Dynamic Prediction and Regulation of Water Resources Carrying Capacity in the Guanzhong Region Based on the LMDI-SD Coupling Model (Postprint)

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Abstract

To achieve dynamic prediction and quantitative regulation of regional water resources carrying capacity, an LMDI-SD coupling model is constructed. The model adopts the Logarithmic Mean Divisia Index (LMDI) decomposition method to identify key driving factors of water consumption changes, constructs a System Dynamics (SD) model to predict water resources carrying capacity, uses the key driving factors of water consumption changes as regulation indicators to conduct comprehensive regulation of economic and social water use, and combines orthogonal experimental design to screen optimal regulation schemes. Applied to the dynamic prediction and regulation of water resources carrying capacity in the Guanzhong region from 2022 to 2035, the results show that: (1) The intensity effect is the key driving factor for the decrease in agricultural water consumption and the increase in domestic and ecological water consumption in the Guanzhong region, while the scale effect is the key driving factor for the increase in industrial water consumption; (2) Under the current development mode, as the increase in total water consumption (37.13%) far exceeds the increase in available water supply (12.25%), the water resources carrying pressure in the Guanzhong region increases year by year, and will be in an overloaded state starting from 2026; (3) The Hanjiang-to-Weihe River Water Transfer Project can effectively alleviate the contradiction between water supply and demand in the Guanzhong region from the "supply side" , but compared with the rapidly growing demand, water resources in some cities still fall short of demand, requiring additional regulation from the "demand side" ; (4) Under the optimal regulation scheme, water resources in the Guanzhong region can be regulated to a critical carrying state, and compared with domestic, ecological, and agricultural water use levels, the regulation range for industrial development scale is larger and should be prioritized. The model possesses good practical application value for regional water resources planning and management within the framework of sustainable development.

Full Text

Preamble

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Abstract: To achieve dynamic prediction and quantitative regulation of regional water resources carrying capacity, this study constructs an LMDI-SD coupling model. The model employs the Logarithmic Mean Divisia Index (LMDI) decomposition method to identify key driving factors of water consumption changes; builds a System Dynamics (SD) model to predict water resources carrying capacity; uses the key driving factors of water consumption changes as regulation indicators for comprehensive control of economic and social water use; and combines orthogonal experimental design to screen optimal regulation schemes. Applied to dynamic prediction and regulation of water resources carrying capacity in the Guanzhong region from 2020 to 2035, the results show that: (1) The intensity effect is the key driving factor for the decrease in agricultural water consumption and the increase in domestic and ecological water consumption in the Guanzhong region from 2010 to 2019, while the scale effect is the key driving factor for the increase in industrial water consumption; (2) Under the current development model, water resources carrying pressure in the Guanzhong region increases year by year, and will be in an overloaded state from 2035, as the increase in total water consumption (37.13%) far exceeds the increase in available water supply (12.25%); (3) The Hanjiang-to-Weihe River Water Transfer Project can effectively alleviate the contradiction between water supply and demand in the Guanzhong region from the "supply side," but compared with rapidly growing demand, water resources in some cities remain in short supply and require regulation from the "demand side" ; (4) Under the optimal regulation scheme, water resources in the Guanzhong region can be regulated to a critical carrying state, and compared with domestic, ecological, and agricultural water use levels, the industrial development scale has a larger regulation range and should be prioritized. The model demonstrates good practical application value for regional water resources planning and management within the sustainable development framework.

Keywords: water resources carrying capacity; dynamic prediction; quantitative regulation; system dynamics; Guanzhong region

Introduction

In recent years, under the combined influence of climate change and human activities, China’ s water resources face severe challenges of tightening resource constraints, serious environmental pollution, and ecosystem degradation. Consequently, China has incorporated ecological civilization construction into national security and comprehensively promoted “dual evaluation” work with carrying capacity assessment as a fundamental component to guide and constrain local governments in planning sustainable economic and social development according to water resources carrying capacity. As water resources planning and management practices deepen, static evaluation alone can no longer meet modern water management needs, making dynamic prediction and regulation a new research hotspot.

