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Evaluation of Adaptive Utilization Capacity of Water Resources and Analysis of Driving Element: A Case Study of Tarim River Basin

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Abstract: The research on the adaptive utilization of water resources (AUWR) is of great significance to improve the coordinated development among water resources, economic society, and ecological environment in complex environments, and to promote the development of adaptive utilization of regional water resources. Based on the calculation method of harmony theory and the calculation method of the comprehensive co-evolution model, this paper obtains the harmony degree and adaptive utilization capacity of water resources (AUCWR) of each subsystem in the Tarim River Basin (TRB), analyzes the main factors affecting the AUCWR, and finally compares the two methods. The results show that: (1) From 2004 to 2018, the AUCWR in the TRB has gradually improved (harmony theory method: from 0.43 in 2004 to 0.56 in 2018, with a growth rate of 30.23%; comprehensive co-evolution model method: from 0.37 in 2004 to 0.62 in 2018, with a significant increase of 67.57%) and (2) From the perspective of indicators, indicators such as per capita GDP, the proportion of non-agricultural output value in GDP, and per capita net income of rural residents have a greater impact on the AUCWR in the TRB. Using different calculation methods to analyze the temporal and spatial distribution characteristics of the AUCWR in the TRB has important guiding significance for the future development and utilization of water resources, economic and social development, and ecological environment protection.

Keywords: Tarim River Basin; adaptive utilization capacity of water resources; harmony theory; comprehensive co-evolution model

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Citation: Li, X.; Zuo, Q.; Zhai, J.; Zhao, Y.; Wang, Y.; Han, S. Evaluation of Adaptive Utilization Capacity of Water Resources and Analysis of Driving Element: A Case Study of Tarim River Basin. *Water* **2022**, *14*, 3820. https://doi.org/10.3390/w14233820

Academic Editor: Athanasios Loukas

Received: 7 November 2022
Accepted: 21 November 2022
Published: 23 November 2022

1. Introduction

Water resources are basic natural resources, which can provide human beings with clean drinking water, irrigation water, and ecological water [1]. Water is crucial to the sustainable development of societies [2]. Water resources are the major medium of climate change impacts on the environment, ecosystems, and humans, and are increasingly affecting the global economic, social and environmental development [3,4], and the accelerated economic development, population growth, and urban expansion have increased the water shortage, thus highlighting the global systemic risk of water shortage [5,6]. At the same time, the changes in the development and utilization of water resources will also affect the decision-makers' adjustment of water environment policies [7,8]. However, with climate change and economic and social development, the properties and functions of water resources are becoming more diverse, while the linkages with external systems, such as social, economic and ecological systems, are becoming more complex [9,10]. The adaptive development of water resources is a manifestation of their sustainability by adapting to environmental changes, with the increased demand for water resources brought about by increasing population, which leads to water scarcity, excessive groundwater extraction, water pollution, and other problems ensuing [11,12]. The International Association of

Hydrological Sciences (IASH) launched the P.R. (2013–2022) program in 2013, which emphasizes the intersection of nature and society to study human-water relationships, explore the synergistic evolution of human-water systems, and actively promote adaptive research on human-water relationships [13].

Since the 21st century, water resources adaptation research has become an important demand and a hot issue for global and national responses to environmental changes. Many scholars have conducted studies to investigate how water resources systems adapt to the complex and changing environment and the interactions with the economic and social environment [14,15]. The study of water resources adaptation involves many aspects, such as water resources, as well as the economic, social, and ecological environment. Water resources adaptation can be improved by research on optimal water resources allocation, developing water resources management strategies, establishing adaptation models, improving water resources carrying capacity, and reducing water resources-related risks [16–19]. Zhou proposed an integrated optimal allocation model that provides research ideas for complex adaptive systems for water resources management, and applied it in the Dongjiang River Basin in Guangdong Province, China [20,21]. Guided by the idea of adaptive utilization of water resources(AUWR), H.P. discussed how integrated water resources management can achieve adaptive water resources in response to environmental changes, and discuss the specific requirements on how to improve adaptive water resources management and governance [22]; the environmental adaptation of vulnerable water resource systems can be improved by assessing the status of regional water resources in the context of climate change using appropriate models [23].

However, they are all water resources adaptation responses and strategies proposed in response to environmental changes, without proposing water resources development and utilization strategies from the general height of the reciprocal feedback between water resources systems and environmental changes, and have not yet risen to a water resources adaptation and utilization model. Based on this, Zuo elaborated on the AUWR model, the theoretical system framework, and its application issues, and defined the concept of AUWR, the process of water resources development and utilization, following the laws of nature and social development, adapting to the impact of environmental changes such as human activities, climate change, and land surface changes, and ensuring the virtuous cycle of water systems, the chosen water resources utilization [24–26]. On this basis, the concept of adaptive utilization capacity of water resources (AUCWR) is proposed—under the guidance of the theory of adaptive utilization of water resources, based on the evaluation system of AUWR, the effect and overall level of AUWR obtained through quantitative evaluation method.

On the basis of the gradual improvement of the theoretical system of adaptive use of water resources, the quantitative study of the adaptive use of water resources has gradually become a hot issue. Zhang constructed a three-dimensional framework consisting of several risk factor indicators based on water resources resilience theory and established a set of water resources resilience assessment methods to evaluate the resilience of Beijing's water resources system [27]. Yao proposed a comprehensive co-evolution model, based on the conditions of the elements and on the mechanism of their interaction, to study the adaptive development of WRS, it was eventually applied to three rivers in Heilongjiang Province and Shandong Province [28,29]. Adaptive use of water resources is an efficient way to solve complex and uncertain ecosystems and compensate for the limitations of the human-water harmony theory.

In the TRB, artificial oases and desertification processes are increasing [30,31]. As a result, the area of desert-oasis ecological zones is rapidly decreasing and ecological problems are becoming more prominent. At the same time, due to the rapid urbanization of the TRB and the continuous socio-economic development, water demand is also increasing, leading to an increasing conflict between water resources, economic and social development, and ecological environmental protection. Therefore, it is necessary to evaluate the current level of AUCWR in the TRB and to find a reasonable model of water resources development and utilization.

At present, most studies focus on the allocation and regulation of reservoir water resources [32], the adaptive management of water resources for reservoir water resources management [20], and some policies-based water resources management measures are proposed [14]. However, there is insufficient research on the quantitative evaluation of the adaptive use of water resources, especially a set of systematic, perfect, and popularized quantitative evaluation methods. Based on this, this paper uses the team's harmony theory method to systematically evaluate the adaptive use of water resources in the TRB by constructing a system of indicators for evaluating the adaptive use of water resources, and at the same time conducts a comparative analysis with the comprehensive co-evolutionary model method to verify the reasonableness of its results with each other.

In this paper, four main parts of work are done: (a) Systematically proposed a theoretical system of AUWR; (b) Constructing a systematic and complete index system for assessing the adaptive use of water resources; (c) Proposing a method for evaluating the AUCWR in the TRB (harmony theory method), and compared the results with those of the well-established comprehensive co-evolution model method to verify each other; (d) Analyzing the main factors affecting the AUCWR.

2. Theoretical System of AUWR

2.1. Theoretical of AUWR

Adaptive utilization of water resources, sustainable use of water resources, and comprehensive use of water resources are all water resources development and utilization modes, the purpose of which is to ensure the virtuous cycle of water systems, in order to achieve the goal of human-water harmony, but the focus of the three is different. Adaptive use of water resources is a means to address the impact of environmental change, through human regulation measures to mitigate the adverse impact of climate change, human activities, and other water resources, economic, social, and ecological environment.

The theory of adaptive use of water resources takes the human-water system as the research object, through adaptive use of water resources, to achieve sustainable use of water resources and achieve the goal of human-water harmony. Human activities, climate change, and land surface change are the driving factors, which are the source driving force to promote the adaptive use of water resources and the main factors for scientific regulation. The dialectical relationship is that water resources development and protection coexist, the positive and negative impacts of water resources utilization coexist, and the supply side and demand side of the water system coexist and comply with the two laws, four principles, three tasks, and four functions. Adaptive use of water resources needs to consider the balance of human-water relationship transfer, and needs, through a series of regulatory means, to achieve a harmonious balance of adaptation to environmental change transfer, towards the direction of human-water harmony. Its theoretical approach includes a guiding theoretical approach and a basic theoretical approach [25]. As shown in Figure 1.

2.2. Mechanism of AUWR

The core of the mechanism of adaptive use of water resources is the interaction between the three subsystems of water resources, economy, society, and ecology under the influence of climate change and human activities.

