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Modeling and Evaluating the Socio-Economic–Flood Safety–Ecological System of Landong Floodplain Using System Dynamics and the Weighted Coupling Coordination Degree Model

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Abstract: The lower course of the Yellow River is a "hanging river" across the hinterland of China, and the safety of its flood control measures/systems is closely tied to the stability of the nation. Ensuring high-quality, sustainable development of the lower Yellow River floodplain while maintaining flood safety is crucial for the entire Yellow River Basin. Previous studies have primarily focused on the overall development of the Yellow River Basin or the economic–ecological coupling development of cities along the river, often neglecting the flood safety development of the floodplain. This study optimizes the socio-economic–flood-safety–ecological (SFE) system of the typical downstream Landong floodplain within the Yellow River Basin. The system dynamics model (SDM) can simulate the dynamic behavior of SFE systems by constructing mathematical models that incorporate feedback loops and time delays. The primary components include causal loop modules and stock-flow modules. Then, a coupling coordination degree model for the Landong floodplain is established using a comprehensive subjective and objective weighting method, assessing the SFE system's coordination under five scenarios: inertial development, economic development, environmental protection, flood safety, and sustainable development. The results of historical and validity tests indicate that the SDM can effectively simulate the coupling coordination degree of the SFE system. The study results suggest that the coupling coordination degree increases the most under the sustainable development scenario, indicating that the development of the Landong floodplain should not only focus on socio-economic growth, but should also consider flood safety and ecological concerns. In addition, comprehensive regulation from socio-economic, flood safety, and ecological environment indicators are necessary to achieve high-quality, coordinated development. This study has significant implications for policy formulation and management to achieve high-quality and sustainable development in the downstream floodplain of the Yellow River.

Keywords: coupling coordination degree; ecology; flood safety; Landong floodplain; system dynamics; socio-economic impact; socio-economic–flood-safety–ecological system

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1. Introduction

The Yellow River, known as the "Mother River", nurtures Chinese civilization [1]. The downstream of the Yellow River is a typical alluvial compound river channel, including the main channel and the floodplain [2,3]. The floodplain was the main venue for flood discharge, flood detention, and sediment deposition downstream of the Yellow River. It is

also a habitat for millions of people living in the floodplain [4]. The floodplain has the dual attributes of "river-society" [5]. The lives and livelihoods of the residents in the floodplain area were closely intertwined with the Yellow River, and the management and development of this area directly impacted the stability and progress of the local society. However, due to its remote geographical location and the scarcity of natural resources, the economic and social development of the Yellow River floodplain has lagged behind, leading to lower living standards for the residents in the coastal region [6]. The tension between poverty alleviation and flood safety planning has become more acute as the coastal region of the Yellow River Basin experiences rapid economic and social development. The floodplain's development no longer meets the needs of the times and has become a concentrated area of poverty along the Yellow River in the Henan and Shandong provinces. In the face of the potential risks to flood safety in the downstream of the Yellow River [3,7,8], due to the underdevelopment of the floodplain and challenges such as flood losses, it is imperative to investigate ways through which to enhance the downstream Yellow River floodplain and devise effective management strategies to ensure flood safety and promote sustainable social and economic development in the region.

The "Yellow River Basin Ecological Protection and High-Quality Development Plan" put forward new requirements for promoting the sustainable development of floodplains and comprehensive ecological management, etc. Many scholars have also focused on these issues [9–15], Ji believed that swift economic expansion in the Henan region of the Yellow River Basin calls for a holistic strategy to manage land demand and development conflicts, while also aligning economic advancement with ecological protection [16]. Zhu suggested establishing and improving the ecological compensation mechanism and advocating for incorporating ecological benefits into the economic development framework [11]. Lu applied the DPSIR framework to create an environmental benefit assessment system for the Yellow River Basin, examining 70 cities from 2001 to 2020 and uncovering the relationship between industrial value and economic growth [17].

To explore more effective strategies for managing regional high-quality development, scholars have conducted research on the sustainable and coordinated development of the Yellow River Basin [18–24]. For instance, Ren studied the spatiotemporal weighted regression theory and constructed a "social-ecological-policy" ternary system to explore the coordinated development mechanism of the system for the well-being of different regions. They argued that coordinated development requires prioritizing effective and targeted decision making [25]. Wang developed a comprehensive evaluation index system based on the dimensions of ecology, living, and production, utilizing the entropy weight TOPSIS method to establish a comprehensive measurement model and a coupling coordination degree model for the high-quality development levels and coupling coordination degree of 61 cities in the Yellow River Basin. They found significant spatial differences in the high-quality development level of the Yellow River Basin, and the CCD was not substantial in its spatial distribution [9]. Sui devised a comprehensive theoretical framework to assess different provinces in the Yellow River Basin and provided policy recommendations for their sustainable development based on the coupling coordination degree and related factors [26].

The dual attributes of the river-society factors in the floodplain region of the lower Yellow River make flood control a prerequisite for the development of this area. Consequently, coordinating flood safety with other systems has become a key focus of the "Yellow River Basin Ecological Protection and High-Quality Development Plan". However, previous studies have mainly concentrated on the interactions between socio-economic systems and ecological systems, with only a few scholars considering the role of flood safety in the coordinated development of multiple systems. These studies have rarely examined the intricate interconnections between socio-economic, flood safety, and ecological factors in the downstream floodplain of the Yellow River. As shown in Figure 1, the socio-economic–flood (SEF) system represents a complex network of interdependencies among its subsystems [27]. Therefore, investigating the coupled and coordinated development among socio-economic,

flood safety, and ecological factors in floodplain areas is of significant importance for the integrated management and high-quality sustainable development of the downstream floodplain region. Against this backdrop, this study focuses on the Landong floodplain, a typical downstream floodplain of the Yellow River, to address the prominent conflicts and issues of potential flood safety risks, lagging socio-economic development, and significant flood inundation losses in the downstream areas. We established a system dynamics model (SDM) for the SFE system of the Landong floodplain and validated the model's accuracy based on historical data. Under different policy scenarios, the SDM was utilized to track key system variables and to propose a comprehensive subjective and objective evaluation coupling coordination model for system assessment. This model evaluates the coupling coordination relationships of the SFE under various development scenarios. The method demonstrates good spatial and temporal adaptability [28], enabling a more comprehensive and in-depth understanding of the dynamic evolution of the SFE system under different scenarios. The objectives of this study are as follows: (1) to reveal the intrinsic driving mechanisms among the socio-economic development, flood safety, and ecological environments within the dual attributes of a "river channel-society"; (2) to explore the dynamic evolution trends of the coupling coordination degree of the SFE system in the Landong floodplain from 2006 to 2030; (3) to analyze the advantages and disadvantages of different development scenarios in order to identify the optimal scenario for enhancing system coupling coordination; and (4) to examine the strengths of the optimal scenario. This study aims to provide researchers and policymakers with a clearer understanding of the coupling relationships among the socio-economic, flood safety, and ecological factors in the floodplain, offering robust scientific evidence and decision-making support for formulating high-quality, sustainable development policies for the floodplain. It also serves as a valuable guide for implementing and advancing high-quality sustainable development strategies in others downstream floodplains of the Yellow River.

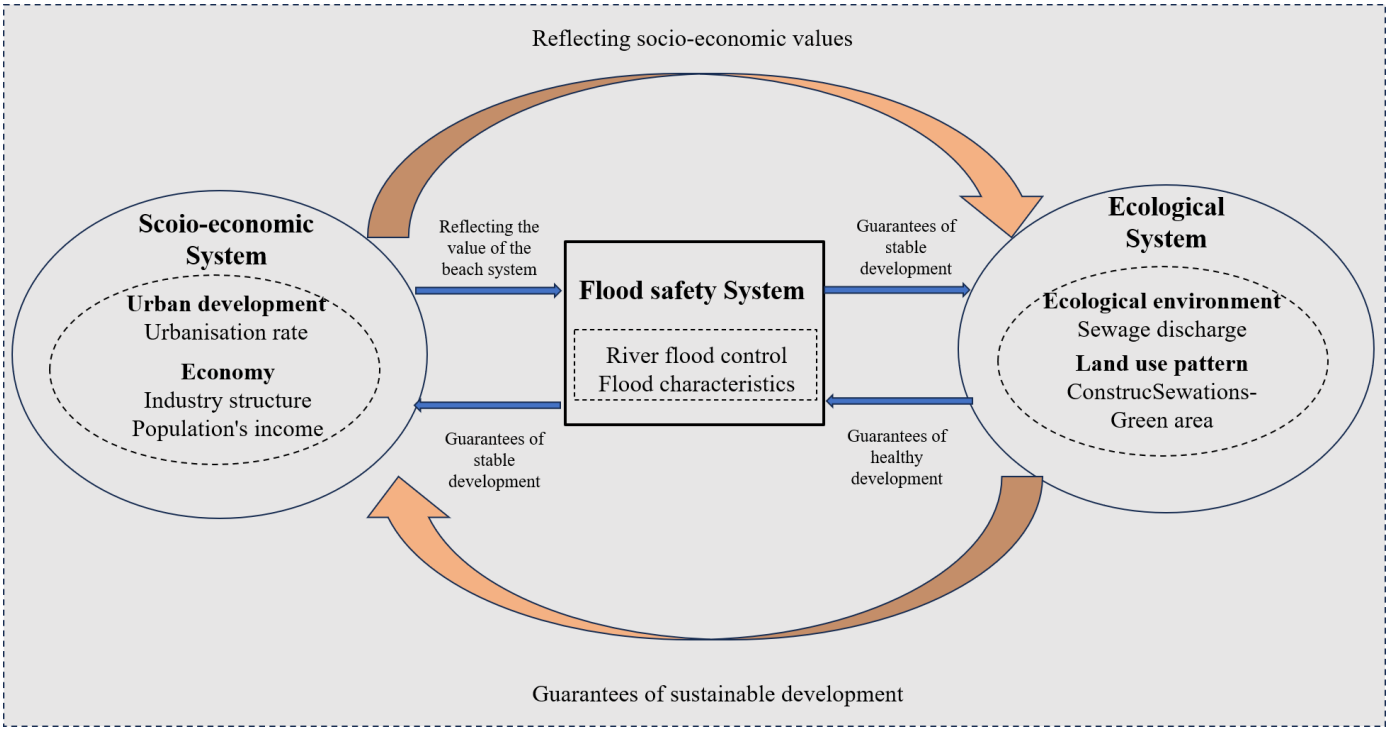

Figure 1. Relationships of the SFE system.

