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Assessment and Prediction of the Collaborative Governance of the Water Resources, Water Conservancy Facilities, and Socio-Economic System in the Xiangjiang River Basin, China

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Abstract: The collaborative governance of subsystems within a river basin can play a critical role in addressing challenges, such as water scarcity, soil erosion, flooding, sedimentation, and water pollution, to achieve sustainable utilization of water resources. However, the current literature only focuses on isolated observations of these subsystems, leading to uncertainty and water resource destruction. This paper examines the evolution of the collaborative governance of water resources, water conservancy facilities, and socio-economic systems through self-organization theory in the Xiangjiang River Basin, China. The coupling theory and gray Grey Model (1,1) model were utilized with panel data from 2000 to 2019 to assess and predict the governance synergies of five subsystems: natural water, water conservancy facilities, water resource development and utilization, ecological environment, and socio-economic systems. There are 22 indicators contributing to these subsystems that were selected. The results indicate an S-shaped trend in collaborative governance for water resources, water conservancy facilities, and socio-economic systems. The elements of each subsystem exhibit both synergistic and competitive relationships. The unpredictable precipitation triggers a butterfly effect, changing systemic governance coordination, which closely relates to developing the natural water subsystem. Effective water conservation and regulation of water conservancy facilities are the keys to improving water-use efficiency and safeguarding water ecology. This study provides insights into the collaborative governance among subsystems and the evolution of the water resources, water conservancy facilities, and socio-economic systems in the Xiangjiang River Basin to promote sustainable water resource utilization.

Keywords: collaborative governance; water resources; water conservancy facilities; socio-economic development

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1. Introduction

In the face of climate change, population growth, and socio-economic development, the sustainable utilization of water resources while preserving nature's self-restoration ability is critical for sustainable development [1,2]. The United Nations World Water Resources Report emphasizes the need to replicate nature's self-organizing development process, focus on constructing water conservancy and water quality facilities, and implement a collaborative governance approach for nature and society. China's 2021 Central Document No.1 similarly highlights the importance of promoting water system connectivity and comprehensive improvement, as well as strengthening the construction of water conservancy facilities and water source protection. However, previous investigations into rebuilding self-organization systems within water systems have often ignored collaboration, resulting in separate and non-synergistic observations, increasing uncertainty, and significant water resource destruction. Therefore, it is crucial to take a collaborative approach to examine the interaction between subsystems, such as water resources, water conservancy facilities, and socio-economic activities.

Water resources, along with water conservancy facilities, are crucial to achieving sustainable socio-economic development [3]. To effectively develop and utilize water resources, a systematic and integrative approach is necessary for water resources, water conservancy facilities, and socio-economic activities. Achieving sustainable utilization of water resources for socio-economic development requires optimizing infrastructure and respecting the carrying capacity of the environment. As such, it is critical to promote natural resource protection and socio-economic activities in a coordinated manner to achieve harmonious coexistence between humans and nature [4,5]. However, the combined effects of climate change [6] and economies of scale [7] have led to increasing water scarcity [8], aging and wear of water conservancy facilities, and degradation of water ecology [9]. These are fundamental issues that restrict sustainable socio-economic development and require urgent coordination and governance in the water sector.

River basin water management systems need to be integrative, inclusive, and consider both natural and man-made factors to effectively manage water resources [10,11]. Stakeholders may have different demands when it comes to water resource utilization, which is why previous studies have explored different aspects such as socio-economic [12], environmental [13], and water conservation facilities [3]. However, few studies have examined the interactions between water, ecology, and socio-economy [14]. There are also gaps in the existing literature, particularly in observing river-basins as a system and their constituents as a subsystem to enhance the efficiency of water use. To ensure sustainable water resource management, it is essential to take a holistic approach that considers all factors that impact water availability and utilization. Only by understanding the complex interactions between natural and human factors can we develop effective strategies for managing water resources and ensuring equitable distribution among all stakeholders.

Effective water resource governance in a river basin is crucial for organizing and coordinating multiple stakeholders towards sustainable water utilization [15]. This involves identifying the various stakeholders in the river basin, improving their ability to share knowledge [16], and enhancing water resource distribution efficiency [17]. Collaborative governance in a river basin has been found to play a significant role in achieving positive ecological outcomes [18]. Transforming from other forms of governance to collaborative governance can improve integrated planning and decision-making processes [19]. This article specifically examines the role of collaborative governance in water resource management, water conservancy facilities, and socio-economic systems based on an evolutionary logic mechanism. By adopting a collaborative approach, stakeholders can work together to achieve common goals and address challenges more effectively. Through collaboration, stakeholders can also share knowledge, build trust, and foster mutual understanding, which are all critical for achieving sustainable water resource management.

Over the last three decades, there has been significant research on multi-user allocation and multi-purpose water resource development and utilization projects by water conservancy engineers and economists. More recent studies have focused on joint scheduling and the optimization of regional water resources, taking into account factors such as water conservation project design and supply-and-demand balance [20]. For example, Arfanuzzaman Md and Atiq Rahman (2017) [21] analyzed various factors, including water resource supply-and-demand, system losses, groundwater levels, and per capita water consumption, to propose a series of social–ecological resilience-building measures, such as the comprehensive regulation of surface water and groundwater, water conservation, water footprint reduction, and a continuous-water-demand governance plan. By optimizing river basin water conservancy, Girard Corentin et al. (2016) establish a minimum-cost and robust investment portfolio model for the development of water resources at scale [20]. These types of studies provide valuable insights into how we can enhance the efficiency of water resource allocation and improve the overall management of water resources.

Several studies have focused on improving the assessment of water resource utilization and developing innovative solutions to enhance the efficiency of water utilization. For example, Cunha Henrique et al. (2019) [22] improved the existing assessment method of single-water-resource utilization, developed a calculation method for the comprehensive utilization of water resources, and created an intelligent collective irrigation system.

Tiwari Ashwani Kumar et al. (2021) [23] utilized geographic information systems to collect data on factors such as slope, elevation, landform, and drainage to assess water pollution levels and provide policy recommendations for the comprehensive management of urban and rural water resources. However, few studies have placed significant emphasis on assessing the safety and carrying capacity of water resources, measuring the sustainable development quantity and ecological quality of water resources in different regions, evaluating the level of modern water conservancy development, or analyzing the interaction between regional water conservancy facilities and socio-economic development. Li Xiaoyun (2017) [24] analyzed the concept, characteristics, and composition of water resource carrying capacity and provided a more comprehensive summary of water resource carrying capacity evaluation methods. Such studies are essential in providing a better understanding of water resource management and can help in developing policies and strategies that promote sustainable water resource utilization.

Several studies have used different models and evaluation methods to assess the relationship between water conservancy facilities and socio-economic development. For example, Mao H H et al. (2011) [25] used a coordinated development model to quantitatively evaluate the level of the water conservancy facilities and economic society in the Haihe River Basin. Yi X B et al. (2013) [26] used the Lorenz curve and Gini coefficient to calculate the coordinated development of water conservancy and socio-economic development in various cities in Guangdong and concluded that there is a positive correlation between water conservancy facilities and socio-economic development. In a different study [27], Huang X F et al. (2017) applied a qualitative and quantitative cloud evaluation model with both fuzzy and random factors to analyze the development level of water conservancy modernization. Finally, Li Y L et al. (2019) [28] constructed a system with input-response-output dimensions and analyzed the spatial heterogeneity and main controlling factors of the green development of water. They concluded that attention should be paid to the water conservancy-informational and production ecology that affects the economic benefits. These studies provide valuable insights into the complex relationship between water resource management and socio-economic development and can help inform policy and decision-making processes aimed at promoting sustainable water resource utilization.

The literature on the use of collaborative governance to manage water resources in river basins is relatively limited, with few studies addressing ecological, socio-economic, and air pollution perspectives [18,29,30]. However, there are some shortcomings in previous research. First, existing studies have not fully considered spatial differences within the same geographic unit and whether synergy is spatially balanced in the region. Second, previous research has not integrated water resources, water conservancy facilities, and socio-economic systems as a whole to study their coordination and change trends. Third, there is a lack of theoretical analysis of the logical relationship between the system and its internal interactions under the coordinated governance of the WCS system (hereafter, the WCS system). To address these gaps, this article uses the self-organization theory to examine the evolutionary logic mechanism of the collaborative governance of water resources, water conservancy facilities, and socio-economic systems, as well as the interrelationships and interweaving effects of the various subsystems. The authors also use coupling theory and the gray GM (1,1) model to build a system governance synergy evaluation and prediction model. Finally, they evaluate and interpret the coordination degree and change law of the WCS system in the Xiangjiang River Basin. This study provides valuable insights into the complex relationship between water resource management, water conservancy facilities, and socio-economic development. It highlights the importance of considering spatial differences and the need for an integrated approach to studying the coordination and change trends of these subsystems. The authors' use of self-organization theory and the gray GM (1,1) model provides a useful framework for analyzing and predicting the synergies of these subsystems.