The impact of climate change on the water resources-economic society-ecological environment system mainly comes from changes in precipitation, temperature, wind speed, humidity, radiation, and other basic meteorological factors caused by changes in atmospheric circulation: on the one hand, it leads to changes in the water cycle process, which in turn produces changes in the supply side and demand side of water resources, on the other hand, it changes the total amount of water resources and spatial and temporal distribution characteristics, thus increasing the risk of extremes. On the other hand, the change in the total water resources and the spatial and temporal distribution characteristics increase the risk of extreme weather events such as floods and droughts, which cause natural disasters and further affect the stability of the economic, social, and ecological environments.

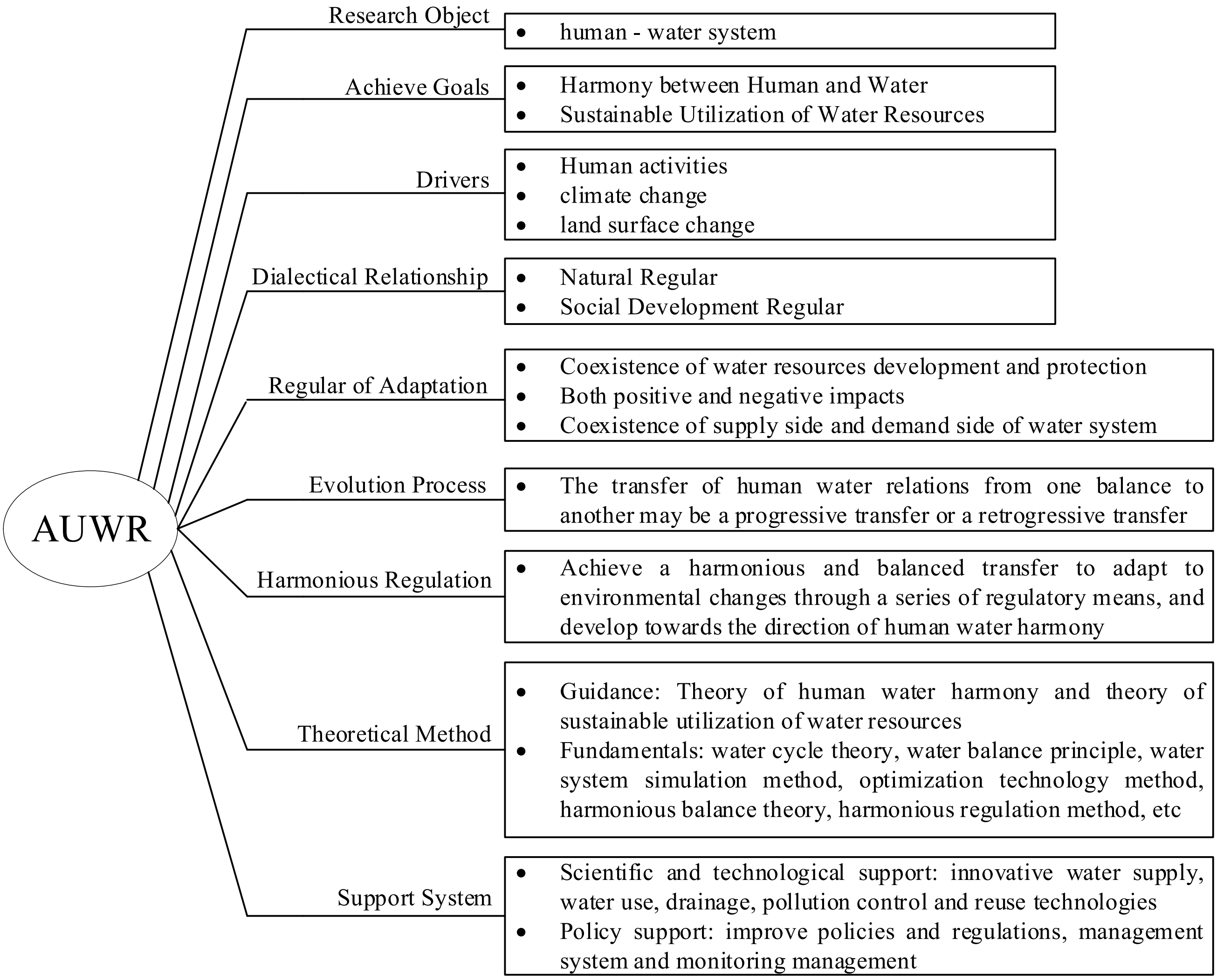

Figure 1. Framework of the theoretical system of AUWR.

The impact of human activities on the water resources-economic society-ecological environment system is: on the one hand, through the transformation of the natural environment to cause changes in water supply potential and natural ecology and environment, on the other hand, through the change of economic and social patterns to cause changes in production and lifestyle, which in turn affects the change of artificial consumption and drainage, resulting in the constant change of water resources and ecological environment state, leading to the imbalance of the original state of the whole system. As shown in Figure 2 [33].

2.3. Framework of Application Rules for AUWR

Adaptive use of water resources involves complex systems and rich contents, so it is necessary to follow certain rules to solve the problems faced by the adaptive use of water resources. In the literature [24], Zuo first proposed a framework of application rules for water resources adaptive use theory, which requires that when applying water resources adaptive use theoretical methods to solve practical problems, it should follow two major laws, conform to four major principles, shoulder three major tasks and have four major functions, as shown in Figure 3.

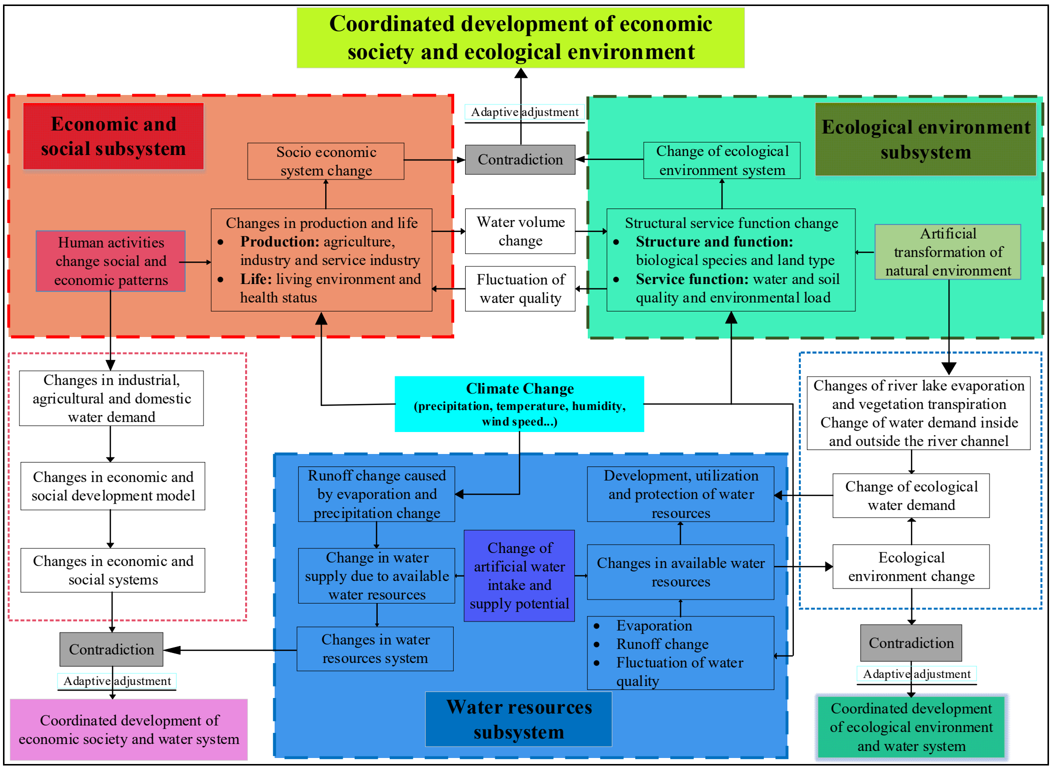

Figure 2. Interaction mechanism of water resources, economic and social systems, and ecological environment affected by climate change and human activities.

