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Harmonious Development between Socio-Economy and River-Lake Water Systems in Xiangyang City, China

Qiting Zuo [1,2], Zengliang Luo [1] and Xiangyi Ding [3,*]

1 School of Water Conservancy & Environment, Zhengzhou University, Zhengzhou 450001, China; zuoqt@zzu.edu.cn (Q.Z.); luozengliang0502@126.com (Z.L.)
2 Center for Water Science Research, Zhengzhou University, Zhengzhou 450001, China
3 Department of Water Resources, China Institute of Water Resources and Hydropower Reasearch, Beijing 100038, China
* Correspondence: dingxiangyi840318@163.com; Tel.: +86-10-6878-1373

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Abstract: River-lake water systems (RLS) are important carriers for matter transformation and energy transmission. Influenced by accelerated social and economic development, the structural, functional, and environmental states of RLS have been seriously damaged. It is an important problem for human beings to coordinate the contradiction between socio-economic development and the protection of RLS. In order to quantitatively study the harmonious relationship between socio-economic development and the state of RLS, the harmony theory method was used to analyze the degree of harmonious development between socio-economy and RLS in this study taking Xiangyang City as an example, and formulating corresponding harmonious optimization schemes. The results indicate that: (1) the state of RLS had a relatively small change during 2009–2014, and its spatial distribution shows a decreasing trend with the Han River as the central axis decreases on both of its sides; (2) before 2011, the driving force of socio-economic development in Xiang yang City mainly originated in the peripheral regions such as Laohekou City, Zaoyang City, and Gucheng County, but after 2011, it migrated rapidly towards Downtown, and reached the maximum in 2014; (3) when the influence of regional socio-economic development on RLS is small, socio-economic development is the main factor driving the change of the overall harmonious development degree of socio-economy and RLS. However when the influence is big, it is combined, driven by socio-economic development and the state of RLS; (4) the main factors affecting the overall harmonious degree of socio-economy and RLS in Xiangyang City include: river length, standard ratio of water quality, water consumption per capita, reservoir regulation capability, farmland irrigation water consumption per Mu (Mu is an area unit in China, 1 Mu approximately equals to 666.67 m^2), and sewage treatment rate. This study can provide a reference for the future analysis of the harmonious development between socio-economy and RLS, as well as in formulating corresponding harmonious optimization schemes in China and other countries in a similar situation.

Keywords: socio-economic development; river-lake water system; harmony theory; harmonious development; Xiangyang City

1. Introduction

As the major carrier of water resources and main participant of the natural and social water cycle, the river-lake water system (RLS) plays an irreplaceable role in regional development and environmental protection. The formation and development of RLS is influenced by many natural factors, such as geology, topography, soil, hydrology, climate, and vegetation, and social factors, such as dredging, sand mining, power, shipping, and aquiculture [1,2]. Moreover, the structure and function of RLS is usually altered to meet the needs of people for water, energy, transportation, recreation, storage, and discharge under the influence of human activities [3,4]. Nowadays, with the rapid development of socio-economy and population growth, humans have changed ecosystems more rapidly and extensively to meet the rapidly growing demand for food, fresh water, timber, fiber, and fuel [5]. While water can contribute to economic development, the latter can pose a significant threat to water resources, if there is no control over effluent release and extraction of the resource [6]. Thus it is necessary and urgent to study the harmonious development relationships between socio-economy and RLS.

The study of human and natural systems experienced a stage change from qualitative analysis to quantitative research. As early as two thousand years ago, the ancient philosophers of China put forward the idea of "harmony between man and nature". For example the thoughts of "Shun Tian" proposed by Zhuangzi are representative. He believed that the laws of nature cannot be changed by the human will, and we, human beings, should conform to these objective laws. Since the start of modern times, with the increasingly serious global environmental problems, the relationship between humans and nature is valued in a real sense, especially after the industrial revolution. People began to reflect on the way to get along with nature in harmony. Representative works during this period include: "Our Plundered Planet" published by Osborn in 1948, "Road to Survival" published by William Vogt in 1948, "Silent Spring" published by Carson in 1962, etc. In the academic field, initially, some qualitative research methods included observation, questionnaire survey, experience judgment and so on. After the 1970s, with the further research of human and nature issues, a large number of quantitative theoretical methods were gradually applied to the study of coupled human and nature systems, and the research of human and natural systems tends to become quantified. The main methods include: the Synergetic theory proposed by the German physicist Hermann Haken in 1971 [7], the System theory proposed by L. Von. Bertalanffy in the mid-20th century [8], the calculation method of ecological carrying capacity proposed by Robert Goodland et al. [9], Set Pair Analysis proposed by Keqin Zhao in 1989 [10], Complexity theory [11], Multi-agent models [12], Ecosystem coupling theory [13] etc. Nowadays, with the further study of system complexity [14–16], the method of multi-disciplinary cross is gradually being applied to the study of relationships between human and nature systems, and the factors to be considered are constantly expanding, including human activities, economy, society, and ecology. For example, contribution of [14] in the study of feedback loops, thresholds, time lags and so on. The research about RLS mostly focuses on impacts of climate changes [17,18], human activities [19,20] and urbanization [21], as well as on ecology and the environment of rivers and lakes. Some comprehensive researches, taking rivers and lakes as the carrier, mainly focus on the coordinated development relationships of ecology, economy, and society to provide decision support for water resources management. Koundouri, et al. [6] described a methodology which aims to achieve sustainable and environmental and socio-economic management of freshwater ecosystem services. Wang et al. [22] devised an integrated ecological-economic-social model to assess the implementation of eco-system-based fisheries management in the Pearl River Estuary (PRE) in the South China Sea. However, the harmonious development relation between socio-economy and RLS has been less discussed from the perspective of the internal system. Socio-economic development and RLS is an organic unity with both factors interacting and affecting each other. It is necessary to research the harmonious development relationships of them from the viewpoint of the system.

Xiangyang City, which is the deputy center city of Hubei province, has a well-developed river system as well as rich vegetation and mineral resources. It is one of the national demonstration cities of green development because of its unique natural geographical features and good ecological environmental situation. Xiangyang City is located between the world's largest continent (Eurasian continent) and the world's largest ocean (Pacific Ocean), belongs to a subtropical monsoon climate, and has the characteristics of severe changes of temperature and rainfall in summer and winter. In summer, solar radiation is strong, rainfall is abundant, humidity is high, and as the evaporation is less than precipitation, the surface runoff increases. In the winter, solar radiation is greatly reduced, the weather is cold and dry, and the rainfall is less. However, in recent years, in order to satisfy the needs of irrigation, power generation, and urban water supply, the development and utilization of RLS has been accelerated in Xiangyang City, and the structure, function and environmental conditions of RLS have been affected seriously. In order to alleviate contradiction between rapidly increased socio-economic development and protection of RLS, relevant adaptive management measures need to be taken urgently in Xiangyang City to ensure complete structure, perfect functioning, and good ecological environment of RLS while realizing stable and rapid socio-economic development. The objectives of this study are to: (1) put forward the research framework of harmonious development between socio-economy and RLS, and introduce a new theory of related research; (2) analyze temporal variation and the spatial distribution pattern of socio-economic development and the state of RLS between 2009 and 2014 in Xiangyang City, respectively; (3) research the harmonious development relationships between socio-economy and RLS, the main influencing factors, and corresponding harmonious optimization schemes in Xiangyang City. This study is of theoretical and practical merit in promoting socio-economic development and maintaining the health of RLS in urban areas.