This article makes a significant contribution to the literature in three ways. First, it systematically examines how to create coordinated governance relationships between the subsystems of the WCS system, which has not been extensively studied previously. The authors draw connections between the changes in the WCS system and its subsystems in the Xiangjiang River Basin from 2000 to 2019. Second, the article provides insights into the dynamic evolution logic of coordinated governance of the WCS system from a systematic perspective. Finally, the study explores differences in governance synergies between water resources, water conservancy facilities, and socio-economic development within the same geographic unit at different times and spaces. These findings have important implications for decision-making and provide a reference point for balancing regional water conservancy facility construction, water resource environmental protection, and socio-economic development. The article highlights the significance of considering the interrelationships and interactions between these subsystems, as well as spatial differences within the same region, to create effective and sustainable governance mechanisms for water resources. Overall, this study provides valuable insights into promoting collaborative governance and sustainable management of water resources in river basins.

2. Theoretical Framework

2.1. The Composition of the WCS System

In this article, the water resources, water conservancy facilities, and socio-economic activities of the Xiangjiang River Basin are studied holistically under the umbrella term "WCS system". This system is made up of a number of interconnected components, including surface water and groundwater, precipitation, water environment, water conservancy engineering facilities, socio-economic activities, and other natural environments [31]. Various humanistic activities such as resource utilization, socio-economic development, and ecological protection create interactive relationships between the different elements within the WCS system. Natural water resources such as precipitation, surface water, and groundwater serve as the fundamental building blocks of this system. The efficient and sustainable utilization of these resources for supporting socio-economic development through the construction of water conservancy facilities and safeguarding the water ecology serves as the central aspect of the WCS system [32,33].

The application of water resources in the WCS system of the Xiangjiang River Basin is fraught with two significant challenges.

1. The uneven distribution of the natural water volume and productivity over time and space is a significant issue that worsens regional socio-economic development. The construction of transitional water-conservancy connectors is inadequate in addressing this problem, leading to insufficient regulation in controlling regional water resources. This, in turn, causes a shortfall in meeting domestic water demands [18];
2. The discharge of pollutants resulting from the utilization of water resources for socio-economic development casts a shadow on the ecological health of the water envi-ronment.

The gradual progress of socio-economic development offers important financial and material resources to support the development and utilization of water resources and to restore the ecological balance of water systems. Therefore, this article examines and integrates the interdependence of water resources, water conservancy facilities, and socio-economic activities under a unified framework referred to as the WCS system. The WCS system is comprised of five subsystems, namely natural water, water conservancy facilities, water resources development and utilization, ecological environment, and socio-economic activities [34]. These subsystems are intricately connected and dependent, working together to govern the entire WCS system. Figure 1 illustrates the composition of the WCS system and the interactions between its subsystems.

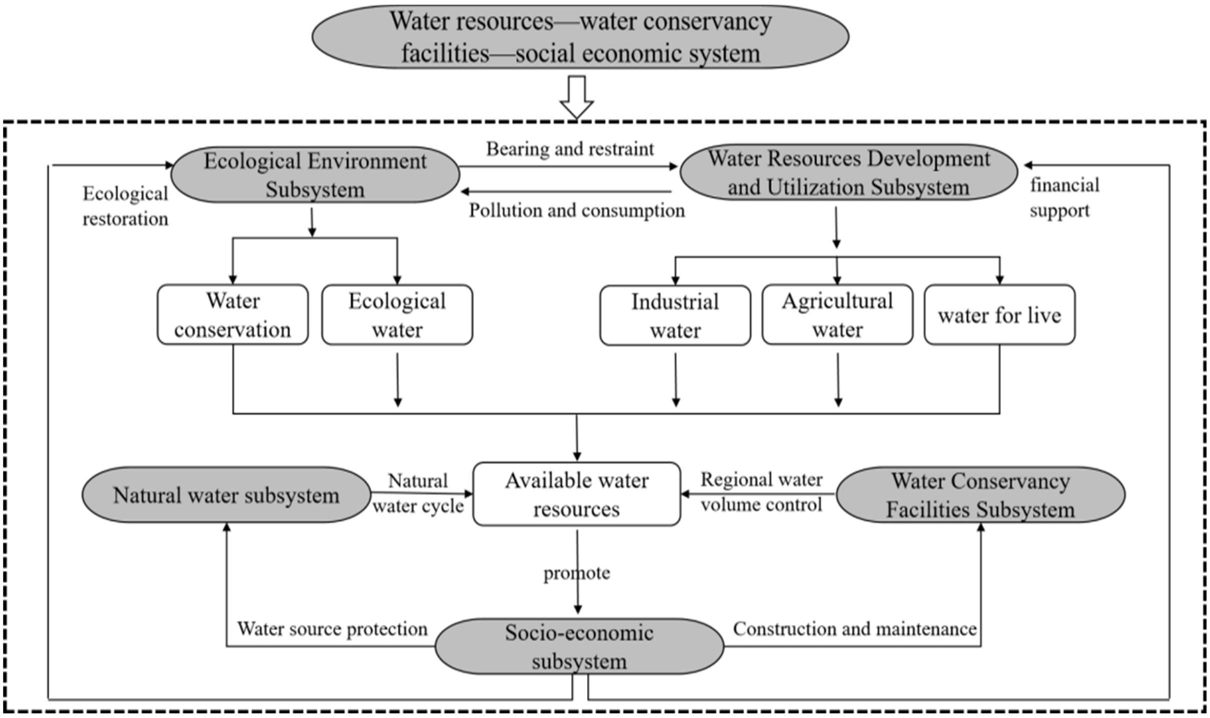

Figure 1. The composition of the WCS system and the interaction between the subsystems.

2.1.1. The Evolutionary Logic Analysis of the Governance Synergy of the WCS System

According to the theory of self-organization, complex systems comprising many elements tend to achieve a steady state of balance in response to external fluctuations without the need for external intervention [35]. The components within the system are capable of self-structuring and repairing without external instructions. The theory of self-organization is grounded on four main aspects. Firstly, Prigogine's dissipation theory, proposed in 1960, suggests that orderly and stable systems can emerge from more disordered ones [36]. Secondly, Hermann Haken developed the concept of synergistic effects in 1971, which revealed that the interaction of an overall or collaborative effect generates numerous open systems [37]. Thirdly, Rene Thom established the catastrophe theory in the 1960s, which states that slight changes in specific parameters of a nonlinear system can cause equilibrium to appear or disappear, leading to significant and abrupt changes in the system's behavior. Finally, Egan created the system evolution theory during the 1960s, which posits that interdependence within a system arises from determinate relationships among its parts or variables, as opposed to random variability [38].

In this study, we derive a self-organization theory that states that the open system is in a dissipative state, each subsystem and the system as a whole will exchange with the external environment in multiple ways through matter, energy, and information over time. The exchange process will produce entropy (dS), expressed as $dS = d_iS + d_eS$, where d_iS is the positive entropy generated inside the system, and d_eS is the entropy produced by the exchange between the system and the outside world, which can be positive or negative [39]. When the $dS < 0$ and $d_iS < |d_eS|$ performance develops over time, the negative entropy obtained by the system will be greater than the internal positive entropy and the total entropy will be reduced. When the total entropy reaches a certain threshold, the system will undergo a sudden change, the transformation from disorder to order will be realized, and the degree of coordination will become higher. Conversely, the system can evolve in the direction of disorder and the degree of coordination will decrease.