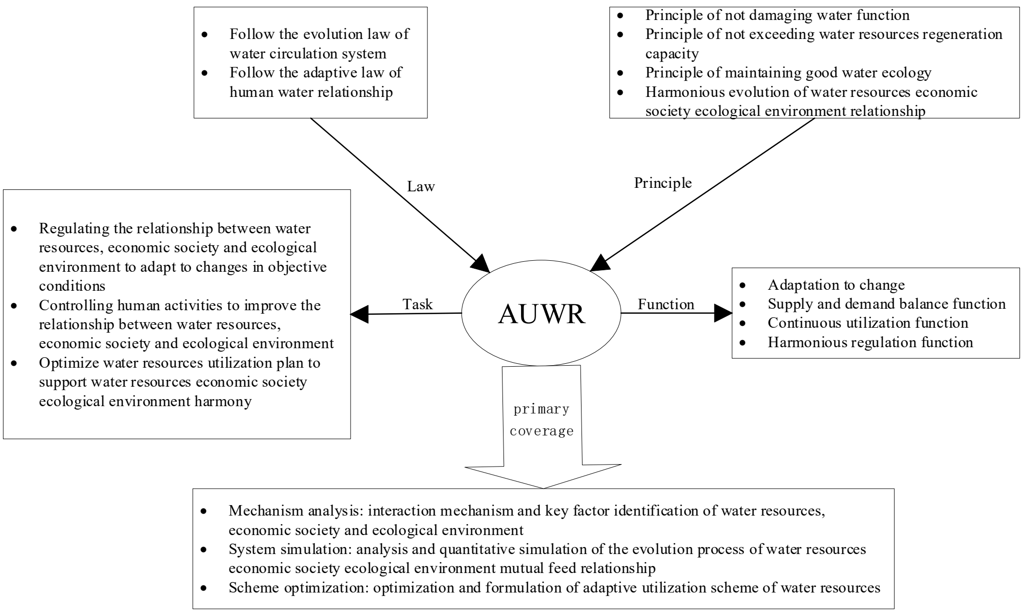

Figure 3. Framework of application rules for AUWR.

3. Materials and Methods

3.1. Study Area

The TRB is located in the northern Tarim Basin of Xinjiang Uyghur Autonomous Region. It originates from the Tianshan Mountains and the Karakorum Mountains, with a total length of 2179 km, making it the longest inland river in China and the fifth-largest inland river in the world [34]. The TRB is composed of three major headwaters, the Hotan River, the Yarkant River, and the Aksu River [35], with a basin area of 1.02 million square kilometers, including 42 counties in five prefectures and 45 regiments in four corps divisions, with a population of more than 12 million people living in the basin. The average annual natural runoff of the TRB is 39.83 billion cubic meters, and the total water resources of the basin are 42.9 billion cubic meters, the main source of runoff in the TRB is glacier melt, accounting for nearly 50% of the runoff, while the remaining runoff sources include precipitation from rain and snow and river base flow [36,37]. The irrational exploitation of water resources has caused a certain impact on the ecological environment and the sustainability of economic development in the TRB. To meet the demand for water for economic and social development and agricultural irrigation (the demand for water for agricultural irrigation is very high, accounting for about 96% of the total water consumption in the TRB) [38], the water resources in the main-stream of the TRB are over-exploited, which has affected the tributaries and the lower streams of the ecosystem, further compressing water for the ecological environment, leading to ecological degradation. The population of the TRB accounts for 46.85% of Xinjiang, the total GDP accounts for 27.68% of Xinjiang, the GDP per capita is far below the average level of Xinjiang, the urbanization level is low, and the economic and social development is generally backward. The study area is mainly composed of five prefectures in the basin, namely Aksu, Bayingol Mongolian Autonomous Prefecture (BMAP), Kizilsu Kirgiz Autonomous Prefecture (KKAP), Kashgar Prefecture (KP), and Hotan Prefecture (HP) (Figure 4).

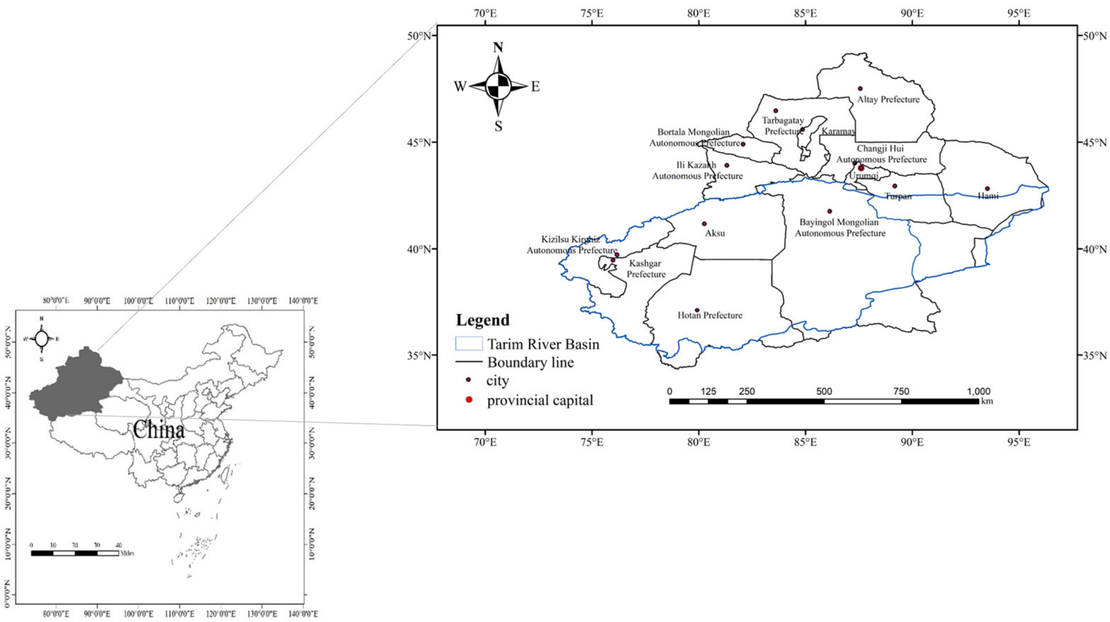

Figure 4. Schematic diagram of Xinjiang and TRB.

3.2. Constructing the Framework of the Element System

The assessment of AUCWR is the basis for rational development and the utilization of regional water resources, sustainable economic and social development, and ecological environmental protection. To assess the AUCWR, it is necessary to build a set of assessment index systems from the two laws, four principles, three tasks, and four functions of the adaptive utilization theory of water resources [24]. Taking into account the water resources endowment conditions, economic and social factors, and the ecological environment of the TRB, 25 evaluation indexes are finally selected, and the AUCWR is used as the target layer to build a system covering the assessment element system of AUCWR covering three guideline layers of water resources, economic society, and ecological environment is constructed, as shown in Table 1. In the table, (+) represents positive indicators and (−) represents negative indicators.

Table 1. Evaluation element system of AUCWR.

Target	Sub-Problem Domain	Element	Unit
Adaptive utilization capacity of water resources (AUCWR)	Water Resource	Precipitation depth (I_1) (+)	mm
		Water yielding modulus (I_2) (+)	10^4 m^3/km^2
		Average per capita water resources (I_3) (+)	m^3/person
		Exploitation rate of water resources (I_4) (−)	/
		Per capita water consumption (I_5) (−)	m^3/person
		Water consumption per 10,000 yuan of GDP (I_6) (−)	$m^3/10^4$ CNY
		Water consumption per 10,000 yuan of industrial added value (I_7) (−)	$m^3/10^4$ CNY
		Average irrigation water consumption per unit area of farmland (I_8) (−)	m^3/hm^2
		Per capita domestic water consumption (I_9) (−)	L/person
	Economic Society	Per capita GDP (I_{10}) (+)	10^4 CNY/person
		Proportion of non−agricultural output value in GDP (I_{11}) (+)	/
		Grain production per cubic meter of water (I_{12}) (+)	kg/m^3
		Per capita disposable income of urban residents (I_{13}) (+)	CNY/person
		Per capita net income of rural residents (I_{14}) (+)	CNY/person
		Urbanization rate (I_{15}) (+)	/
		Population density (I_{16}) (+)	person/km^2
		Natural population growth rate (I_{17}) (+)	/
		Water popularization rate of urban population (I_{18}) (+)	/
	Ecological Environment	Forest coverage rate (I_{19}) (+)	/
		Green coverage rate of built-up area (I_{20}) (+)	/
		Ecological environment water consumption rate (I_{21}) (+)	/
		COD emission per capita (I_{22}) (−)	t/10^4 person
		Ammonia nitrogen emissions per capita (I_{23}) (−)	t/10^4 person
		Per capita discharge of sewage and wastewater (I_{24}) (−)	m^3/person
		Fertilizer application intensity (I_{25}) (−)	kg/hm^2

3.3. Methods

3.3.1. Calculate Element Weights

The methods of determining the weights of the index system can be generally divided into two categories: subjective assignment method and objective assignment method. The objective assignment method includes such methods as the mean square difference method, principal component analysis method, entropy method, representative calculation method, etc. The subjective assignment method includes the subjective weighting method, expert survey method, hierarchical analysis method, comparative weighting method, multivariate analysis method, fuzzy statistics method, etc. In this paper, the entropy weighting method is used to determine the weights in the evaluation study of the effect of demonstration [39].