2. Materials and Methods

2.1. Overview of the Study Area

The Landong floodplain is a typical downstream floodplain of the Yellow River, and it is formed on a low floodplain due to extensive silt deposition following the 1855 breach and course change at Tongwaxiang in Lankao, Henan. It is located on the right bank at the great bend where the Yellow River transitions from an east–west to a northeast flow at Dongbatou; this section is characteristic of a meandering river [29]. This area encompasses the northern floodplain in Lankao County, Henan Province, and the southern floodplain in Dongming County, Shandong Province (as illustrated in Figure 2). It has a population of approximately 500,000 and approximately 600 km^2 of arable land. The Landong floodplain frequently experiences droughts, floods, and sediment disasters, with numerous opportunities for overbank flooding, creating extremely challenging production environments. Following overbank flooding, floodwaters frequently inundate crops. The river segment within the floodplain extends from the Dongbatou critical engineering site to the Laojuntang guiding project. Due to the incomplete layout of river control and critical engineering structures, they fail to fully protect the floodplain and villages. During flood season, overbank flooding occurs frequently, leading to recurring floods, a fragile ecological environment, and severe constraints on socio-economic production activities. The overall situation in the Landong floodplain reflects the actual conditions of the floodplain throughout the year, making it highly comprehensive and representative for research purposes.

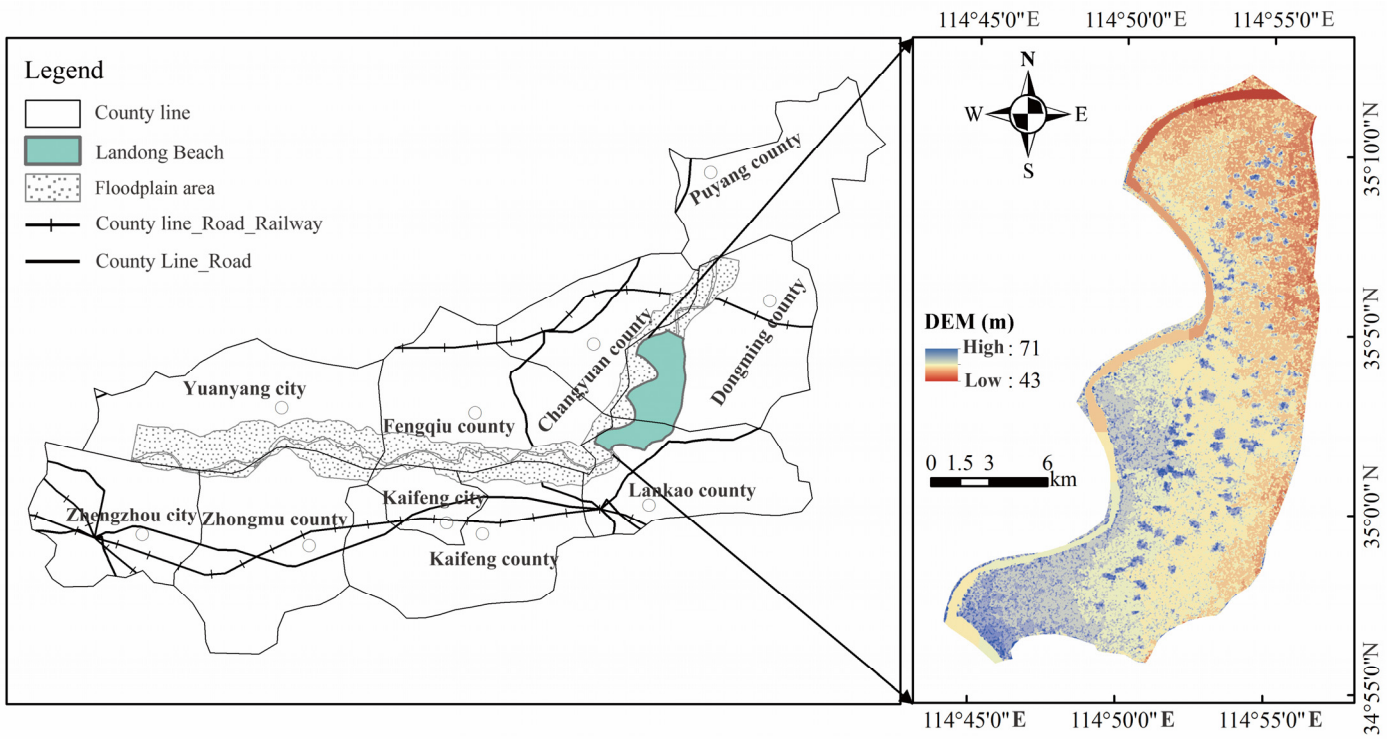

Figure 2. Diagram of the study area.

Since the founding of the People's Republic of China, the Landong floodplain has experienced numerous overbank floods. With rapid economic development, some residents have relocated from the floodplain, and some villages have built elevated platforms to mitigate flood damage. Nevertheless, the floodplain still remains home to hundreds of thousands of people. Therefore, this study aims to analyze and evaluate the coordinated development relationships among various systems within the Landong floodplain, seeking scientific management strategies to promote the healthy and synergistic development of the socio-economic, flood safety, and ecological systems in the downstream floodplain of the Yellow River.

2.2. Data Processing

The comprehensive evaluation index system and historical data used by the SDM were derived from relevant studies in the field. Following preliminary screening, these data are relatively detailed and reliable. These data include the Kaifeng Statistical Yearbook, Heze Statistical Yearbook, Lankao Statistical Yearbook, Dongming Statistical Yearbook, China County Statistical Yearbook, Water Resources Bulletin, the flood safety data provided by the Yellow River Water Conservancy Research Institute, and relevant government work reports. The data encompass socio-economic, flood safety, and ecological environment data from 2006 to 2020. Given that some data had to be obtained indirectly and were influenced by practical applications and the varying capabilities of different cities, inconsistencies exist in the compilation standards of the statistical yearbooks across these cities. Moreover, there are differences in the directories and contents of different chapters. To address the issue of missing data for certain variables in a few years, methods such as mean interpolation, regression analysis, and variable deletion were employed. The specific data sources are detailed in Table 1.

Table 1. Data sources.

Data Types	Sub-Area Indicators	Data Sources
Socio-Economic	Total population, Birth rate, Mortality rate, Rural population, Urban population, Population exodus, Urbanization rate, Value added of primary industry, Value added of secondary industry, Value added of tertiary industry, Industrial output, GDP, Rural disposable income, Per capita disposable income of urban residents, Crop production, Rural disposable income, Cropland area, Effective irrigated area, Sown area, and Gross power of agricultural machinery	2006–2020 Kaifeng Statistical Yearbook, Heze Statistical Yearbook, Lankao Statistical Yearbook, Dongming, Statistical Yearbook, and China County Statistical Yearbook.
Flood Safety	Waterway aspect ratio, Peak flow, River bend coefficient, Flatwater flow, and Mainstream swing variation	The Yellow River Institute of Water Resources Research (YRIWRR) provided statistical data from 2006 to 2020 for the reach from Jiahetan to Gaocun. The mean interpolation method was used for the width-to-depth ratio and bending coefficient of the river section.
	Peak flow, Flatwater flow, and Inundated area	The water inflow and inundation area in the 1977 and 1996 research statistics were used.
Ecological	Domestic sewage discharge, Industrial effluent discharge, Residential water quotas, Industrial water quotas, Agricultural water use, Domestic water consumption, Industrial water consumption, Suitable ecological runoff guarantee rate, and Ecological water recharge	Kaifeng Water Resources Bulletin, Heze Water Resources Bulletin, 2006–2020.
	Green area and Construction site area	Land-use classification statistics using satellite imagery data from 2006 to 2020.

2.3. Methods

2.3.1. System Dynamic Modeling (SDM) of the SFE

System dynamics (SD) is a simulation methodology that was introduced by J.W. Forrester in 1956, and it was initially referred to as industrial dynamics [30]. At its core, the SDM seeks to elucidate the dynamic behavior of systems through the identification and analysis of internal feedback loops, time delays, and nonlinear relationships. SDM

utilizes quantitative analysis and simulation techniques to explore and predict the long-term behavior of systems, elucidating the causal relationships and feedback mechanisms within a system [31], identifying systemic problems and devising solutions. The SDM is particularly suited for the comprehensive study of complex, multi-level, multi-sector, and nonlinear large-scale systems at both macro and micro levels [32,33]. This approach assists researchers and decision makers in gaining a deeper understanding of the intrinsic mechanisms and long-term dynamics of a system. The behaviors of systems in SD are based on real-world scenarios and arise from the various causal relationships within the system [34]. Although SD focuses on closed social systems, it is not constrained by linear assumptions, allowing for the improvement of system behavior through parameter and structural adjustments. The SDM utilizes Vensim (version number 10.1.5) software to create a visual representation of a model. Internally, it uses precise relationships to depict the connections between variables, while, externally, it is presented as a causal loop diagram. The main implementation steps are as follows: determining the research content and system boundaries; selecting model variables; setting the model running time, step size; drawing causal loop diagrams; drawing stock flow diagrams; entering equations; testing model completeness and sensitivity; and setting up multi-scenario analyses. SDM is divided into four main types of equations in describing the relationship between different variables: state equations, rate equations, auxiliary equations, and table functions.