The self-organization theory suggests that the WCS system, due to its openness, will exchange various forms of material, energy, and information with the external environment. This is manifested in the fact that natural rainfall, water resources utilization, water environment carrying capacity, and water conservancy facilities construction, among other factors (Figure 2), affect the synergy of the WCS system's governance. During the period of ecological bearing, these factors promote each other, resulting in obvious positive effects on each subsystem, which continuously enhances synergy, leading to an upward trend in the system's governance. However, as social and economic development continues, the water conservancy facilities become worn and aged, water resources become scarce, and the water ecology falls into deficit. At this point, negative effects begin to appear in each subsystem, although they have yet to reach the critical stage and exhibit only small fluctuations. The WCS system can assimilate and absorb these minor fluctuations through self-organization mechanisms, thus retaining its original structure and governance synergy unchanged. Therefore, during this stage, the WCS system's governance synergy is altered by small fluctuations but remains predominantly stable and positive overall.

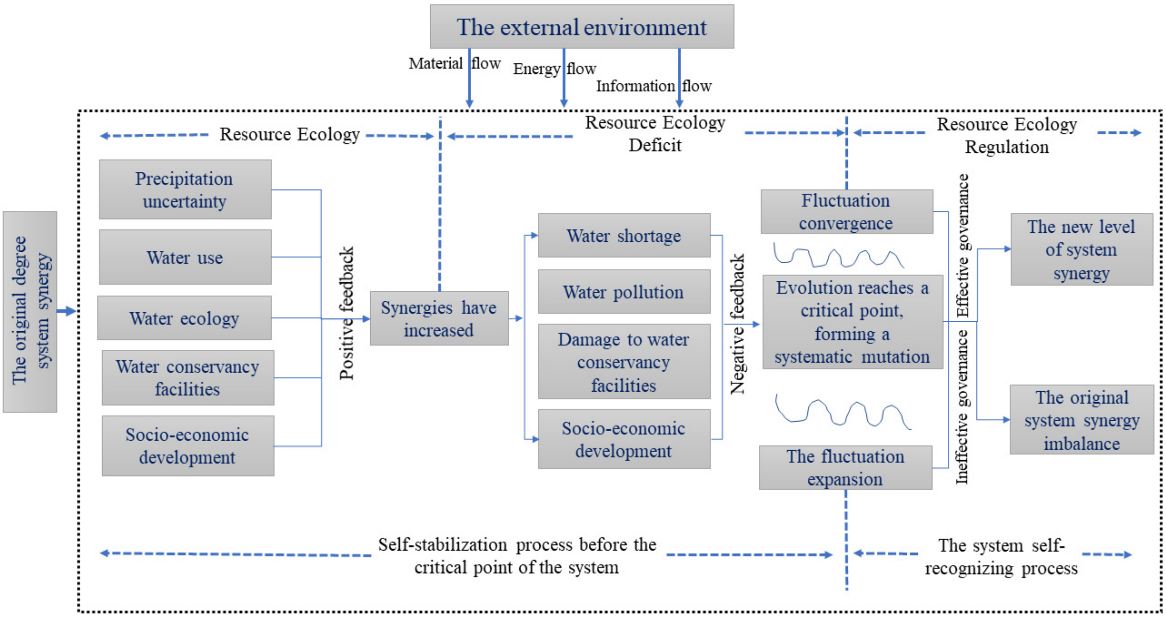

Figure 2. The evolution mechanism of the WCS system's governance synergy.

When the water conservancy facilities reach a state of aging, the availability of water resources becomes severely limited, and the water ecological environment is significantly damaged, the negative effects on each subsystem become pronounced. These factors exceed the tolerable range of the WCS system, resulting in significant and abrupt changes that exhibit large fluctuations. The self-organization mechanisms of the WCS system cannot assimilate and absorb these disruptive changes. Even minor disturbances may rapidly expand and transmit, breaking down the original structure and governance synergy of the WCS system. Consequently, this can cause a mutation and bifurcation in the system's governance synergy.

2.1.2. The Change Process of the WCS System's Governance Synergy

If the WCS system adopts forceful governance measures, such as enhancing water-resource-utilization efficiency, investing in and maintaining water conservancy facilities, and implementing comprehensive water environmental management, then the system's autonomous resilience can be improved. This, in turn, leads to the decoupling of water resource consumption and pollution from social and economic development. As a result, positive entropy inside the system exceeds the negative entropy obtained from external sources, leading to an imbalance in the coordination of various subsystems. Additionally, the overall coordination of system governance exhibits a tendency to decline and remain constrained by factors such as the wear-and-tear of water conservancy facilities, water environmental pollution, and excessive use of water resources.

The result of bifurcation may be new evolution, collapse, or degeneration (Figure 3). The direction of system governance synergy depends on the implementation of governance measures. If measures such as the integration of resource utilization and environmental protection, the adjustment and optimization of water conservancy planning, the adjustment of economic structure, the investment of irrigation facilities, technical reform, policy formulation, and other measures can be taken to improve the self-recovery of the system, it will promote the positive evolution of the system governance synergy. The specific performance is $dS < 0$ and $d_iS < |d_eS|$. The internal positive entropy of the system is less than the external negative entropy. The development of each subsystem will be coordinated; the overall coordination degree of system governance will reach a new height, forming a new structure, function, and order and then forming a new stable mode, and will continue to develop to a higher level, with a rising differentiation trend. However, if governance and regulation are not in place, it will promote the negative evolution of system governance synergy. The specific performance is $dS > 0$ and $d_iS > |d_eS|$, which indicates that the positive entropy inside the system is greater than the negative entropy obtained from the outside and the coordination of all subsystems is unbalanced, which will tend to decline and degenerate. The degree of coordination will show a downward trend of differentiation, which will continue to be subject to the constraints of water conservancy facilities' wear, water environmental pollution, and the excessive use of water resources.

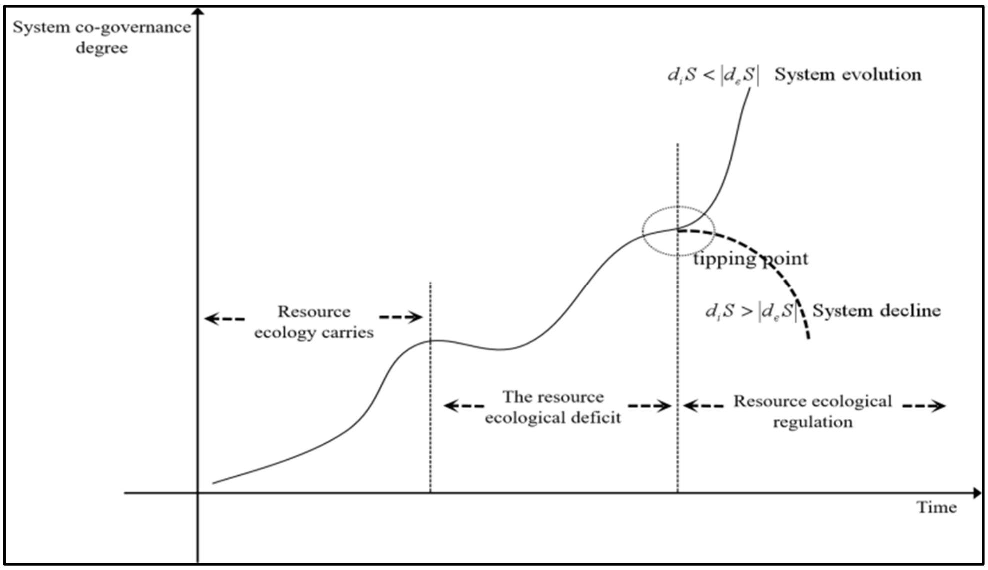

Figure 3. The change process of the WCS system's governance synergy. Note: co-governance refers to collaborative governance.

The constituent subsystems of the WCS system exhibit both opposing and unified characteristics, as well as cooperative and competitive dynamics in collaborative governance. Over time, the co-evolution of the WCS system is boundless and follows an infinite sequence of bifurcation paths. However, due to the geographical conditions, resource allocation, social economy, ecological environment, and other factors, the co-evolution of the WCS system is restrained. The evolution trend of the system's governance synergy generally demonstrates a non-linear change feature resembling the shape of the letter "S" (Figure 3). With appropriate governance and regulation, and by enhancing governance capacity through technical, management, policy, and institutional measures, the WCS system can be promoted to evolve more systematically and improve the level of governance synergy.

