation, accelerating industrialization, and increasing the proportion of tertiary industry will be crucial for green development in the Tarim River Basin.

3.2 Future Trend Prediction

Using the calibrated system dynamics model, we selected decision variables related to economic development and water use (population growth rate, secondary/tertiary industry GDP growth rates, agricultural irrigation water quota, farmland irrigation area, and ecological water use) to develop different future scenarios. The model was then used to predict total water consumption and carrying coefficients for the prediction period (2020-2030), providing references for sustainable development pathways.

Current Development Scenario: Based on historical trends, agricultural irrigation area in some Tarim River Basin regions began declining after 2015. According to the *Xinjiang Total Water Use Control Plan*, Xinjiang Production and Construction Corps will reduce irrigation area by 2.16×10^{3} hm^2 by 2020, and the Tarim River Basin will reduce irrigation area by 3.57×10^{3} hm^2 by 2030, likely explaining the declining trend. Following historical patterns, we linearly predicted agricultural irrigation area for each prefecture ([Figure 4: see original paper]), while maintaining other parameters consistent with historical values (). Ecological water use showed a decreasing trend historically but is expected to increase based on the *Tarim River Basin Water Resources Comprehensive Utilization Plan* and the need to reduce agricultural occupation of ecological water. Therefore, we used quadratic curve fitting for predictions.

Under the current scenario, water resource overload will gradually worsen. By 2025, the basin' s carrying coefficient will reach 1.20, exceeding the redline by 20%. By 2030, it will reach 1.32, exceeding the redline by 32%. Spatially, Kizilsu will remain most severely overloaded, with a 2030 carrying coefficient of 1.38 (exceeding its redline by 38%). Aksu and Hotan will reach coefficients of 1.15 and 1.14, respectively, with gradually worsening overload. Kashgar and Bayingolin will show gradually decreasing coefficients, reducing overload risk.

Sustainable Development Scenario: To achieve sustainable water resource use (total water consumption below redlines by 2030), we designed a scenario focusing on reducing irrigation water quotas. Considering the basin' s grain security tasks, agricultural irrigation area continues linear growth as shown in [Figure 4: see original paper]. Population growth rates and secondary/tertiary industry GDP growth rates remain consistent with the current scenario. Referencing China' s 13th Five-Year Plan for special water-saving actions in severely water-deficient regions like southern Xinjiang, we reduced irrigation water quotas to achieve basin-wide sustainability.

Under this scenario, water resource overload will gradually ease. By 2025, the basin' s carrying coefficient will be 0.95 (5% below redline), and by 2030, it will be 0.91 (9% below redline), achieving sustainable status. Spatially, Kizilsu remains most overloaded (2030 coefficient = 1.30), but its small redline value (4.30×10^{8} m^3) does not significantly impact the overall basin trend. Notably, Hotan's overload will still slowly worsen despite the lower irrigation quota, suggesting a need for stricter water-saving measures.

To achieve sustainability by 2030, the irrigation water quota must be reduced to below 5.70×10^{3} m$^3\cdot$hm^{-2}, and agricultural irrigation area must be limited to below 2.60×10^{6} hm^2. This quota is slightly higher than Israel' s current level (5.25×10^{3} m$^3\cdot$hm^{-2}), indicating that Tarim River Basin agricultural water-saving technology and scale must reach or approach Israel' s current level by 2030. Irrigation water quotas under the sustainable scenario are shown in .

Annual water resources for the Tarim River Basin and its prefectures are shown in [Figure 5: see original paper]. Kizilsu' s water resources are about half of Bayingolin' s (the highest), yet its redline is less than one-tenth of Bayingolin' s, suggesting management authorities should consider appropriately increasing Kizilsu' s water resource redline.

---

4. Conclusion

This study constructed a system dynamics model to quantitatively assess current status and future trends of water resource carrying capacity in the Tarim River Basin. Results indicate that water resources across the basin and its prefectures are currently overloaded, exceeding redlines by approximately 10% in 2016, with agricultural water use being the primary cause. Short-term predictions show that under current trends, overload will severely worsen over the next decade, exceeding redlines by 32% by 2030. Under a sustainable development scenario, water resources will gradually achieve sustainable status, falling below redlines by 9% by 2030.

Based on basin conditions and water resource redlines, we designed a sustainable scenario where agricultural water conservation and industrial transformation are key development directions. As agriculture is the largest water-consuming sector, vigorously promoting water-saving irrigation technologies is essential. To achieve sustainability by 2030, irrigation water quotas must be reduced to below 5.70×10^{3} $m^3 \cdot hm^{-2}$ and irrigation area limited to below 2.60×10^{6} hm^2. Since secondary and tertiary industry water consumption per unit GDP is far lower than agriculture, accelerating industrial transformation to increase their GDP proportion is crucial. The basin should maintain rapid growth in secondary and tertiary industries, particularly accelerating service sector development to promote economic growth while reducing water resource dependence.

References

[1] Liu Yanhui, Li Yangbing, Liang Xinyuan, et al. Study on water resource carrying capacity evaluation and change in China[J]. Resources and Environment in the Yangtze Basin, 2019, 28(5): 80-91.

