Postprint: Sustainability Simulation of Ecological Environment and Socio-economic Development in the Yellow River Basin Based on SD Model

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Abstract

To achieve ecological protection and high-quality development in the Yellow River Basin, it is essential to address the sustainability challenges between the basin' s ecological environment and socio-economic development. Employing the system dynamics methodology, we construct four subsystems—social, economic, resource, and environmental—and design six scenarios: status quo maintenance, social development prioritization, economic development prioritization, resource conservation prioritization, environmental protection prioritization, and coordinated development. Through simulation and modeling of these different scenarios, we explore the optimal solution for achieving sustainable development of the ecological environment and socio-economy in the Yellow River Basin. The results indicate that under the coordinated development scenario, the socio-economy of the Yellow River Basin experiences rapid growth, with total population and Gross Domestic Product (GDP) projected to increase by 10.93% and 499.05%, respectively, by 2030; resource utilization efficiency improves significantly, with water consumption per unit GDP and energy consumption projected to decrease by 78.31% and 68.16%, respectively, by 2030; pollutant emissions can be effectively reduced, with industrial Chemical Oxygen Demand (COD) emissions and industrial sulfur dioxide (SO2) emissions projected to decrease by 80.64% and 80.17%, respectively, by 2030. Compared with other scenarios, coordinated development represents the optimal solution for achieving sustainable development of the ecological environment and socio-economy in the Yellow River Basin.

Full Text

Abstract

To realize ecological protection and high-quality development in the Yellow River Basin, it is essential to address the sustainability challenges at the intersection of ecological environment and socio-economic development. This study employs system dynamics methodology to construct four subsystems—society, economy, resources, and environment—and designs six scenarios: maintaining the status quo, prioritizing social development, prioritizing economic development, prioritizing resource conservation, prioritizing environmental protection, and collaborative development. Through simulation and analysis of these different scenarios, the study identifies the optimal pathway for achieving sustainable development of both ecological environment and socio-economy in the Yellow River Basin. The results demonstrate that under the collaborative development scenario, the total population and gross domestic product (GDP) of the Yellow River Basin will increase by 10.93% and 499.05% respectively by 2030, while pollutant emissions can be effectively reduced (industrial chemical oxygen demand (COD) and sulfur dioxide (SO_2) emissions will decrease by 80.64% and 80.17% respectively), and resource use efficiency will improve (water and energy consumption per unit GDP will decline by 78.31% and 68.16% respectively). Compared with other scenarios, collaborative development represents the optimal solution for achieving sustainable development of ecological environment and socio-economy in the Yellow River Basin.

Keywords: Yellow River Basin; ecological environment; socio-economy; sustainable development; system dynamics model

1 Introduction

In September 2019, President Xi Jinping chaired a symposium in Zhengzhou and proposed a major national strategy for ecological protection and high-quality development in the Yellow River Basin. Xi emphasized that the Yellow River Basin constitutes an important ecological barrier and economic zone in China, as well as a crucial region for winning the battle against poverty. In March 2021, the 14th Five-Year Plan explicitly called for solid progress in ecological protection and high-quality development in the Yellow River Basin, with improvements to the institutional mechanisms for coordinated regional development. According to the China Water Resources Bulletin and China Statistical Yearbook, the Yellow River Basin' s total water resources amount to 7.97×10^{10} m^3, accounting for 2.75% of the national total and 27.80% of the Yangtze River Basin. The basin' s GDP represents 26.5% of the national total, while its population comprises 30.3% of the national population, with per capita GDP at 23.9×10^{3} yuan, below the national average. The Yellow River Sediment Bulletin indicates that over the past 20 years, continuous sedimentation in the main river channel has raised the riverbed by 53.83 m at the Xiaolangdi Reservoir area and 62.90 m at the tributary Dayu River section. The basin currently faces critical challenges including ecological vulnerability, water scarcity, and imbalanced sediment-water relationships, which severely constrain its development quality.

High-quality development represents a transformation of growth drivers and economic structure after reaching a certain scale, characterized by optimized economic structure, coordinated socio-economic development, and significantly improved living standards. For the Yellow River Basin, high-quality development should prioritize ecological protection, promote central city agglomeration under market-driven and innovation-driven mechanisms, achieve coordinated regional development, and satisfy people's aspirations for a better life. The concept must unify ecological protection and economic development, using sustainable development and ecological conservation as breakthrough points for comprehensive quality improvement. The 14th Five-Year Plan also emphasizes the principle that "lucid waters and lush mountains are invaluable assets," advocating sustainable development strategies and promoting comprehensive green transformation of economic and social development. Achieving ecological protection and high-quality development in the Yellow River Basin requires addressing the sustainability issues at the nexus of ecological environment and socio-economic development.