The following equation of state is mainly used to describe the state of the variable at each point in time:

$$LK = LJ + DT(IR.JK - OR.JK), \tag{1}$$

where LK and LJ denote the state of variable J at the moment K and J; JK is the time difference between the moment K and J; DT denotes the simulation time, the size of which is equal to JK; and $IR.JK$ and $OR.JK$ are the velocity variables.

The following rate equation is an equation that expresses the amount of change per unit time of a system, and it corresponds to the rate variable:

$$IR.JK - OR.JK = \frac{LK - LJ}{DT}. \tag{2}$$

Auxiliary equations are equations used to describe the relationship between level and rate variables, corresponding to intermediate variables.

The table function represents the changes between some variables in the model showing a non-linear relationship, which need to be represented by non-linear data.

In this study, Vensim PLE (version number 10.1.5) software was used to construct a system dynamics model (SDM) of the socio-economic–flood (SEF) system to simulate the future development of the floodplain [35]. This approach effectively captures the specific trends in the driving factors of complex systems' coupling coordination degree (CCD) and other internal variables [36]. The spatial boundary of the model covers the Landong Floodplain, which includes Lankao County and Dongming County, and the temporal boundary spans from 2006 to 2030, with 2006 as the historical base year and 2021 as the starting year of this study. The period from 2006 to 2020 serves as the model validation phase, while 2021 to 2030 constitutes the prediction phase, with a time step of one year.

2.3.2. Causality of System Variables

The causal loop relationship diagram in the SDM illustrates the causal relationships between crucial indicator variables within the SFE system and aids in analyzing the dynamic behavior of the system [37]. This diagram offers initial insights and references for constructing stock and flow diagrams [38]. By integrating the internal constraints of relevant variables in the Landong floodplain system of the lower reaches of the Yellow River and their mutual feedback mechanisms, we developed the causal loop diagram for the main variables in the SFE system. In this diagram, positive (+) causal chains represent reinforcing loops, while negative (−) causal chains represent balancing loops with a weakening inhibitory effect [39,40]. The causal loop diagram is shown in Figure 3.

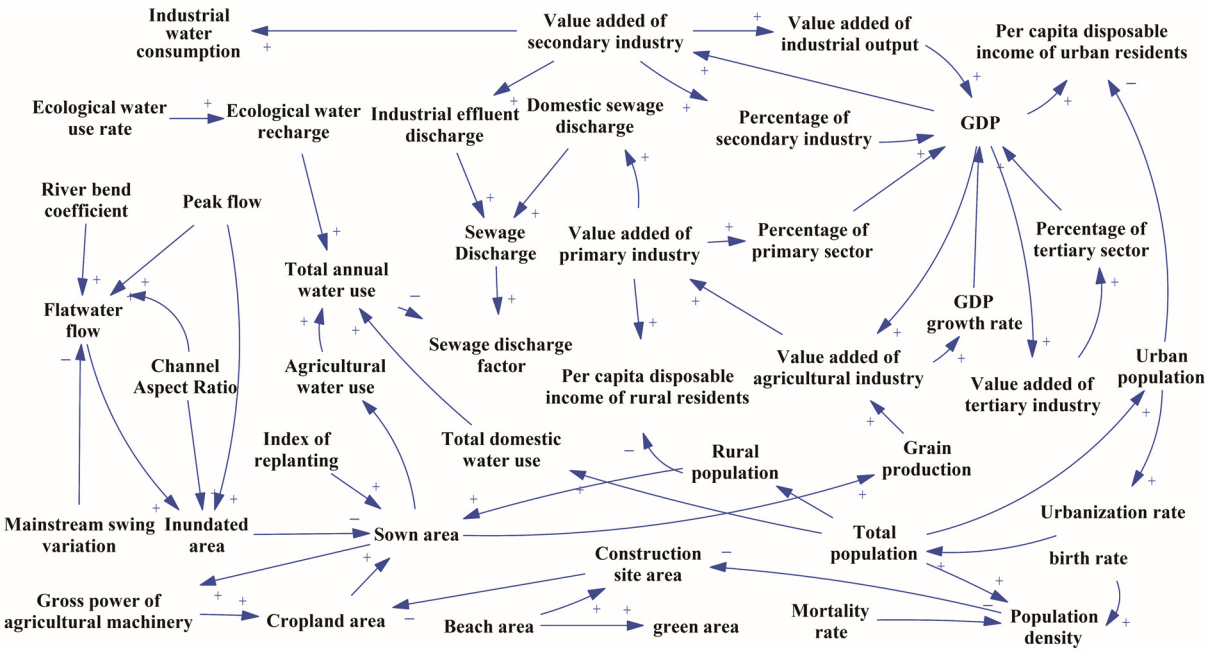

Figure 3. Causal loop diagram of the SFE system.

The socio-economic subsystem provides a macro-level reflection of the economy and the daily quality of life for residents [41]. The flood safety subsystem primarily examines the impact of various flood magnitudes and river segment characteristics on the floodplain system. The ecological environment subsystem focuses on the total water use and total wastewater discharges for both production and domestic use in the floodplain, as well as the environmental conditions that affect the entire system [42]. The human exploitation and utilization of the floodplain drive economic growth but inevitably lead to substantial consumption of natural resources. During rapid social expansion and industrialization, the overuse of land and water resources in the floodplain causes alterations to the topography and geomorphology, subsequently impacting flood safety [43]. Additionally, rapid population growth leads to the over-exploitation of resources, exerting immense pressure on the local ecological environment's carrying capacity.

2.3.3. System Flow Diagram Construction

The aforementioned causal feedback loops do not fully represent the accumulations within the system, necessitating the inclusion of auxiliary variables that link the primary variables to describe the system's structure and interrelationships. When constructing an SDM, it is crucial to determine the attributes of each variable based on their characteristics and changes over time. The model's variables include state, rate, and auxiliary variables [44]. State variables describe indicators that accumulate over time and are often accompa-nied by rate variables. Rate variables depict the speed and trends of changes in horizontal variables, while auxiliary variables connect and influence state and rate variables. They form an integrated system through the combination and interaction of multiple variables. The SDM in this study comprises 3 state variables (the GDP, Total population, and the Cropland area), 4 rate variables (the Volume of change in GDP, Change in cropland area, and the Number of population increases and decreases), and 51 variables (the other remaining variables). The stock-flow diagram of the SFE system is illustrated in Figure 4.

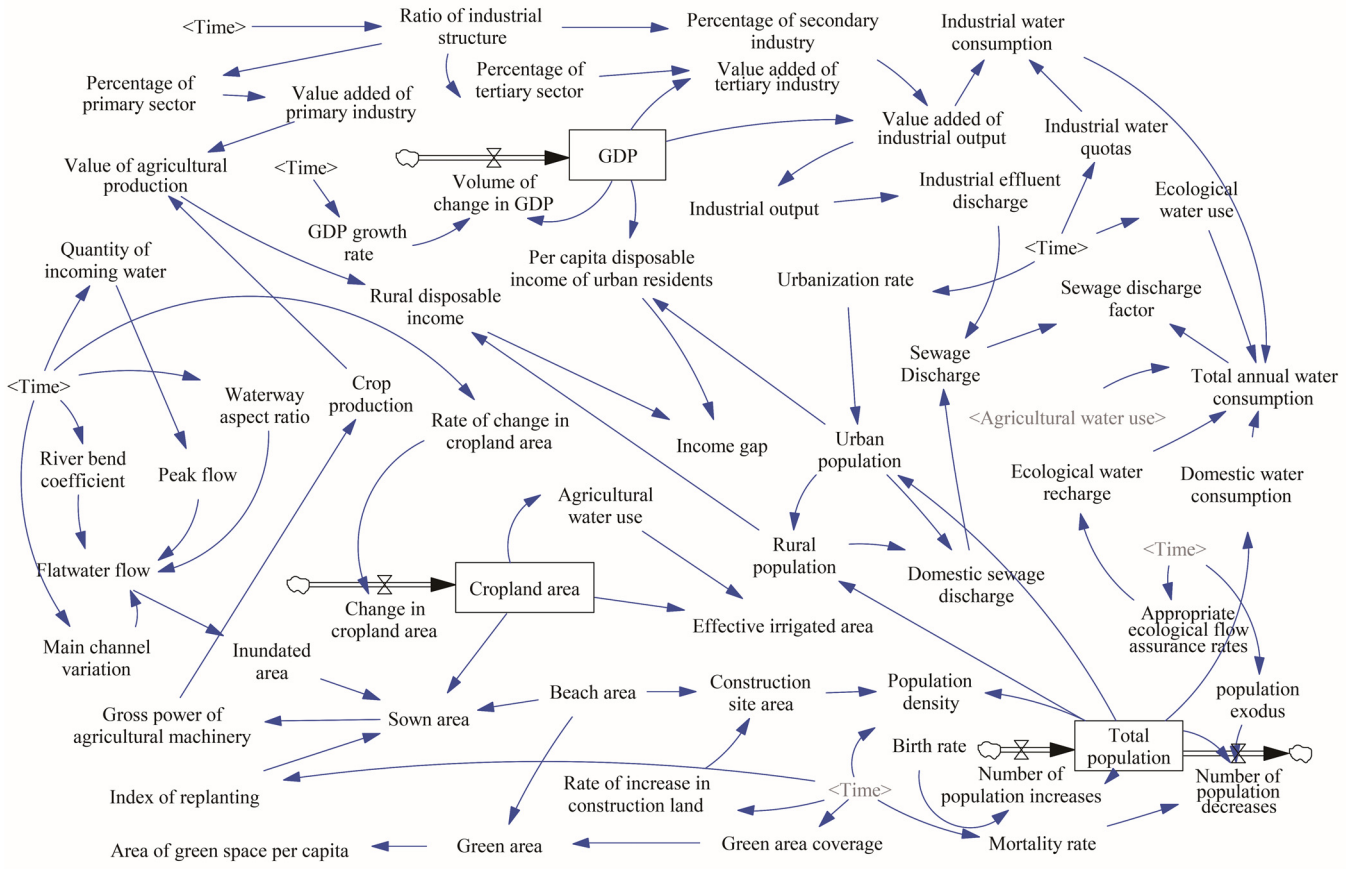

Figure 4. Stock and flow diagram of the SFE system.