The entropy weighting method is used to calculate the objective weights [40]. Generally speaking, if the information entropy of an index is smaller, it indicates that the greater the degree of variation of the index value, the more information it provides, the greater the role it can play in the comprehensive evaluation, and the greater its weight. The steps to determine the weights by the entropy method are as follows.

1. The data are standardized and normalized.

$$Y_{ij} = \frac{X_{ij} - min\left(X_{ij}\right)}{max\left(X_{ij}\right) - min\left(X_{ij}\right)} \tag{1}$$

$$Z_{ij} = \frac{Y_{ij}}{\sum_1^n Y_{ij}} \tag{2}$$

2. Seek the information entropy of indicators

$$E_j = -\ln(\mathrm{n})^{-1}\sum_{1}^{n} Z_{ij} ln Z_{ij} \tag{3}$$

3. Determine the weight:

$$W_j = \frac{1-E_j}{\sum 1-E_j},\ j = 1,2,\ldots,\mathrm{m} \tag{4}$$

where, W_j is the weight.

3.3.2. Harmony Methods

Through the evaluation of using the harmony methods [41], we can reflect the harmony degree on the whole, the state, and level, as well as the spatial and temporal changes, and provide the basis for the evaluation of harmony problems and the search for harmony strategies. It mainly adopts the evaluation method of "single indicator quantification—multiple indicators synthesis—multiple criteria integration", as follows:

1. Single-indicator quantification: It includes quantitative and qualitative indicators, and each indicator has a harmonious degree (called *SHD*) with the value range of [0, 1]. In order to facilitate calculation and comparative analysis, the quantitative description of single indicator harmony can be quantified by using segmented linear affiliation function quantification method for positive indicators, negative indicators, and bidirectional indicators respectively, and mapping each indicator to [0, 1] uniformly. Among them, the harmony degree of positive and negative indicators is calculated as follows [42].

$$SHD_k = \begin{cases} 0 & x_k \le a_k \\ 0.3(\frac{x_k-a_k}{b_k-a_k}) & a_k < x_k \le b_k \\ 0.3+0.3(\frac{x_k-b_k}{c_k-b_k}) & b_k < x_k \le c_k \\ 0.6+0.2(\frac{x_k-c_k}{d_k-c_k}) & c_k < x_k \le d_k \\ 0.8+0.2(\frac{x_k-d_k}{e_k-d_k}) & d_k < x_k \le e_k \\ 1 & e_k < x_k \end{cases} \quad SHD_k = \begin{cases} 1 & x_k \le e_k \\ 0.8+0.2(\frac{d_k-x_k}{d_k-e_k}) & e_k < x_k \le d_k \\ 0.6+0.2(\frac{x_k-x_k}{c_k-d_k}) & d_k < x_k \le c_k \\ 0.3+0.3(\frac{b_k-x_k}{b_k-c_k}) & c_k < x_k \le b_k \\ 0.3(\frac{a_k-x_k}{a_k-b_k}) & b_k < x_k \le a_k \\ 0 & a_k < x_k \end{cases} \tag{5}$$

where, SHD_k is the harmony degree of the k-th index, k = 1, 2, . . . , n, n is the number of indicators; a_k, b_k, c_k, d_k, e_k is the worst value, poor value, pass value, better value and best value of the k-th index.

2. Multi-indicator synthesis: it can be calculated by multi-indicator weighting method, according to the single indicator affiliation weighted by the weight.

$$HD = \sum_{j=1}^{n} w_j \mu_j \in [0,1] \tag{6}$$

where, μ_j is the harmony of the kth indicator SHD_j, w_j is the weight. It can also be calculated according to the single indicator affiliation weighted by exponential weights.

$$HD_t = \prod_{j=1}^{n} (\mu_j)^{w_j} \in [0,1] \tag{7}$$

where, w_j is the weight.

3. Multi-criteria integration: It can be calculated using a weighted average or index weighting method.

$$\text{AUCWR} = \sum_{t=1}^{T} w_t HD_t \text{ or AUCWR} = \sum_{t=1}^{T} (HD_t)^{\beta_t} \tag{8}$$

where $\omega_t,\ \beta_t$ are the weights of the t-criteria, $\sum_{t=1}^{T} \omega_t = 1$, $\sum_{t=1}^{T} \beta_t = 1$, and the other symbols are the same as before.

On the basis of the constructed index system for assessing the adaptive capacity of water resources, the problem of adaptive use of water resources is understood as a dynamic and harmonious balance of water resources-economy-society-ecology-environment system. The goal is to maximize the harmony of the water resources-economic-social-ecological environment system. The overall harmony degree is calculated by using the comprehensive evaluation method of "Single Indicator Quantification—Multi-Indicator Integration—Multi-Criteria Integration" (SMI-P method) of the harmony theory. Firstly, we quantify each indicator and calculate the individual indicator harmony degree, then we assign and weight each indicator to calculate the harmony degree of each criterion layer, and finally, we weight each criterion layer to calculate the harmony degree.

3.3.3. Comprehensive Co-Evolution Model Methods

According to the comprehensive co-evolutionary model proposed in each reference [28,29], the adaptive capacity of the influencing factors to environmental changes is measured by calculating the absolute adaptability, and the relative adaptability is used to describe the adaptability of the interaction between the influencing factors, based on the characteristics of mutual adaptation between different influencing factors or indicators in the theory of adaptive use of water resources. The combination of absolute and relative adaptability is used to evaluate the AUCWR. The method is divided into the following steps.

1. Division of criterion layers and determination of weights

According to the index system established above, the criterion layer is divided into three aspects: water resources, economic and social factors, and ecological environment. The weights are determined using the entropy weighting method above to ensure that the weights of the influencing factors are consistent between the harmony theory and the comprehensive co-evolutionary model approach.

2. Calculation of absolute adaptability of factors

In order to effectively reduce the influence brought by the uncertainty of the relationship between factors, the gray correlation analysis method is first used to determine the correlation degree between individual factors; the gray correlation degree method is as follows.

$$\alpha_{ij} = \frac{\min\limits_{i}\min\limits_{j}\left|X_{oj} - X_{ij}\right| + \rho\max\limits_{i}\max\limits_{j}\left|X_{oj} - X_{ij}\right|}{\left|X_{oj} - X_{ij}\right| + \rho\max\limits_{i}\max\limits_{j}\left|X_{oj} - X_{ij}\right|} \tag{9}$$

where ρ denotes the resolution factor, usually taken as 0.5 [43] where X_{oj} represents the optimal value of the jth factor.

$\overline{\alpha_{ij}}$ as the average value of each point between X_{ij} and X_{oj}, $\overline{\alpha} = \frac{1}{n}\sum\limits_{1}^{n} \alpha_{ij}$; $\epsilon_{ij} = \alpha_{ij} - \overline{\alpha_{ij}}$; where ϵ_{ij} is used to represent the fluctuation value between the factors α_{ij}, the system adaptation, and finally the absolute adaptation of the factors is derived as follows:

$$f_j^C = 1 - \sqrt{\left(\overline{\alpha_{ij}} - 1\right)^2 + \sum_{I=1}^{n} {\epsilon_{ij}}^2 * W_j} \tag{10}$$

where: f_j^C represents the absolute factor fitness; W_j represents the factor weights.

3. Calculation of the relative fitness of factors

$$f_j^R = \frac{0.5 + HD_j - AHD}{0.5 + HD_j} * f_j^C \quad (11)$$

where: f_j^R represents the absolute suitability of the factors; HD_j represents the Hemming distance between the actual and ideal values in the evaluation matrix; AHD represents the average of the hemming distance of each element; 0.5 represents the smoothing factor. HD and AHD are calculated by the formula between the original literature.

4. Factor adaptation calculation

The article combines the absolute and relative fitness of the factors with the weights to calculate the fitness of the factors with the following formula.

$$f_j^S = W_j * f_j^C + \left(1 - W_j\right) * f_j^R \quad (12)$$

where: f_j^S represents the adaptation of the factors.

