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Quantitative Measurement of the Sustainable Water Resource Development System in China Inspired by Dissipative Structure Theory

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Received: 25 July 2018; Accepted: 24 October 2018; Published: 1 November 2018

Abstract: In an attempt to ensure sustainable water resource development, this paper constructs a comprehensive scientific index evaluation system focused on the macro socio-economic-ecological environment. Inspired by the theory of dissipative structure, the sustainable development system of water resources is regarded as a complex and huge dissipative system. In order to effectively measure the coordinated development status and orderly evolution trend of the system, this paper uses the information entropy method to construct the measurement model of the water resources system and analyze its internal entropy flow changes. The empirical analysis of the water resources in China from 2007 to 2016 found that coordinated water resource subsystem development could achieve sustainable development, and that over the examined period, the sustainable water resource development system in China became more orderly and coordinated; therefore, the sustainable development aim is gradually being achieved.

Keywords: dissipative structure theory; information entropy; quantitative evaluation; sustainable development system; water resources

1. Introduction

The availability of water resources is vital for economic and social development [1]. However, with the growth in national economies and the global economy, water scarcity has become a problem in many regions of the world, which has resulted in severe and sometimes violent water conflicts between human needs and ecosystem survival, and as a result has presented great challenges for water resource sustainability [2–4]. The 2015 United Nations world water development report stated that "by 2025, two thirds of the global population will face water shortages". Water sustainability, therefore, is an important sustainable development goal (SDG) [4], which means that water resources need to be rationally utilized to fulfil the human population's continuing needs for life, production, and economic development as well as to ensure ecosystem protection; that is, sustainable water resource development requires the coordinated development of resources, the environment, and socio economics. In the past few decades, China has been confronted with more serious droughts and water shortages, primarily because of rapid economic development and the consequent over-exploitation and utilization of regional water resources. This excessive water withdrawal for socio-economic development has also resulted in increasingly serious ecological environmental problems such as land subsidence, land fissures, seawater intrusion, the drying up of rivers, lake wetland atrophy, estuarine ecological environmental degradation, and severe water pollution [5], all of which have affected local, regional, and national economies and have put future development in jeopardy. Therefore, sustainably developing water resources has become increasingly important.

However, to accurately develop sustainable water resource development systems, it is necessary to evaluate the sustainability of existing practices and initiatives, explore the impact mechanisms and evolving trends in sustainable water resource development systems, and conduct associated assessments and projections to ensure coordinated development [6]. Therefore, the purpose of this paper is to develop a model that is able to accurately evaluate and measure the coordinated development level and the evolutionary trends for sustainable water resources. These developments assist in understanding the current state of the water evolution system and provide recommendations for future sustainable development.

The remainder of this article is organized as follows. In Section 2, a comprehensive literature review on sustainable water resource development is given. In Section 3, an indicator system for sustainable water resource development is constructed, and in Section 4, the research methods, applicability, and specific steps are described. In Section 5, a case analysis is given to demonstrate the applicability of the indicator system, and in Section 6, a detailed results analysis is given. The conclusion and future prospects are given in Section 7.

2. Literature Review

2.1. Research on the Sustainable Development of Water Resources

Research on the sustainable development of water resources has mainly focused on the sustainable use of water resources, the construction of measurement index systems, and the selection of measurement methods.

(1) Relevant water resource sustainability concepts. The earliest research that focused on the sustainable utilization of water resources was in the 1980s [7], and in 1992, a basic sustainable utilization of water resource theory was elaborated at an international conference on water resources and the environment (ICWE) in Ireland, at which the relationships between water resource systems and the environment were clarified, the status and function of water resources in the environment and associated development were established, and research directions for water resource systems and sustainability were proposed [8]. In 2000, the "water framework directive" adopted by the European Union ensured that water resource sustainable development was adopted as policy [9]. The United Nations published the first comprehensive analysis and assessment of global freshwater resources in its "United Nations Water Development Report" in 2003, in which all aspects of water resources and their management countermeasures were discussed, and suggestions were given on sustainable utilization, use efficiency improvements, and the careful management of the increasingly scarce freshwater resources [10]. In 2015, the "World Water Resources Development Report" was released by UNESCO, which elaborated on the relationship between water resources and the important factors associated with overall sustainable development such as food, the environment and economic development, to raise awareness of the importance of protecting and managing water resources [11].

(2) Sustainable water resource development indicator systems have been widely investigated. However, due to differences in research focus and regional water resource distributions, the indicator systems have varied considerably. Pülzl et al. [12] claimed that one of the key factors for achieving sustainable futures was finding a balance and fairness between the environment, the economy, and society, which required an understanding of the dynamic relationships between the environmental, economic, and social indicators. Based on a review of the sustainable water resource development process, Juwana, Muttil and Perera [13] proposed six elements for a sustainable water resource utilization index to assist decision-makers in prioritizing the related issues, challenges and plans. Men et al. [14] constructed an evaluation index system for sustainable water resource utilization from the three aspects of society, the economy, and the ecological environment, and then evaluated the sustainable utilization of water resources in Beijing based on rough sets and fuzzy theory. Ioris,

Hunter, and Walker [15] established a water resource management index system that included the environmental, social, and economic aspects of sustainable development on the basin scale, and analyzed the key factors affecting the sustainable use of water resources. Based on an evaluation of the sustainable use of water resources in the Manas river basin, Yang et al. [16] believed that sustainable water resource development needed to fully consider the economic, social, and ecological environment dimensions. Hara et al. [17] listed the water resource sustainability assessment indicators (ESI) developed by Columbia university and Yale university: socio-economic dimensions (measured by water resource acquisition and natural population growth), environmental dimensions (measured by sewage treatment rates and wastewater discharges), and resource dimensions (measured by water resource supply and quantity).