2. Study Area and Data

2.1. Study Area

Xiangyang City, which is located in the northwest of Hubei Province and the plain hinterland of the middle reaches of the Han River, has a total area of 197,000 km^2 (Figure 1). It includes seven administrative divisions, Zaoyang City, Yicheng City, Laohekou City, Nanzhang County, Gucheng County, Baokang County, and Downtown. The study area belongs to a subtropical monsoon climate transition zone, and has a north-south transitional climate characteristic of four distinctive seasons, warm weather, sufficient sunshine, moderate rainfall, hot and rainy in summer, and cold and dry in winter. Precipitation, with a decreasing trend from southwest to northeast, is abundant within the area, and the average annual precipitation is about 800–1000 mm. Precipitation is unevenly distributed during the year, and the depth of runoff is about 309.5 mm. The average annual evapotranspiration is about 941 mm, and the average annual temperature is about 15.1–16.9 °C. River systems are well-developed in Xiangyang City with a total of large and small rivers of 649, mainly including Han River, Xiaoqing River, Tangbai River, White River, Tang River, Gun River, Sha River, South River, North River, Man River, Ju River, Zhang River, etc. In recent years, socio-economy has been growing fast in Xiangyang City. Great efforts have been made in traditional industries and emerging industries, and an industrial system has been formed with the mainstay of equipment manufacturing, new energy vehicles, new energy and new materials, electronic information, pharmaceutical engineering, and intensive processing of agricultural products. In 2014, the city's total GDP reached 312.93 billion yuan, accounting for 11.4% of Hubei province. The rapid development of the social economy has caused serious impacts on rivers and lakes. Therefore, it has become urgent and necessary to study the harmonious development relations between socio-economy and RLS.

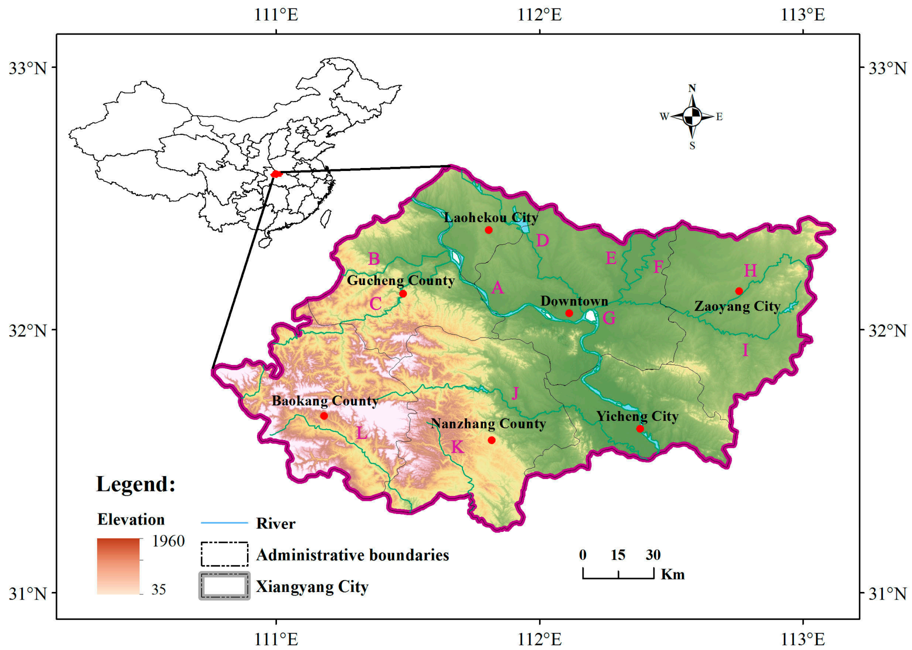

Figure 1. Location of the Study Area, Rivers and Administrative Divisions. **A**: Han River; **B**: North River; **C**: South River; **D**: Xiaoqing River; **E**: White River; **F**: Tang River; **G**: Tangbai River; **H**: Sha River; **I**: Gun River; **J**: Man River; **K**: Zhang River; **L**: Ju River.

2.2. Data

Socio-economy and RLS data covering the period of 2009–2014 are used to analyze the temporal and spatial variation characteristics of social economy development, the state of RLS, and their harmonious development relationships. Socio-economic development data were obtained mainly from the Statistical Review, Water Resources Bulletin, and Environment Quality Bulletin of Xiangyang City. Some data were provided by Xiangyang's Hydrological Bureau and the Statistical Bureau and Environmental Protection Bureau. RLS state data including the river network and, the reservoirs, were extracted from remotely sensed imagery and DEM (Digital Elevation Model).

3. Methodology

3.1. Research Idea

3.1.1. Theory Basis

Socio-economic development cannot be separated from the support of RLS, and will inevitably have a negative impact on its structural, functional and environmental state. If the ideal pattern of regional development is understood as the high level of socio-economic development and the good condition of RLS, then, from the systematic perspective, how to study the harmonious relationship between them is an urgent problem needing to be solved. The harmony theory which innovatively combines the society system with the water system, is a systematic method used to quantitatively study the harmonious relationship between the two systems [23]. It has the following characteristics: (1) the concept of "Harmony" has been advocated to handle relationships between human and nature systems in the harmony theory; (2) the harmony theory advocates understanding contradictions and conflicts existing in harmonious issues, such as human and nature systems, allowing the existence of "differences", and advocates to dealing with these contradictions and conflicts with a harmonious attitude; (3) the harmony theory insists on a people-oriented, comprehensive, coordinated, and sustainable scientific development view, to solve all kinds of problems faced by nature and human society; (4) the harmony theory pays close attention to the dialectical relationship between humans and nature, advocates the idea of harmony between humans and nature, and thinks that it is necessary and possible to achieve a coordinated development between humans and nature; (5) the harmony theory insists on the basic point of view of system theory and advocates that system theory should be used in the study of harmony. The structural, functional and environmental state of RLS is comprehensively represented by the state index of RLS (RLSI) which varies from 0 to 1, and larger values represent a better state of RLS and vice versa. The socio-economic development index (SEDI), which also varies from 0 to 1, is used to represent the level of regional economic and social development, and larger values illustrate a higher level and vice versa. In order to analyze the harmonious development degree between socio-economy and RLS, the harmonious development index P with a variation range from 0 to 1 is proposed based on the harmony theory. The larger values illustrate a higher harmonious development degree and vice versa.

In addition, the overall harmonious development degree of socio-economy and RLS is divided into four types based on the values of RLSI and SEDI (Table 1). Type I: RLSI and SEDI are both equal to or greater than 0.7 (It should be noted that, based on the evaluation results in the regions with highly developed socio-economy and good state of RLS in China, we found that, when the SEDI reaches 0.7, the level of socio-economic development is slightly higher than the average level of highly developed regions, and when the RLSI reaches 0.7, the state of RLS is slightly higher than the average level of good RLS state regions. Therefore, 0.7 was selected as the threshold for both RLSI and SEDI). In this case, the state of RLS is good and the level of socio-economic development is high, belonging to an acceptable situation on current level of socio-economic development and state of RLS. Type II: RLS is equal and greater than 0.7, but SEDI is less than 0.7. In this case, the state of RLS is good, but the level of socio-economic development is low. Great efforts should be focused on socio-economic development while maintaining a good state of RLS. Type III: SEDI is equal or greater than 0.7, but SEDI is less than 0.7. In this case, the state of RLS is poor, and the level of socio-economic development is high. Great efforts should be focused on the improvement of the state of RLS while taking socio-economic development into account. Type IV: RLSI and SEDI are both less than or equal to 0.7. In this case, the state of RLS is poor and the level of socio-economic development is low. This type easily occurs in the areas where the structure of RLS is relatively not developed, so the harmonious development of socio-economy and RLS should be taken into account.

Table 1. Harmonious development types of regional socio-economy and river-lake water systems (RLS).