5. Calculation of AUCWR

Based on the results of the factor adaptability, the calculated data are standardized to obtain the standard value X_{Ij}^* for each indicator and consequently the survival adaptability of the target layer. In order to maintain consistency with the Harmony Theory approach, the target layer is here designated as the AUCWR, and thus the formula for calculating the AUCWR is obtained as:

$$D_i = \sum_{j=1}^{m} \frac{f_j^S}{\sum_{j=1}^{m} f_j^S} * X_{Ij}^* \quad (13)$$

where D_i represents the AUCWR of the ith evaluation object, where i represents the calculation year (2004–2018); m represents the number of factors.

3.3.4. Obstacle Degree Model Methods

The obstacle degree model can assess the degree of influence of each factor on the final goal by analyzing the magnitude of the obstacle effect of different indicators in the assessment index system [44]. Obstacle degree models are widely used in assessing land use impact factor assessment, ecological security assessment, and other fields. In this paper, the obstacle degree model is introduced to analyze the degree of contribution of impact factors in order to better regulate the AUCWR. The specific steps are as follows.

The obstacle degree Q_i (the degree of influence of each subsystem or each indicator on the AUCWR is calculated by introducing the factor contribution degree w_j (the weight of a single indicator on the total target) and the indicator deviation degree I_i (the distance between the actual value of each indicator and the optimal value, expressed as the difference between 1 and the standardized value X_{ij} of each indicator), which is calculated as follows:

$$Q_i = \frac{I_i \times w_i}{\left(\sum_{i=1}^{m} I \times w_i\right)} \quad (14)$$

where $I_i = 1 - X_{ij}$, X_{ij} is the normalized value of the indicator.

3.4. Data Sources

The data used in this paper are all from Xinjiang and the Aksu, BMAP, KKAP, KP, and HP regions yearbooks from 2005–2019, and the statistics are from 2004–2018.

4. Results

4.1. Element Thresholds and Weights

4.1.1. Element Thresholds

According to the single indicator quantification in the harmony theory method, the thresholds of 25 indicators in the evaluation index system are divided, and the thresholds are divided into five nodes according to the single indicator quantification calculation formula, which are optimal, better, medium, worse and worst in order, and the final 25 indicator thresholds are divided in Table 2.

Table 2. Element threshold division table.

Element	Threshold Division					Element	Threshold Division				
	Worst	Poor	Moderate	Better	Best		Worst	Poor	Moderate	Better	Best
I_1	39	150	400	600	850	I_{14}	1000	4000	7000	10,000	13,000
I_2	3	6	9	12	15	I_{15}	0.2	0.4	0.6	0.8	1
I_3	1000	6000	12,500	19,000	25,000	I_{16}	5	11	17	24	30
I_4	1	0.8	0.6	0.4	0.2	I_{17}	3	6.5	10	20	30
I_5	7000	5500	3500	2000	500	I_{18}	0.2	0.4	0.6	0.8	1
I_6	10,000	7500	5000	3000	1000	I_{19}	0.005	0.02	0.04	0.1	0.16
I_7	1000	700	400	200	50	I_{20}	0.2	0.4	0.6	0.8	1
I_8	1200	950	700	450	200	I_{21}	0.005	0.01	0.02	0.035	0.05
I_9	150	125	100	75	50	I_{22}	200	150	100	75	50
I_{10}	0.5	1.75	3	5	7	I_{23}	20	15	10	6	2
I_{11}	0.2	0.4	0.6	0.8	1	I_{24}	100	65	30	17.5	5
I_{12}	0.1	0.2	0.3	0.4	0.5	I_{25}	100,000	75,000	50,000	30,000	10,000
I_{13}	5000	12,500	20,000	30,000	40,000						

4.1.2. Element Weights

According to the entropy weighting method, a total of 25 indicators in three subsystems of TRB, namely, water resources, economic and social factors, and ecological environment, are weighted as shown in Table 3.

Table 3. Water resources subsystem element weights.

System	Element Weight										
Water Resources subsystem	Element	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	Total
	Weight	0.043	0.038	0.049	0.036	0.032	0.035	0.027	0.037	0.028	0.325
Economic and Social subsystem	Element	I_{10}	I_{11}	I_{12}	I_{13}	I_{14}	I_{15}	I_{16}	I_{17}	I_{18}	Total
	Weight	0.075	0.055	0.042	0.028	0.050	0.043	0.045	0.041	0.045	0.424
Ecological Environment subsystem	Element	I_{19}	I_{20}	I_{21}	I_{22}	I_{23}	I_{24}	I_{25}			Total
	Weight	0.039	0.044	0.056	0.027	0.026	0.027	0.032			0.251

Among them, the economic and social subsystem weight is larger, accounting for 0.424, the water resources subsystem has the second largest weight, accounting for 0.325, and the ecological environment subsystem has the smallest weight of 0.251. Among the indicators, the per capita water resources in the water resources subsystem has the largest weight of 0.049, in the economic and social subsystem, the per capita GDP has the largest weight of 0.075, and in the ecological environment subsystem, ecological environmental water use rate, the largest weight is 0.056.

4.2. Evaluation of AUCWR

4.2.1. Temporal and Spatial Variation Characteristics of AUCWR in TRB

The results obtained based on the harmony theory method are shown in Figure 5a. In general, the AUCWR in the TRB demonstrates a fluctuating upward trend, the results show that this trend is in line with the current development situation of the Tarim River Basin [45]. The AUCWR in the TRB increased from 0.43 in 2004 to 0.56 in 2018, with a growth rate of 30.23%. The AUCWR is mainly concentrated in the range of 0.40–0.60, with an annual average value of 0.497, which indicates that the adaptability among water resources, economic and social, and ecological environment subsystems is in the near-adaptation stage, and the level of adaptive development in the basin is moderate. The adaptive use capacity levels of water resources from 2004 to 2018 are all in the near-adaptation stage. According to the growth rate of the AUCWR, the development of the AUCWR in the basin demonstrates an increasing trend from 2004 to 2006 (average annual growth rate of 2.57%); during the period of 2006–2010, the AUCWR in the basin reveals a fluctuating, increasing trend (average annual growth rate of 1.38%); from 2010–2012, the AUCWR in the basin indicates a fluctuating downward trend (average annual decrease rate of 2.25%); from 2012 to 2018, the AUCWR in the basin verifies an upward trend (average annual growth rate of 1.17%). The adaptive development level of AUCWR in the basin has increased during the period 2004–2018 (average annual growth rate of 0.08%), but the rising level is low.

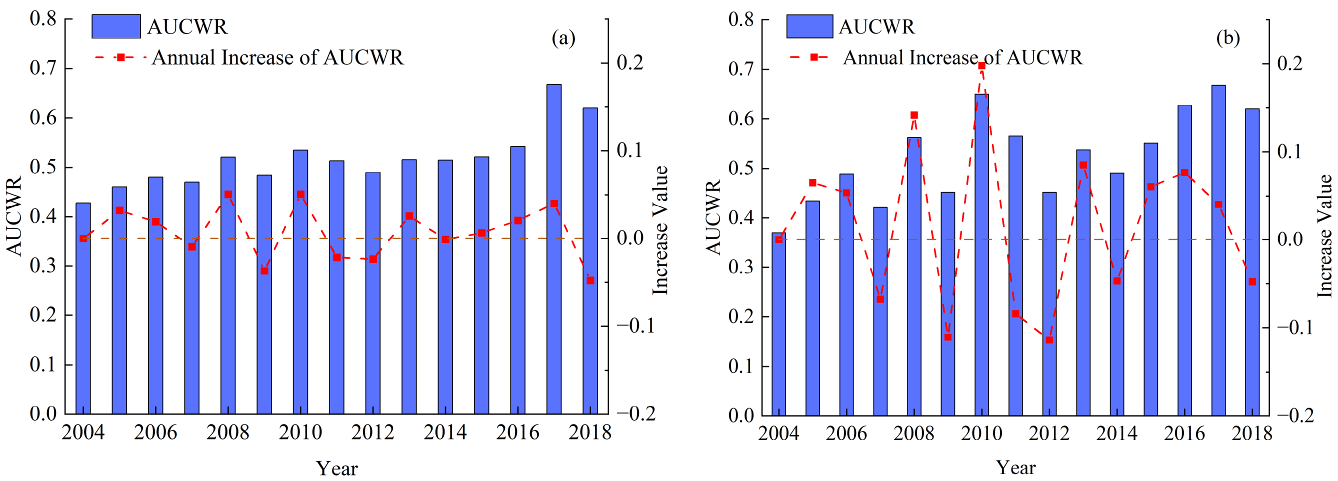

Figure 5. AUCWR and changes in the TRB. (**a**): calculation results of the harmony theory method. (**b**): calculation results of the comprehensive co-evolutionary model method.