2.3.4. Model Parameters and Equation Setup

Variables are connected through external arrows and internal equations, with the arrow's starting point typically representing the causal variable and the endpoint representing the effect variable. The equations describe the key interactions and interrelationships among the variables within the system, expressing the causal relationships between them. The equations in the system can take the following forms:

(1) Integral type

In the context of parameter variables, "INTEG" denotes the integration of changes based on the initial value. The integral type function is applied to the level variable, as illustrated in Table 2.

Table 2. Integral type equations.

Indicator Variables	Equation Relating a Variable	Variable Meaning	Unit
GDP	INTEG (Change in GDP, 33.92)	Cumulative GDP	10^9 CNY
Total population	INTEG (Number of population increases–Number of population decreases–Population exodus, 35.35)	Total cumulative population	10^4
Cropland area	INTEG (Change in cropland area, 42.21)	Cumulative amount of arable land area	10^3 hm^2

(2) Table functions

Setting up table functions involves first determining the variable ranges and their value intervals. Next, the function's changing trends must be identified, and any critical points need to be pinpointed. The primary table functions included in this study are as follows: GDP growth rate = [(2006, −0.03) − (2020, 1)]; Rate of change in cropland area = [(2006, −0.2) − (2020, 30)]; Urbanization rate = [(2006, 0) − (2020, 1); Suitable

ecological runoff guarantee rate = [(2006, 0.7) − (2020, 1)]; Ecological environment water supplementation rate = ([(2006, 0) − (2020, 40)]; and River segment width-to-depth ratio = ([(2006, 6) − (2020, 8)]. Units: Dmnl.

(3) Ordinary relational equations

The establishment of the fundamental relationships primarily references several key documents, with relevant parameters primarily sourced from the Water Resources Bulletin. Some of the quotas are based on the "Quota for Agricultural and Rural Domestic Water Use in Henan Province", the "Quota for Industrial and Urban Domestic Water Use in Henan Province", and the "Central Plains Economic Zone Plan" (2012–2020). These parameters were adjusted to align with the actual development conditions of the Landong floodplain. The ordinary relational equations for the main variables in the model are shown in Table 3.

Table 3. Ordinary relational equations.

Indicator Variables	Equation Relating a Variable	Variable Meaning	Unit
Change in GDP	GDP growth rate × GDP	Economic development growth rate	10^9 CNY
Value added of primary industry	Percentage of primary sector × GDP	Technical level and efficiency of primary sector	10^9 CNY
Value added of secondary industry	Percentage of secondary industry × GDP	Technical level and efficiency of secondary sector	10^9 CNY
Value added of tertiary industry	Percentage of tertiary sector × GDP	Technical level and efficiency of tertiary production	10^9 CNY
Rural disposable income	Rural disposable income/Rural population	Per capita income level of rural residents	CNY
Income gap	Per capita disposable income of urban residents–Per capita disposable income of rural residents	Urban–rural income gap	CNY
Urban population	Total population × Urbanization rate	Urban population base	10^4
Rural population	Total population − Urban population	Rural population base	10^4
Population density	Total population/Construction site area	Population distribution	10^3 people/km^2
Sown area	Index of replanting × Cropland area–Inundated area	Crop sown area situation	10^3 hm^2
Industrial effluent discharge	Industrial output × Discharge of effluent per unit of industrial estate	Impact of industrial effluents on the water environment	10^4 m^3
Domestic sewage discharge	Urban population × Sewage discharge per capita in cities + Rural population × Rural sewage discharge per capita	Impact of domestic sewage on the water environment	10^4 m^3
Sewage discharge	Industrial effluent discharge + Domestic sewage discharge	Sewage discharge	10^4 m^3
Total annual water consumption	Industrial water consumption + Domestic water consumption + Agricultural water use + Ecological water use	Total water consumption by sector	10^9 m^3
Sewage discharge factor	Sewage Discharge/Total annual water consumption	Sewage discharge ratio	/
Green area coverage	Green area/Total area of the study area	Characterize the extent to which ecological conditions support the environment	/
Area of green space per capita	Green area/Total population	Characterizing the pressures of population activities on the environment	km^2/10^4 people

(4) Fitting relational equations

For variables that cannot be directly assigned values and lack conventional logical relationships, regression analysis was employed to process and fit the collected data, thereby identifying the logical relationships between variables. Table 4 presents the regression-fitted equations derived from annual data. Specifically, the ecological environment water supplementation amount was modeled as a function of the suitable ecological flow guarantee rate (the independent variable) and the ecological environment water supplementation amount (the dependent variable). The correlation between the flatland flow, mainstream swing variation, and peak flow was significant; thus, their time series data were used to fit the relationship equations. Here, peak flow refers to the peak flow meeting designated flood safety standards. The inundation area was fitted using flood data from 1977 and 1996.

Table 4. Fitting relational equations.

Indicator Variables	Equation Relating a Variable	Variable Meaning	Unit
Per capita disposable income of urban residents	0.47 × GDP/Total population	Per capita income level of urban residents	CNY
Ecological water recharge	0.868–0.308 × Suitable ecological runoff guarantee rate	Water use in the ecosystem	10^9 m^3
Flatwater flow	9765.78–2.25 × Mainstream swing variation + 0.0003 × Peak flow	Incoming water flow in the floodplain	m^3/s
Inundated area	2.34×10^9 + 0.000213 × Flatwater flow	Flooding of the floodplain	m^2
Ecological water use	0.868–0.308 × Suitable ecological runoff guarantee rate	Water use in the ecosystem	10^9 m^3

2.3.5. SD Model Historical Validation and Sensitivity Analysis

Before conducting a simulation, the system dynamics model (SDM) must undergo validity testing and sensitivity analysis. Validity testing includes structural rationality testing and historical testing. The structural rationality of the model was tested using the "Units Check" and "Check Model" functions in Vensim (version number 10.1.5) software. The "Units Check" function ensures consistency in the units of the variables and parameters across all equations and formulas within the model. The "Check Model" function confirms the logical correctness of equations, parameters, and variables. These tests guarantee dimensional consistency, the appropriateness of equations under extreme conditions, and the correctness of model boundaries. The results indicate that the model passed the rationality tests. Historical testing involved comparing the model's output with actual historical data to evaluate its accuracy and adaptability, thereby guiding its refinement and optimization. If the errors of various indicators in the model are within a 10% margin, this suggests a high degree of alignment between the model and the real-world situation [45,46]. The historical test formula is shown in Equation (3):

$$E_i = \frac{M_i - m_i}{m_i} \times 100\%, \quad (3)$$

where E_i is the historical validation error value, and M_i and m_i denote the simulation results and historical data values of the variables, respectively.

Sensitivity analysis is a method used to test whether the internal responses of the SDM to changes in important indicators align with logical variations. By observing the direction and magnitude of these changes, one can assess the reliability and sensitivity of the model [47].

$$L_D = \left| \frac{\Delta D_{(t)} X_{(t)}}{D_{(t)} \Delta X_{(t)}} \right|, \quad (4)$$

where t represents time; L_D denotes the sensitivity of the state variable D to the parameter X; $D_{(t)}$ and $X_{(t)}$ are the values of D and X at time t, respectively; and $\Delta D_{(t)}$ and $\Delta X_{(t)}$ are the increments of D and X at time t, respectively [48].

For n state variables (D_1, D_2, D_3, ... D_{n-1}, D_n), the average sensitivity of any parameter X at time t is given by the following:

$$L_D = \frac{1}{n} \times \sum_{i=1}^{n} L_{D_i}, \quad (5)$$

where L_{D_i} represents the sensitivity of D_i; L is the average sensitivity of parameter X across n state variables; and n is the number of state variables.