Type	RLSI	SEDI	Description
I	$\geq$0.7	$\geq$0.7	Good state of RLS and high level of socio-economic development
II	$\geq$0.7	<0.7	Good state of RLS and low level of socio-economic development
III	<0.7	$\geq$0.7	Poor state of RLS and high level of socio-economic development
IV	$\leq$0.7	$\leq$0.7	Poor state of RLS and low level of socio-economic development

3.1.2. Research Framework

The statistical data covering 2009 to 2014 was used to comprehensively analyze the state of RLS and the level of socio-economic development in Xiangyang City. Additionally, the harmonious development schemes of socio-economy and RLS were studied based on the harmony theory. The study steps include: (1) The index system reflecting the harmonious development degree of socio-economy and RLS is constructed based on systematic, representative and easily accessible principles from the aspects of socio-economy and RLS, respectively; (2) RLSI and SEDI are calculated separately using the method of single index quantification and multiple index synthesis (SI-MI), and the overall harmonious development index P is calculated based on RLSI and SEDI; (3) The temporal and spatial variation characteristics of the state of RLS are analyzed as well as the level of socio-economic development and overall harmonious development degree of Xiangyang City; (4) Comprehensive regulation combing with the harmony equilibrium regulation model is carried out and adaptive optimization solutions and countermeasures are proposed, in order to improve the harmonious development degree of socio-economy and RLS in Xiangyang City. The research framework is shown in Figure 2.

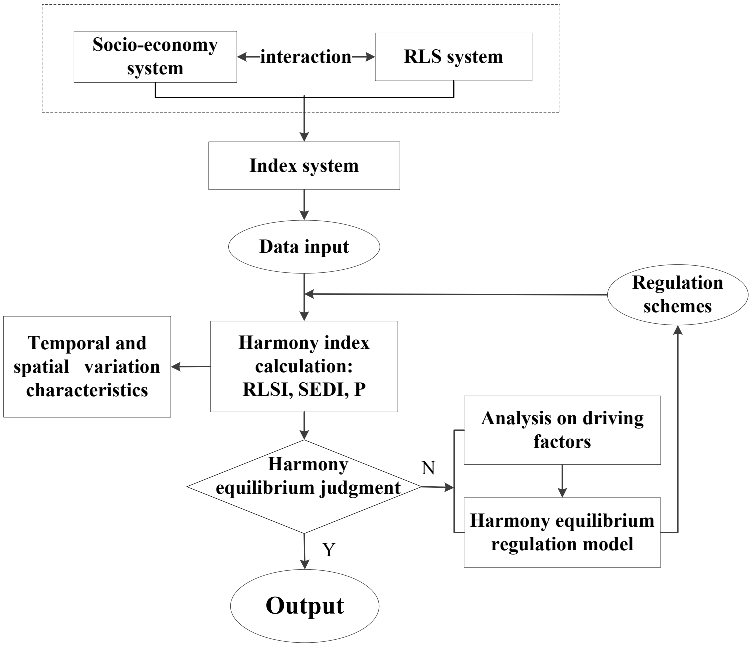

Figure 2. Framework of harmonious development between socio-economy and river-lake water systems (RLS) in Xiangyang City.

3.2. Construction of Index System

A good condition of RLS can be understood as being an integrated structure, a perfect function, and a good ecological environmental condition. The level of socio-economic development is usually measured from the two aspects of society and economy. Therefore, the indexes of the state of RLS are selected from the aspects of structural subsystem, functional subsystem, and environmental subsystem based on systematic, representative and easily accessible principles (Table 2). The structural subsystem is an important reflection of the structural change of RLS, which can usually be expressed from the point of view of three aspects: quantity structure, structure law, and connectivity. Therefore, the drainage density and water surface rate are selected to reflect the change of quantitative characteristics of RLS; the area and length ratio of backbone rivers, and the river network development coefficient are selected to reflect the change of RLS in law; the longitudinal connectivity is selected to reflect the change of connectivity of RLS. Industry, agriculture, and urban development mainly depend on the surface water due to the abundant rivers in the Xiangyang City, and a large number of reservoirs have been built. Additionally, surface water pollution caused by human activities has a great influence on the river and lake functions. Therefore, surface water supply and reservoir regulation ability are selected to reflect the change of the functional status of RLS, and the water quality standard river length ratio is selected to reflect the change of the environmental state of RLS. Indexes of socio-economic development are selected from the two aspects of social subsystem and economic subsystem (Table 2). Xiangyang City is the main grain producing area of China, and agricultural non-point source pollution has a great impact on rivers and lakes ecosystems. In recent years, industry in the city has been developing rapidly, and the demand for water is increasing. However, the existing sewage treatment capacity is limited and needs to be upgraded urgently. Therefore, considering the layout of the industrial structure and future development trends in the city, indexes including water consumption per capita, water consumption per 10,000 yuan of GDP, water consumption per 10,000 yuan of industrial added value, farmland average per irrigation water consumption, and sewage treatment rate are selected to reflect its social development; GDP per capita and GDP growth rate are selected to reflect its economic development.

Table 2. Evaluation index system of harmonious development between socio-economy and RLS.

Goal Level	Category Level	Subsystem Level	Index Level	Number
Harmonious development of socio-economy and RLS	Socio-economy	Social subsystem	Water consumption per capita (m^3/person)	X_{11}
			Water consumption per 10,000 yuan of GDP (m^3/10,000 yuan)	X_{12}
			Mu of farmland irrigation water consumption (m^3/mu)	X_{13}
			Water consumption per 10,000 yuan of industrial added value (m^3/10,000 yuan)	X_{14}
			Sewage treatment rate (%)	X_{15}
		Economic subsystem	GDP per capita (yuan)	X_{21}
			GDP growth rate (%)	X_{22}
	RLS	Structural subsystem	Drainage density (1/km)	X_{41}
			Water surface rate (%)	X_{42}
			Area and length ratio of backbone rivers (km)	X_{43}
			River network development coefficient (-)	X_{44}
			Riverbank stability (-)	X_{45}
			Longitudinal connectivity (-)	X_{46}
		Functional subsystem	Surface water supply (10^8 m^3)	X_{51}
			Reservoir regulation ability (-)	X_{52}
		Environmental subsystem	Water quality standard river length ratio (%)	X_{53}

3.3. Calculation of RLSI and SEDI

The SI-MI method uses the harmonious calculation results achieved by a certain calculation method to synthetically represent the harmonious degree of the harmony problem by establishing an index system and evaluation criteria. The method includes three aspects: establishing the index system, determining the evaluation criteria, and selecting the quantitative calculation method. The comprehensive indexes of RLSI and SEDI reflecting the overall level of the system are calculated using the method of SI-MI from the perspective of systematic analysis [24].