3. Materials and Methods

Section 3.1 describes the study area's location, while Section 3.2 outlines the data sources for each indicator representing the various subsystems included in this paper. The specific indicators used to assess the degree of collaborative governance within the WCS system are presented in detail in Section 3.3. Finally, Section 3.4 explains the coupling model and the grey GM (1,1) model employed to evaluate and predict the governance synergy of the WCS system.

3.1. Study Area

The Xiangjiang River Basin is located in Hunan Province, China, covering an area of approximately 94,346 km^2 with longitudes ranging from 109.5° E to 111.1° E and latitudes from 38.2° N to 39.8° N. However, according to Figure 4, the actual area covered is 94,721 km^2. Situated into the radiation zone of the Yangtze River Economic Belt and South China Economic Circle, this basin is home to the Xiangjiang River, a crucial first-level tributary of the Yangtze River and Hunan's mother river. Moreover, this river stretches over 670 kilometers in Hunan and has more than 1300 tributaries across eight cities, namely Yongzhou, Chenzhou, Hengyang, Loudi, Zhuzhou, Xiangtan, Changsha, and Yueyang. With an average rainfall between 1000 and 1800 mm, the Xiangjiang River Basin has a substantial advantage in terms of water resources.

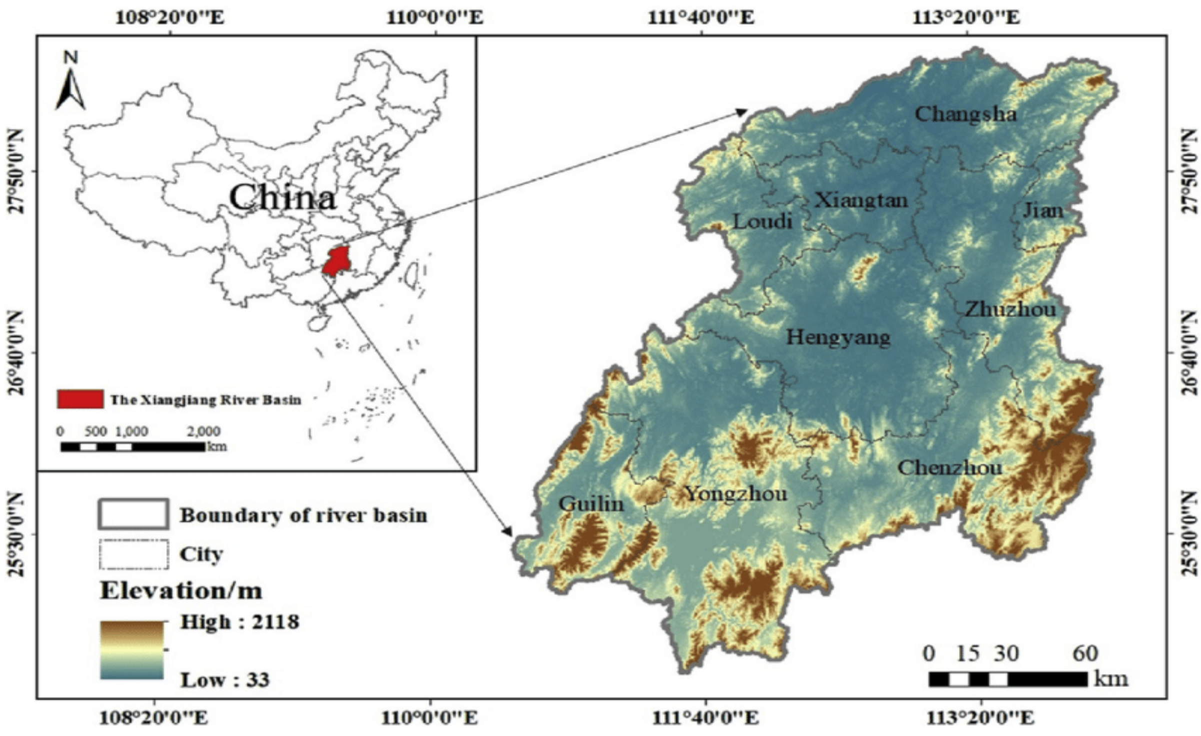

Figure 4. Map of the Xiangjiang River Basin, Hunan Province, China.

This area is densely populated with cities and towns and has a concentrated population, developed economy, rich culture, and convenient transportation. It is the core area and golden zone for Hunan's development, gathering over 70% of the province's large- and medium-sized enterprises. With a total population of 37.74 million by 2019, the Xiangjiang River Basin is the core area of the province's economic and social development. The GDP and industrial value added in 2019 reached approximately 1220.5 billion RMB and 484.2 billion RMB, respectively, accounting for about 76.7% and 82.2% of the total GDP and industrial value added in Hunan Province.

Despite having a solid foundation for development and bright prospects, the Xiangjiang River Basin faces various socio-economic and environmental challenges. As the traditional extensive development model has not substantially changed, watershed resources and ecological environmental issues have become increasingly prominent in recent years, leading to mounting pressure for sustainable development. Moreover, the uneven distribution of precipitation across time and space, coupled with recurring droughts and floods, poses significant challenges to the basin's development

Currently, the Xiangjiang River Basin lacks an established overall coordination and management system. There is a lack of cooperation mechanisms for upstream and downstream linkage. It is crucial to accelerate the establishment and improvement of a development mechanism that balances ecological environmental protection and construction, considering the macro environment holistically. Urgent demands for changing the current development mode exist, and new institutional arrangements, governance systems, and development paradigms are necessary.

3.2. Data Sources

The panel data of 22 indicators presented in Table 1 were drawn from the Hunan Water Resources Bulletin at http://slt.hunan.gov.cn/slt/xxgk/tjgb/index.html (accessed on 23 July 2021); the Hunan Statistical Yearbook at http://tjj.hunan.gov.cn/hntj/tjsj/tjnj/index.html (accessed on 23 July 2021); the Statistical Bulletin of National Economic and Social Development of Hunan Province at http://www.hunan.gov.cn/hnszf/zfsj/tjgb/202003/t20200319_11815838.html (accessed on 23 July 2021); the China Water Resources Statistics Yearbook at http://www.stats.gov.cn/tjsj/ndsj/ (accessed on 2 October 2020); and the Hunan Ecological Environment Status Bulletin at http://sthjt.hunan.gov.cn/sthjt/xxgk/zdly/hjjc/hjtj/index.html (accessed on 23 July 2021) during the period from 2000 to 2019. Details of the data sources are presented in the Supplementary Material (Table S1).

Table 1. Variable selection and descriptive statistics.

	Subsystems	Indicators	Description	Mean	SD
1	Natural water subsystem	Average annual rainfall	Mean annual precipitation (mm)	0.444	0.188
		Water resource per capita	Per capita water resources (m^3/person)	0.421	0.202
		Total water resource	The total water resources (100 million m^3)	0.441	0.200
2	Water Conservancy Facilities Subsystem	Water conservancy construction investment in agriculture and forestry	Investment in agriculture, forestry and water conservancy (CNY 10,000)	0.454	0.349
		Number of reservoir	Reservoir seat number/individual entries	0.843	0.112
		Reservoir storage capacity	Year-end storage capacity (ten thousand m^3)	0.528	0.289
		Length of embankments	Length of embankments (km)	0.383	0.449
		Effective irrigated area of farmland	Effective irrigated area of farmland (10,000 hm^2)	0.477	0.392
3	Water resource development and utilization subsystem	Water consumption (GDP)	GDP water utilization CNY 10,000 (m^3)	0.678	0.346
		Industrial added value water	Industrial added value water in CNY 10,000 (m^3/t)	0.729	0.267
		Water consumption per unit of grain yield	Per capita water use (m^3)	0.642	0.318
		Comprehensive water consumption per capita	Total supply of water (hundred million m^3)	0.571	0.189
		Total water supply	CNY 10,000 of industrial added value water (m^3)	0.482	0.234
		Water utilization rate	Utilization rate of water resources (%)	0.375	0.186

Table 1. *Cont.*

	Subsystems	Indicators	Description	Mean	SD
4	Ecological Environment subsystem	Green coverage area	Green coverage area (hm^2)	0.494	0.335
		Sewage discharge	Quantity of waste water effluent (10,000 m^3)	0.417	0.273
		Sewage treatment rate	Treatment rate of domestic sewage (%)	0.561	0.372
5	Socio-economic Subsystem	Water quality compliance rate	Water quality standard rate of water functional area (%)	0.676	0.260
		Food production	grain output/t	0.667	0.280
		Per capita disposable income	Per capita disposable income (CNY)	0.417	0.361
		Gross regional product	Gross regional domestic product (CNY 10,000)	0.556	0.297
		Regional fiscal revenue	Regional revenue (CNY 10,000)	0.476	0.386