(3) Sustainable water resource measurement methods. There has been significant progress in the development of methodological tools for measuring sustainability, with composite comprehensive evaluation methods and multivariate statistical analysis methods having been commonly applied. To measure the water resource sustainability, water footprint evaluation methods [4], projection pursuit methods [16,18], and support vector machines [19] have been applied. Under the belief that the effective management of regional water resources can be achieved by establishing a multi-level calculation model and analysis program, Pianosi et al. [20] studied water management problems in HoaBinh using a multi-objective decision-making management method. Cabrera et al. [21] used an AHP (Analytic Hierarchy Process) methodology to build a comprehensive water resources management model that quantified the model indicators and improved decision-making processes to meet new local needs. Umapathi et al. [22] used a multi-time scale approach to study water resources in Queensland, southeast Australia, calculated the per capita water resource utilization in the region, and analyzed the specific consumption issues associated with the water resource recycling processes. Feng et al. [23] used set pair analysis and an entropy weight method to estimate the sustainable utilization of water resources in the Sanyuanliu area of the Tarim River.

2.2. Summary of Research Innovations

From the literature review, it can be seen that significant research has been conducted on the sustainable development of water resources such as the construction of water resource sustainability indicators and measurement methods, all of which have provided theoretical directions for sustainable water resource development. However, these have been continuously extended because of the need to fully consider the society-economy-ecology interactions and other relevant sustainable development system factors. Further, while research has paid some attention to the socio-economic-ecological water resource environment, many factors have not been comprehensively considered such as the contribution made by the resources and technologies generated by society to the development and utilization of resources or the role that coordinated socio-economic-resource-ecological environmental development has on the sustainable water resource development. The sustainable development prerequisite is that the socio-economic-technological development cannot exceed the resource environment carrying capacity; therefore, any sustainable water resource development system needs to include the socio-economic-ecological environmental interrelationships, recycling, and the renewable resource developments. Only by determining the interactions and influences of the various factors can the sustainable water resource development be comprehensively and accurately reflected. When assessing water resource sustainability indicators, some scholars have used qualitative analysis and subjective evaluations (such as the AHP method), both of which have strong subjectivity that can affect the scientific rigor of the research results. Further, many scholars have performed assessments on the macro level, and there have been few studies that have examined the internal mechanisms or evolutionary trends in sustainable water resource development.

Therefore, this paper takes a systems science perspective and introduces dissipative structure theory and an information entropy model [24] to examine the internal mechanisms and the evolutionary trends in the sustainable water resource development in China. The theory of dissipative structure explains the complexity and dynamics in the sustainable water resource system and the information entropy model is used to analyze the entropy changes; thereby providing a comprehensive analysis of the coordinated development and evolutionary trends in the sustainable water resource development system.

Therefore, there are three main innovations in this paper. Based on previous research results and considering the related socio-economic, resource, and environmental factors, this paper systematically and comprehensively constructs an index evaluation system for sustainable water resource development to provide a reliable reference for further objective research and analysis.

Based on systems theory, this paper analyzes and studies the internal evolutionary mechanism of the sustainable water resource development system by focusing on the mutual evolutionary relationships in the water resource subsystems, which overcomes the shortcomings in previous research on the analysis of the subsystem coupling relationships.

A combination of dissipative structure theory and an information entropy model is applied to the analysis and research to assess the structural characteristics of the evolution in the sustainable water resource development system through an examination of the entropy value changes and an analysis of the coordinated development and evolutionary trends in a time series.

3. Construction and Analysis of a Positive and Negative Entropy Flow Index System

As sustainable water resource development is affected by changes in the socio-economic-ecological environment, a balanced and effective sustainable development operating system is required. Therefore, the construction of the sustainable water resource development system requires a comprehensive analysis of the interactions in the sustainable socio-economic-ecological environment. In the theory of dissipative structure, the process of thermodynamic entropy increase is a spontaneous process from order to disorder; the negative entropy flow can reduce the total entropy of the system to avoid equilibrium, maintain the non-equilibrium state, and then generate a new ordered structure [25]. The factors that lead to the entropy increase of China's water resources sustainable development system are resource depletion, population factors, and urban conversion rates. Factors contributing to the total entropy reduction of the system include economic support, ecological compensation, and technological innovation [26]. In this paper, the entropy increase and entropy decrease factors of China's water resources sustainable development system are sought by using thermodynamic entropy change theory. This helps to clarify the influencing factors of the water resources system and build a more comprehensive and scientific water resources system indicator system, because the positive entropy flow and negative entropy flow balance can coordinate the orderly development of the system to a certain extent.

When constructing the sustainable water resource development system indicators, it is necessary not only to consider the rationality of the evaluation indicators but also to ensure there is sufficient comparability and applicability over a reasonably long period of time. In view of this and based on the principles of systemization, scientificity, representativeness, usability, and operability, this paper analyzed both the socio-economic subsystem and resource-environmental subsystem, from which an index system was built for sustainable water resource development, as shown in Table 1.

The sustainable water resource development index system consists of two criteria layers: The socio-economic subsystem and the resource-environmental subsystem (first level index), and the evaluation index (secondary index). The logic for the index indicator selection is as follows.