3.3.1. Harmony Index of Single Indexes

The harmony degree is an important index to express the harmonious degree of participants, such as socio-economic system and RLS system, quantitatively. For a harmonious problem, the following five questions should be solved before the calculation of the harmony degree: (1) Harmony participators: the participators of a harmonious problem; (2) Harmony objective: objectives that must be met by participators to achieve the harmony state in a harmonious problem; (3) Harmony regulation: regulations or constraints developed for achieving the harmony objectives; (4) Harmony factor: the factors that need to be considered for the harmony participators to achieve the whole harmony; (5) Harmony action: the general term of specific behaviors taken by harmony participators for harmony factors. Two types of methods could be used to calculate the harmony index of single indexes, the quantitative calculation method based on the harmony degree equation and the quantitative calculation method based on the fuzzy membership function.

a. Calculation method of harmony index based on the harmony degree equation [25,26]

The harmony degree equation proposed by Zuo [23] is an important calculating method for the quantitative expression of the harmonious development degree of participants. The harmony degree equation for single indexes can be calculated as follows:

$$HD = ai - bj \tag{1}$$

where *HD* is the harmony degree of a specified index F, $HD \in [-1, 1]$. The greater value of *HD* (or closer to 1), the higher of the harmony degree. The variables *a* and *b* are the unity degree and the difference degree, respectively. $a, b \in [0,1]$ and $a + b \leq 1$. The unity degree *a* expresses the proportion of harmony participants in accordance with harmony rules with the same goal. The difference degree *b* expresses the proportion of harmony participants with divergent harmony rules and goals. The specific meaning of the harmony equation is expressed in Zuo et al. [25].

b. Calculation method of harmony degree based on fuzzy membership function

Zadeh [27] proposed the method of fuzzy membership function in dimensionless treatment of indicators. In the indicator system, each indicator has a harmony degree with the value ranges from 0 to 1. In order to quantify the harmony degree of a single indicator, the following assumptions are made: there are five eigenvalues for each index: the best, good, general, poor and worst value. When the index value is less than or equal to the worst value, the harmony degree of the indicator is 0; when the indicator value is equal to the poor value, the harmony degree of the indicator is 0.3; when the indicator value is equal to the general value, the harmony degree of the indicator is 0.6; when the indicator value is equal to the good value, the harmony degree of the indicator is 0.8; when the indicator value is equal to the best value, the harmony degree of the indicator is 1. So, single indexes are mapped to the range of 0 to 1 using the fuzzy membership function of $\mu_k(x) = f_k(x)$, $\mu_k \in [0,1]$. They are divided into positive and negative indexes based on relationships with the harmony degree. The values of the harmony degree of positive indexes increase with the increase of index values, and reverse for the negative indexes. Calculation curves and mathematical expression of harmony degree of positive and negative indexes are shown in Figure 3 and Formula (2), respectively.

$$SI_i = \begin{cases} 0 & x_i \leq a_i \\ 0.3\left(\frac{x_i - a_i}{b_i - a_i}\right) & a_i < x_i \leq b_i \\ 0.3 + 0.3\left(\frac{x_i - b_i}{c_i - b_i}\right) & b_i < x_i \leq c_i \\ 0.6 + 0.2\left(\frac{x_i - c_i}{d_i - c_i}\right) & c_i < x_i \leq d_i \\ 0.8 + 0.2\left(\frac{x_i - d_i}{e_i - d_i}\right) & d_i < x_i \leq e_i \\ 1 & e_i < x_i \end{cases}; \quad SI_i = \begin{cases} 1 & x_i \leq e_i \\ 0.8 + 0.2\left(\frac{d_i - x_i}{d_i - e_i}\right) & e_i < x_i \leq d_i \\ 0.6 + 0.2\left(\frac{c_i - x_i}{c_i - d_i}\right) & d_i < x_i \leq c_i \\ 0.3 + 0.3\left(\frac{x_i - b_i}{c_i - b_i}\right) & c_i < x_i \leq b_i \\ 0.3\left(\frac{x_i - a_i}{b_i - a_i}\right) & b_i < x_i \leq a_i \\ 0 & a_i < x_i \end{cases} \quad (2)$$

where SI_i is the harmony degree of index *i* at time *T*, $SI_i \in [0,1]$; a_i, b_i, c_i, d_i and e_i are eigenvalues of index *i*; x_i is the value of index *i* at time *T*.

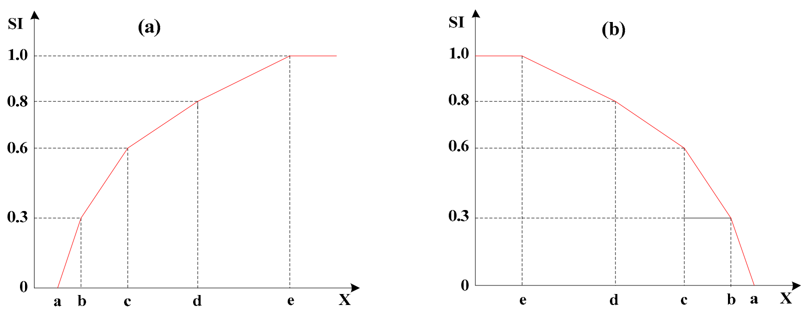

Figure 3. Calculation curves of harmony degree: (**a**) positive indexes; (**b**) negative indexes.

3.3.2. RLSI

Multiple index synthesis is the weighted calculation process for the harmony degree of a single index. Assuming that the value of a quantitative index is $Y^i(T)$ at time T, then its harmony degree calculated using Formula (2) is $SI_i(Y^i(T))$. RLSI is expressed as:

$$RLSI(T) = f(x) = \beta_1 \sum_{i=1}^{n_1} w_i SI_1\left(Y_1^i(T)\right) + \beta_2 \sum_{i=1}^{n_2} w_i SI_2\left(Y_2^i(T)\right) + \beta_3 \sum_{i=1}^{n_3} w_i SI_3\left(Y_3^i(T)\right) \quad (3)$$

where $RSNI(T)$ is the state index of RLS at time T, $RSNI(T) \in [0,1]$, and the closer to 1 of the value, the better the state of RLS. β_1, β_2, and β_3 are the weights of structural subsystem state index, functional subsystem state index, and environmental subsystem state index, respectively, $\beta_i \in [0,1]$, and $\sum_{i=1}^{m} \beta_i = 1$. n_1, n_2 and n_3 are numbers of performance indicators of the three types of subsystem state indexes; w_i is the weight of index i.

3.3.3. SEDI

The calculation method of SEDI is similar to RLSI. They are both based on the calculation results of the single index harmony degree. The concrete calculation formula is listed as follows:

$$SEDI(T) = g(y) = \beta_4 \sum_{i=1}^{n_4} w_i SI_4\left(Y_4^i(T)\right) + \beta_5 \sum_{i=1}^{n_5} w_i SI_5\left(Y_5^i(T)\right) \quad (4)$$

where $SEDI(T)$ is the socio-economic development index at time T, $SEDI(T) \in [0,1]$, and the closer to 1 of the value, the higher the socio-economic development level. β_4 and β_5 are the weights of economic subsystem and social subsystem, respectively, $\beta_i \in [0, 1]$, and $\beta_4 + \beta_5 = 1$. n_4 and n_5 are the number of performance indicators of economic subsystem and social subsystem. w_i is the weight of index i.

3.4. Calculation of Harmonious Development Index

The harmonious development index P is introduced to reflect the overall harmonious development degree of socio-economy and RLS comprehensively based on the calculation results of RLSI and SEDI.

$$P = \alpha f(x) + \beta g(y) \quad (5)$$

where P is the harmonious development index of socio-economy and RLS. α and β are the weights of $f(x)$ and $g(y)$ respectively, and $\alpha + \beta = 1$. In this paper, $\alpha = 0.6$, $\beta = 0.4$.

3.5. Optimization Method of Harmony Regulation Scheme

In order to maximize the overall harmonious development index, the harmonious regulation schemes are optimized using the harmony equilibrium regulation model with harmony equilibrium as the constraint conditions for iteration termination. Harmony equilibrium is a relatively dormant and temporarily acceptable equilibrium state for stakeholders while considering their interests and the overall harmonious goal. The basic form of the harmony equilibrium regulation model is listed as follows [26]:

$$\begin{cases} Z = HD(X) \geq HD_0 \\ G(X) \leq 0 \\ X \geq 0 \end{cases} \quad (6)$$

where X is the decision vector; $HD(X)$ is the overall harmonious degree of socio-economy and RLS; HD_0 is the minimum value of the harmony degree that meets the requirement of harmony equilibrium, that is, the target threshold of harmony degree; $G(X)$ is a set of constraints, which should be written such that the value of each specific constraint is less than or equal to 0 in the (if the constraint condition is greater than or equal to 0, it can be transformed to less than or equal to 0 by taking the negative) [25].