Water resources carrying capacity prediction methods include system dynamics, artificial neural networks, and others. System dynamics, with its powerful dynamic feedback mechanism, can fully reflect the nonlinear, complex time-varying, and multiple feedback characteristics of water resources carrying systems, and has been widely applied in water resources planning and management. Existing studies on regulation scheme setting can be divided into two approaches: one based on model parameter sensitivity analysis using orthogonal experimental design, and the other based on regional development plans subjectively set by experts. However, current regulation scheme development inadequately considers regional water consumption change driving factors, lacks driving mechanism support, and relatively few studies establish regulation schemes based on driving factors.

Water resources carrying capacity is an important indicator measuring the coordination degree between regional development and resources. Since its proposal in the 1980s, research has yielded fruitful results. Early studies focused on concept definition, evaluation method exploration, and comprehensive assessment. With the deepening of water resources planning and management, research has gradually expanded to dynamic prediction and regulation. To construct an integrated model for dynamic prediction and quantitative regulation of water resources carrying capacity, this paper employs the Logarithmic Mean Divisia Index (LMDI) method to identify driving factors of water consumption changes, uses system dynamics to predict water resources carrying capacity, adopts key driving factors of water consumption changes as regulation indicators for comprehensive control of economic and social water use, and combines orthogonal experimental design to screen optimal regulation schemes. Applied to the Guanzhong region, this model provides practical application value for regional water resources planning and management within the sustainable development framework.

The Guanzhong region is located in central Shaanxi Province, bordering the Loess Plateau to the north and the Qinling Mountains to the south, extending from Baoji in the west to Weinan in the east, covering an area of approximately 55,000 km^2 and comprising five cities (Fig. [Figure 1: see original paper]). The region has a warm temperate semi-humid and semi-arid climate with an average annual rainfall of 525.7 mm. Situated in the lower reaches of the Yellow River Basin, the Wei River flows through the region. Surface water is difficult to utilize due to high sediment content, making groundwater the main water supply source. In 2020, the Guanzhong region' s GDP reached 2,162.55 billion yuan with a permanent population of 25.852 million, accounting for 63.4% and 65.5% of the province' s total respectively, while its water resources only accounted for 18.6% of the province' s total. The per capita water resources are only 334 m^3, 15.7% of the national average. As Shaanxi' s economic center and population agglomeration area with relative water scarcity and uneven spatiotemporal distribution, coupled with high development intensity and serious pollution, the contradiction between limited resources and unlimited demand is increasingly prominent, necessitating greater attention to efficient utilization, rational development, and protection of water resources.

1.2 Data Sources

Economic and population data were obtained from the *Shaanxi Statistical Yearbook* (2010-2021), water resources data from the *Shaanxi Water Resources Bulletin* (2010-2021), and environmental protection data from the *National Second Pollution Source Census Domestic Source Emission Coefficient Manual*. Model prediction year parameters were set according to the *14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives Through 2035* and the *Shaanxi Province "14th Five-Year Plan" for Water Conservancy Development* of Shaanxi Province and each city.

2.1.1 Water Consumption Decomposition

The LMDI identity decomposes the research object into a product of several driving factors through mathematical identity transformation. Let W be total water consumption, which consists of agricultural, industrial, domestic, and ecological water consumption. Let W_i be the water consumption of sector i ($i = 1, 2, 3, 4$ representing agriculture, industry, domestic, and ecology respectively). The driving factors of water consumption change for sector i are divided into three categories: Q_i, S_i, and D_i, representing intensity effect, structural effect, and scale effect respectively. The total water consumption factor decomposition model based on the LMDI identity can be expressed as:

$$W = \sum_i Q_i S_i D_i$$

Considering the differences in influencing factors of water consumption, different factors are used to characterize the driving effects for different sectors. Based on Equation (1), each sector' s water consumption is decomposed separately.