The results obtained based on the comprehensive co-evolutionary model method are shown in Figure 5b. On the whole, the AUCWR in the TRB also shows a fluctuating upward trend, and the fluctuation state is more intense. The AUCWR in the TRB has a large value of change. As a whole, it increased from 0.37 in 2004 to 0.62 in 2018, with a significant increase of 67.57%. The annual average value of the AUCWR is 0.526, with a moderate level of adaptive development of the system. The year 2004 has the lowest AUCWR, and the adaptive level is at the basic non-adaptive stage; 2015–2009 and 2011–2015 are at the near adaptive stage, while 2010 and 2016–2018 are at the AUCWR. The AUCWR in 2010 and 2016–2018 are all at the basic adaptive stage. Based on the magnitude of changes in adaptive capacity, the harmony theory method calculations show similar trends: a gradual increase during 2004–2006 (with an average annual increase of 5.93%), a fluctuating increase from 2006–2010 (with an average annual increase of 4.04%), a gradual decrease from 2010–2012 (with an average annual decrease of 9.89%), and a fluctuating up (with an average annual increase of 1.91%), and 2014–2017 gradually up (with an average annual increase of 5.91%). By and large, the level of adaptive development of the AUCWR in the basin increased during 2004–2018 (average annual growth rate of 0.2%), but the level of increase is limited.

The AUCWR in the TRB is assessed by the harmony theory method and the comprehensive co-evolutionary model method, and the results of both calculation methods show that the AUCWR in the TRB is not high during 2004–2018 (mean value of the harmony theory method: 0.497; the mean value of the comprehensive co-evolutionary model method: 0.526), but the development trend is good and the capacity gradually improved. The adaptive use of water resources in the TRB is limited, and the AUCWR is around 0.6 after improvement (calculated by the harmony theory method: 0.56; calculated by the comprehensive co-evolutionary model method: 0.62), which is near the passing level. The current problems should be addressed, and solutions should be proposed to improve the overall AUCWR in the TRB.

The results of the AUCWR assessment of the TRB calculated by the two methods are shown in Figure 6a,b. The analysis reveals that the calculated overall change trends of the TRB and each prefecture are consistent and demonstrate an increasing trend; secondly, the average value of the AUCWR in the TRB from 2004 to 2018 calculated by the harmony theory method is 0.497, and the result calculated by the integrated coevolutionary model method is 0.526, which is basically similar to the water resources of each prefecture. The results are similar to the AUCWR in each state. In general, the results of the two calculation methods are consistent, and the results of the two methods can be combined to make a comprehensive assessment of the AUCWR in the TRB and each state. Therefore, in the following assessment of the AUCWR in each state, in order to focus on the analysis of the changes between the states, the calculation results are averaged using the calculation results of the two methods (Figure 6c).

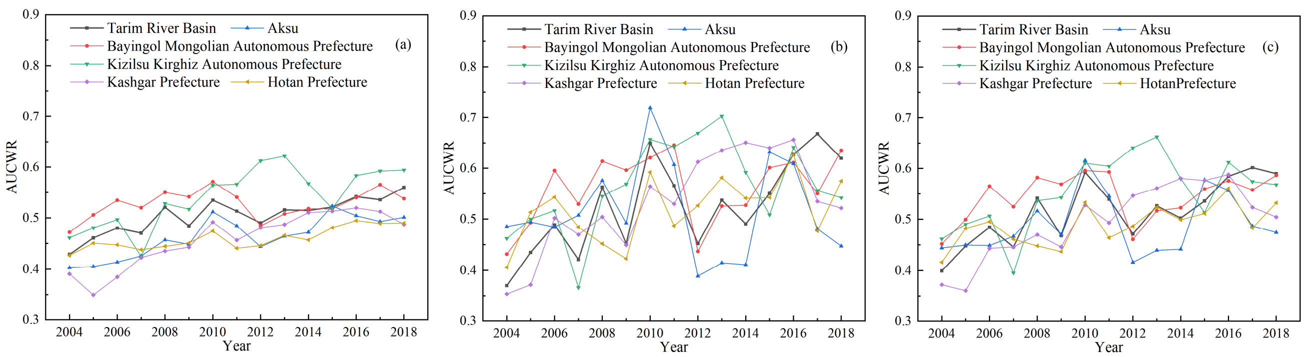

Figure 6. AUCWR and changes of various prefectures in the TRB. (**a**,**b**): calculation results of the harmony theory and the comprehensive co-evolutionary model method. (**c**): average of the results calculated by the two methods.

Using the two methods, by analyzing the AUCWR in the five prefectures (Aksu, BMAP, KKAP, KP, and HP regions) belonging to the TRB from 2004 to 2018, we obtained the trend graph of the AUCWR in each prefecture, as shown in Figure 6a,b, and combined the results of the two calculations to obtain the trend graph of the AUCWR in each prefecture, as shown in Figure 6c.

The results verify that, in terms of temporal trends, the AUCWR in all states of the TRB has similar trends, with all five regions showing fluctuating upward trends. The growth rates of Aksu, BMAP, KKAP, KP, and HP regions are 14.01%, 24.45%, 28.87%, 24.76%, and 14.81%, respectively, with the largest increase in the KKAP region and the smallest increase in the Aksu region. The fluctuation of the KKAP region is more dramatic, and its standard deviation of AUCWR from 2004 to 2018 reaches 0.056, which is larger than the remaining four prefectures. At the same time, there is little difference in the mean value of AUCWR in each prefecture. The average AUCWR of the TRB from 2004 to 2018 is 0.52. The average AUCWR of the BMAP and KKAP regions is larger than that of the TRB, 0.54 and 0.55, respectively, while the average AUCWR of the Aksu, KP, and HP regions is smaller than that of the TRB, 0.49, 0.50, and 0.49, respectively. By analyzing the trends and average values of the AUCWR in the TRB as a whole and in each state, we found that the AUCWR in each state is not high at present and still has great potential for development. The trend of fluctuating growth is the same as that of the TRB, but the growth rate is not large.

4.2.2. Temporal and Spatial Variation Characteristics of System Adaptability in TRB

The system adaptability of the three subsystems of water resources, economic and social factors, and ecological environment in the TRB and the five prefectures is obtained according to Equation (5) to Equation (8), as shown in Figure 7.