4. Results and Discussion

4.1. Temporal and Spatial Variation Characteristics of the RLS State

4.1.1. Temporal Variation Characteristics

The calculation results of RLSI in each partition are shown in Table 3, and the condition of inter-annual variation of RLSI is shown in Figure 4a. As can be seen from Figure 4a, the value of RLSI is small (varying between 0.62 and 0.69), and shows a slowly growing trend from 2009 to 2014, and the growth rate is 0.56%. It illustrates that the state of RLS in Xiangyang City is poor, but moving towards a better direction between 2009 and 2014. We speculate that this is consistent with the actual situation of the green sustainable development strategy carried out vigorously in Xiangyang City in recent years (The systems of water resources protection, river-lake health security, and water management have been primarily established after nearly a decade of construction of water conservancy and reform of water management system in Xiangyang City. These efforts provide an important support and guarantee for the improvement of RLS's ecological environment). The inter-annual variation of RLSI shows a characteristic of decrease-increase-decrease, i.e., a decreasing tendency from 2009 to 2010, an increasing tendency from 2010 to 2013, and then a decreasing tendency again until 2014. The main reason for this change may be that the government of Xiangyang City adopted a series of protection and restoration measures for RLS under the appeal of the national strategy of Interconnected River System Network proposed in 2009, such as remediation of pollution sources and river dredging. These measures have greatly promoted the improvement of the state of RLS in the short term. However, after 2013, with the fading of national policy heat, the government investment intensity in protection and restoration of RLS was reduced. The state of RLS began to decline after a slow rise in the short time, and eventually almost returned to the same level as in 2009. The sensitivity of RLSI is related to the property of the selected indexes. The structural indexes are less affected by human activities in the short term, but the functional and environmental indexes are opposite, and they have a high contribution to the change of RLSI. Therefore, the functional and environmental changes of RLS are the main reasons for the fluctuation of the state of RLSI over a short time.

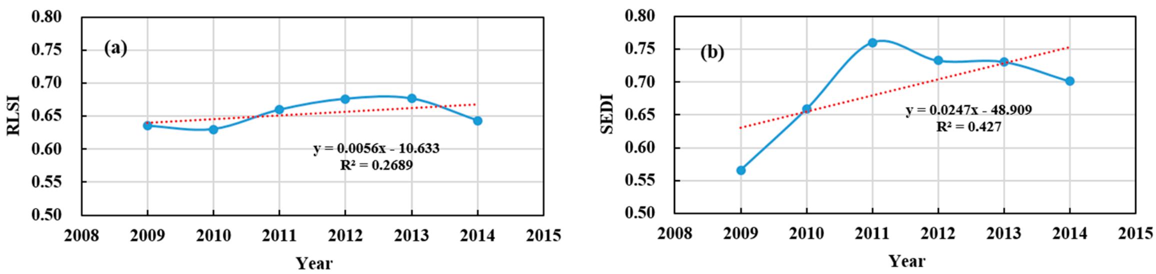

Figure 4. Inter-annual variation curve of SEDI and RLSI. (**a**) RLSI; (**b**) SEDI. The red line is the trend line of RLSI and SEDI, respectively.

Table 3. Calculation results of RLSI from 2009 to 2014 in Xiangyang City.

Administrative Divisions	2009	2010	2011	2012	2013	2014
Zaoyang City	0.62	0.62	0.60	0.58	0.58	0.55
Yicheng City	0.61	0.61	0.67	0.72	0.73	0.65
Laohekou City	0.74	0.73	0.76	0.77	0.76	0.75
Nanzhang County	0.65	0.65	0.66	0.67	0.68	0.69
Gucheng County	0.61	0.60	0.69	0.67	0.68	0.65
Baokang County	0.54	0.53	0.55	0.60	0.61	0.54
Downtown	0.68	0.67	0.69	0.72	0.69	0.68

For the specific circumstances of each administrative division (Figure 5), the values of RLSI are different in each region, which vary between 0.5 and 0.8 from 2009 to 2014. Among the administrative divisions, Zaoyang City shows a gradually descending tendency, Nanzhang County shows a gradually increasing tendency, and the rest of the regions change in volatility with increase and decrease. These illustrate that the backgrounds of RLS in different regions are different and it is the corresponding investment of restoration which leads to the differences of state of RLS. Zaoyang is the main grain producing area of Xiangyang City. As the RLS is not developed, water shortage is serious in Zaoyang City, agricultural development has a great impact on RLS, therefore, the decrease of RLSI is obvious.

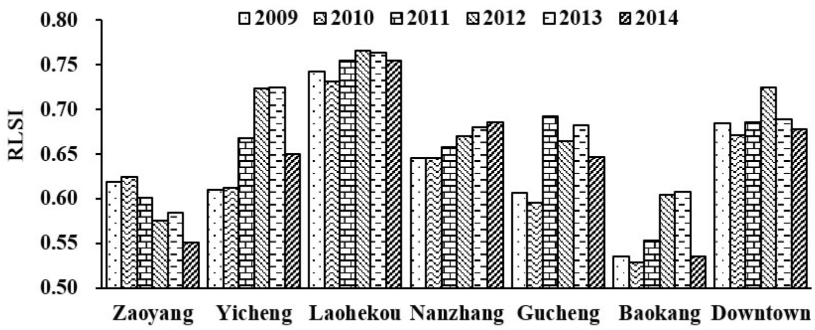

Figure 5. Temporal variation process of RLSI in different regions of Xiangyang City.

4.1.2. Spatial Variation Characteristics

Considering the spatial characteristic, the high value zone of RLSI is distributed mainly on both sides of the Han River, and the low value zone is distributed mainly in the east and west of the city. Therefore, influenced by socio-economic development and the natural structural and functional state of RLS, RLSI in Xiangyang City shows a spatial distribution pattern with the Han River as an axis decreasing on both wings (Figure 6a). It can be seen from each partition that Laohekou city was the biggest region for RLSI from 2009 to 2014 with an average annual value of 0.73 (Figure 5). It is chiefly because the RLS in Laohekou city is more developed, and has a better structural state compared with other regions, so it has a better carrying capacity for socio-economic development. In addition, the level of socio-economic development in Laohekou city is relatively lower compared with other regions, which has a smaller influence on RLS (Figure 6b). RLSI in Baokang County and Zaoyang City is lower (Figure 6b). The reasons are manifold. On the one hand, the RLS in Baokang and Zaoyang is relatively less developed, which has a poor carrying capacity for socio-economic development. On the other hand, socio-economic development in these two regions, where heavily polluting industries are widely distributed, is faster than other regions, which affects the functional and environmental state of RLS greatly (Figure 6b).

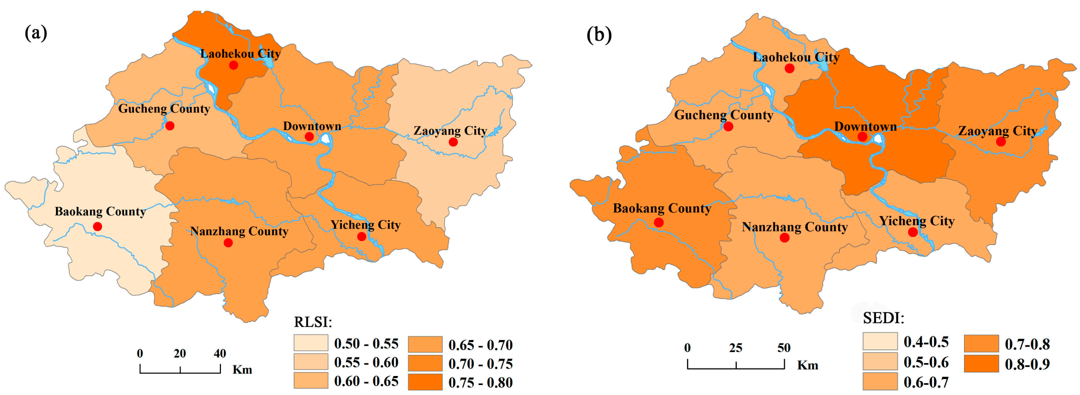

Figure 6. Spatial distribution pattern of RLSI and SEDI in Xiangyang City. (**a**) RLSI; (**b**) SEDI. The red dot is the location of the government.