Agricultural water consumption W_1 can be decomposed as:

$$W_1 = \sum_j Q_{1,j} S_{1,j} D_1$$

where $W_{1,1}$ is farmland irrigation water consumption (10^8 m^3), $W_{1,2}$ is forestry, animal husbandry, and fishery water consumption (10^8 m^3); A is irrigation area (10^4 hm^2); G_f is forestry, animal husbandry, and fishery added value (10^8 yuan); G is regional GDP (10^8 yuan); $Q_{1,1} = \frac{W_{1,1}}{A}$ is water consumption per unit irrigated area (m$^3 \cdot$ hm^{-2}), representing the intensity effect driving agricultural water consumption change; $Q_{1,2} = \frac{W_{1,2}}{G_f}$ is water consumption per 10,000 yuan of forestry, animal husbandry, and fishery added value (m$^3 \cdot 10^4$ yuan^{-1}), representing the intensity effect; $S_{1,1} = \frac{A}{F}$ is irrigation rate of cultivated land (%), $S_{1,2} = \frac{G_f}{G}$ is the proportion of forestry, animal husbandry, and fishery added value in GDP (%), representing the structural effect; $D_1 = F$ is cultivated land area (10^4 hm^2), representing the scale effect.

Industrial water consumption W_2 can be decomposed as:

$$W_2 = Q_2 S_2 D_2$$

where G_I is industrial added value (10^8 yuan); G is regional GDP (10^8 yuan); $Q_2 = \frac{W_2}{G_I}$ is water consumption per 10,000 yuan of industrial added value (m$^3 \cdot 10^4$ yuan^{-1}), representing the intensity effect driving industrial water consumption change; $S_2 = \frac{G_I}{G}$ is the proportion of industrial added value in GDP (%), reflecting the driving effect of regional development structure on industrial water consumption change; $D_2 = G$ is regional GDP (10^8 yuan), representing the scale effect driving industrial water consumption change.

Domestic water consumption W_3 can be decomposed as:

$$W_3 = \sum_j Q_{3,j} S_{3,j} D_3$$

where $W_{3,1}$ and $W_{3,2}$ are urban and rural domestic water consumption (10^8 m^3) respectively; P_1 and P_2 are urban and rural population (10^4 persons); $Q_{3,1} = \frac{W_{3,1}}{P_1}$ and $Q_{3,2} = \frac{W_{3,2}}{P_2}$ are per capita urban and rural domestic water consumption (m$^3 \cdot$ person^{-1}); $S_{3,1} = \frac{P_1}{P}$ and $S_{3,2} = \frac{P_2}{P}$ are the proportions of urban and rural population in total population (%); $D_3 = P$ is total population

(10^4 persons). $Q_3 = \sum_j Q_{3,j}S_{3,j}$, $S_3 = \sum_j S_{3,j}$, and $D_3 = \sum_j D_{3,j}$ represent the intensity, structural, and scale effects driving domestic water consumption change respectively.

Ecological water consumption W_4 can be decomposed as:

$$W_4 = Q_4 S_4 D_4$$

where W_4 is ecological water consumption (10^8 m^3); $Q_4 = \frac{W_4}{P}$ is per capita ecological water consumption ($\mathrm{m}^3 \cdot \mathrm{person}^{-1}$), representing the intensity effect driving ecological water consumption change; $S_4 = \frac{W_4}{W}$ is the proportion of ecological water consumption in total water consumption (%), representing the structural effect; $D_4 = P$ is total population (10^4 persons), representing the scale effect.