The socio-economic subsystem reflects the socio-economic promotion of water resources and the socio-economic counter-effect on water resources. At the same time, sustainable socio-economic development not only focuses on the mutual influences between the water resources and current socio-economic growth, but also on the mutual sustainable influence between the water resources and the degree of social economic future evolution. Therefore, it covers various socio-economic factors such as economic policies, economic activities, urban conversion rate, and population density. The aim is to optimize the socio-economic structure and improve the socio-economic development level to ensure the resource conditions and carrying capacity of the ecological environment. Therefore, in the socio-economic subsystem, the per capita GDP, GDP growth rate, water consumption at 10,000 CNY of GDP, industrial water consumption added value of 10,000 CNY, industrial pollution treatment wastewater investment, completed water resources project construction investment, and water conservancy science and technology project investment reflect not only the economic development and growth status, but also the relationship between the economy and water resource management improvement. The natural population growth rate, per capita water consumption, average water consumption per mu of irrigated cultivated land, urbanization rate, water conservancy construction projects under construction in that year, and the national water conservancy system employees reflect the population size and societal evolution as well as the connections with sustainable water resource development.

Table 1. Sustainable water resource development measurement index system.

Object Layer	Rule Layer	Indicator Attribute	Indicator Layer	Data Source
Sustainable water resource development system	Socio-economic subsystem (S)	Entropy reduction	Water consumption of 10,000 CNY GDP (m^3) C11	[27]
			Natural population growth rate (%) C12	[28]
			Per capita water consumption (m^3) C13	[28]
			Industrial added value water consumption 10,000 CNY (m^3) C14	[29]
			Average water consumption per mu of irrigated cultivated land (m^3) C15	[27]
			Urbanization rate (%) C16	[27]
			Per capita GDP (CNY) C17	[28]
		Entropy increase	GDP growth rate (%) C18	[28]
			Industrial pollution treatment wastewater investment (10,000 CNY) C19	[28]
			Completed investment in water resource project construction (100 million CNY) C20	[27]
			Water conservancy construction projects under construction that year (items) C21	[27]
			Investment in water conservancy science and technology projects (100 million CNY) C22	[27]
			Employees in the national water conservancy system (10,000 persons) C23	[27]
	Resource-environmental subsystem (R)	Entropy reduction	Proportion of total water supply to total water resources (%) C24	[28]
			Water supplement in the artificial ecological environment (100 million m^3) C25	[27]
			Total discharge of waste water (100 million t) C26	[29]
		Entropy increase	Total water supply in the country (100 million m^3) C27	[27]
			Total water stored in reservoirs at the end of the year (100 million m^3) C28	[29]
			Per capita water resources (m^3/person) C29	[29]
			Average annual precipitation (mm) C30	[29]
			Average water yield per unit area (10,000 m^3/km^2) C31	[27]
			Surface water resources (100 million m^3) C32	[29]
			Groundwater resources (100 million m^3) C33	[29]
			Urban sewage treatment rate (%) C34	[29]
			Comprehensive control area for soil and water loss (10,000 km^2) C35	[27]
			Water quality ratio (%) C36	[27]

Note: Indicator attribute reflects the change in the indicator leads to the total entropy change of the water resources system.

The resource-environmental subsystem has two main functions. First, it provides a material basis for socio-economic system development. Resource sustainability is mainly reflected in whether the total recycling resources meet the needs of society and other flora/fauna; however, as water shortages are bottlenecks that restrict socio-economic development, resource sustainability is particularly important. Second, the sustainable resource-environmental subsystem provides a high-quality living environment and also supports the circulation and self-cleaning functions of the water resources, which is fundamental to sustainable water resource development. As excessive consumption and water resource waste can deplete resources and cause environmental pollution, water resource exploitation and utilization should be focused on the ecological environment and should advocate a circular green, low-carbon economy. Therefore, in the resource-environment subsystem, the proportion of total water supply to total water resources, total water supply in the whole country, total water stored in the reservoir at the end of the year, per capita water resources, annual average precipitation, average water yield per unit area, surface water resources, and groundwater resources reflect the richness of the water resources and the resource recycling capacity, all of which are key to sustainable resource development. The water supplement in the artificial ecological environment, the total waste water discharge, the urban sewage treatment rate, the comprehensive soil and water loss control, and the water quality ratio reflect the water resource environment greening and pollutant discharge and treatment statuses, which are the basic elements for sustainable environmental development.

In addition, the theory of dissipative structure shows that the indicators of each subsystem are not limited to the internal reaction of the total system, but also play an important role in each subsystem, that is, the indicators of the subsystems will also react with each other. There are positive impacts (for example, an increase in the per capita GDP will increase industrial pollution treatment wastewater investment) and inverse feedback (for example, an increase in the total discharge of waste water will reduce water quality ratio) between the indicators, and the constant constraints between them keep the entire sustainable water resources development system in a dynamic equilibrium.

However, these two sustainable water resource development indicator subsystems interact with the aim of achieving dynamic equilibrium to promote coordinated and sustainable water resource development. For example, the sustainable development of the socio-economic subsystem cannot be separated from the resource environment as this provides the material basis. The rapid progress in the socio-economic subsystem in turn drives resource environment development, such as increasing the resource utilization rate and controlling environmental greening. So as not to adversely affect the sustainable carrying capacity of the resource environment, socio-economic development reacts to the resource environment to ensure sustainable water resource development through continuous iteration. Therefore, to analyze sustainable water resource development, it is necessary to consider the relationships and independencies between the two sub-system indicators.

4. Measurement Method for the Sustainable Water Resource Development System

4.1. Measurement Mode

Nobel laureate Belgian physicist, Ilya Prigogine developed the theory of dissipative structure, the core idea of which was that non-linear open systems far from equilibrium continuously exchange material and energy with the outside world, and when a change in a certain parameter fluctuates and reaches a certain system threshold, the system undergoes an abrupt change—a non-equilibrium phase change—from the original chaotic state to an ordered state in time, space, or function [30]. The Sustainable Water Resources Development System is an open, complex dissipative structure composed of economic, social, resource and environmental factors. The mechanism is shown in Figure 1. The system exchanges material, energy, and information with the external environment and can experience a benign or a malignant evolution. Therefore, it has the characteristics of a dissipative structure that spontaneously changes its macroscopic ordered state in time, space and function to form a new stable ordered structure [31]. The operating process for the sustainable water resource development system meets the four conditions for the formation and maintenance of dissipative structures.