2 Data and Methods

2.1 Data Sources

Data were primarily obtained from the China Statistical Yearbook, China Urban Statistical Yearbook, and provincial statistical yearbooks of Shanxi, Inner Mongolia, Shandong, Henan, Sichuan, Shaanxi, Gansu, Qinghai, and Ningxia, as well as government work reports and statistical bulletins of the nine provinces and regions traversed by the Yellow River Basin.

2.2 Model Construction

2.2.1 System Dynamics System dynamics, as a methodology for studying system feedback structure and dynamic behavior, can effectively handle nonlinear, multi-level, multi-feedback complex systems. Compared with traditional methods, system dynamics enables qualitative and quantitative analysis of complex dynamic feedback systems, examining current status and evolutionary trends. The Yellow River Basin' s development involves complex relationships among social activities, economic activities, and natural systems, with intricate interactions among social, economic, resource, and environmental elements. This necessitates a systematic scientific approach to study the large system of socio-economy and resource environment from multi-factor and multi-level perspectives. System dynamics can effectively reflect nonlinear feedback relationships between the system and its internal components and conduct reasonable medium- to long-term policy simulations, making it widely applicable in sustainable development research.

2.2.2 SD Model Flow Chart The main variables in the SD model include state variables, rate variables, and auxiliary variables. State variables describe the system' s current status and reflect information accumulation; rate variables directly change state variables and reflect their rate of change; auxiliary variables represent information calculated from other variables. The relationship between state and rate variables manifests as dynamic changes in the system, expressed as:

$$S(t) = S_0 + \int_0^t (F_{\text{in}} - F_{\text{out}})dt$$

where $S(t)$ represents the value of state variable S at time t, S_0 is the initial value, and F_{in} and F_{out} represent input and output flows of the state variable, respectively.

Combining the interrelationships among subsystems, equations between variables were established and a system flow chart was constructed using Vensim software (Figure 1).

[Figure 1: see original paper]

2.2.3 SD Model Subsystem Construction **Social Subsystem:** This subsystem examines appropriate social development levels under given economic scale, resource consumption, and ecological environment conditions. Human activities generate economic value, resource consumption, and pollution emissions that affect all subsystems. Increased population raises resource demand and consumption while elevating pollutant emissions, thereby exacerbating environmental pollution. The system uses total population as a level variable, net population growth as a rate variable, and other variables as auxiliary variables.

Economic Subsystem: This subsystem investigates how economic scale and structure influence resources and environment. Following industrial classification methods, the economic subsystem includes three major industries. Value-added outputs are determined by their respective growth rates, while different industrial structures create varying resource consumption levels. The economic subsystem affects watershed ecological governance capacity through pollution control investments.

Resource Subsystem: This subsystem examines resource consumption patterns under specific socio-economic development levels and how resource consumption changes affect socio-economic development. The system focuses on water resources and energy consumption, including agricultural, industrial, domestic, and ecological water use. Resource consumption and economic aggregate mutually influence each other: economic growth drives resource consumption increases, while resource constraints restrict economic development.

Environmental Subsystem: This subsystem investigates environmental carrying capacity under specific socio-economic development levels and how ecological changes affect socio-economic development. The system directly influences watershed environmental quality and is closely related to human health and ecological civilization. To explore dynamic cycling relationships of pollutants, the system examines chemical oxygen demand (COD) and ammonia nitrogen in wastewater, sulfur dioxide (SO_2) and nitrogen oxides (NO) in exhaust gases, and generation, treatment, and emission volumes of industrial solid waste. Pollutant treatment volumes are influenced by pollution control investment levels.

The main variables of the social, economic, resource, and environmental subsystems are presented in Table 1.