The LMDI decomposition includes additive and multiplicative approaches, both yielding consistent and unique results. The additive approach decomposes the change in the research object into the sum of driving effects of several factors, making the process more intuitive and concise. Therefore, the additive decomposition method is adopted to decompose the water consumption change of each sector as follows:

$$\Delta W_i = \Delta W_i^Q + \Delta W_i^S + \Delta W_i^D$$

where W_i^0 and W_i^t represent the initial and final water consumption of sector i respectively; ΔW_i^Q, ΔW_i^S, and ΔW_i^D represent the contributions of intensity, structural, and scale effects to water consumption change (10^8 m^3). The larger the absolute value of the contribution, the more significant the promoting or inhibiting effect. The calculation formula is:

$$\Delta W_i^Q = \frac{W_i^t - W_i^0}{\ln(W_i^t) - \ln(W_i^0)} \ln\left(\frac{Q_i^t}{Q_i^0}\right)$$

where Q_i^0, S_i^0, D_i^0 and Q_i^t, S_i^t, D_i^t are the initial and final values of the three driving factors respectively.

2.2.1 Model Construction

System dynamics studies system behavior and function by analyzing system components and their internal dynamic feedback mechanisms. Based on systematic analysis of water resources carrying capacity, this paper divides the water resources carrying system into four subsystems—water resources, domestic water, production water, and ecological water—from the perspective of water supply and consumption. These subsystems are interconnected and constrained by water resources, jointly affecting the water resources carrying status of the Guanzhong region.

1) **Water Resources Subsystem**: Includes available water supply and total water consumption. Available water supply reflects the supporting

capacity of water resources for economic and social development, comprising surface water, groundwater, reclaimed water, and external water transfers. Total water consumption reflects the pressure of economic and social development on water resources, being the sum of production, domestic, and ecological water consumption. The Water Resources Carrying Index (WRCI) evaluates water resources carrying status, calculated as the ratio of total water consumption to available water supply. The evaluation criteria are: $\text{WRCI} < 0.9$ for bearable, $0.9 \leq \text{WRCI} < 1$ for critical, and $\text{WRCI} > 1$ for overloaded.

2) **Domestic Water Subsystem**: Domestic water consumption comprises urban and rural domestic water, calculated using the quota method. Population is the core variable, determined by birth rate, death rate, and mechanical growth rate. Urbanization rate divides the total population into urban and rural populations to reflect the impact of population structure changes on domestic water consumption.

3) **Production Water Subsystem**: Reflects the pressure of economic production activities on the water resources carrying system, including agricultural and industrial modules. Agricultural water comprises farmland irrigation and forestry-animal husbandry-fishery water. Farmland irrigation water is calculated using the irrigation quota method, affected by the effective utilization coefficient of irrigation water. The output value scale of forestry-animal husbandry-fishery and industry is an important indicator reflecting water demand and development level, with water consumption calculated by the water quota per 10,000 yuan of output value.

4) **Ecological Water Subsystem**: Includes in-stream and off-stream ecological water. In-stream ecological water consumption is 10% of the multi-year average runoff, deducted once when determining surface water availability. Off-stream ecological water consumption refers to water used to ensure healthy urban ecosystem circulation and development goals, including green space, river-lake landscape, and environmental sanitation water, closely related to urban development scale and calculated using the per capita quota method.

In each subsystem, basic elements are simplified into appropriate variables. Variables insensitive to time changes are set as constants, such as runoff coefficient, industrial and domestic sewage discharge coefficients. Variables with cumulative effects, such as industrial added value, forestry-animal husbandry-fishery added value, total population, and cultivated land area, are set as state variables, with rate variables reflecting their change speed. Auxiliary variables serve as transitions between variables. Variables changing over time and nonlinearly related to time are described using table functions.

Vensim software is the most widely used system dynamics modeling tool, with three versions: Vensim PLE, Vensim Professional, and Vensim DSS. This study uses Vensim.PLE x32 to establish a water resources carrying capacity SD model containing 4 state variables, 38 auxiliary variables, and 23 table functions. The system feedback relationships are shown in Fig. [Figure 2: see original paper].