(1) It is an open rather than an isolated system composed of economic, social, resource, and environmental factors. The material goods needed for socio-economic development come directly or indirectly from the water resource environment subsystem, and the various technologies and management modes generated by the socio-economic subsystem also directly or indirectly affect the state of the water resource environment subsystem.

(2) It exists in a state that is far from equilibrium, with the distribution of the various subsystem elements being different and unbalanced. The continuous material and energy interactions and exchanges with the external system continue to keep the system from equilibrium; therefore, the state of the system is constantly oscillating between rebirth and destruction and the system evolution is unbalanced.

(3) There is a non-linear structure between the sustainable water resource development system and the subsystems. The system does not change proportionally with the changes in certain subsystem elements. For example, the economy develops at the expense of the resource environment, which leads to a decline in coordinated system development, which in turn affects the evolution and development of the overall system. In addition, due to the different conditions and environments in the competition and coordination between the subsystems, there is a nonlinear positive and negative feedback mechanism in the system and subsystem evolution.

(4) It is continually stimulated by the outside world (such as by national policies), which results in countless "small fluctuations". When the fluctuations reach a certain level, the system produces "huge fluctuations" and a new dissipative structure is formed after which the current state jumps to a new orderly state; therefore, there is a continuous push forward.

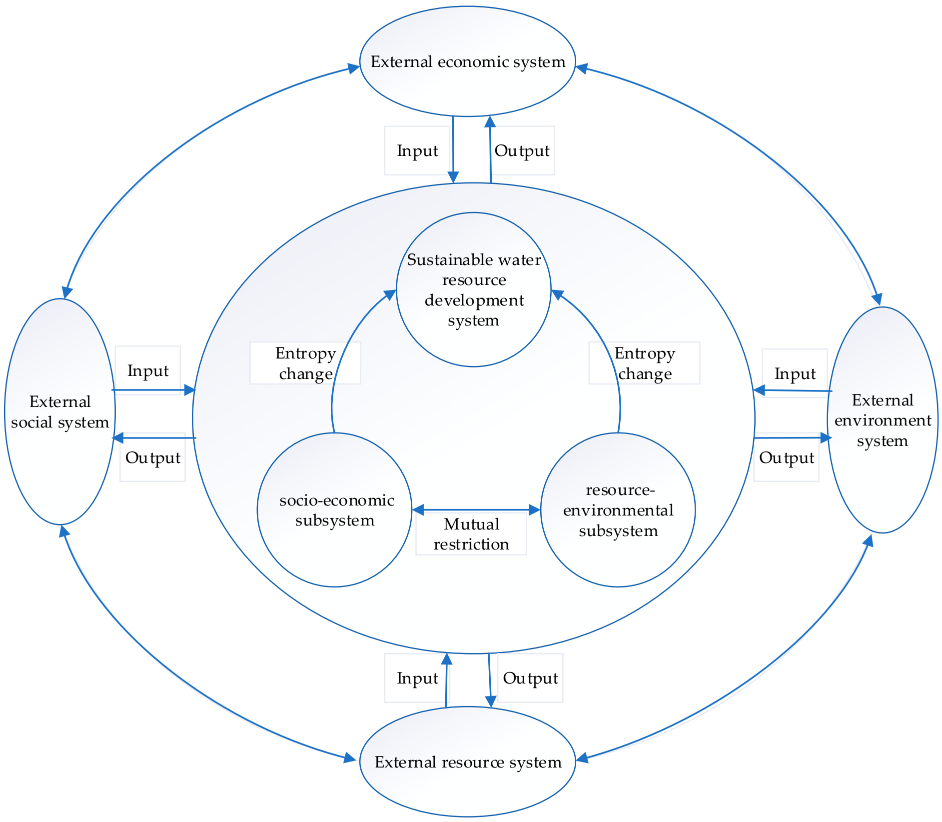

Figure 1. Dissipative structure of the sustainable water resource development system.

The dynamic evolution of the dissipative structure is manifested by changes in the entropy, which is a concept used to express the degree of reduction in a system's effective energy. Therefore, an entropy change (including entropy flow and entropy generation) model can be used to judge the efficiency changes in the dynamic evolution of the water resource dissipation structure to assess whether sustainable water resource development is in order. The total entropy change of the system (ds) is equal to the sum of the "entropy generation" (ds_1) and the "entropy flow" (ds_2); that is, $ds = ds_1 + ds_2$. Without the influence of the external environment, the total entropy (ds) of a complex system continuously increases and develops towards chaos and disorder, which eventually leads to system collapse. To form a dissipative structure, the evolutionary system needs to be in a continuous exchange with the external factors to increase the negative entropy system flow, so that the total system entropy fluctuates within a certain range and the entire evolutionary system is sustainable. Therefore, the theory of dissipative structure is completely applicable to sustainable water resources development systems, and it is reasonable to apply the theory of dissipative structure to sustainable water resources development systems. Based on this, this paper constructs the sustainable water resources assessment index system by using the theory of dissipative structure thermodynamic entropy change, and then constructs the system measurement model by means of information entropy (Shannon entropy). In this paper, the information entropy method is used to calculate the annual information entropy and index information entropy of the system. On the one hand, it reflects the orderly and evolutionary trend of sustainable development of water resources by calculating the total entropy change (S) of each year. On the other hand, the comprehensive development degree (D) and the coordinated development degree (C) are determined by calculating the index information entropy to characterize the coordinated development of the water resources sustainable development system. The measurement model is shown in Figure 2.