2.3.6. Multi-Scenario Settings

This study was designed to analyze the dynamic behavior of the complex socio-economic, flood safety, and ecological environment system in the Landong floodplain. It aimed to discern the optimal simulation scenarios for system coupling coordination and to delineate the dynamic responses of different influential variables within the integrated system. The objective was to offer a clear visualization of abstract relationships. Field investigations in the Lantong riparian area, combined with local development plans (such as the "Yellow River Basin flood safety Plan", the "Integrated Plan for the Yellow River Basin (2012–2030)", the "Outline of the Yellow River Basin Ecological Protection and High-Quality Development Plan", the "Fourteenth Five-Year Plan for National Economic and Social Development and Vision 2035 of Kaifeng City", and the "Fourteenth Five-Year Plan for National Economic and Social Development and Vision 2035 of Heze City") and consideration of the socio-economic, flood safety, and ecological realities of the Landong floodplain area led to a preliminary screening of sensitivity parameters. A total of 7 sensitive parameters were selected as control variables: GDP growth rate, Urbanization rate, Green area coverage, Suitable ecological runoff guarantee rate, Ecological water use rate, Peak flow, and Mainstream swing variation. The parameters were adjusted across multiple dimensions, including the rapid economic advancement in the riparian zone, the intensification of environmental conservation measures, the enhancement of flood safety standards, and the coordination of holistic development strategies. The socio-economic, flood safety, and ecological development statuses of the riparian area were analyzed and compared across various prioritized development scenarios. Five scenario models were established by adjusting parameters from distinct perspectives, encompassing inertial development, economic prioritization, environmental conservation, flood safety enhancement, and sustainable development. These scenarios were crafted by focusing on rapid economic progression, bolstering environmental protection initiatives, upgrading flood safety measures, and fostering comprehensive growth.

The inertial development model is primarily focused on maintaining historical development trajectories, that is, the prevailing trend of development. It projects future scenarios based on existing design criteria and pertinent data. The economic development scenario is geared toward accelerating GDP growth and urbanization rates as key policy levers, with the objective of rapid economic expansion and across-the-board growth in all industries and sectors. This scenario postulates a 2% and 3% enhancement in GDP growth and urbanization rates, respectively, over the inertial development scenario. The environmental protection scenario is centered on enhancing green coverage and ecological water usage rates as primary regulatory objectives. Its goal is to conserve and improve the local ecological environment, actively aligning with initiatives for ecological civilization. In this scenario, the green coverage rate and ecological water usage rate are increased by 5% and 2%, respectively, compared to the inertial development scenario. The flood safety scenario ensures the efficacy of flood control infrastructure by diminishing the variation in mainstream oscillation and elevating defense criteria. It achieves a reduction in mainstream oscillation variation by 20 m and sets the flood defense criterion at 8000 m^3/s. Additional flood control measures are based on data from the year 2020. Finally, the sustainable

development scenario takes a holistic approach by integrating mid-to-high-level regulatory variables from the previously mentioned development strategies. It aims to achieve sustainable development and long-term societal advancement through a coordinated regulation of various dimensions. The specific parameter adjustments for each scenario are delineated in Table 5.

Table 5. The floodplain SFE SDM regulation parameters.

Control Indicators	Inertial Development	Economic Development	Environmentally Friendly	Flood Safety	Sustainable Development
GDP growth rate/%	10	12	9	9	11
Urbanization rate/%	42	45	43	42	43
Green area coverage rate/%	33	35	38	36	38
Suitable ecological runoff guarantee rate/%	90	88	92	95	92
Ecological water use rate/%	22	20	24	24	23
Peak/$m^3 \times s^{-1}$	6000	5500	6000	8000	7000
Mainstream swing variation/m	170	160	155	150	165

2.4. Coupled Coordination Degree Evaluation Model (CCD)

2.4.1. Evaluation Indicator System Establishment

In accordance with the principles of scientific rigor, comprehensiveness, hierarchy, representativeness, and operability, as well as the structural characteristics of the SFE system [49–51] and being in line with the principles of the sustainable and coupled coordinated development of the floodplain, this study took into account diverse demands and their interrelated constraints. Consequently, a set of indicators were initially selected from the system dynamics (SD) model to formulate the indicator system, which is presented in Table 6.

Table 6. Interpretation of the evaluation indicators.

Target Level	Tier 1 Indicator Guideline Level	Secondary Indicator Level	Indicator Properties
Level of coordinated development of the EFE system coupling in the lower Yellow River floodplain	Socio-economic	GDP per capita	+
		Percentage of primary sector	+
		Percentage of secondary industry	+
		Percentage of tertiary sector	+
		Sown area	+
		Per capita disposable income of rural residents	+
		Urbanization rate	+
	Flood safety	River bend coefficient	−
		Waterway aspect ratio	−
		Mainstream swing variation	−
		Peak flow	+
		Flatwater flow	+
	Ecological	Industrial effluent discharge	−
		Domestic sewage discharge	−
		Ecological water use rate	+
		Suitable ecological runoff guarantee rate	+
		Green area coverage	+
		Construction site area	+
		Ecological water recharge	+

2.4.2. Data Preprocessing

This study employed a normalization method to standardize the raw data, aiming to reduce the differences between various indicator variables [52]. The formula is detailed below.

For the positive indicators:

$$r_{ij} = \frac{n_{ij} - \min(n_{ij})}{\max(n_{ij}) - \min(n_{ij})}. \quad (6)$$

For the negative indicators:

$$r_{ij} = \frac{\max(n_{ij}) - n_{ij}}{\max(n_{ij}) - \min(n_{ij})}, \quad (7)$$

where i is the year; j is the index; n_{ij} denotes the original indicator value; max(n_{ij}) and min(n_{ij}) denote the maximum and minimum values in the original data set, respectively; and r_{ij} denotes the original and standardized values j in year i.

2.4.3. Comprehensive Evaluation of Subsystems

In this study, primary indicators were challenging to quantify directly, and the Analytic Hierarchy Process (AHP) was better suited for determining the subjective weights. Therefore, AHP was used to address the complex decision-making analysis issues associated with the coupled system in the research area [53]. Secondary indicators were readily quantifiable, and the application of the entropy weight method for calculating objective weights helped to mitigate the impact of subjective biases [54]. Each of these methods have their respective strengths and limitations, but they can also complement each other to a certain degree. Therefore, this study adopted a combined subjective and objective weighting method [55], specifically the integration of the entropy weight method and AHP. This combined method enhanced the scientific validity and precision of the indicator weights, thereby providing a more accurate reflection of the relative importance of different indicators. The formula for the AHP is as follows:

$$A = (a_{ij})_{n\times n} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}, \quad (8)$$

$$\overline{W_i} = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} (i, j = 1, 2, \cdots n), \quad (9)$$

$$W_i = \frac{\overline{W_i}}{\sum_{i=1}^{n} \overline{W_i}} (i = 1, 2, \cdots n), \quad (10)$$

where a_{ij} is the ratio scale, indicating the relative importance of element i compared to element j at the same level; $\overline{W_i}$ represents the n-th root of the product of the ratios; and W_i is the weight value.

AHP consistency test:

$$CI = \frac{\lambda_{max}}{n-1}, \quad (11)$$

$$CR = \frac{CI}{RI}, \quad (12)$$

where λ_{max} denotes the maximum eigenvalue of the judgement matrix; CI is the consistency index; CR is the consistency ratio; and RI is the average random consistency index. When $CR < 0.1$, the judgement matrix A is considered to have satisfactory agreement.

In order to analyze the impact of each indicator on the SFE system in different year intervals, the 15-year data from 2006 to 2020 were divided into 5-year intervals for the calculation of indicator weights. The entropy weighting method was used to calculate the objective weights of the indicators separately in each subsystem, and the hierarchical analysis method was carried out between subsystems. By scoring from 20 experts, we determined the coupling factors between pairs of indicators and selected the relatively important indicators. A judgement matrix was obtained, as shown in Table 7.

Table 7. Subsystem importance scale.

Level I Indicators	A	B	C
Socio-economic (A)	1	1/2	3
Flood safety (B)	2	1	2
Ecological (C)	1/3	1/2	1

The entropy method of assignment was calculated as follows [56]:

$$AR = \begin{bmatrix} r_{11} & \cdots & r_{1j} \\ \vdots & \ddots & \vdots \\ r_{i1} & \cdots & r_{ij} \end{bmatrix}_{m \times n}, \quad (13)$$

$$e_j = -k\sum_{i=1}^{m} r_{ij} ln r_{ij}, \quad (14)$$

$$W_j = \frac{1 - e_j}{\sum_{j=1}^{m}(1 - e_j)}, \quad (15)$$

where R represents the comprehensive evaluation matrix; i and j denote the i-th evaluation object and its corresponding j-th value, respectively (where i = 1,2,. . .,n); e_j is the entropy value; and W_j is the indicator weight determined by the entropy weight method.

2.4.4. Evaluation of the SFE System Coupling Harmonization

The coupling coordination degree (CCD) model assesses the levels of coordinated development between two or more systems, elucidating the coupling relationships or interdependencies among different systems. This facilitates an understanding of the dynamic interactions between systems [57]. By constructing mathematical models and standardizing indicators, the CCD model yields quantitative evaluation outcomes, which support the comparison and analysis of coupling coordination states across various scenarios. This method provides policymakers and managers with scientific evidence to optimize system management and decision-making processes. The lower reaches of the Yellow River constitute a complex multi-system region that necessitates the harmonization of development across diverse systems. Implementing a CCD model can effectively address the challenges of high-quality development in this area, enhance the efficiency and level of socio-economic progress, and preserve ecological equilibrium. This paper employs the CCD model to conduct a quantitative examination of the coupling coordination within the socio-economic–flood-safety–ecological (SFE) system. The formula is detailed below [58,59].