2.2.2 Model Settings

The model uses city administrative divisions as spatial boundaries and 2010–2035 as the temporal boundary, with 2010–2021 as the validation period and 2022–2035 as the prediction period. The prediction step is 1 year, with 2021 as the base year. Based on statistical data, state variable initial values are set as shown in Table .

2.2.3 Parameter Estimation

Parameters to be estimated include constant values and decision variable values for prediction years. Based on 2010–2021 statistical data for each city, parameters are estimated using mathematical statistics and trend analysis methods, adjusted according to development plans.

1) **Constant Values**: Runoff coefficient takes the arithmetic mean of historical data. Industrial and urban domestic sewage discharge coefficients reference the *First National Pollution Source Census Urban Domestic Source Emission Coefficient Manual* and *Second National Pollution Source Census Domestic Source Emission Coefficient Manual*, as shown in Table .

2) **Decision Variable Values for Prediction Years**: Six variables including birth rate, death rate, mechanical growth rate, cultivated land irrigation rate, cultivated land area change rate, forestry-animal husbandry-fishery added value growth rate, and industrial added value growth rate reflect average levels of social structural changes and economic development. Urbanization rate values are taken from each city' s *14th Five-Year Plan*. Reservoir capacity values are from the *Shaanxi Province "14th Five-Year Plan" for Water Conservancy Development*. Variables reflecting water use levels, including unit area farmland irrigation water consumption, per capita domestic water consumption, and water consumption per 10,000 yuan of industrial added value, are predicted using the average annual change method and adjusted according to *14th Five-Year Plan* development goals. External water transfer refers to Han River water transferred by the Hanjiang-to-Weihe Project, with values taken from the *Shaanxi Province Hanjiang-to-Weihe River Water Transfer Project Proposal Water Receiving Area Water Resources Allocation Plan*.

2.2.4 Model Validation

Model validation aims to determine whether the model can accurately reflect system behavior and change patterns. This study validates the model from two aspects: rationality and effectiveness. Running Vensim.PLE x32' s Check Model and Unit Check modules validates model structure and dimensional rationality, with both results showing "Model is OK," indicating model rationality. Three representative variables—population, industrial added value, and total water consumption—are selected to validate model effectiveness. The relative error between simulated and actual values during the validation period is less than 10% (Table), indicating good simulation performance and model effectiveness for simulating and predicting water resources carrying capacity in the Guanzhong region.

2.3 Water Resources Carrying Capacity Optimization Regulation

Orthogonal experimental design is a multi-factor, multi-level experimental design method that selects representative sample combinations from comprehensive experiments based on orthogonality, featuring high efficiency and economy. The steps for water resources carrying capacity regulation using orthogonal experimental design are: (1) Define regulation objectives; (2) Set regulation indicators: Select key driving factors of water consumption changes for each sector as regulation indicators based on LMDI decomposition results; (3) Establish regulation basis: Considering differences in economic and social development trends, water resources conditions, and development/utilization capacity across regions, select indicators from cities with relatively reasonable development speed and water resources utilization levels within the Guanzhong region as regulation basis; (4) Develop regulation schemes: Determine indicator level numbers based on current values and regulation basis, then select appropriate orthogonal tables to develop regulation schemes; (5) Regulation results: Simulate regulation scheme results using the SD model, compare water resources carrying indices of different schemes with regulation objectives, and select the scheme with the smallest absolute difference as the optimal regulation scheme.