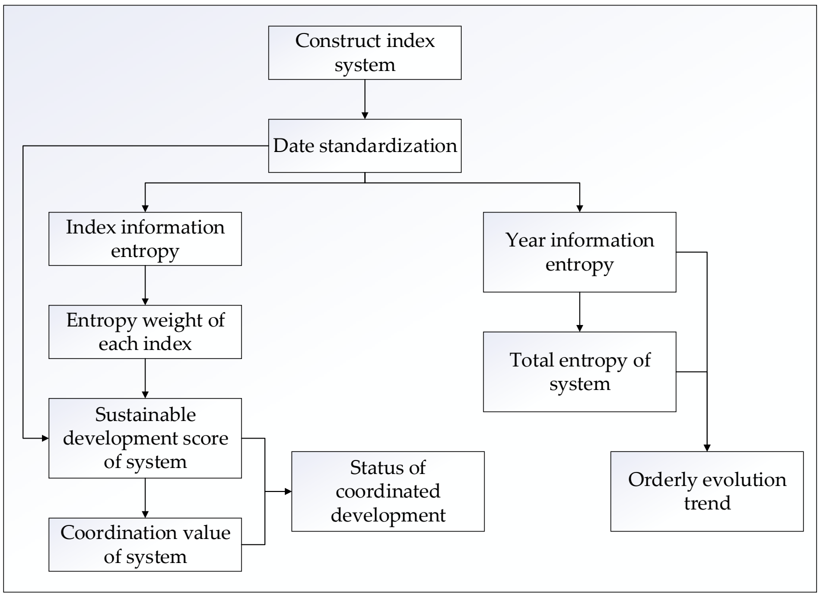

Figure 2. Measurement model for the sustainable water resource development system.

4.2. Measurement Steps

The specific steps for the quantitative measurement model for the sustainable water resource development system are as follows.

(1) Indicator data standardization

To eliminate the influences of the different dimensional and quantitative original variable sequences and to ensure the reliability of the measurement results, the data preprocessing needs to be standardized before calculation, for which the positive and negative indicator values represent different meanings; for the positive indicator value, the higher the better, and for the negative indicator value, the lower the better. Therefore, different algorithms are needed to standardize the data for the positive and negative indicators. In this paper, the initial measurement matrix is standardized using a linear method. Suppose there is an evaluation system with n measures of m years, where X_{ij} is the normalized value for the original data.

When x_{ij} is a positive entropy flow indicator:

$$X_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{1}$$

When x_{ij} is a negative entropy flow indicator:

$$X_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})}. \tag{2}$$

where x_{ij} is the measure value for the j-th indicator in the i-th year.

(2) Determination of the entropy weights for each index

The principle of information theory states that the smaller the information entropy of the index, the more information the index provides, the higher the order of the system, and the higher the weight of the index in the comprehensive evaluation. Changes in information entropy can determine the actual sustainable water resource development system level. To eliminate the influence of the subjective factors as much as possible, the entropy weight method is used to determine the weights. The formula for calculating the information entropy value E_j and entropy weight w_i for each index is:

$$E_j = -\frac{1}{lnm} \sum i = 1^m \frac{X_{ij}}{X_j} ln \frac{X_{ij}}{X_j} (j = 1,\ 2, \ldots, n) \tag{3}$$

$$w_j = \frac{1 - E_j}{n - \sum_{j=1}^{n} E_j} (j = 1,\ 2, \ldots, n) \tag{4}$$

in which, $X_j = \sum_{i=1}^{n} X_{ij}$.

(3) Calculation of annual entropy information

The orderliness and evolutionary trends in the sustainable water resource development system are reflected by the annual entropy information, which is calculated based on an annual sequence.

$$S_i = -\frac{1}{lnm} \sum_{j=1}^{n} \frac{X_{ij}}{X_i} ln \frac{X_{ij}}{X_i} (i = 1,\ 2, \ldots, m) \tag{5}$$

in which, $X_i = \sum_{j=1}^{n} X_{ij}$.

(4) Calculation of the System's Sustainable Development Score and the Coordination Value

The degree of coordinated development in the sustainable water resource development system can be analyzed using the system sustainability scores and the coordination values. The additive theory of information entropy states that the entropy weight w_k of the sustainable water resource development subsystem is equal to the sum of the index entropy weight w_i of its index layer. The specific steps for calculating the sustainability scores of the water resources subsystem and the main system (D_{ik} and D_i) are as follows:

$$w_k = \sum_{j=1}^{s} w_j \tag{6}$$

$$D_{ik} = \sum_{j=1}^{s} X_{ij} w_k \tag{7}$$

$$D_i = \sum_{k=1}^{t} D_{ik} w_k \tag{8}$$

in which D_{ik} is the sustainability score of the k-th subsystem in the i-th year, D_i is the total system sustainability score in the i-th year, s is the number of subsystem indicators, and t is the number of subsystems.

Coordination refers to a coordinated, harmonious relationship between two or more systems or system elements. The system coordination degree is a quantitative index that describes the level of coordination and development in the system subsystems and embodies the coordination and health of the internal system elements or the system development process, and reflects the system movement trends from disorder to order. The formula for calculating the system coordination degree C_i is:

$$C_i = \left| u_i * v_i / \left| \frac{u_i + v_i}{2} \right|^2 \right|^h (i = 1,\ 2, \ldots, m) \tag{9}$$

in which u_i is the development level of the socio-economic water resource subsystem in the i-th year, v_i is the development level value of the resource-environmental subsystem in the i-th year, and h is the discrimination coefficient; then $h = 4$ [32,33]. The coordination degree value C_i is between 0 and 1, with the higher the value, the better the coordination of the subsystems in that year. The coordination degree is divided into eight grades [33,34], as shown in Table 2.