(1) Calculation of the comprehensive evaluation index:

$$Af(x) = \sum_{i=1}^{m} w_i \cdot x_i, \quad (16)$$

$$g(y) = \sum_{i=1}^{n} w_i \cdot y_i, \quad (17)$$

$$h(z) = \sum_{i=1}^{k} w_i \cdot z_i. \quad (18)$$

(2) Calculation of coupling:

$$C = \frac{3\sqrt[3]{f(x) \times g(y) \times h(z)}}{[f(x) + g(y) + h(z)]}. \quad (19)$$

(3) Calculation of CCD:

$$D = \sqrt{C \cdot T}, \quad (20)$$

$$T_{xyz} = af(x) + bg(y) + ch(z), \quad (21)$$

where C denotes the coupling degree; D represents the coupling coordination degree; T_{xyz} is the comprehensive safety evaluation index for the three subsystems; and a, b, and c are the weights of the three subsystems. Here, the safety evaluation indices of the three subsystems are considered equally important; thus, $a = b = c = 1/3$ [60]. The classification standards for evaluating the coupling coordination degree are shown in Table 8.

Table 8. CCD standardized grading.

D	**[0~0.1]**	**[0.1~0.2]**	**[0.2~0.3]**	**[0.3~0.4]**	**[0.4~0.5]**
Type of coordination	Extreme disarray	Severe disarray	Moderate disarray	Mild disarray	Approaching disarray
D	[0.5~0.6]	[0.6~0.7]	[0.7~0.8]	[0.8~0.9]	(0.9~1.0]
Type of coordination	Reluctantly coordinated	Primary coordination	Intermediate level coordination	Effectively coordinated	High-quality coordination

3. Results

3.1. SDM Historical Validation and Sensitivity Analysis

3.1.1. Historical Verification

Historical testing involves comparing the model's output with actual historical data to evaluate the model's accuracy and adaptability, thereby guiding its refinement and optimization [61]. The model's initial simulation year was set at 2006, with an annual time step. The historical statistical data spanned from 2006 to 2020. A high degree of concordance between the model's results and the actual data was suggested if the errors in various indicators were all less than 10% following error analysis [62]. The calculation of the relative error is presented in Equation (22). The results of the historical data verification for the four major variables are shown in Figure 5.

$$C_i = \frac{R_i - r_i}{r_i} \times 100\%. \quad (22)$$

In the equation, C_i represents the historical validation accuracy of the variable, while R_i and r_i, respectively, denote the simulated results and the historical data value of the variable.

The findings indicate that the historical data and simulation data for the Landong floodplain in the owner reaches of the Yellow River exhibited a generally consistent trend in terms of GDP, crop sown area, total population, and gross power of agricultural machinery. The average errors were 3.9%, 7.0%, 7.9%, and 3.3%, respectively. Except for a simulation error of 18% for the sown area during the period 2008–2010, all the other errors were generally within ±10%, indicating that the simulation results were relatively accurate. This suggests that the model effectively simulated the complex system of the Landong floodplain in the downstream Yellow River, providing a dependable foundation for scenario simulation and forecasting in this area.

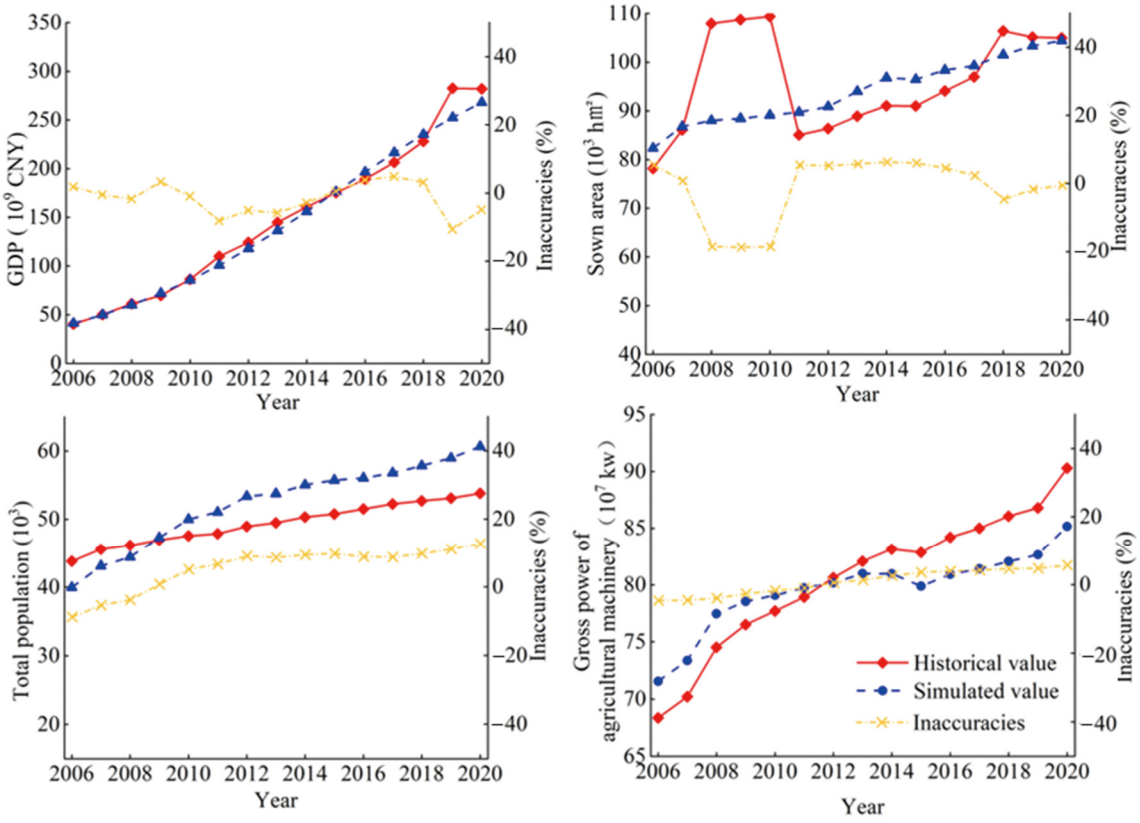

Figure 5. Historical data test results.

3.1.2. Sensitivity Analysis

The SFE system encompasses a multitude of parameters and variables. Following preliminary data processing and simulation, seven key parameters and five variables within the system were identified for further analysis. A sensitivity analysis model was constructed to examine the influence of the parameter variations on the outputs of the model's variables. Utilizing data from 2006 to 2020, the effect of incrementally increasing each parameter by 5% on the five variables was assessed. The sensitivity index (SQ) of each parameter to the individual variables was computed according to Equation (2). Subsequently, Equation (3) was employed to calculate the average sensitivity of the variables to the parameters, which reflects the impact of the parameters on the overall system model. The results presented in Table 9 indicate a significant correlation between the GDP growth rate and the five variables, with an average sensitivity value of 0.052. The average sensitivity of the five parameters to the system was less than 10%, implying that the system exhibited a high degree of stability [63].

Table 9. Sensitivity analysis results.

	GDP Growth Rate	Urbanization Rate	Peak Flow	Ecological Water Use	Appropriate Ecological Flow Assurance Rates	Green Area Coverage	Mainstream Swing Variation
GDP	0.231	0.002	0.000	0.000	0.001	0.000	0.000
Total population	0.001	0.001	0.000	0.000	0.000	0.000	0.000
Per capita disposable income of rural residents	0.012	0.02	0.000	0.000	0.000	0.000	0.001
Sown area	0.005	0.001	0.002	0.001	0.002	0.004	0.012
Sewage discharge factor	0.010	0.002	0.000	0.001	0.000	0.000	0.000
Mean value of sensitivity (S)	0.052	0.005	0.000	0.000	0.001	0.001	0.003

The primary objective of developing the model was to examine the impact of economic development planning and flood safety indicators on the socio-economic–flood-safety–ecological (SFE) system within the Landong floodplain of the lower Yellow River. Analysis of the system's causality loop diagram and flow diagram revealed that GDP is a pivotal factor in interconnecting the various subsystems, a finding that was corroborated by the results of the sensitivity model analysis. Consequently, the GDP growth rate, which exhibited the highest sensitivity, was selected as the regulatory variable. The range for the GDP growth rate was established from −10% to 10%, with −10%, −5%, 5%, and 10% serving as the test scenarios. Figure 6 depicts the comparative changes in GDP (in 10^9 CNY), total population (in 10^4), crop sown area (in 10^3 hm^3), the per capita disposable income of rural residents (in CNY), the domestic sewage discharge (in 10^4 m^3), and the ecological water replenishment (in 10^4 m^3).