3.3. Variable Selection and Descriptive Statistics

Table 1 outlines a detailed list of indicators used to measure the degree of collaborative governance within the WCS system. The natural water subsystem focuses on the number of resources and per capita possession, utilizing indicators such as the total water resources, annual rainfall, and per capita water resources. Additionally, the subsystem of water conservancy facilities considers flood control, water storage, and food security, selecting indicators such as investment in agricultural, forestry, and water conservancy construction, dike length; number of reservoirs; and year-end storage capacity. Concerning water consumption and utilization efficiency, the subsystem of water resources development and utilization selects indicators such as water utilized for every CNY 10,000 of industrial added value, water for unit grain output, per capita comprehensive water consumption, and water resources utilization **rate**. Furthermore, the ecological environment subsystem focuses on the pollution and treatment of water resources, utilizing indicators such as sewage discharge, sewage treatment rate, and water quality compliance rate in water function areas. Lastly, the socio-economic subsystem primarily focuses on capital accumulation and utilizes indicators such as regional fiscal revenue, per capita disposable income, and grain output. Overall, there are a total of five subsystems and twenty-two evaluation indicators utilized to measure the degree of collaborative governance within the WCS system.

Accurately estimating the total amount of available water resources in a region can be challenging due to various factors, such as water consumption in the atmospheric cycle, production and daily life, and the level of technological advancement in water resource utilization. Thus, this paper does not provide an exact amount of regional available water resources. Instead, indicators such as CNY 10,000 GDP water consumption, CNY 10,000 industrial added value water consumption, unit grain output water consumption and per capita comprehensive water consumption, among others, found in the water resources development and utilization subsystem can be used to show the current water consumption. Table S3 presents the Xiangjiang River Basin WCS system coordinated governance index information. The implementation and application of the index data from each constituent subsystem within the WCS system rely on the system governance collaborative evaluation model. This method requires calculating the contribution value of each index to the subsystem order degree, determining the subsystem's order degree, and finally obtaining the WCS system's governance synergy degree.

3.4. Methods

Based on the self-organization theory, this paper examines the evolution of collaborative governance in the Xiangjiang River Basin, China. We apply the coupling and gray GM (1,1) model using panel data from the 2000–2019 period to evaluate and predict the governance synergy of five subsystems including; the natural water subsystem, water conservancy facilities subsystem, water resource development and utilization subsystem, ecological environment subsystem, and socio-economic subsystem.

As the indispensable basic resources and supporting facilities for social and economic development, water resources and water conservancy facilities play a key role in realizing regional sustainable development. However, at present, under the intertwined influence of climate change and resource development, China's water resource shortage, the aging and wear of water conservancy facilities, water ecological degradation, and other problems continue to overlap and become increasingly prominent. This shows the characteristics of systematization and complexity, which have become two of the important problems restricting the sustainable development of the social economy. Therefore, the management of water resources needs to follow the system concept and pay attention to the coordinated management with the water conservancy facilities and social economy. Coupling theory is originally a physical concept, which refers to the phenomenon that two (or more) systems or motion forms affect each other through various interactions. The coupling degree describes the degree of interaction between systems or elements. From the perspective of synergetics, the coupling effect and its degree determine the change trend and direction of the system. Therefore, this paper uses the coupling model to analyze the coordinated governance of water resources, water conservancy facilities, and social economy.

The grey GM (1,1) model used to predict the development synergy of water resources, water conservancy facilities and the socio-economic system can improve the accuracy of the results, but this method is only limited to short-term prediction and is not suitable for long-term prediction. There are similar studies of applying coupling theory and the grey GM (1,1) model in the literature. For example, Nie X and Zhang Z W (2020), Wang Weixin et al. (2020) [40,41] made a quantitative analysis of the coupling relationship between resources and the environment and social and economic development; Xu Hui (2021) [42] and Liu Guofeng (2021) [43] predicted the coupling relationship between resource utilization, the ecological environment, and economic growth and its development trend. The construction of models for the evaluation and prediction of governance-synergy is presented in the following Section 4.2.

3.4.1. Evaluation of the Existing Governance Synergy

In coupling theory, the order parameter index is a key variable used to measure the degree of the coordinated governance of the system; it determines the change process of the system from disorder to order. The degree of coupling is a measure of this synergy. The coupling degree, therefore, is used to construct a system governance collaborative evaluation model [44]. The collaborative governance evaluation model consists of two parts: the degree of order of the subsystems and the degree of subsystem governance synergy.

1. Subsystem Order Degree

In this paper we use i to represent the five constituent subsystems, $i \in [1, 5]$; j represents the order parameter index of each subsystem, $j \in [1, n]$; and = (,,) represents the j-th order parameter index of the i-th subsystem. The formula for the order degree S_i of the subsystem is, therefore:

$$S_i = \sum_{j=1}^{n} w_j \, u_{ij}(\delta_{ij}) \qquad \left(w_j \geq 0 \text{ And } \sum_{j=1}^{n} w_j = 1\right) \tag{1}$$

w_j in the above formula is the entropy weight of each index,
$u_{ij}(\delta_{ij})$ is the contribution value of each index to the order degree of the subsystem.
We then derive the following two equations:

$$w_j = (1 - d_j) / \sum_{j=1}^{n} (1 - d_j), d_j = -\frac{1}{\ln t} \cdot \sum_{t=1}^{h} \left(x_{ij} / \sum_{t=1}^{h} x_{ij} \right) \ln \left(x_{ij} / \sum_{t=1}^{h} x_{ij} \right) \tag{2}$$

$$u_{ij}(\delta_{ij}) = \begin{cases} (\delta_{ij}-\beta_{ij})/(\alpha_{ij}-\beta_{ij}) & \delta_{ij} \text{ is the positive order parameter} \\ (\alpha_{ij}-\delta_{ij})/(\alpha_{ij}-\beta_{ij}) & \delta_{ij} \text{ is the negative order parameter} \end{cases} \tag{3}$$

Whereas,
d_j in the above formula is the information entropy of each index;
t is the number of years evaluated;
x_{ij} is the normalized value of the original data;
α_{ij} is the upper limit of the order parameters;
β_{ij} is the lower limit of the order parameter.

The greater the value of $u_{ij}(\delta_{ij})$, the greater the contribution to the order of the subsystem. Avoiding the occurrence of 0 and 1, we enlarge and reduce the extreme values of the order parameter by 1% as the upper limit and lower limit of the critical point.

2. Subsystem Governance Synergy Degree

$$C = \left[\prod_{i=1}^{n} S_i / \left(\frac{1}{n}\sum_{i=1}^{n} S_i\right)^{n}\right]^{k} \tag{4}$$

$$D = \sqrt{C \times T}, T = aS_1 + bS_2 + \cdots + eS_5 \tag{5}$$

Whereas,
D is the coordination degree of WCS system governance;
C is the degree of coupling among various subsystems;
i is the number of subsystems;
k is the adjustment coefficient, and $k \geq 2$ (k = 2);
T is the coordination index;
a, b, c, d, and e are the undetermined coefficients.

Since the various subsystems influence each other and are indispensable to each other, we adopt Chen's principle to assign weights to all undetermined coefficients as 1/2 [45] (Chen Z, 2020).

3.4.2. Prediction of the Future Governance Synergy

The Xiangjiang River Basin system is in an open state, and each subsystem and the system as a whole can continuously exchange material, energy, and information with the external environment over time. The entire system includes indicators such as reservoirs, domestic water production and consumption, water quality compliance rate, and regional fiscal revenue. These indicators are easy to measure. The system also includes uncertain natural precipitation, total water resources, and other indicators. In this way, a system containing both obvious and uncertain information applies to the gray GM (1,1) model [46]. This article adopts the gray GM (1,1) model for the WCS system's governance synergy prediction.