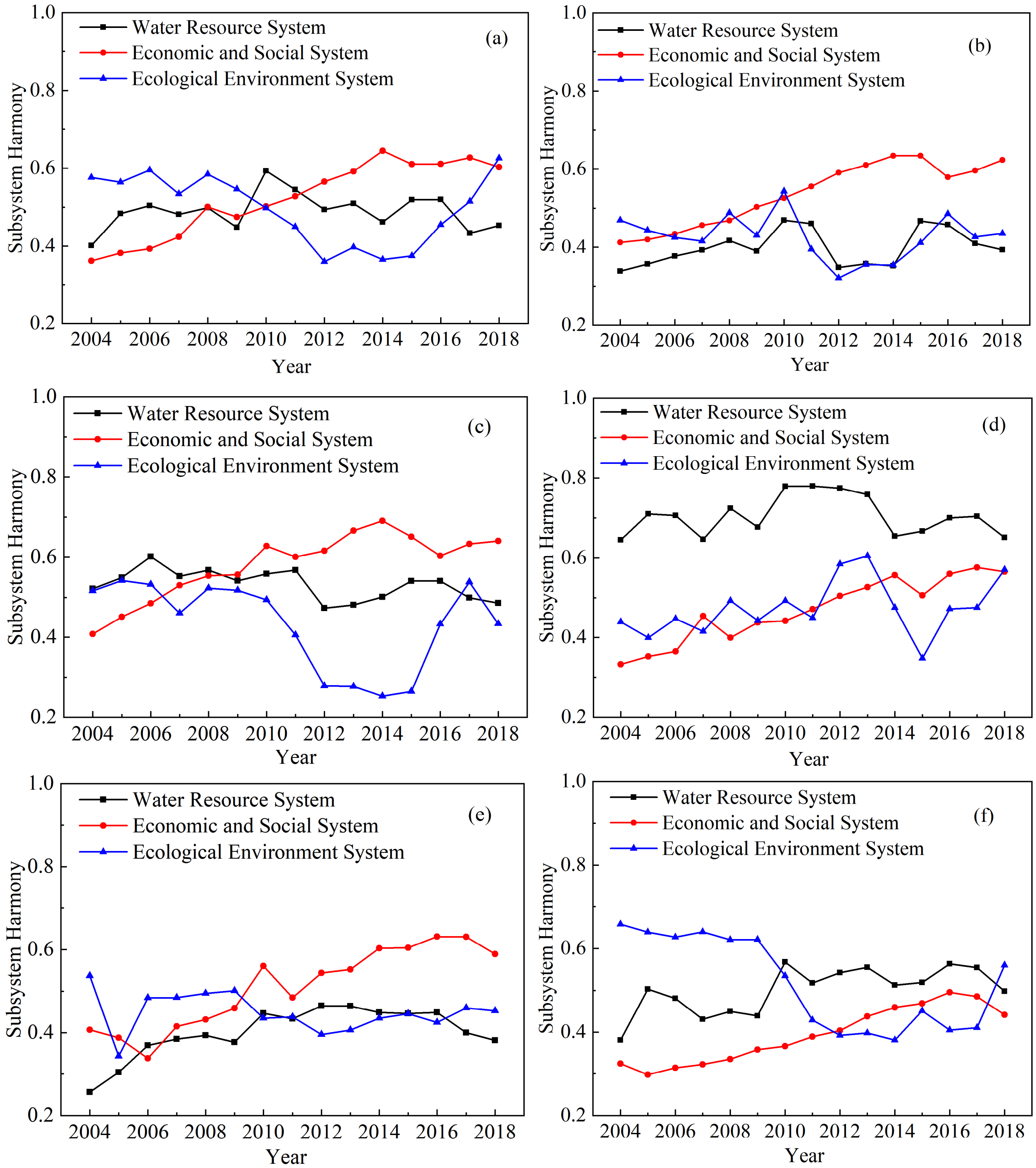

Figure 7. Trend of adaptation of each system in the TRB and the states. (**a**): trend of adaptation of each system in the TRB. (**b**–**f**): trend of adaptation of each system in the Aksu, BMAP , KKAP, KP, and HP regions.

Figure 7a confirms the adaptability of each subsystem in the TRB, which ranges from 0.4 to 0.6, indicating that the adaptability of each subsystem is at a medium level in the study area. From 2004 to 2018, the change in the adaptability of the water resources system is small (average annual growth rate of 5.2%), and although the water resources subsystem reveals an upward trend, the trend is not obvious, and by 2018, the adaptability of the water resources subsystem is significantly lower than that of the economic and social and ecosystem subsystems. It can no longer meet the needs of economic and social development and ecological protection. During 2004–2018, the economic and social subsystem adaptation degree indicates a rapid upward trend (average annual growth rate of 24%), and the level of economic and social development steadily increased during this period, but after 2014, it decreased, which may be due to the fact that with the increase of ecological environmental protection, the development of certain environmentally crude enterprises is restricted to a certain extent, which caused the growth of economic and social development certain impact, but generally speaking, the momentum of economic and social development is good. During the period of 2004–2014, the adaptability of the ecological and environmental subsystem indicates a decreasing trend (the average annual decrease rate is 21%), but during the period of 2014–2018, the adaptability of the ecological and environmental subsystem indicates an upward trend and an obvious upward trend (the average annual growth rate is 26%). It indicates that before 2014, the economic and social development of the TRB might be to a certain extent at the expense of the ecological environment. Strongly affected by human activities, the ecological environment is damaged to some extent, the ecological environment is becoming worse and worse, the ecological carrying capacity is gradually increasing [46], and the research shows that the changes in human activities and climate have a significant impact on the ecological environment and oasis changes in the TRB [47]. With the introduction of the policy of ecological protection, the ecological environment is obviously improved and implies a good development trend after increasing ecological protection and management.

Figure 7b–f show the changes in the adaptability of each subsystem in the five prefectures, among which, the adaptability trends of each subsystem in BMAP, Aksu, KP, and HP regions are consistent with those of the TRB, all showing a decreasing trend of the adaptability of the ecological environment subsystem, and an increasing trend of the adaptability of the water resources and economic and social subsystems, while the adaptability of the water resources, economic and social, and ecological environment subsystems in KP. The adaptation of water resources and economic and social subsystems in the KKAP regions shows an increasing trend, which indicates that the KKAP region is better than the other four states in environmental protection. Relevant research results also show that this trend is in line with the actual situation [48,49].

4.3. Element Analysis

4.3.1. Analysis of Element Change Characteristics

The adaptability of the subsystems is influenced by the changes in their internal elements. Figure 8 shows the average growth rate of each subsystem index, and the results show that the main factors affecting the adaptive development of the water resources, economic and social, and ecological environment subsystems are water consumption per 10,000 yuan of industrial added value (I_7), per capita domestic water consumption (I_9), water consumption of 10,000 yuan of GDP (I_6), per capita net income of rural residents (I_{14}), per capita GDP (I_{10}), per capita disposable income of urban residents (I_{13}), ecological environment water consumption rate (I_{21}), and fertilizer application intensity (I_{25}).

Since the increase in per capita domestic water consumption (I_9, growth rate 7.57%) is significantly higher than the annual precipitation depth of the water resources subsystem (I_1, growth rate 1.04%), it may lead to the crowding out of a large amount of ecological and environmental water and a significant decrease in the ecological environmental water consumption rate (I_{21}, decrease rate 5.97%), together with the inadequate environmental protection measures, all these combined effects may lead to the adaptation of the ecological and environmental subsystem declining. Additionally, to solve these problems, while developing and utilizing water resources and promoting economic development, we should strengthen ecological environmental protection and promote the integrated development of water resources, society, and ecology.