4.2. Temporal and Spatial Variation Characteristics of Socio-Economic Development

4.2.1. Temporal Variation Characteristics

The calculation results show that SEDI ranging from 0.55 to 0.8 shows an increasing tendency from 2009 to 2014, and the growth rate is 2.5% (Table 4 and Figure 4b). This illustrates that the level of socio-economic development in Xiangyang City presents a trend of constant growth during 2009–2014. According to the process of inter-annual changes, the level of socio-economic development in Xiangyang City, with 2011 as the dividing point, shows a tendency of first increasing and then decreasing. Only when socio-economic development has reached a certain level, namely that RLS is not sufficient to support the needs of socio-economic development, will the state of RLS be changed. Compared with Figure 4a, before 2011, RLSI and SEDI showed an increasing trend. It shows that there has been almost no effect of socio-economic development on the state of RLS during this period. The cause for this phenomenon is closely related to the good natural structure of the water system and a low level of socio-economic development in Xiangyang City before 2011, and the government's attention on the management and restoration of RLS under the guidance of national policy (mainly the strategy of Interconnected River System Network proposed by the Chinese government). However, after 2011, when the development of socio-economy reached a certain level, it had a greater influence on RLS, and with the decrease of government investment in the management and restoration of RLS, the state of RLS began to decline. The decline in the state of RLS after 2011 is the result of cumulative effects of human activities before 2011. This cumulative effect may be completed in a few years or as long as 10 years, 20 years, or even longer, and depends on whether the cumulative effect has reached the critical threshold that can cause damage to the state of RLS. The determination of the critical threshold needs further study.

Table 4. Calculation results of SEDI from 2009 to 2014 in Xiangyang City.

Administrative Divisions	2009	2010	2011	2012	2013	2014
Zaoyang City	0.55	0.66	0.77	0.74	0.69	0.72
Yicheng City	0.55	0.58	0.77	0.73	0.70	0.69
Laohekou City	0.65	0.72	0.81	0.79	0.74	0.69
Nanzhang County	0.55	0.66	0.79	0.65	0.70	0.63
Gucheng County	0.60	0.72	0.81	0.77	0.76	0.65
Baokang County	0.61	0.75	0.78	0.79	0.76	0.71
Downtown	0.45	0.52	0.59	0.65	0.76	0.81

From the situation of each partition (Figure 7), the level of socio-economic development in Downtown was the lowest in 2009, then showed a constantly growing trend, with a growth rate of 7.3%. The rest of the regions show a tendency of first increasing and then decreasing. It can be seen from the change of SEDI in each region that the driving force of socio-economic development mainly originated in the surrounding areas of Xiangyang City before 2011, such as Laohekou, Zaoyang, and Gucheng. However, after 2011, it began to transfer to Downtown, and reached a maximum in 2014. According to the actual situation of rapid increase for the level of socio-economic development from 2009 to 2014 in Downtown, it is estimated that Downtown was designed as the core for social and economic development before 2009 in the urban development planning of Xiangyang City. However, due to the limited data, the socio-economic development level cannot be assessed before 2009 in different regions of Xiangyang. However, the trend mentioned above is consistent with the strategic planning of Xiangyang City implemented in recent years with the purpose of building Downtown as the focus of social and economic development by consulting the relevant departments.

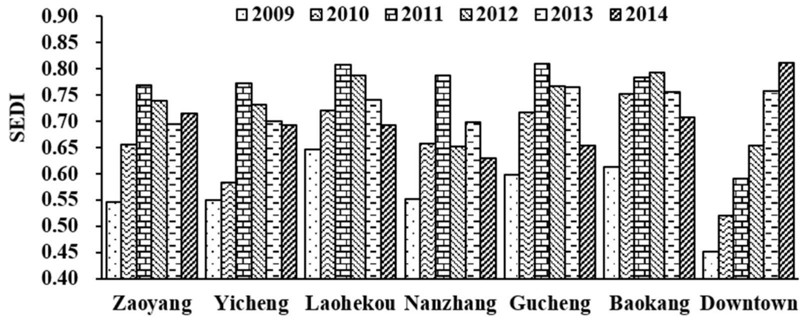

Figure 7. Temporal variation process of SEDI in Xiangyang City.

4.2.2. Spatial Variation Characteristics

From the view of spatial distribution (Figure 6b), the high value zone of socio-economic development in Xiangyang City is mainly gathered in the vicinity of Downtown, followed by its surrounding areas such as Baokang, Zaoyang, Laohekou, Gucheng, Nanzhang, and Yichang. This is mainly because the socio-economic development in Xiangyang City transferred rapidly to Downtown, pushing it to be the highest area for socio-economic development. Baokang and Zaoyang with abundant natural resources such as iron, copper, and phosphate ore, have a natural resources advantage for socio-economic development. A huge industrial system with the main pillar industries of equipment manufacturing, electronic information, deep processing of agricultural products has been formed in Laohekou, Gucheng, Nanzhang, and Yicheng.

4.3. Temporal and Spatial Variation Characteristics of the Overall Harmonious Development Degree

4.3.1. Temporal Variation Characteristics

The calculation results of the harmonious development index (P) of Xiangyang City from 2009 to 2014 are shown in Table 5. It can be seen from Table 5 that the overall harmonious development index in Xiangyang city ranges from 0.5 to 0.8, implying big temporal and spatial differences in the overall harmonious development degree in Xiangyang City. From Figures 5, 7 and 8, the overall harmonious development degree in Xiangyang City except for Downtown can be divided into three stages: (1) Stage I (2009–2010), the value of P increased gradually. The value of RLSI and SEDI were small in this stage, but the change of SEDI with a similar trend with P, was relatively large compared with RLSI. This shows that the small value of P is jointly decided by the state of RLS and socio-economic development, and its change is mainly driven by the development of the social economy; (2) Stage II (2011–2012), the value of P reached the maximum. In this stage, as the change of RLSI was small, its influence on the overall harmonious development index could almost be ignored. However, SEDI increased quickly compared with Stage I. This demonstrates that social economy may be the main factor driving the increase of P; (3) Stage III (2013–2014), the value of P reduced gradually. In this stage, RLSI and SEDI began to decrease, and the variation extent of SEDI was larger than RLSI. This suggests that the value of P was driven by RLS and socio-economic development, but the contribution of socio-economic development was greater. Inter-annual variation trend of the overall harmonious development index is similar to SEDI in Figures 7 and 8, showing a trend of growing in Downtown, first increasing and then decreasing in other regions. Based on the analysis above, when the effect of regional social and economic development on RLS is relatively small, the former is the main factor driving the variation of the overall harmonious development degree, but when this effect reaches a certain level, it will be driven by socio-economic development and RLS. According to the analysis above, we believe that there are complex internal relations between the socio-economic system and RLS. That is a mutual feedback relationship with mutual restraint and promotion. The relationship of the socio-economic system and RLS is like the two ends of a balance in the current situation with limited resources and environment. Extreme changes on either side (too large or too small) will lead to an imbalance of harmony between the two systems. Only by achieving the balance with mutual adaptation, can they be improved at the same time.

Table 5. Overall harmonious development degree of socio-economy and RLS in Xiangyang City.