We set the sequence $x^{(0)}(i) = \{x^0(1), x^0(2), \ldots\ldots, x^0(n)\}$ to be the degree of system governance synergy; $x^{(1)}(k)$ is the original sequence of the $x^0(i)$ accumulatively generated sequence and is denoted as $x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i), k = 1, 2, \ldots, n. \hat{x}^{(1)}(k) = \left(x^{(0)}(1) - \frac{b}{a}\right)e^{-ak} + \frac{b}{a}$ is the gray system prediction equation, and the parameters a and b in the equation are estimated by the least square method:

$$\hat{U} = \begin{pmatrix} a \\ b \end{pmatrix} = \left(B^T B\right)^{-1} B^T Y, Y = \begin{pmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{pmatrix}, B = \begin{pmatrix} -\left(\frac{1}{2}\right)x^{(1)}(2) + x^{(1)}(1) & 1 \\ -\left(\frac{1}{2}\right)x^{(1)}(3) + x^{(1)}(2) & 1 \\ \vdots & \\ -\left(\frac{1}{2}\right)x^{(1)}(k) + x^{(1)}(k-1) & 1 \end{pmatrix} \tag{6}$$

After obtaining the parameters a and b, we can substitute the parameters into $\hat{x}^{(1)}(k) = \left(x^{(0)}(1) - \frac{b}{a}\right)e^{-ak} + \frac{b}{a}$ according to the reduction equation $\hat{x}^{(0)}(k) = \hat{x}^{(1)}(k) - \hat{x}^{(1)}(k-1)$ of the GM (1,1) model, thus we have calculated $\hat{x}^{(0)}(k)$ to obtain the predicted value.

4. Results and Discussion

4.1. The Evaluation of the Existing Governance Synergy

4.1.1. Results of Subsystem Order Degree

The order degree of the five major subsystems over the years in the 2000–2019 period is presented in Figure 5. The overall order of the five subsystems shows a "wave-shaped" upward trend. It can be found that the uncertainty of rainfall has caused huge fluctuations in the orderliness of the natural water subsystem. The largest average rainfall gap over the years is 864 mm. The orderliness of rainy years increased, especially in 2002, 2010, and 2019. The degree of order in drier years declined, with 2007, 2011, and 2018 seen as more typical. This shows that the natural water system is easily affected by rainfall [47]. The amount of rainfall first affects the number of water resources available for surface water and groundwater. Moreover, the amount of rainfall affects social and economic activities, and ultimately fluctuates the degree of coordination of the entire system.

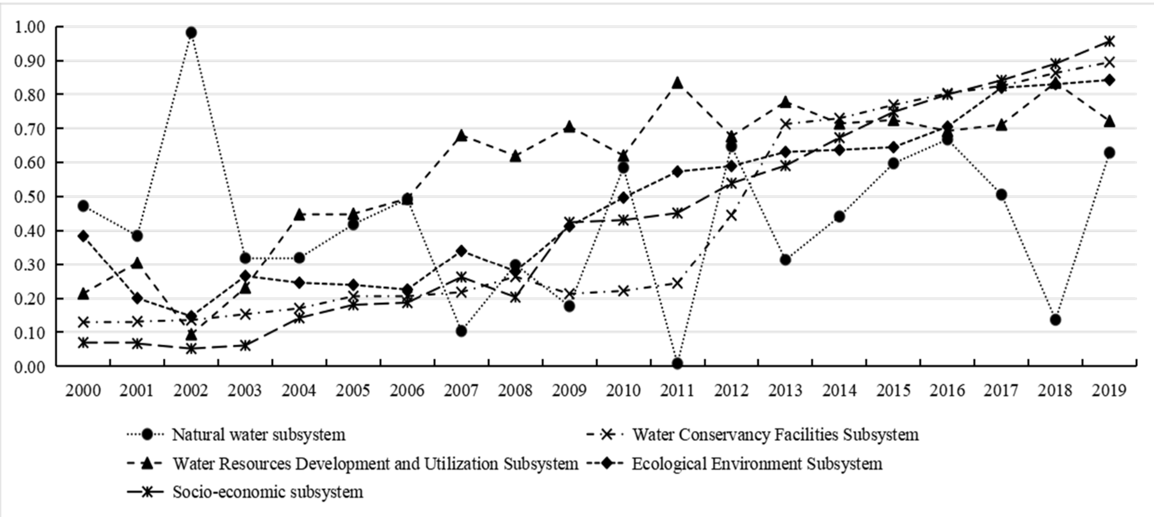

Figure 5. The order degree of each subsystem from 2000 to 2019.

The water conservancy facility subsystem and the socio-economic subsystem contribute significantly to the system's synergy with 27.6%, and 31.9%, respectively. The order degree of the water conservancy facilities subsystem increased significantly from 2011 to 2013. Among them, the number of reservoirs, the length of dykes, and the investment in water conservancy construction increased significantly. The three-year average growth rate of the three indicators exceeded 2%. The order degree of the socio-economic subsystem showed 2008 as the drop point and then increased, mainly because the region suffered low temperatures, rain, snow, and freezing disasters in 2008, which affected social and economic activities.

It is worth noting that the order degree of the two subsystems (the socio-economic subsystem and the water conservancy facilities subsystem) has shown a common upward trend. The analysis suggests that it may be due to the year-on-year improvement of infrastructure such as reservoirs, dikes, and water conservancy construction investment in the basin, which has alleviated the uncertainty of natural precipitation. The water conservancy facility subsystem provides stable water resources for agricultural irrigation, industrial production, and people's everyday lives, guaranteeing the safety of food production in the socio-economic subsystem, increasing per capita disposable income and regional GDP, and ultimately promoting the orderly rise of the socio-economic subsystem [3]. The connection between the socio-economic subsystem and the water conservancy facility subsystem shows that, under the premise of limited natural water resources, the investment and construction of water conservancy facilities are of great significance to socio-economic development and will have a positive impact on the operation of the system. The future regulation of the production and domestic water utilization investment and the maintenance of water conservancy facilities will have a huge impact on the improvement of the synergy of the entire river basin.

The water resource utilization subsystem and the ecological environment subsystem have the second-highest contributions to the WCS system, at 18.32% and 16.53% respectively [48]. Except for the decrease in the orderliness of the two subsystems, the increase in water consumption and sewage discharge of CNY 10,000 increased industrial added value in 2002. In the following years, the government paid more attention to the construction of ecological civilization and environmental protection, as well as the greening construction of water conservation and sewage treatment in the Xiangjiang River Basin, which increased the orderliness of the two subsystems. The reasonable adjustment of the water resources utilization efficiency and sewage treatment rate, protection of water ecological environment, and other measures are, therefore, vital to the coordinated governance of the WCS system in the Xiangjiang River Basin. This can leave other systems with high-quality water and better drive them to coordinate development strategies.

4.1.2. The Contributions of Indicators to the Order of Subsystems

Table 2 presents the contribution value of each order parameter index to the order degree of the subsystem for the years 2000–2019. In general, there is a low contribution of each index to the order degree of the subsystem, showing that there is room for growth. The per capita water resource, investment in agriculture, forestry, and water conservancy construction, length of dikes, water resource utilization, green coverage; sewage treatment volume, and other indicators reflect the low contribution to the construction of water conservancy facilities, water resources utilization, and ecological protection.

Table 2. The contributions of indicators to the order of subsystems over the 2000–2019 period.