[2] Xu Zhi, Ma Jing, Wang Hao, et al. Key indicator and critical condition for the water resource carrying capacity in the Yangtze River Estuary[J]. Journal of Tsinghua University (Science and Technology), 2019, 59(5): 364-372.

[3] Qi Zhihua, Chen Haitang, Lin Xing, et al. Assessment of present regional water environmental carrying capacity and its countermeasures: A case study of Taizhou City[J]. Chinese Journal of Environmental Management, 2012(3): 46-50.

[4] Xu Youpeng. A study of comprehensive evaluation of the water resource carrying capacity in the arid area[J]. Journal of Natural Resources, 1993, 8(3): 229-237.

[5] Shi Yafeng, Qu Yaoguang. Water resources carrying capacity and its reasonable use of Urumqi River[M]. Beijing: Science Press, 1992: 94-111.

[6] Xia Jun, Zhu Yizhong. The measurement of water resources security: A study and challenge on water resources carrying capacity[J]. Journal of Natural Resources, 2002, 17(3): 262-269.

[7] Duan Qingchun, Liu Changming, Chen Xiaonan, et al. Preliminary research on regional water resources carrying capacity conception and method[J]. Acta Geographica Sinica, 2010, 65(1): 82-90.

[8] Chen Yaning, Hao Xingming, Chen Yapeng, et al. Study on water system connectivity and ecological protection countermeasures of Tarim River Basin in Xinjiang[J]. Bulletin of Chinese Academy of Sciences, 2019, 34(10): 1156-1164.

[9] Kelimu, Jiang Furen. Present situation of water resources endowment, development and utilization and long term strategic countermeasures in Xinjiang[J]. Water Resources and Hydropower Engineering, 2019, 50(12): 57-64.

[10] Wang Guangyan, Wang Yuanjian, Gui Dongwei. A review on water resources research in Tarim River Basin[J]. Arid Land Geography, 2018, 41(6): 1151-1159.

[11] Zhao Shaojun. Evaluation of ecological environmental carrying capacity of the Tarim River Basin[J]. Water Conservancy Science and Technology and Economy, 2018, 24(1): 1-7.

[12] Wang Ranghui, Ma Yingjun. Coupling relation among substance and energy as well as information in mountain basin system in arid zone: Taking mountainous system around Tarim Basin as an example[J]. Journal of Mountain Science, 2001, 19(5): 398-402.

[13] Chen Yaning, Xu Changchun, Hao Xingming, et al. Fifty year climate change and its effect on annual runoff in the Tarim River Basin, China[J]. Journal of Glaciology and Geocryology, 2008, 30(6): 921-929.

[14] Luo Wanyun, Lu Yuwen, Chen Yaning. Planting industry ecological compensation standard study based on guarantee ecological water: A case study of the mainstream of Tarim River Basin[J]. Water Saving Irrigation, 2016(5): 71-80.

[15] Xinjiang water resources bulletin[R]. Urumqi: Department of Water Resources of Xinjiang Uygur Autonomous Region, 2008—2016.

[16] Xinjiang statistical yearbook[M]. Beijing: China Statistical Press, 2009—2017.

[17] Zhang Na. High efficient water-saving irrigation development and 13th Five-Year Plan in Xinjiang Uygur Autonomous Region[J]. China Water Resources, 2018, 847(13): 50-59.

[18] Jia Lei, Zhen Rui. Enlightenment of agricultural water resources management pattern and water saving experience of Israel[J]. Heilongjiang Agricultural Sciences, 2015(2): 156-158.

[19] Li Chuan. Study on the water resources carrying capacity of Liaoning along Bohai Region for key industries[J]. Shenyang: Northeastern University, 2012.

[20] Meng Fanhao, Jiapaer Guli, Bao Anming, et al. Analysis on the relationship between agriculture water consumption of four source rivers and the change of ecosystem structure of the mainstream in Tarim River Basin in recent 50 years[J]. Journal of Natural Resource, 2016, 31(11): 1832-1843.

[21] Zhang Z, Hu H, Tian F, et al. Groundwater dynamics under water saving irrigation and implications for sustainable water management in an oasis: Tarim River Basin of western China[J]. Hydrology and Earth System Sciences, 2014, 18(10): 3951-3967.

[22] Huang Y, Li Y P, Chen X, et al. Optimization of the irrigation water resources for agricultural sustainability in Tarim River Basin, China[J]. Agricultural Water Management, 2012, 107(10): 74-85.

[23] Wei Guanghui, Gui Dongwei, Zhao Xinfeng. Irrigation area carrying capacity in Tarim River Basin in different years[J]. Arid Land Geography, 2018, 41(2): 230-237.

[24] Zhang Xiaoqing, Gui Dongwei, Li Lijun. Water resources allocation along the mainstream of Tarim River[J]. Arid Land Geography, 2018, 41(2): 248-254.

[25] Yi Xiaoyan, Wu Yong, Yin Changbin, et al. The enlightenment of Israel's efficient utilization of land and water resources to the green development of agriculture in China[J]. Chinese Journal of Agricultural Resources and Regional Planning, 2018, 39(10): 37-42.

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