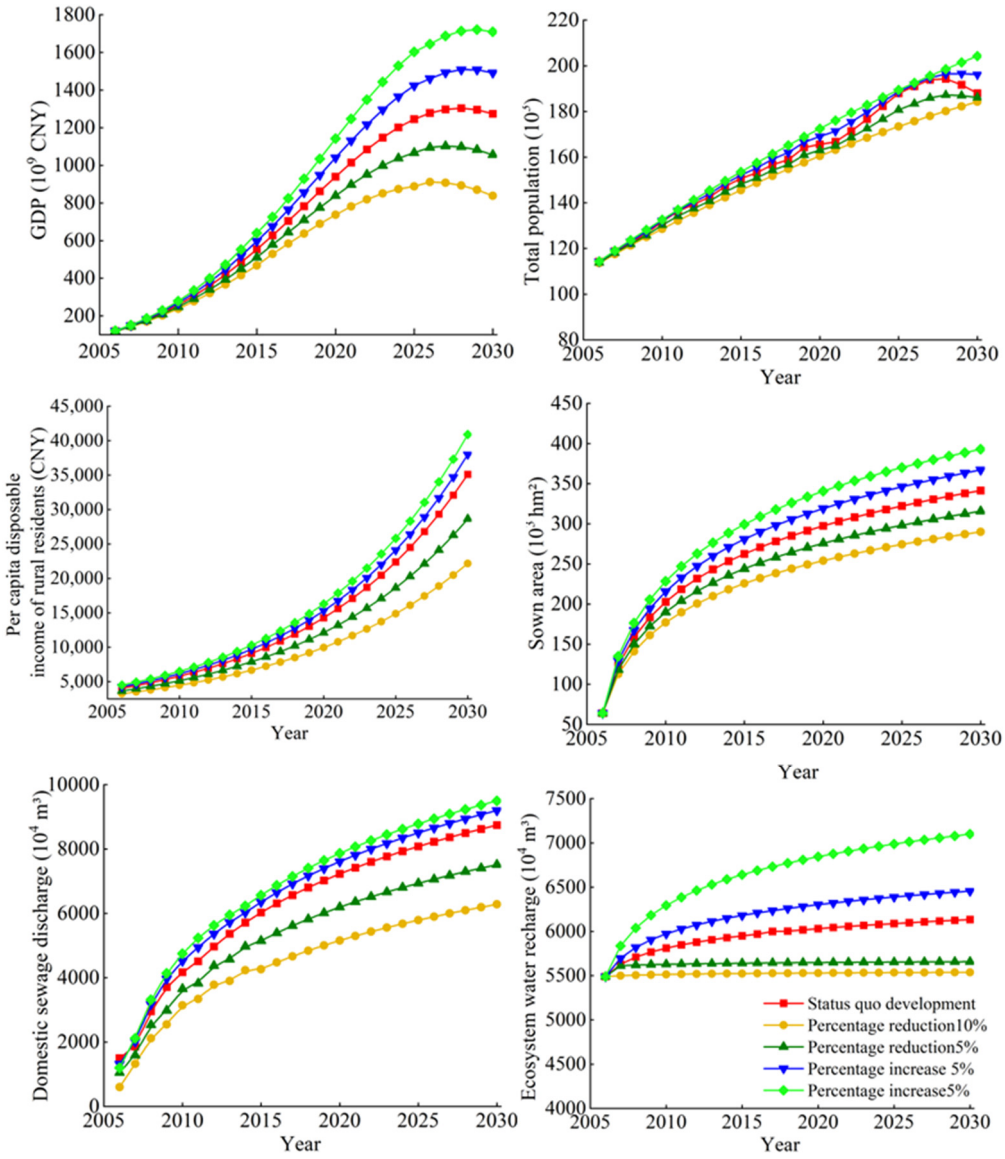

Figure 6. Comparison chart of the sensitivity test.

From the perspective of adjusting individual indicators, the GDP growth rate, when modified across multiple scenarios of varying degrees, exhibited a consistent pattern of growth, indicating high sensitivity. The total population showed negligible changes, suggesting low sensitivity. Both the crop sown area and the per capita disposable income of the rural residents demonstrated a certain level of sensitivity; however, their variations

remained within typical ranges, with the sown area being slightly less sensitive than the per capita disposable income. Domestic and industrial sewage discharge exhibited parallel trends in response to fluctuations in the GDP growth rate. Rapid economic growth exerted environmental pressure. Simultaneously, as the pace of economic development intensified, the volume of water replenishment for the ecological environment increased proportionally, with the relative rate of increase in water demand being more pronounced, although the overall scale of change remained modest. Economic development triggered an upsurge in water demand across the primary, secondary, and tertiary industries, culminating in an elevated annual total water demand.

3.2. Model Analysis of Different Development Scenarios

By adjusting and configuring the aforementioned parameters, the model was simulated across five distinct scenarios. The primary focus was on investigating the impacts of flood safety structures on the economic, social, and ecological development of the coastal region, as illustrated in Figure 7. The simulation analysis involved selecting six key indicators from the system: the GDP, crop sown area, total population, domestic sewage discharge, per capita disposable income of rural residents, and the sewage discharge coefficient.

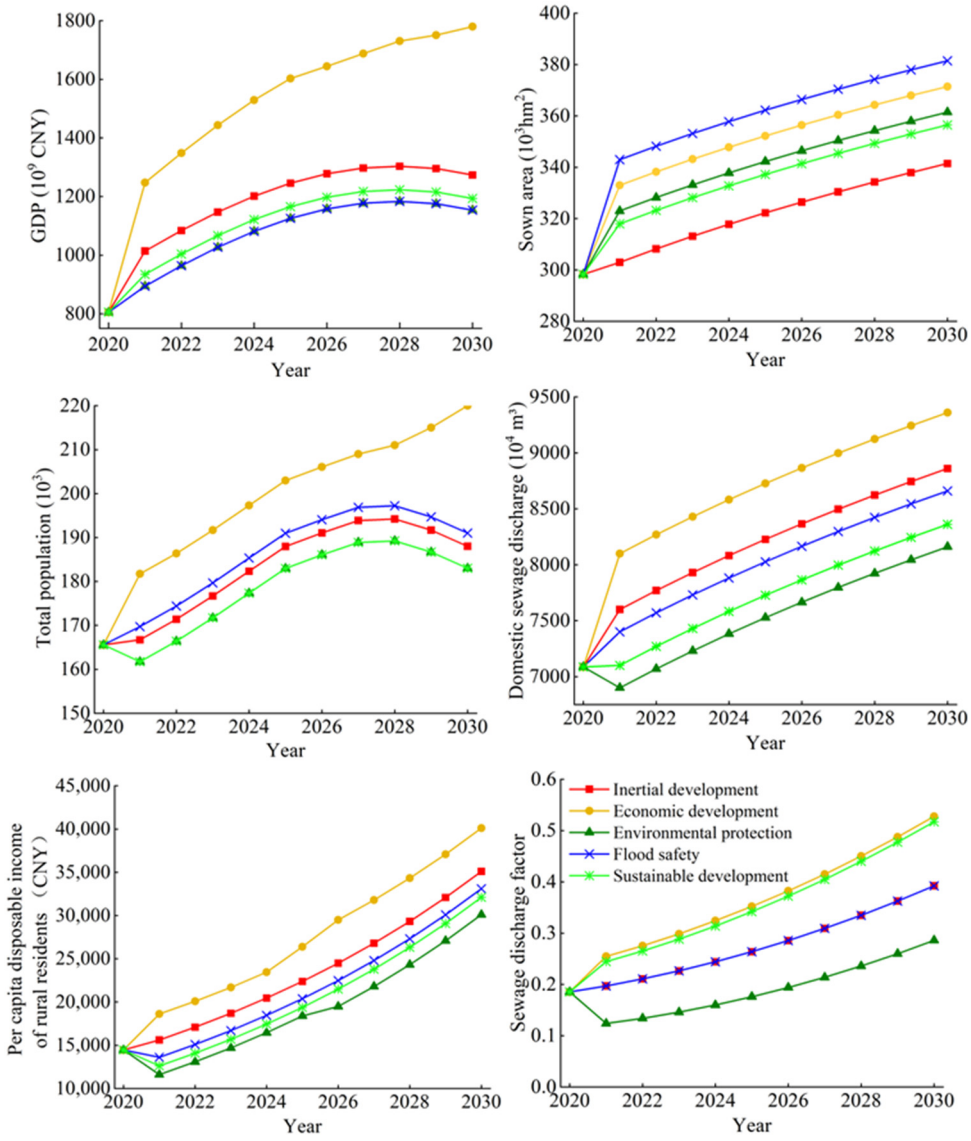

Figure 7. Comparison chart of the system simulation results.

(1) S1: Inertial developmental

The inertial development model maintained the parameters from 2020 without alteration, projecting development through to 2030 based on the current development trajectory. As forecasted in Figure 7 under the inertial development model, both the GDP and the per capita disposable income of the rural residents in the Landong floodplain continue to grow rapidly. By 2030, the GDP is projected to increase to CNY 127.365 billion, and the per capita disposable income for rural residents is expected to reach CNY 12,286.61. In the current development scenario, the growth rate of the crop sown area remains relatively stable, and it is primarily influenced by variations in arable land area and restricted by the total area of the floodplain and the cropping index. The total population exhibits a trend of stability or even decline, whereas domestic sewage discharge continues to rise steadily. The sewage discharge coefficient follows a trajectory similar to that observed in the flood safety model.

(2) S2: Economic Development

The economic development model prioritizes the acceleration of urbanization and rapid economic growth [64], with the highest growth rates assigned to economic and population urbanization. As depicted in Figure 7, under the economic development model, the GDP, total population, and per capita disposable income of rural residents are at their peak levels across the five development scenarios. The GDP is projected to attain CNY 178 billion by 2030, which is the highest among the four scenarios. This demonstrates that manipulating the GDP growth rate and urbanization rate has a significant impact on economic development. However, the rapid economic growth also leads to considerable environmental pollution, with the domestic sewage discharge in 2030 forecasted to approximately triple the amount from 15 years prior, exerting significant pressure on the ecological environment. This underscores the imperative of implementing corresponding environmental conservation measures in tandem with economic growth pursuits.

(3) S3: Environmental Protection

The environmental protection model was designed to enhance the usage rate of the ecological water and green coverage while mitigating pollution intensity. In this model, the per capita disposable income of rural residents was the lowest among the scenarios. The GDP was forecasted to reach CNY 115.365 billion by 2030, which is substantially lower than that projected by the inertial development model. A focus on environmental protection alone may somewhat constrain economic development. The level of domestic sewage discharge is minimal, suggesting that adjusting the ecological water usage rate is an effective means of controlling pollution sources and thus reducing ecological pressure. This system exhibits the lowest pollution discharge among the sustainable development models; however, it also shows greater flexibility in economic development compared to other systems.