2.2.4 Scenario Design Based on resource-environment foundation theory and sustainable development theory, combined with President Xi Jinping' s speech at the Yellow River Basin Ecological Protection and High-Quality Development Symposium and the State Council' s Yellow River Basin Comprehensive Plan (2012-2030), 13 control variables were selected from the four subsystems: net population growth rate, employed population proportion, primary industry value-added growth rate, secondary industry value-added growth rate, tertiary industry value-added growth rate, agricultural water use growth rate, industrial water use growth rate, domestic water use growth rate, ecological water use growth rate, energy consumption elasticity coefficient, industrial wastewater treatment investment, industrial waste gas treatment investment, and industrial solid waste treatment investment. Six development scenarios were designed for simulation to explore appropriate development models:

Scenario 1 (Maintaining Status Quo): The Yellow River Basin maintains its current development trajectory. All model parameters remain unchanged based on existing research [**?**].

Scenario 2 (Prioritizing Social Development): Emphasizes rapid population growth and improved employment conditions. Based on statistical yearbooks of Yellow River Basin provinces and relevant research [**?**], net population growth rate and employed population proportion are moderately increased.

Scenario 3 (Prioritizing Economic Development): Emphasizes the importance of economic growth. Based on statistical yearbooks and research [**?**], parameters related to economic growth are appropriately amplified, with primary, secondary, and tertiary industry value-added growth rates increased by 5%, 10%, and 15% respectively.

Scenario 4 (Prioritizing Resource Conservation): Emphasizes improving water and energy use efficiency. Based on water usage research [**?**, **?**] and actual conditions in Yellow River Basin provinces, agricultural, industrial, domestic, and ecological water use growth rates and energy consumption elasticity coefficient are moderately reduced.

Scenario 5 (Prioritizing Environmental Protection): Emphasizes strengthening ecological protection, controlling environmental pollution, and improving environmental quality. Based on environmental investment research [?, ?] and actual environmental protection investments in Yellow River Basin provinces, industrial wastewater, waste gas, and solid waste treatment investments are increased by 20%, 25%, and 30% respectively.

Scenario 6 (Collaborative Development): Emphasizes the combined effects of different policies. Based on comprehensive research [?, ?], the scenario coordinates socio-economic development, resource conservation, and environmental protection by adjusting variable magnitudes accordingly, with all adjustment ranges smaller than those in specific single-focus scenarios to promote balanced development.

The scenario design parameters are detailed in Table 2.

3 Results

3.1 Model Validation

As models are abstractions of reality under certain conditions, ensuring simulation quality requires validation of model authenticity and effectiveness before running simulations with Vensim software [?]. To verify model consistency with reality, simulated values for 2007-2018 were compared with historical data for representative variables including total population, GDP, total water consumption, total energy consumption, industrial COD treatment volume, industrial ammonia nitrogen treatment volume, industrial SO_2 treatment volume, industrial NO treatment volume, and completed pollution control investment. Validation results are presented in Table 3. When relative error is less than 10%, simulation performance is considered satisfactory [?]. Table 3 shows all variables have relative errors below 5%, indicating high consistency between model outputs and actual data, good predictive capability, and suitability for simulation.

3.2 Simulation Results

Using Vensim software, six scenarios for sustainable development of ecological environment and socio-economy in the Yellow River Basin were simulated, with results presented in Table 4.

Scenario 1 (Maintaining Status Quo): By 2030, total population and employed population will reach 4.39$\times10^{8}$ and 2.73$\times10^{8}$ respectively, representing increases of 9.66% and 17.31% over 2007. GDP will reach 35.88$\times10^{12}$ yuan, a 57.72% increase. Water and energy consumption per unit GDP will be 0.55 t and 47.18 t respectively, decreases of 70.65% and 71.04% from 2007. Industrial COD and SO_2 emissions will be 45.50$\times10^{4}$ t and 240.31$\times10^{4}$ t respectively, decreases of 70.42% and 63.60%. These results reflect improvements under enhanced central government emphasis on ecological protection and civilization construction.

Scenario 2 (Prioritizing Social Development): Total population, employed population, and GDP increase by 11.48%, 20.13%, and 406.31% respectively. Water and energy consumption per unit GDP decrease by 70.00% and 56.32%. Industrial COD and SO_2 emissions decrease by 69.37% and 68.72%. Social development outpaces other scenarios, while economic growth is slower than Scenario 3.

Scenario 3 (Prioritizing Economic Development): Total population, employed population, and GDP increase by 9.12%, 16.34%, and 531.27% respectively. Water and energy consumption per unit GDP decrease by 74.70% and 65.31%. Industrial COD and SO_2 emissions decrease by 63.60% and 61.98%. Economic growth significantly exceeds other scenarios, while social development is slightly slower than Scenario 2.