Table 2. Coordination level division.

Coordination Value Ci	0.90~1	0.70~0.89	0.60~0.69	0.50~0.59	0.40~0.49	0.30~0.39	0.10~0.29	0~0.09
Coordination Level	High quality coordination	Good coordination	Moderate coordination	Barely coordinated	On the verge of disorder	Disorder	Moderate disorder	Severe disorder

5. Case Analysis

The main purpose of this study is to analyze the coordinated development degree and orderly evolutionary trends in China's sustainable water resource development system. The sources of the initial data is shown in Table 1, some of which were converted from the initial data using the related calculation formulas. Inspired by the dissipative structure's information entropy theory [35–37], separate mathematical analyses were required to study the positive and negative entropy flow trends in the data in Table 1. As an indicator system has both positive and negative entropy flow indicators, it is necessary to standardize the index to eliminate the dimensional influences. The entropy value and entropy weights for each sustainable water resource development system index were calculated using Formulas (1)–(4), the results for which are shown in Table 3.

Table 3. Entropy value and entropy weight of each index.

Object Layer	Index	Entropy Weight	Index Code	Entropy Value	Entropy Weight
Sustainable water resources development system	Socio- economic subsystem (S)	0.55	C11	0.922	0.027
			C12	0.948	0.018
			C13	0.881	0.042
			C14	0.926	0.026
			C15	0.837	0.057
			C16	0.887	0.039
			C17	0.884	0.041
			C18	0.815	0.065
			C19	0.839	0.056
			C20	0.865	0.047
			C21	0.892	0.038
			C22	0.819	0.063
			C23	0.914	0.030
	Resource-environmental subsystem (R)	0.45	C24	0.924	0.027
			C25	0.943	0.020
			C26	0.929	0.025
			C27	0.909	0.032
			C28	0.890	0.038
			C29	0.905	0.033
			C30	0.878	0.043
			C31	0.893	0.037
			C32	0.895	0.037
			C33	0.877	0.043
			C34	0.926	0.026
			C35	0.865	0.047
			C36	0.875	0.044

The annual information entropy of the sustainable water resource development in China was calculated using Formulas (1), (2) and (5), and is shown in Table 4.

Table 4. Annual information entropy for the sustainable water resource development system in China.

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Socio-economic Entropy Change	−0.597	−0.612	−0.752	−0.624	−0.837	−0.659	−0.620	−0.644	−0.609	−0.524
Resource-environmental Entropy Change	−0.505	−0.678	−0.511	−0.749	−0.407	−0.722	−0.745	−0.723	−0.734	−0.774
Total Entropy Change	−1.102	−1.290	−1.264	−1.373	−1.244	−1.381	−1.364	−1.366	−1.343	−1.298

The sustainable water resource development scores and coordination values for the indicator entropy weights in Table 3 were calculated using Formulas (6)–(9), with the coordination level being divided according to Table 2. The results are shown in Table 5.

Table 5. Score and coordination values for the sustainable water resource development system in China.

Year	Socio-Economic Subsystem	Resource-Environment Subsystem	Sustainable Development Score	Coordination Value	Coordination Level
2007	0.235	0.108	0.178	0.55	Barely coordinated
2008	0.207	0.177	0.193	0.976	High quality coordination
2009	0.193	0.094	0.148	0.6	Moderate coordination
2010	0.239	0.275	0.255	0.98	High quality coordination
2011	0.296	0.116	0.215	0.426	On the verge of disorder
2012	0.291	0.281	0.287	0.999	High quality coordination
2013	0.238	0.262	0.249	0.991	High quality coordination
2014	0.264	0.26	0.262	0.999	High quality coordination
2015	0.272	0.296	0.283	0.993	High quality coordination
2016	0.322	0.411	0.362	0.943	High quality coordination

6. Results Analysis

Inspired by the theory of dissipative structures, the orderly degree and the evolutionary trends in China's sustainable water resource development system were judged by the entropy changes, after which the comprehensive development degree and the coordinated development degree were determined from the index information entropy. To better and more intuitively observe the evolutionary development trends in the overall system and in each subsystem and the coordinated subsystem development, a coordinated development trend diagram (Figure 3) and an evolutionary trend diagram (Figure 4) for China's sustainable water resource development system were generated from the data in Tables 4 and 5.