(4) S4: Flood Safety

The flood safety model primarily modifies the sensitivity parameters associated with flood peak-flow resistance and mainstream fluctuations, upgrading the fundamental protective infrastructure to withstand flood flows of 8000 m^3/s. By 2030, the crop sown area is projected to be 1.4 times larger than it was 15 years prior. The per capita disposable income of residents exhibited a development trend akin to that of the environmental protection and flood safety models, suggesting that guaranteeing flood safety can stabilize agricultural land use and resident income levels. Nonetheless, enhanced flood safety standards may catalyze population growth within the floodplain and intensify land use conflicts.

(5) S5: Sustainable Development

The sustainable development model seeks to harmonize economic growth with environmental conservation and fundamental flood safety measures. This model employs a balanced approach to regulating economic development and flood safety, achieving a near-synchronous advancement of ecological and economic dimensions. It fosters steady

economic growth, satisfies essential ecological needs, and ensures a baseline level of flood safety. As depicted in Figure 7, the GDP, crop sown area, and per capita disposable income of rural residents under the sustainable development model are at intermediate levels among the five development scenarios. Additionally, the sewage discharge coefficient is slightly lower compared to that of the economic development model.

3.3. Analysis of the Degree of Coupled Harmonization under Different Development Scenarios

This study utilized a system dynamics (SD) model to simulate the trajectory of the changes in the coupling coordination degree under various scenarios within the Landong floodplain, and it then compared these scenarios (Figure 8). The width-to-depth ratio and sinuosity coefficient of the river section were both based on the 2020 values. The development trends across the five scenario models exhibited significant variations. Unlike the inertial development model, which exhibited a gradual upward trend, the coupling coordination degrees of the other models displayed a marked upward trend. Under the inertial development model, the coupling coordination degree of the socio-economic–flood-safety–ecological systems in the Landong floodplain ranged from 0.47 to 0.53, consistently maintaining a relatively low level, with its development potential being far below that of the other models. Through adjustments targeting various aspects, the coupling coordination degree range for the economic development model was 0.61 to 0.84, and, for the flood safety model, it was 0.64 to 0.79. The economic development and flood safety models exhibited high coupling coordination in the early stages. However, their development trajectories were less favorable than those of the sustainable development model in the later stages, with the sustainable development model demonstrating the highest overall growth rate. The coupling coordination degree range for the environmental protection model was 0.58 to 0.75, aligning with the flood safety model post-2028. The sustainable development model had a coupling coordination degree range of 0.58 to 0.87, representing the fastest-growing model. Although the growth rates of the coupling coordination degrees differed significantly among the models, all trends were positive. Based on the comprehensive quality of the coupling coordination degree, the ranking was as follows: the sustainable development model, the economic development model, the flood safety model, the environmental protection model, and the inertial development model.

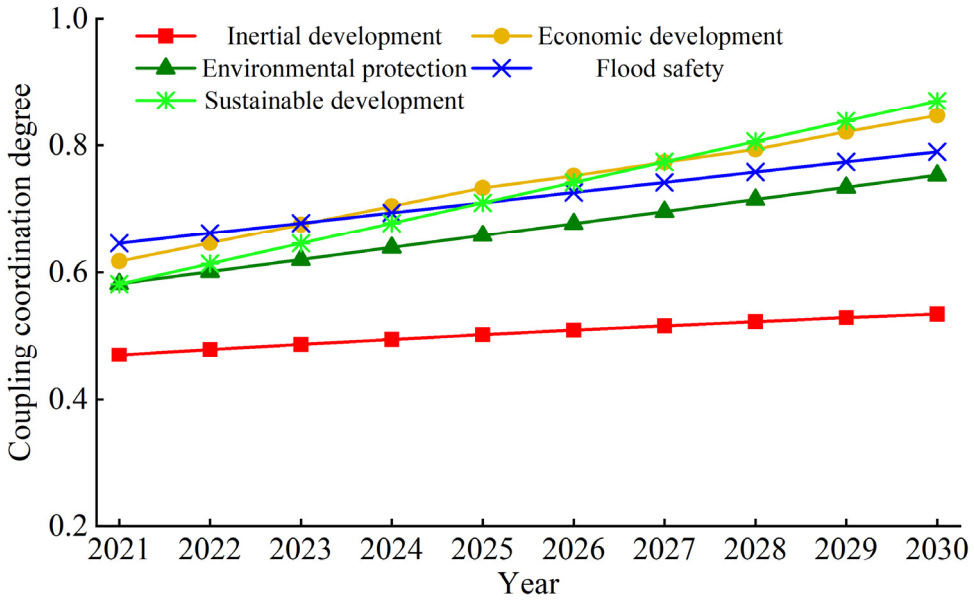

Figure 8. The CCD of the different development scenarios.

The evaluation of the coupling coordination degree levels is presented in Table 10. It is clear that only the inertial development model approached a state of near imbalance, barely

achieving coordination by 2025. The evaluation results were relatively poor, suggesting that the floodplain lacked sustainability and coupling coordination under the current development model. This model's development primarily relies on past inertia, disregarding new challenges and opportunities brought by changing times and social progress, leading to the neglect of environmental protection and flood safety issues and thereby posing risks to future sustainable development.

Table 10. The CCD level of different development scenarios.

	Inertial Development	Economic Development	Environmentally Friendly	Flood Safe	Sustainable Development
2021	Approaching disarray	Primary coordination	Reluctantly coordinated	Primary coordination	Reluctantly coordinated
2022	Approaching disarray	Primary coordination	Primary coordination	Primary coordination	Primary coordination
2023	Approaching disarray	Primary coordination	Primary coordination	Primary coordination	Primary coordination
2024	Approaching disarray	Intermediate level coordination	Primary coordination	Primary coordination	Primary coordination
2025	Reluctantly coordinated	Intermediate level coordination	Primary coordination	Intermediate level coordination	Intermediate level coordination
2026	Reluctantly coordinated	Intermediate level coordination	Primary coordination	Intermediate level coordination	Intermediate level coordination
2027	Reluctantly coordinated	Intermediate level coordination	Primary coordination	Intermediate level coordination	Intermediate level coordination
2028	Reluctantly coordinated	Intermediate level coordination	Intermediate level coordination	Intermediate level coordination	Effectively coordinated
2029	Reluctantly coordinated	Intermediate level coordination	Intermediate level coordination	Intermediate level coordination	Effectively coordinated
2030	Reluctantly coordinated	Effectively coordinated	Intermediate level coordination	Intermediate level coordination	Effectively coordinated

The economic development model achieved a good coordination state by 2030, indicating that rapid economic growth under this model can lead to favorable coupling coordination and sustainability. However, reaching a good coordination state is relatively delayed, with slow initial development. During the economic growth process, issues such as environmental protection and flood safety may be overlooked, necessitating comprehensive consideration of these non-economic factors to ensure balanced development in terms of economy, society, environment, and safety.

The evaluation results of the environmental protection model suggest that substantial investment in environmental protection can lead to good sustainability and coordination. However, this model may encounter challenges in other economic and social aspects. The flood safety model evaluation results demonstrate that adequately implementing flood safety measures can support sustainable development goals while addressing environmental and economic needs. However, economic and social development may be somewhat constrained under this model, necessitating thorough analysis and consideration.

The sustainable development model shows favorable evaluation results, with GDP and urbanization rates set at medium-high development levels and a flood defense standard of 7000 m^3/s. This developmental framework achieves a favorable state of coordination by the year 2028. It takes into account not only economic, environmental, and flood safety variables, but also ensures the synchronization and equilibrium among these variables. Therefore, choosing a sustainable development model is crucial for future progress. To

achieve sustainable goals, we must balance environmental protection, flood safety, and economic growth through good coordination.

4. Conclusions

This paper utilized the downstream region of the Landong floodplain along the Yellow River as a case study, utilizing a system dynamics model (SDM) to simulate and quantify the level and scope of development coordination in accordance with the coupling coordination degree standard. Overall, all five development scenarios significantly improved the coupling coordination degrees, but adjustments focused on single aspects did not substantially enhance the coupling coordination degree. The sustainable development scenario, which balanced the regulation of all three aspects, achieved the best improvement in CCD. However, the development of the Landong floodplain should not only prioritize socio-economic growth, but should also consider flood safety and ecological factors. A comprehensive approach is needed, taking into account socio-economic, flood safety, and ecological indicators for coordinated development with high quality. Based on these findings, scientific management strategies for the coordinated development of the floodplain were proposed: (1) protect the riparian farmland and basic agricultural land without compromising flood safety functions; (2) enhance ecological restoration efforts to jointly create a harmonious environment; and (3) optimize the industrial structure to achieve high-quality development. This approach aims to promote the coordinated development of the system, providing new insights for implementing the high-quality development strategy in the Yellow River Basin at this stage. The theoretical model can also be extended to the research and practice of other floodplains, offering a reference for regions facing similar complex challenges.

However, this study has limitations as the socio-economic–flood-safety–ecological (SFE) system is complex with many indicator variables. The SD modeling in this study has overlooked or simplified some relationships among these variables. Furthermore, there are variations in statistical bulletin standards among different regions, resulting in notable data deficiencies for specific variables. Despite efforts to address these gaps through techniques like data imputation and literature review, disparities persist between the imputed values and the actual values, potentially causing inaccuracies in the construction of the system model. Hence, additional improvements are required. On the other hand, the socio-economic, flood safety, and ecological systems are dynamically changing entities involving numerous and complex factors. Future research could expand the model construction perspective beyond the evaluation index system to more comprehensively consider the connections and interrelationships among indicators. Moreover, to analyze development differences across regions, regulatory models tailored to the development priorities of specific regions could be constructed.

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