δ_{ij} Order Parameter	2000	2003	2006	2009	2012	2015	2018	2019	Mean
δ_{11}	0.473	0.160	0.413	0.252	0.725	0.662	0.299	0.571	0.444
δ_{12}	0.490	0.377	0.518	0.136	0.615	0.552	0.055	0.623	0.421
δ_{13}	0.454	0.376	0.527	0.163	0.624	0.599	0.102	0.680	0.441
δ_{21}	0.012	0.093	0.325	0.194	0.392	0.715	0.909	0.990	0.454
δ_{22}	0.719	0.729	0.739	0.740	0.958	0.961	0.962	0.939	0.843
δ_{23}	0.646	0.650	0.689	0.691	0.988	0.072	0.195	0.290	0.528
δ_{24}	0.003	0.026	0.031	0.053	0.068	0.926	0.974	0.987	0.383
δ_{25}	0.056	0.054	0.085	0.163	0.759	0.820	0.932	0.946	0.477
δ_{31}	0.069	0.207	0.521	0.775	0.916	0.964	0.979	0.999	0.678
δ_{32}	0.463	0.233	0.547	0.746	0.908	0.960	0.999	0.980	0.729
δ_{33}	0.186	0.038	0.717	0.812	0.979	0.895	0.759	0.752	0.642
δ_{34}	0.165	0.449	0.511	0.703	0.594	0.631	0.691	0.826	0.571
δ_{35}	0.220	0.135	0.415	0.400	0.432	0.707	0.858	0.687	0.482
δ_{36}	0.242	0.361	0.275	0.652	0.203	0.276	0.724	0.268	0.375
δ_{41}	0.606	0.061	0.055	0.274	0.423	0.607	0.943	0.982	0.494
δ_{42}	0.381	0.997	0.443	0.521	0.461	0.388	0.134	0.013	0.417
δ_{43}	0.105	0.086	0.176	0.478	0.771	0.909	0.976	0.986	0.561
δ_{44}	0.632	0.811	0.876	0.578	0.744	0.051	0.797	0.921	0.676
δ_{51}	0.505	0.037	0.842	0.890	0.864	0.954	0.641	0.602	0.667
δ_{52}	0.002	0.037	0.107	0.238	0.444	0.629	0.892	0.989	0.417
δ_{53}	0.154	0.204	0.290	0.624	0.545	0.722	0.916	0.990	0.556
δ_{54}	0.001	0.028	0.072	0.408	0.554	0.826	0.933	0.990	0.476

Notes: The description of the order parameters presented in Table S2. For example, "δ_{11}" refers to "Average annual rainfall".

The similar situation of such large changes in indicators is largely due to the influence of natural and human factors. For example, the dike length was 0.003 in 2003 and 0.068

in 2012; but this rose to 0.926 in 2015. This is because the government pays attention to flood control and strengthens the construction of river and lake embankments. Another example is that the grain yield was 0.037 in 2003, because the average annual rainfall was less, which was a typical dry year and affected the grain harvest.

4.1.3. WCS System's Governance Synergy Degree

Looking at the trend over the years, as shown in Figure 6, the WCS system's governance coordination degree of the Xiangjiang River Basin takes 2011 as the critical point, showing a phased "S"-shaped development trend. Specifically, the system governance coordination degree between 2000 and 2011 is between 0.01 and 0.13; from 2012 to 2019, the synergy of system governance has risen to 0.36. However, the overall level is still not high, with an average of 0.1344 in synergy over the past two decades.

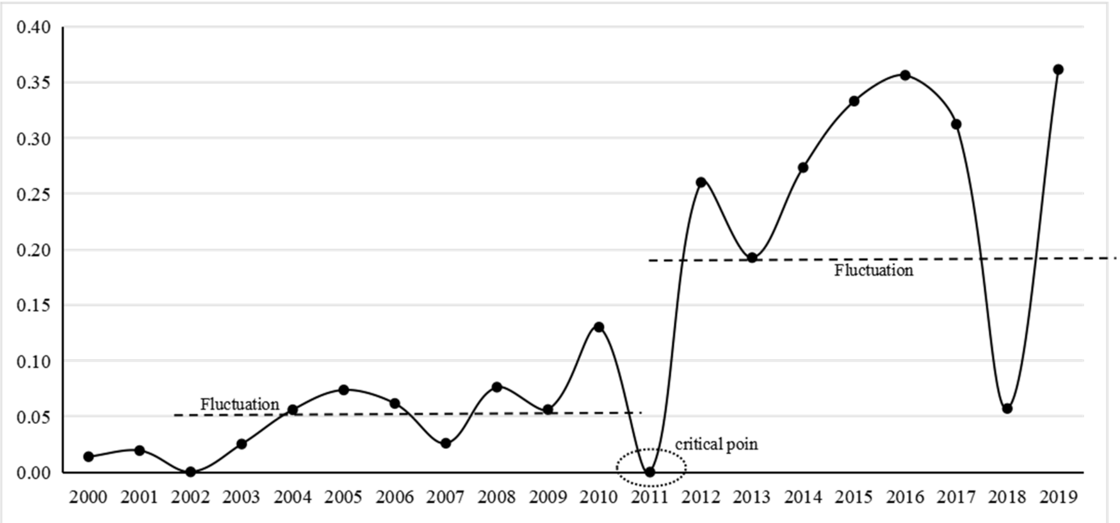

Figure 6. WCS system's governance synergy degree in the Xiangjiang River Basin.

Figure 6 presents the WCS system's governance synergy degree in the Xiangjiang River Basin. It can be seen that the degree of coordination of the system governance suddenly dropped in 2007, 2011, 2018, and at other time points, mainly due to the impact of natural precipitation. The change in rainfall causes a butterfly effect, which leads to a decrease of the reservoir capacity of the water conservancy facility subsystem. The reduction of storage water resources indirectly affects farmland irrigation water, industrial water, and domestic water consumption. Moreover, it ultimately causes a decline in food production, a decrease in per capita disposable income, and a slowdown in the growth of regional GDP and fiscal revenue in the socio-economic subsystem.

On the other hand, the system governance coordination degree steadily increased in 2005, 2012, 2016, and at other time points, especially in the 2011–2012 period where it reached 0.26. The growth in positive sequence parameters such as the river basin green coverage, sewage treatment rate, water conservancy construction investment, per capita disposable income, and regional GDP is responsible for this growth. The green coverage area increased by 81.9%, the sewage treatment rate increased by 11.2%, and the investment in water conservancy construction increased by 66.5%. Moreover, there was a decline in negative sequence parameters such as water consumption per CNY 10,000 of GDP, water per 10,000 yuan of industrial added value, and per capita comprehensive water consumption, where the water consumption for the three indicators decreased by 27.9%, 28.4%, and 0.4% respectively.

Although the overall level of system coordination over the period from 2000 to 2019 is not high, its growth rate is still 34.7%, which reflects that the WCS system of the Xiangjiang

River Basin is well-coordinated and that internal entropy is reduced. The WCS system as a whole evolves to a harmonious and orderly state.

4.1.4. The Governance Synergy Degrees of the Upstream, Midstream, and Downstream Regions of the Xiangjiang River Basin

Figure 7 presents the governance synergy degree of the WCS system in the upstream, midstream, and downstream regions of the Xiangjiang River Basin over the period rang from 2000 to 2019. Low points can be seen in the years 2002, 2002, 2011, and 2018. It develops an "S" shape, and the fluctuation points are mainly affected by rainfall. In accordance with the perspective of regional differences, spatial imbalances have been observed in the regions of 0.1159 upstream, 0.1074 midstream, and 0.1275 downstream. The overall level of governance synergy among the three regions is lower. It can be found that the synergy increased after 2004 and 2007, with an average increase of 31%. The reason for the growth is that Hunan Province is driven by the country's central rise strategy and the radiation of the two-oriented society. The second reason for the growth is due to policy measures taken by the government, such as water resource management assessment measures. Special funds for investment in water ecological construction and protection, water resource allocation guarantees, and social and economic development in the basin are relatively sufficient. This series of comprehensive measures has promoted the continuous increase in the degree of coordination, and the coordination degree of the governance of the upper, middle, and lower reaches of the Xiangjiang River Basin, rendering a WCS system that is still changing into a stable and orderly state.

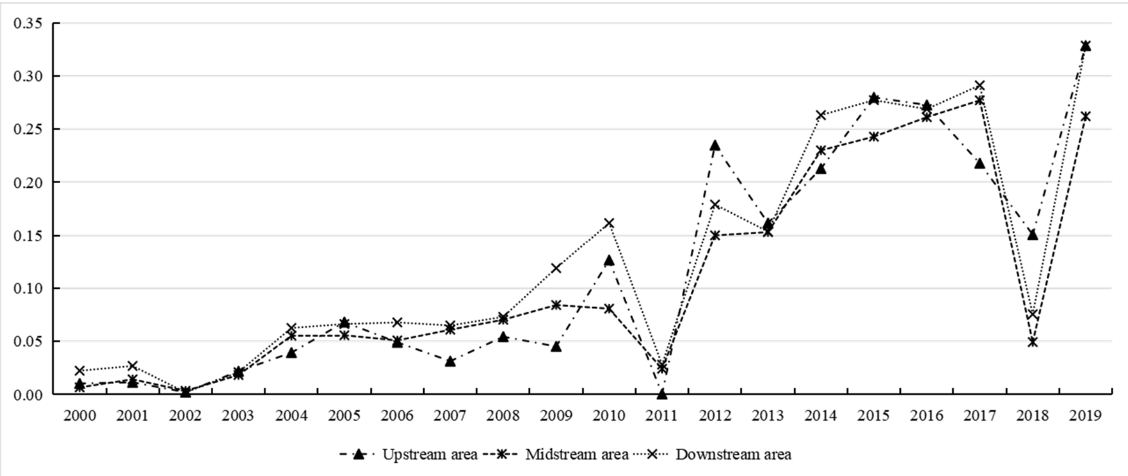

Figure 7. WCS governance synergy degree in the upstream, midstream, and downstream regions of the Xiangjiang River Basin.