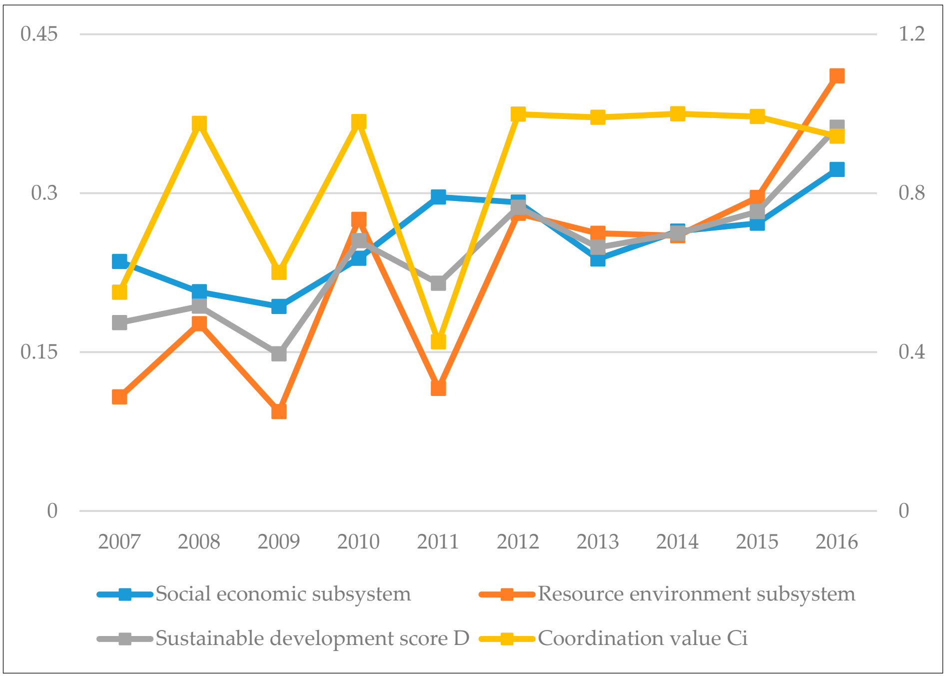

Figure 3. Sustainable development degree for China's sustainable water resource development system's subsystems. Note: the coordination value corresponds to the right coordinate axis.

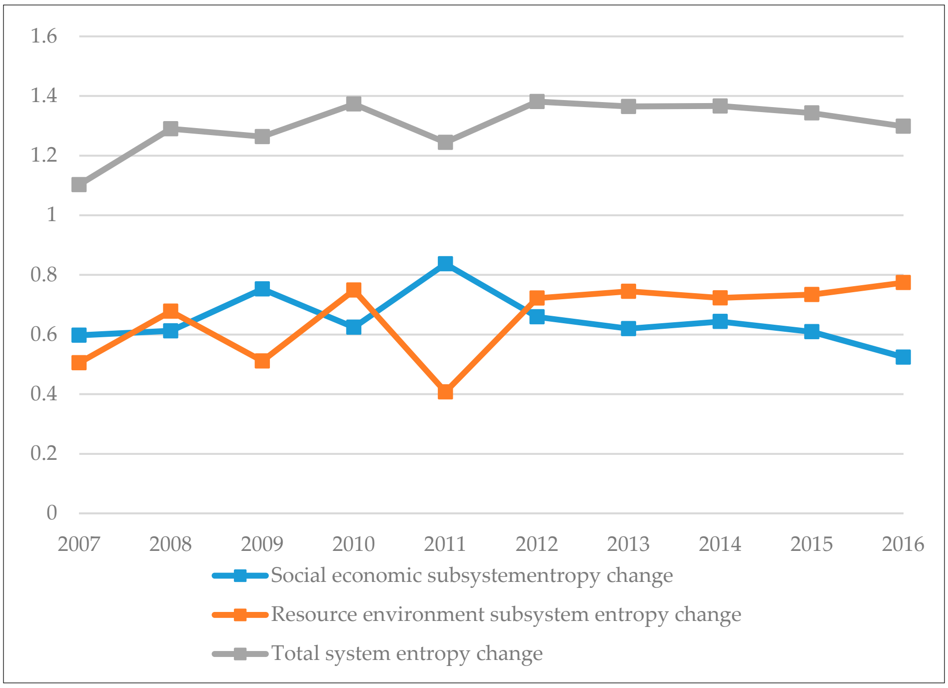

Figure 4. Evolutionary trends for China's sustainable water resource development system.

After analyzing the data in Figures 3 and 4, the following conclusions were drawn.

(1) Analysis of the comprehensive development degree and coordinated development degree of the sustainable water resource development system in China. It can be seen from Table 5 and Figure 3 that there has been a well-coordinated and orderly development in the sustainable water resource development system. From 2007 to 2016, the sustainable water resource development level has generally increased rapidly. The comprehensive development degree increased from 0.178 (2007) to 0.362 (2016), with an average annual growth rate of 1.84%, and the sustainable development level

generally increased. From 2007 to 2012, the sustainable water resource development was fluctuating, which indicated that during this period, the relationship between the socio-economic environment and the resource environment was uncoordinated; that is, as the socio-economic environment was rapidly developing, there was a failure to rationally exploit, utilize, or control the resource environment. From 2012–2016, however, there was transition from a fluctuating to a high quality coordination. 2012 was a turning point because the socio-economic subsystem and the resource-environmental subsystem were highly coordinated for the first time, laying the foundation for the sustainable and rapid development of water resources in the future. From 2012 to 2015, the coordinated value for China's sustainable water resource development was stable at around 0.94 to 0.99, indicating a very good coordination situation. This was mainly because the government was attaching greater importance to the coordinated and sustainable development of the social economy, resources, and the environment as part of the transformation in China's economic structure (the transformation of resource allocation and economic development mode) for which there has been increased investment in the resource environment such as the construction of reservoirs and the South-to-North Water Transfer Project, which has reduced the pressure on the resources and the environment and led to a better coordination of the sustainable water resource system.

The comprehensive development degree of the socio-economic water resource subsystems initially had a downward trend but over time an upward trend appeared, which indicated that the socio-economic water resource subsystem was developing in a healthy and orderly direction. As can be seen from Table 5 and Figure 3, the socio-economic subsystem development from 2007 to 2011 first declined and then increased. 2009 (0.19) had the lowest comprehensive development in the 10 years, which was mainly the result of the global financial crisis and several natural disasters. The turning point in the socio-economic water resource subsystem development was in 2011 when the Chinese government began to focus on resource environment and socio-economic development, which led to a recovery in the resource environment and coordinated development with the socio-economic environment. From 2011–2016, to meet the resource environment development needs, the socio-economic water resource subsystems rose steadily and the sustainable development level gradually improved. During this period, as China intensified its water resource environment improvements such as improving compensation mechanisms and afforestation efforts, and the South-to-North Water Transfer Projects, the socio-economic and resource environments became coordinated. If the current state is maintained or improved, the socio-economic subsystem is expected to become healthier.