Administrative Divisions	2009	2010	2011	2012	2013	2014
Zaoyang City	0.59	0.64	0.67	0.64	0.63	0.62
Yicheng City	0.59	0.60	0.71	0.73	0.72	0.67
Laohekou City	0.70	0.73	0.78	0.77	0.75	0.73
Nanzhang County	0.61	0.65	0.71	0.66	0.69	0.66
Gucheng County	0.60	0.64	0.74	0.71	0.72	0.65
Baokang County	0.57	0.62	0.65	0.68	0.67	0.60
Downtown	0.59	0.61	0.65	0.70	0.72	0.73

The overall harmonious development degree in Laohekou City, where RLSI was larger compared with the other regions, was always the biggest from 2009 to 2014 (Figure 8). As can be seen from Figures 5 and 7 the overall harmonious development index in Downtown showed a rapid growth trend under the driving of socio-economic development. Taking 2011 as the dividing point, the variation tendency of the overall harmonious development index in the rest of the regions is consistent with SEDI, which shows a trend of first increasing first and decreasing. The change of RLSI is relatively small comparing with SEDI in each region, indicating that the driving effect of RLSI on the overall harmonious degree is not obvious. In conclusion, the state of RLS is an important foundation for socio-economic development, and the latter is the main factor driving the change of the overall harmonious development degree in Xiangyang City.

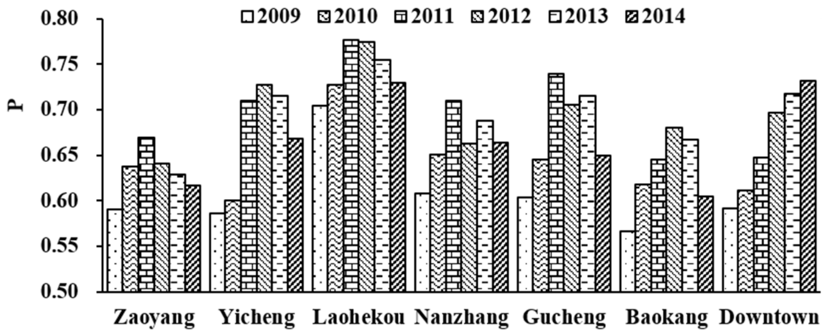

Figure 8. Temporal variation process of the overall harmonious development degree in Xiangyang City.

4.3.2. Spatial Variation Characteristics

Taking 2009 and 2014 as examples, the spatial distribution patterns of the overall harmonious degree in Xiangyang city were analyzed (Figure 9). In 2009, the overall harmonious development degree in Laohekou was the maximum, followed by Gucheng and Nanzhang, and that of Downtown, Baokang, Gucheng, and Zaoyang were the minimum. According to Table 1, Laohekou City belongs to Type II of harmonious development of socio-economy and RLS, and other regions belong to Type IV. By 2014, the level of overall harmonious development in each region was improved except for Gucheng County, and shows a spatial pattern in which the overall harmonious development degree in Laohekou and Dowentown were maximum, followed by Nanzhang and Yicheng, and that of Gucheng, Baokang, and Zaoyang were minimum. Among them, Laohekou City belongs to Type II; Downtown, Zaoyang, and Baokang belong to Type III; Nanzhang, Yichang, and Gucheng belong to Type IV. The following conclusions can be obtained that social economy is the development focus of Laohekou City while ensuring RLS is in good condition; Downtown, Zaoyang, and Baokang have a higher level of socio-economic development where the protection of the RLS state is the key for further efforts; balanced development of the social economy and protection of RLS should be focused in Nanzhang, Yicheng, and Gucheng.

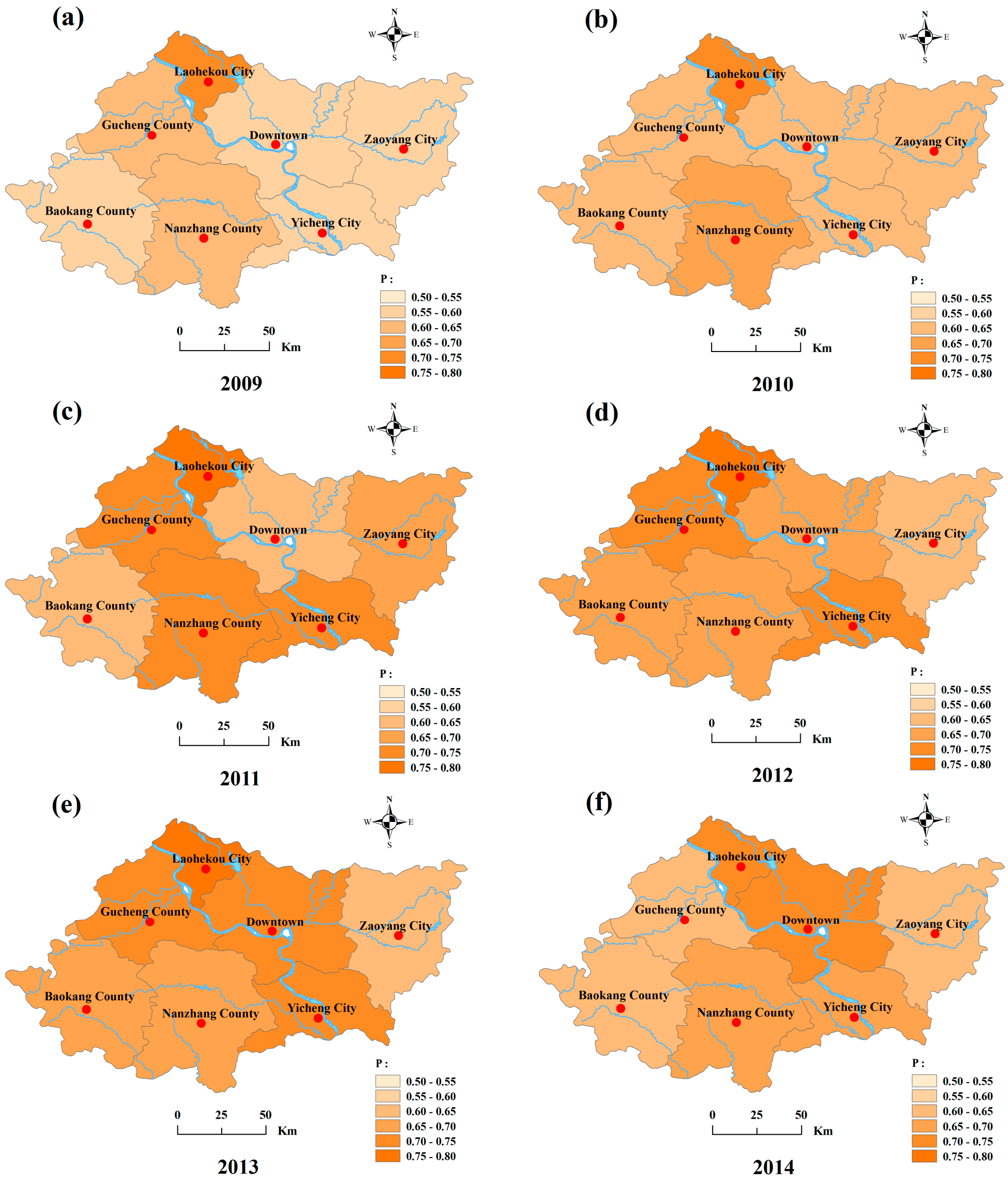

Figure 9. Spatial distribution pattern of the overall harmonious development index in Xiangyang City during 2009~2014. (**a**) 2009; (**b**) 2010; (**c**) 2011; (**d**) 2012; (**e**) 2013; (**f**) 2014.