3.1.1 Water Consumption Analysis

Based on the Shaanxi Water Resources Bulletin, water consumption in the Guanzhong region from 2010 to 2021 was analyzed from both total volume and structure perspectives. The results show that total water consumption in the Guanzhong region changed in an "increase-decrease-increase" fluctuating pattern, increasing from 48.75$\times 10^{8}$ m^3 in 2010 to 53.18$\times 10^{8}$ m^3 in 2015, then decreasing to 46.71$\times 10^{8}$ m^3 in 2021, with a cumulative reduction of 2.11$\times 10^{8}$ m^3. The increase in total water consumption is both an inevitable result of expanded development scale and increased population, and reflects improved water use efficiency. The Guanzhong region has made large-scale adjustments to water consumption structure, with agricultural, industrial, domestic, and ecological water consumption ratios changing from 63.4%:16.4%:12.6%:7.6% in 2010 to 55.35%:9.83%:25.82%:8.99% in 2021. As the largest water consumption sector, agricultural water consumption showed a fluctuating downward trend with a cumulative decrease of 5.03$\times 10^{8}$ m^3, and its proportion was compressed year by year. Industrial water consumption showed the largest decreasing trend, with an average annual reduction of 0.31$×10^{8}$ m^3 and a significant decline in proportion. In contrast, domestic and ecological water consumption showed varying degrees of increase, with ecological water consumption increasing most significantly from 0.82$×10^{8}$ m^3 to 4.2$×10^{8}$ m^3, an increase of 3.38$×10^{8}$ m^3 (412% growth).

3.1.2 Water Source Change Analysis

Based on the Shaanxi Water Resources Bulletin, water sources in the Guanzhong region include surface water, groundwater, external water transfer, and unconventional water. Surface water is supplied by storage, diversion, and pumping projects; groundwater is supplied by motor-pumped wells; unconventional water includes reclaimed wastewater, rainwater utilization, and mine water reuse. From 2010 to 2021, the water source structure changed significantly, with surface water, groundwater, external water transfer, and unconventional water accounting for 59.2%-62.1%, 31.8%-40.1%, 0.83%-4.33%, and 1.2%-4.33% respectively. As the main water source, surface water showed small variations with an average consumption of 28.5$×10^{8}$ m^3 and relatively stable proportion (59.2%-62.1%). Groundwater consumption decreased year by year from 30.85$×10^{8}$ m^3 to 19.5$×10^{8}$ m^3, with proportion declining annually. External water transfer and unconventional water consumption increased year by year, with unconventional water proportion increasing significantly by 4.33%, effectively relieving pressure on conventional water sources.

3.1.3 Identification of Water Consumption Change Driving Factors

Using the LMDI decomposition model (Equation 2), driving factors of agricultural, industrial, domestic, and ecological water consumption changes in the Guanzhong region were identified (Table). The cumulative decomposition effect for total water consumption is negative, indicating a decreasing trend consistent with actual water consumption processes. The scale effect is positive, inhibiting water consumption reduction, while intensity and structural effects are negative, promoting reduction. The scale effect has the largest absolute value, contributing most to water consumption change, making it the key driving factor for water consumption reduction from 2010 to 2021.

For each sector, the intensity effect has the largest absolute value in agricultural, domestic, and ecological water consumption decomposition, indicating it contributes most to these sectors' water consumption changes. In agricultural water consumption, the intensity effect is negative, showing that despite expanded production scale promoting increased consumption, agricultural water intensity significantly decreased due to implementation of the strictest water resources management system, agricultural water price adjustment, and promotion of water-saving irrigation technology, leading to decreased consumption. For domestic and ecological water consumption, the intensity effect is positive, indicating that as living standards improve and ecological protection awareness strengthens, water demand continues to increase. In industrial water consumption decomposition, the scale effect has the largest absolute value and is positive, indicating it is the key driving factor for industrial water consumption increase.

3.2 Water Resources Carrying Capacity Prediction Under Current Development Model

This study constructs city-level water resources carrying capacity SD models for each city as basic units, then integrates them to simulate and predict water resources carrying capacity for the entire Guanzhong region. Model integration involves superimposing city-level model data from water resources, population, and economic perspectives to obtain total available water supply and water consumption for the Guanzhong region, then calculating the water resources carrying index to identify carrying status.