Over time, the comprehensive resource-environmental subsystem development first fluctuated and then rose steadily, which indicated that the control, management, and exploitation of the water resource environment was maturing, and also reflected the transformation of the sustainable water resource development from unreasonable and unsound to rational and standardized. The water resource environment subsystem development was fluctuating from 2007–2012, with the lowest comprehensive development degree being 0.094 (2009), indicating that this year was the most unstable development stage. The resource-environmental subsystem development level entered a steady rising stage from 2012–2016, primarily because during this "12th Five-year plan" period, the government gave a high priority to the sustainable use of resources and environmental greening, the construction of large reservoirs, the South to North water transfer project, and significant reductions in pollutant emissions. Therefore, it can be observed that the state policies aimed at water environment protection have had a positive effect on sustainable water resource development in China. If the current trends continue, the resource environment carrying capacity will continue to increase and the sustainable water resource development level will further improve.

(2) Analysis of the orderly development degree and evolutionary trends in China's sustainable water resource development system. From the data in Table 4 and the change trends reflected in Figure 4, it can be seen that from 2007 to 2016, the total entropy showed an upward trend of fluctuation in general and a downward trend in recent years, which indicates that China's water resources

system is moving from uncoordinated to healthy and orderly development, the level of sustainable development is constantly improving, and the whole system is moving towards a more harmonious "dynamic balance". From 2007 to 2012, the total entropy fluctuation trends were similar to those of the resources and environment subsystem, which indicated that China's sustainable water resource development was more dependent on the resource environment; that is, the socio-economic impact was less than the resource environment impact. From 2012 to 2016, the total entropy trend was similar to the total socio-economic subsystem entropy, indicating that socio-economic growth was weak, and its contribution to sustainable water resource development was becoming weaker. The entropy of the socio-economic subsystem has changed from volatility to steady decline, indicating that the level of social and economic development and development is steadily rising. The entropy of resource and environment subsystems develops from volatility to a stable trend, which indicates that the development and utilization of China's water resources environment is moving from disorder to standardization and rationalization. However, in recent years, the entropy of the resources and environment subsystem has been stable but high, and the entropy of the social and economic subsystem has been declining, which indicates that the coordination between the social and economic development of water resources and the resources subsystem in China is not perfect, and the decline of the entropy of the social and economic subsystem is obtained at the expense of resources and the environment.

7. Conclusions and Future Prospects

This paper used statistical water resource data from 2007 to 2016 in China to construct a sustainable water resource development index system from two dimensions: socio-economic and resource environment. Entropy theory was used to analyze the entropy flow changes and measure the coordinated development level and orderly evolutionary trends in the system. The conclusions from this analysis were as follows.

(1) The sustainable water resource development system is a complicated giant system that through the exchange of material, energy, and information with the external environment, develops an orderly state in time, space, or function; therefore, the sustainable water resource development system completely conforms with the characteristics of dissipative structure theory. The information entropy model was able to effectively identify the evolutionary processes in the sustainable water resource development system, with the changes in information entropy reflecting the coordination, order degree, and evolutionary trends. The highlighting of the internal system improvements thereby provides a decision basis for further improvements.

(2) The analysis of entropy flow changes showed how the negative effects of irrational and unhealthy subsystem development directly affected sustainable water resource development, and how coordinated subsystem development positively influenced sustainable water resource development. Therefore, in the future, there needs to be an increased focus on the coordinated development of the socio-economic and resource environments, with a particular focus on the resource environment.

(3) Overall, the comprehensive sustainable water resource development level in China improved significantly from 2007 to 2016. Although in the early stage the unreasonable exploitation and utilization of the resource environment resulted in large fluctuations in comprehensive sustainable water resource development, the comprehensive development level steadily improved over time.

In general, the research focus of this paper can be summarized in three points. First, to conduct a comprehensive, objective analysis of China's sustainable water resource development, 26 indicators from the two socio-economic and resource environment dimensions were proposed to establish a relatively complete indicator system. Then, a model was developed, inspired by dissipative structure and information entropy theory to interpret the system information entropy changes, analyze the internal subsystem changes, and identify the overall water resource system changes, thereby obtaining a clear picture of the orderly development degree and the evolutionary trends. Finally, this paper analyzed the sustainable water resource development degree in China and gave targeted recommendations for future development planning to address each subsystem's weak links.

This study, however, had some limitations. The sustainable water resource development indicator system is a multi-level, multi-dimensional and multi-structural system. Due to data collection limitations, this paper mainly considered measurable indicators but did not consider the other factors (such as policies and institutions) that can affect sustainable development. In addition, being aimed at analyzing the evolutionary trends in the macro system, this paper did not identify the specific influencing mechanisms or the influence degree for each factor. These issues need further analysis and discussion in future research.

Author Contributions: The study was designed by R.Z. in collaboration with all co-authors. Data was collected by R.Z. The first and final drafts were written by R.Z. The drafts were critiqued by X.L. and C.L. The results were analyzed by C.L. and R.Z. The research and key elements of the models were reviewed by H.L. The writing work of corresponding parts and the major revisions of this paper were completed by R.Z.

Funding: This research is funded by the Department of Education Research Fund (No. 17YJC790094), The Fundamental Research Funds for the Central Universities (No. 2018skqy-pt160), The Sichuan Provincial Technology Bureau Soft Science Foundation (2016ZR0017).

Acknowledgments: Authors would like to thank the reviewers of this journal for helpful comments and suggestions. Any errors and all views expressed remain our own.

Conflicts of Interest: The authors declare no conflict of interest.

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