4.2. Prediction of Future Governance-Synergy in the WCS System of the Xiangjiang River Basin

Substituting the coordination degree in the WCS system of the Xiangjiang River Basin from 2010 to 2019 into Equation (6), we have estimated parameters ($a = -0.1182$, $b = 0.0451$) and calculated using the gray GM (1,1) model: the forecast period is 5 years and the coordination degree of the WCS system governance from 2000 to 2024 has been obtained.

The prediction in Figure 8 indicates that the coordination degree of the WCS system governance in the Xiangjiang River Basin will show an overall upward trend from 2020 to 2024. It is predicted that the coordination degree of system governance will be between 0.4701 and 0.5955 from 2020 to 2022, and will be in a medium coordination state. The system governance synergy degree will reach 0.6703 in 2023, entering a highly synergistic state. In 2024. The system governance synergy will further increase, reaching 0.7. Therefore, it is speculated that the WCS system governance coordination degree of the Xiangjiang River Basin will maintain a relatively high marginal growth rate in the period between

2020 and 2024. However, it may be disturbed by natural precipitation and other natural disasters, causing fluctuations in the degree of the coordination of system governance.

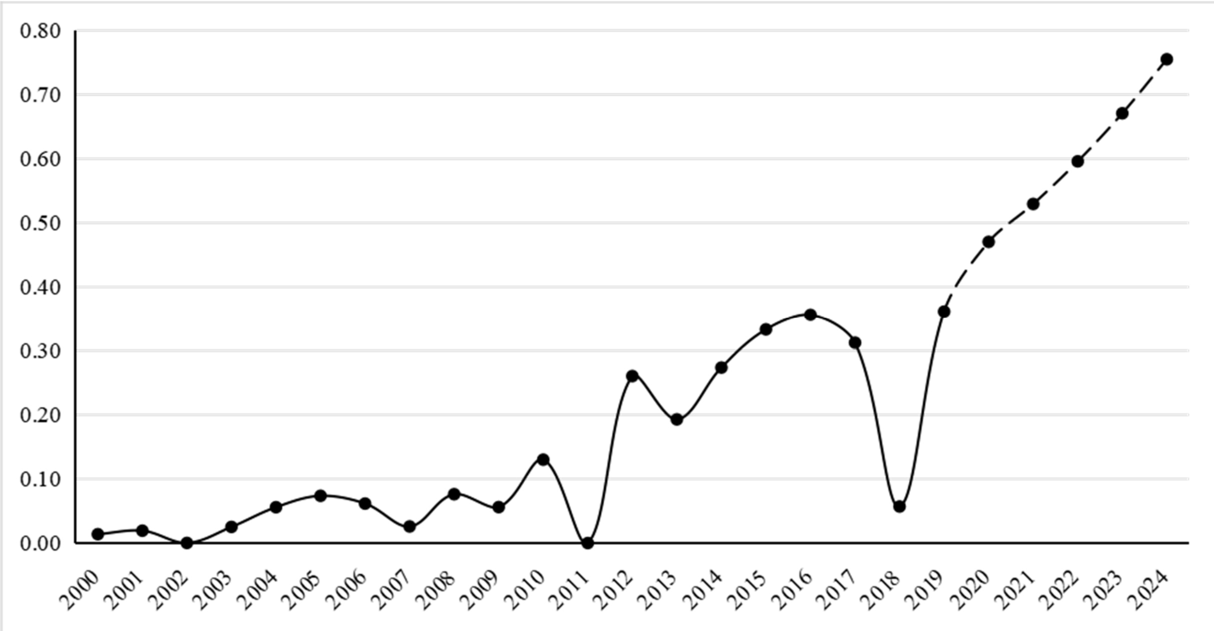

Figure 8. Governance-synergy prediction in the Xiangjiang River Basin.

Research should analyze the content and structure of the WCS system's collaborative governance, analyze the interrelationship of each constituent subsystem and the evolution mechanism of system collaborative governance, and build a model to evaluate the development trend of WCS system governance synergy, which could provide practical guidance and reference for the collaborative development of local water resources, water conservancy facilities and socio-economic systems. Taking the order degrees of the water resources development and utilization subsystem and the ecological environment subsystem in Figure 5 as examples, the order degrees of the two subsystems decreased in 2002, and the contribution of the order degrees of the two subsystems to the system synergy in other years was on the rise. From the perspective of specific indicators, the decrease in the order degreees of the two subsystems in 2002 was due to the large negative impact of the increase in water consumption and sewage discharge of industrial added value. Accordingly, the government should reasonably adjust the utilization efficiency of water resources and the sewage treatment rate, pay more attention to the construction of ecological civilization and environmental protection, pay attention to the greening construction and sewage treatment of water conservation in the basin, promote the orderly rise of the two subsystems, and better promote the coordinated operation of other systems.

5. Conclusions and Recommendation

The analysis revealed several key findings. Firstly, the WCS system's governance showed an S-shaped trend, with subsystems having both cooperative and competitive traits. The evolution process had fluctuations and non-linear features. The evolution process was influenced by factors such as natural precipitation, investment in water conservancy facilities, maintenance, water environment, and water-resource efficiency.

Secondly, from 2000 to 2019, the WCS system governance coordination degree of the Xiangjiang River Basin showed a phased S-shaped change, with 2011 as the critical point. The overall level of coordination was not high, and the upper, middle, and downstream regions had obvious differences. However, the average annual growth rate was up to 34.7%, suggesting a harmonious and orderly development. Thirdly, this study revealed a close relationship between natural precipitation, water conservancy facility development, and changes in the coordination degree of system governance. The utilization of water resources and the ecological environment significantly contributed to the overall system synergy, with contributions of 18.32% and 16.53% respectively. Finally, based on the analysis, the WCS system in the Xiangjiang River Basin is predicted to improve coordination in the next five years (2020–2024). It is expected to reach a highly coordinated stage by 2024.

This study's findings suggest several implications for policymakers. Firstly, the government should prioritize the investment and maintenance of water conservancy infrastructure projects to ensure an efficient water resource allocation and supply system. Additionally, increasing the utilization rate of water resources development is crucial. The allocation of water resources should be determined based on the relationship between socio-economic development and the availability of water resources. An accurate understanding of differences in water use efficiency in the upper, middle, and lower reaches of the river basin could improve the pertinence of water use policies and regulate the matching pattern of productivity development and water resources. Furthermore, regions and industries with low water consumption and utilization rates should be provided with water conservation awareness programs. In contrast, rules and regulations such as water rights transactions should be clarified for regions and industries with high water consumption and utilization rates. By implementing these measures, policymakers can effectively regulate water use and promote sustainable water resource management practices.

To ensure sustainable water resource management, policymakers should prioritize water conservation and ecological protection by supporting water and soil conservation projects, improving sewage treatment facilities, promoting natural restoration in the system, and maintaining the self-purification ability of rivers, lakes, and other water bodies. Additionally, the institutional guarantee system should be strengthened through comprehensive plans, management assessment systems, and responsible departments focusing on the protection of the quantity and quality of water resources, including strengthening water source protection, managing the water-saving system, improving the efficiency of water use, and strictly implementing river quality supervision to prevent pollution. Policymakers must also handle the relationship between trans-regional water conservancy facilities, socio-economic factors, and the water resource environment to provide long-term stable development.

Reasonable adjustments are needed for effective collaborative governance, ensuring moderation to maintain system synergy and dynamic balance. However, external factors can complicate the relationship between governing factors. Therefore, this paper's coordination analysis is a preliminary exploration with limitations; future research should critically investigate the WCS system using multi-level references to support our findings.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15203630/s1, Table S1: Subsystems, indicators and data source. Table S2: Order parameter index. Table S3: Xiangjiang River Basin WCS system coordinated governance index information.

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