Under the current development model, the economic and social structure and water resources development/utilization level of the Guanzhong region develop according to regional planning. Available water supply is determined as a table function through comprehensive analysis of water resources availability, water supply project capacity, and water consumption control indicators. Analysis of 2020–2035 results (Table) shows that under the current development model, water resources carrying pressure in the Guanzhong region increases year by year, shifting from critical to overloaded status from 2035. During 2020–2035, total population is projected to increase by 3.25 million, permanent resident urbanization rate will reach 75%, industrial added value will increase by 162.55 billion yuan, and total water consumption will increase by 37.13%, far exceeding the available water supply increase (12.25%). The *Xi' an City "14th Five-Year Plan" for Affordable Rental Housing Development* predicts an average annual population increase of 250,000 in the Guanzhong region, consistent with this study' s projection. Results indicate that due to population growth, rapid urbanization, and industrial expansion, the water consumption increase far exceeds available supply, causing water resources carrying status to shift from critical to overloaded.

The Hanjiang-to-Weihe River Water Transfer Project is a major water allocation project to alleviate water supply-demand contradictions in the Guanzhong region. According to the *Shaanxi Province Hanjiang-to-Weihe River Water Transfer Project Proposal Water Receiving Area Water Resources Allocation Plan*, the project will supply 4.55$×10^{8}$ m^3, 1.12$×10^{8}$ m^3, and 1.04$×10^{8}$ m^3 to Xi' an, Xianyang, and Weinan respectively by 2025, and 5.26$×10^{8}$ m^3, 1.29$×10^{8}$ m^3, and 1.12$×10^{8}$ m^3 by 2035. Comparison of water resources carrying indices before and after project implementation (Fig. [Figure 5: see original paper]) shows that the project significantly reduces water resources carrying indices in receiving cities, but all remain above 1 except Tongchuan City. This indicates that inter-basin water transfer measures effectively alleviate the contradiction between economic-social development and water scarcity from the "supply side," but water resources will remain in long-term "supply shortage" overload status relative to rapidly growing demand, requiring "demand side" regulation to explore water resources development/utilization patterns matching economic-social development.

3.3 Water Resources Carrying Capacity Optimization Regulation

Using orthogonal experimental design, this study conducts holistic, phased, and comprehensive regulation for cities remaining in overloaded status after Hanjiang-to-Weihe Project implementation, namely Xi' an, Tongchuan, Baoji, and Weinan. Holistic regulation applies the same regulation ratio to all cities; phased regulation conducts regulation in 2025, 2030, and 2035; comprehensive regulation applies control to all water use sectors.

Regulation Objective: Based on the theory of maximum water resources development scale, the regulation objective is set as the critical carrying state upper limit (WRCI = 1) for overloaded cities, aiming to achieve water resources decoupling while minimizing changes to economic-social development, water use structure, and consumption levels.

Regulation Indicators: Using key driving factors of water consumption changes in the Guanzhong region as regulation indicators for overloaded cities. Table shows intensity effects are key driving factors for agricultural, domestic, and ecological water consumption changes, while scale effects are key for industrial water consumption changes. Combined with the SD model, five table functions are selected as regulation indicators: unit area farmland irrigation water consumption, urban per capita domestic water consumption, rural per capita domestic water consumption, per capita ecological water consumption, and industrial added value growth rate.

Regulation Basis: Considering regional differences in development trends, water resources conditions, and utilization capacity, indicator values from cities with relatively reasonable development speed and water use levels within the Guanzhong region are used as regulation basis. Industrial added value and rural per capita domestic water consumption regulation basis values reference Tongchuan City; unit area farmland irrigation water consumption references Xianyang City; urban per capita domestic water consumption references Weinan City; per capita ecological water consumption references Baoji City (Table).

Regulation Scheme Development: The difference between each indicator' s regulation basis and current value is divided into four equal parts to create four levels (Table). An orthogonal table is selected to develop regulation schemes based on indicator count and level numbers (Table).