4.4. Harmony Regulation Schemes

According to the experience of experts, when the value of the overall harmonious development index of socio-economy and RLS reaches 0.8, it can meet the strategic needs of the national construction of the Ecological Civilization [28–31]. Otherwise, harmony equilibrium judgement is needed based on the analysis of driving factors and the harmony equilibrium regulation model [32]. According to Table 3, all the regions in Xiangyang City do not meet the requirements under the status quo. Therefore, the main driving factors influencing the overall harmonious degree in Xiangyang City were analyzed first, and then the goal of harmony equilibrium was set to 0.8 for the harmonious regulation in each region.

4.4.1. Analysis of Main Driving Factors

The major factors affecting the harmonious development degree of socio-economy and RLS were obtained using the method of reverse index analysis based on five types of performance indicators, i.e., Economic subsystem, Social subsystem, Structural subsystem, Functional subsystem, and Environmental subsystem. The main driving factors for each region are listed in Table 6.

Table 6. Main driving factors for each region in Xiangyang city.

Administrative Divisions	Main Driving Factors
Zaoyang City	Water quality standard river length ratio
Yicheng City	Surface water supply, Reservoir regulation ability, Water quality standard river length ratio
Laohekou City	Surface water supply, Water consumption per capita, Riverbank stability
Nanzhang County	Longitudinal connectivity, Surface water supply, Reservoir regulation ability
Gucheng County	Longitudinal connectivity, Surface water supply, Reservoir regulation ability, Water consumption per capita, Farmland average per Irrigation water consumption
Baokang County	Water surface rate, Area and length ratio of backbone rivers, Longitudinal connectivity, Surface water supply, Reservoir regulation ability
Downtown	Area and length ratio of backbone rivers, River network development coefficient, Longitudinal connectivity, Water consumption per capita, Farmland average per Irrigation water consumption, Sewage treatment rate

4.4.2. Optimization of Harmonious Regulation Schemes

Indexes with small values of harmony degree were selected as the focus of regulation using the optimal selection method of the harmony actions set. Taking downtown as an example, indexes with lower harmony degree in 2014 mainly include: Area and length ratio of backbone rivers (X_{43}, 0.69), River network development coefficient (X_{44}, 0.03), Longitudinal connectivity (X_{46}, 0.5), Water consumption per capita (X_{11}, 0.38), Farmland average per Irrigation water consumption (X_{13}, 0.75), Sewage treatment rate (X_{15}, 0.44). Indexes of Area and length ratio of backbone rivers, and River network development coefficient belong to the natural river network features, which are not possible for improvement in a short time. They could not be considered temporarily. According to the current level of science and technology, Farmland average per Irrigation water consumption is very difficult to improve in Xiangyang City, so it was ignored in this regulation. Therefore, three indexes were selected: Longitudinal connectivity, Water consumption per capita, and Sewage treatment rate. According to the principle of harmony equilibrium and the regulation flow of Figure 3, harmonious regulation in Downtown was carried out [32]. The specific process is shown in Table 7.

Table 7. Harmony regulation results of socio economy and RLS in Downtown.

X_{47}	X_{11}	X_{15}	*P*	X_{47}	X_{11}	X_{15}	*P*	X_{47}	X_{11}	X_{15}	*P*
0.60	0.45	0.60	0.78	0.70	0.45	0.60	0.79	0.80	0.45	0.60	0.79
		0.70	0.79			0.70	0.79			0.70	0.80
		0.80	0.79			0.80	0.80			0.80	0.80
	0.50	0.60	0.79		0.50	0.60	0.79		0.50	0.60	0.79
		0.70	0.79			0.70	0.79			0.70	0.80
		0.80	0.79			0.80	0.80			0.80	0.80
	0.55	0.60	0.79		0.55	0.60	0.79		0.55	0.60	0.80
		0.70	0.79			0.70	0.80			0.70	0.80
		0.80	0.80			0.80	0.80			0.80	0.80

It can be seen from Table 7 that the regulation schemes which meet the requirements of harmony equilibrium include: scheme one, with $X_{47} = 0.60$, $X_{11} = 0.55$, and $X_{15} = 0.80$; scheme two, with $X_{47} = 0.70$, $X_{11} = 0.45$, and $X_{15} = 0.80$; scheme three, with $X_{47} = 0.70$, $X_{11} = 0.50$, and $X_{15} = 0.80$; scheme four, with $X_{47} = 0.70$, $X_{11} = 0.55$, and $X_{15} = 0.70$; scheme five, with $X_{47} = 0.70$, $X_{11} = 0.55$, and $X_{15} = 0.80$; scheme six, with $X_{47} = 0.80$, $X_{11} = 0.45$, and $X_{15} = 0.70$; scheme seven, with $X_{47} = 0.80$,

X_{11} = 0.45, and X_{15} = 0.80; scheme eight, with X_{47} = 0.80, X_{11} = 0.50, and X_{15} = 0.70; scheme nine, with X_{47} = 0.80, X_{11} = 0.50, and X_{15} = 0.80; scheme ten, with X_{47} = 0.80, X_{11} = 0.55, and $X_{1}5$ = 0.60; scheme eleven, with X_{47} = 0.80, X_{11} = 0.55, and X_{15} = 0.70; scheme twelve, with X_{47} = 0.80, X_{11} = 0.55, and X_{15} = 0.80. Harmony regulation methods in other regions are similar to Downtown. Due to the limited space, they will not be discussed here.

5. Conclusions

The impact of human activities on RLS is becoming more and more serious with the accelerating progress of socio-economy development. Issues of water pollution and river fragmentation caused by irrational exploitation and utilization lead to the structural damage of RLS, and the function of RLS cannot be carried out effectively. How to coordinate the relationship between socio-economy and RLS is an urgent task faced by human beings. In this paper, Xiangyang City was selected as an example to research the harmonious development degree between socio-economy and RLS based on the method of harmony theory, Harmonious regulation schemes were proposed from the perspective of harmony equilibrium. Our findings can be summarized as follows:

1. The state of RLS in Xiangyang City shows a spatial distribution pattern with the Han River as the central axis decreases on both its sides. The Han River system, the main river system within Xiangyang City, is the major support of socio-economic development in Xiangyang City. The structural and functional state of the river systems had been changed due to human activities. In spite of this, the micro layout of the river systems formed under the action of natural evolution has not changed greatly in Xiangyang city. Therefore, the spatial distribution pattern of river systems in Xiangyang City still takes the Han River as the center. This is consistent with the natural distribution law of river systems.
2. When the influence of socio-economic development on the state of RLS is small, the former is the main factor driving the variation of degree of the overall regional harmonious development. However, when the influence is big, socio-economic development and RLS both drive the variation of degree of regional overall harmonious development. The driving force of socio-economic development in Xiangyang City mainly originated in the surrounding areas such as Laohekou, Zaoyang, and Gucheng before 2011. However, after 2011, it shifted towards Downtown, and reached the maximum in 2014. Socio-economic development is the main driving factor for the change of the overall harmonious degree.
3. The overall harmonious development degree is higher in Downtown and Laohekou City. Downtown is mainly driven by socio-economic development, so the state of RLS should be the focus for further construction. Laohekou is mainly driven by the state of RLS, and has a great potential for socio-economic development which should be the focus for further construction. The level of socio-economic development in Zaoyang and Baokang is high, and RLS should be the focus for further construction. Coordinate development of socio-economy and RLS should be considered in Nanzhang, Gucheng, and Yicheng.
4. The factors affecting the overall harmonious degree in Xiangyang City mainly include: river length, standard ratio of water quality, water consumption per capita, reservoir regulation capability, Mu of farmland irrigation, water consumption, and sewage treatment rate. These indexes should be treated as the main regulation objectives for harmonious development between socio-economy and RLS in Xiangyang City.

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