Scenario 4 (Prioritizing Resource Conservation): Total population, employed population, and GDP increase by 10.17%, 18.23%, and 448.58% respectively. Water and energy consumption per unit GDP decrease by 67.02% and 77.59%. Industrial COD and SO_2 emissions decrease by 74.09% and 76.97%. Resource conservation and pollution reduction outperform Scenario 1.

Scenario 5 (Prioritizing Environmental Protection): Total population, employed population, and GDP increase by 9.66%, 17.31%, and 391.05% respectively. Water and energy consumption per unit GDP decrease by 72.47% and 60.07%. Industrial COD and SO_2 emissions decrease by 87.67% and 85.83%. Pollution reduction significantly exceeds other scenarios.

Scenario 6 (Collaborative Development): Total population, employed population, and GDP increase by 10.93%, 19.62%, and 499.05% respectively. Water and energy consumption per unit GDP decrease by 78.31% and 68.16%. Industrial COD and SO_2 emissions decrease by 80.64% and 80.17%. This scenario outperforms others in socio-economic development speed, resource conservation, and pollution reduction.

3.3 Scenario Selection

To more intuitively compare development across scenarios, simulation results for each subsystem were analyzed. Figure 2 shows that total population maintains an upward trend across all six scenarios, with Scenarios 2 and 6 exhibiting higher growth rates. GDP also shows upward trends, with Scenarios 3 and 6 demonstrating faster economic growth. Water and energy consumption per unit GDP exhibit decreasing trends, with Scenarios 4 and 6 showing more rapid declines. Pollutant emissions decrease across all scenarios as pollution control investments increase, with Scenarios 5 and 6 showing particularly significant emission reductions.

Comprehensive analysis of simulation results indicates that Scenario 6 (collaborative development) simultaneously achieves rapid socio-economic development, improved resource use efficiency, and effective pollutant emission reduction.

Therefore, collaborative development is identified as the optimal pathway for sustainable development of ecological environment and socio-economy in the Yellow River Basin.

[Figure 2: see original paper]

4 Conclusions and Recommendations

This study constructs an SD model to simulate sustainable development of ecological environment and socio-economy in the Yellow River Basin. Four subsystems were established: social, economic, resource, and environmental. Six development scenarios were designed and simulated after model validation. Results show: (1) The SD model demonstrates good simulation performance and accurately reflects reality; (2) The collaborative development scenario represents the optimal solution for balancing socio-economic development with resource and environmental protection, accelerating social and economic progress while improving resource efficiency and ecological conditions in the Yellow River Basin.

Based on simulation results from the collaborative development scenario, the following policy recommendations are proposed:

Promote Coordinated Development Across Upper, Middle, and Lower Reaches: Social development increases employment and leverages demographic dividends to drive high-quality economic growth, while rapid economic development intensifies resource and environmental pressures. Therefore, upstream, midstream, and downstream regions should collaborate, targeting Yellow River Economic Belt construction as a strategic goal. Following differentiated development approaches based on main functional zones, regions should establish and adhere to resource consumption ceilings, ecological protection red lines, and environmental quality bottom lines, achieving win-win outcomes for socio-economic development and ecological conservation.

Adjust Industrial Spatial Structure and Improve Resource Efficiency: The Yellow River Basin' s sustainability requires holistic planning. Industrial spatial structure should be adjusted to achieve complementary advantages and mutual benefits. Based on regional comparative advantages, industrial restructuring and upgrading should be promoted across the basin to enhance industrial complementarity and connectivity, improve resource demand structure, increase resource use efficiency, and reduce pollutant emissions, thereby alleviating environmental pressure from economic development. New technologies should be developed and introduced to promote energy-efficient products and emerging industries, achieving social, economic, and environmental benefits in pursuit of a green economy.

Improve Public Participation and Supervision Systems: The public are both beneficiaries of environmental protection and victims of environmental degradation. Public ownership consciousness should be strengthened to encourage actual participation in policy implementation and fulfillment of corresponding obligations. Sustainable development in the Yellow River Basin must rely on public support, as effective participation facilitates environmental law enforcement, reduces policy supervision costs, ensures transparent implementation, and complements performance evaluation systems. Public participation is crucial for strengthening policy implementation and supporting high-quality development in the Yellow River Basin.

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