Regulation Results: City-level SD models simulate water resources carrying indices for 16 schemes in Xi'an, Tongchuan, Baoji, and Weinan. Comparing 2035 carrying indices with regulation objectives, the scheme with smallest absolute difference is selected as optimal (Table). Xi' an' s Scheme 6 has the smallest ABS(WRCI-1) value, making it optimal; Tongchuan' s Scheme 5 is optimal; Baoji and Weinan' s smallest ABS(WRCI-1) values both appear in Scheme 13, making it optimal. Under optimal schemes, all cities' water resources carrying status shifts from overloaded to critical.

Under optimal regulation schemes (Table), Xi' an reduces unit area farmland irrigation water consumption, industrial added value growth rate, urban and rural domestic water quotas, and per capita ecological water consumption by 7.5%, 15.0%, 7.5%, 7.5%, and 7.5% respectively; Tongchuan reduces all five indicators by 5.0%; Baoji and Weinan reduce them by 7.5%, 15.0%, 7.5%, 7.5%, and 7.5% respectively. Industrial added value regulation amplitude is much larger than other indicators, indicating industrial scale will develop at high levels with large regulation space and should be prioritized. Water consumption level indicators such as unit area farmland irrigation water consumption, urban/rural domestic water quotas, and per capita ecological water consumption have been greatly improved and have relatively small regulation space. Under optimal schemes (Fig. [Figure 6: see original paper]), Xi' an and Baoji' s water resources carrying indices are regulated to 0.98, while Tongchuan and Weinan' s are regulated to 0.99, approaching or reaching the critical state upper limit and achieving the regulation objective of maximizing economic-social development within water resources carrying capacity constraints.

4 Discussion and Conclusion

To achieve dynamic prediction and quantitative regulation of water resources carrying capacity in the Guanzhong region, this study establishes an LMDI-SD coupling model integrating LMDI decomposition, system dynamics, and orthogonal experimental design. The model predicts water resources carrying elements and indices, identifies key driving factors of sectoral water consumption changes, uses these factors as regulation indicators for comprehensive control of economic-social water use in overloaded cities, and screens optimal regulation schemes through orthogonal experimental design. The results show:

1) The intensity effect is the key driving factor for agricultural water consumption decrease and domestic/ecological water consumption increase in the Guanzhong region from 2010–2019, with contributions of -7.30$×10^{8}$ m^{3}, 3.47$×10^{8}$ m^{3}, and 1.19$×10^{8}$ m^{3} respectively. The scale effect is the key driving factor for industrial water consumption increase, with a contribution of 6.85$×10^{8}$ m^{3}.
2) Under the current development model, due to concentrated population increase, rapid urbanization, and continuous industrial expansion, total water consumption in the Guanzhong region is projected to increase by 37.13% from 2020–2035, far exceeding the available water supply increase (12.25%). Water resources carrying pressure increases yearly, reaching an overloaded state by 2035 (WRCI = 1.12).

3) The Hanjiang-to-Weihe River Water Transfer Project effectively alleviates the contradiction between economic-social development and water scarcity from the supply side, but water resources in some cities remain in long-term "supply shortage" overload status relative to rapidly growing demand, requiring demand-side regulation.
4) Under optimal regulation schemes, water resources in the Guanzhong region can be regulated to a critical carrying state. Compared with domestic, ecological, and agricultural water use levels, industrial development scale has larger regulation range and should be prioritized. By constraining industrial expansion speed, improving agricultural water use efficiency, and slowing domestic/ecological water consumption growth, effective improvement in water resources carrying status can be achieved, promoting sustainable and coordinated development between economic society and water resources.

It should be noted that this study conducts water resources carrying capacity regulation from the supply side using key driving factors of sectoral water consumption as indicators for comprehensive control of economic-social water use. While this meets the regulation objective of keeping total water consumption within bearable range, the comprehensiveness within each sector is insufficient. However, it clarifies key directions for rational water use planning. Sectoral water consumption is driven by intensity, scale, and structural effects; single-factor regulation cannot effectively improve water resources overload status, requiring regulation of other driving factors to ultimately achieve water resources bearability and promote sustainable coordinated development between economic society and water resources.

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