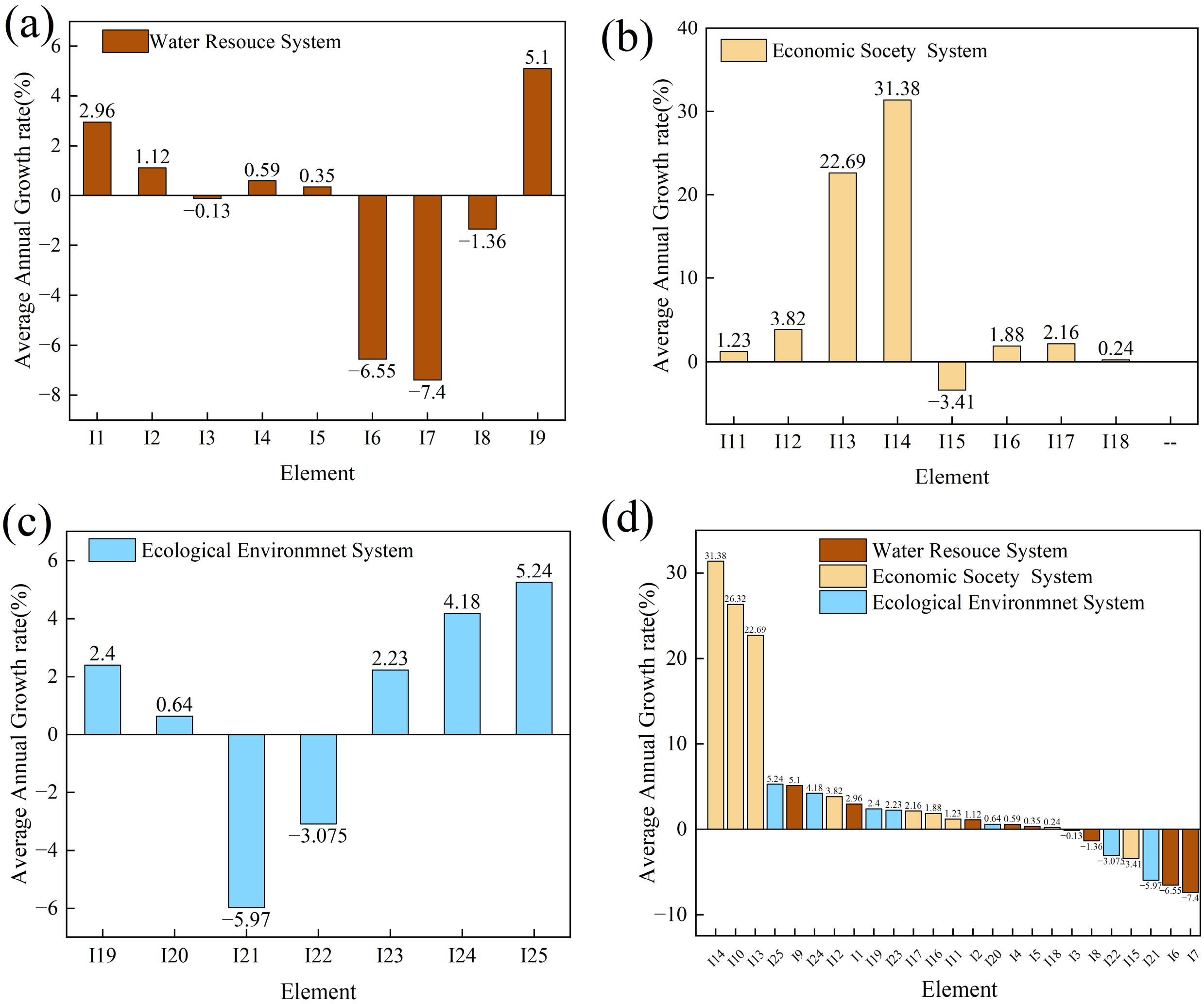

Figure 8. Average annual growth rate of each subsystem element. (**a**–**c**): the average annual growth rate of three subsystems. (**d**): ranking of average annual growth rate of three subsystems.

With industrial upgrading and progress in water conservation technology, rapid economic development can also be driven without affecting basic domestic water consumption, which is mainly reflected in the water consumption per 10,000 yuan of GDP (I_6, decline rate 7.01%), water consumption per 10,000 yuan of industrial added value (I_7, decline rate 7.78%) and average irrigation water consumption per unit area of farmland (I_8, decline rate 0.43%), per capita GDP (I_{10}, growth rate of 26.32%), per capita disposable income of urban residents (I_{13}, growth rate of 22.69%), and per capita net income of rural residents (I_{14}, growth rate of 31.38%) on the indicators, which are also the main reasons for the improvement of the economic and social subsystem adaptation.

Due to the western development strategy, the arable land area has been expanding while the economy is developing rapidly, with an increased rate of 83.8% in 2018 compared to 2004, which has increased the water demand to some extent. Although the amount of water resources in the TRB has increased, the water resources development and utilization rate remain high (72.64% on average), which is already higher than the internationally accepted limit of 40% and has reached a bottleneck. Therefore, it is necessary to improve water use efficiency, strengthen water conservation measures and improve water saving efficiency. The changes in water consumption per 10,000 yuan of GDP (I_6, decline rate 7.78%), water consumption per 10,000 yuan of industrial added value (I_7, decline rate 7.78%), and average irrigation water consumption per unit area of farmland (I_8, decline rate 0.43%) are precisely the expression of water use efficiency improvement and the increase in the adaptation of water resources subsystem. However, the increasing water demand and the unreasonable allocation of water resources are also the main reasons for limiting the further improvement of the water resources subsystem.

In order to promote the coordinated development of water resources, economy, society, and ecological environment, it is necessary to actively carry out economic restructuring while developing and utilizing water resources, taking into account the endowment conditions of water resources, and driving the sustainable and stable development of the economy. At the same time, it is also necessary to focus on protecting the ecological environment, limiting unreasonable development of arable land, accelerating the construction of grassland and other ecological projects, reasonably allocating and dispatching water resources, realizing the healthy development of rivers, and coordinating the coordination between economic development and ecological protection. From the root cause, the water resources management system should be strengthened to coordinate the harmonious relationship between economic development and ecological environment, source and tributaries, upstream and downstream, based on water resources development and utilization, and improve the management system and system to realize the rational use of water resources.

4.3.2. Element Sensitivity Analysis

Using the barrier degree model to calculate the barrier degree of impact factors, the barrier degree of each subsystem and each indicator in the TRB from 2004 to 2018 is obtained, and the results are shown in Table 4. From Table 4, it can be concluded that there are differences in the barrier degrees of water resources, economic and social, and ecological environment subsystems on the AUCWR. In terms of temporal changes, the barrier degree of the water resources system increases year by year, but the growth rate is small, with an average annual growth rate of only 0.105%; the barrier degree of the economic and social subsystem gradually decreases, with an average annual reduction rate of 0.081%; the barrier degree of the ecological environment subsystem fluctuates more, first decreasing and then increasing, with an overall upward trend, but there is a large decrease in 2018. From the analysis of the three major subsystem barrier degree values, the economic and social subsystem has the largest barrier degree with an average value of 51.45%, followed by the water resources subsystem with an average barrier degree of 30.37%, while the ecological environment subsystem has the lowest barrier degree with an average value of only 18.18%. This shows that the economic and social subsystem is the main constraint subsystem affecting the improvement of the AUCWR in the TRB. Therefore, in order to further improve the AUCWR in the TRB, we should focus on the economic and social subsystem, further consider the development and utilization of water resources, ecological and environmental protection and economic and social development, effectively improve the level of coupled and coordinated development among water resources, economic and social factors, and the ecological environment, promote the healthy and sustainable development of the basin, and continuously improve the AUCWR.

Taking the 2018 data as an example, the barrier degree of each indicator to the overall system of the basin is analyzed, and the results are obtained as shown in Table 5. In terms of the barrier degree values of each indicator, the top indicators are mainly the economic and social subsystem indicators, and the top five indicators in the barrier degree of this system are per capita GDP (I_{10}), the proportion of non-agricultural output value in GDP (I_{11}), per capita net income of rural residents (I_{14}), population density (I_{16}), and water penetration rate of the urban population (I_{18}); the top three indicators in the barrier degree of the water resources system. The top three obstacles in the water resources system are average per capita water resources (I_3), precipitation depth (I_1), and water yielding modulus (I_2); the top three obstacles in the ecological environment subsystem are ecological environment water consumption rate (I_{21}), green coverage rate of built-up area (I_{20}), and forest coverage rate (I_{19}). On the whole, the indicators with a higher barrier degree have a greater impact on the AUCWR. Therefore, when analyzing and regulating the AUCWR in the future, the indicators with a higher barrier degree can be regulated.

Table 4. Subsystem level barriers to AUCWR in 2004–2018 (%).

Year	Water Resources	Economic and Social	Ecological Environment	Year	Water Resources	Economic and Social	Ecological Environment
2004	29.51	52.30	18.19	2012	30.53	51.24	18.23
2005	29.74	52.32	17.94	2013	30.60	51.14	18.25
2006	29.95	52.18	17.88	2014	30.86	50.79	18.35
2007	30.08	51.84	18.08	2015	30.70	51.00	18.30
2008	30.32	51.51	18.17	2016	30.57	50.98	18.45
2009	30.36	51.51	18.13	2017	30.60	50.94	18.46
2010	30.31	51.46	18.23	2018	30.98	51.17	17.86
2011	30.51	51.31	18.18				

Table 5. Subsystem level barriers to AUCWR in 2018 (%).

Element	Obstacle	Element	Obstacle	Element	Obstacle	Element	Obstacle	Element	Obstacle
I_1	4.04	I_6	3.42	I_{11}	6.72	I_{16}	5.53	I_{21}	3.69
I_2	3.65	I_7	2.68	I_{12}	5.06	I_{17}	5.19	I_{22}	1.97
I_3	4.69	I_8	3.53	I_{13}	3.28	I_{18}	5.46	I_{23}	1.91
I_4	3.40	I_9	2.51	I_{14}	5.80	I_{19}	2.80	I_{24}	1.98
I_5	3.04	I_{10}	8.76	I_{15}	5.36	I_{20}	3.24	I_{25}	2.26

5. Discussion

The AUCWR in the TRB is calculated by the harmony theory method and the comprehensive co-evolutionary model method, and the results are compared and analyzed as shown in Figure 9. According to Figure 9, the range of AUCWR in the TRB calculated by the two methods is not very different, with the range of 0.4–0.6 for the harmony theory calculation and 0.33–0.67 for the coevolutionary model method. The results calculated by both methods show a fluctuating upward trend from the overall time period of 2004–2016, followed by a consistent trend every two years, such as a gradual increase from 2004–2006, a fluctuating trend from 2006–2011, and then a gradual increase from 2012–2016. Taken together, the results of AUCWR calculated by the two methods can corroborate each other and increase the reliability of the results. Further, from the viewpoint of the magnitude of change, the harmony theory method has a small change and shows a steady upward trend overall, with the largest change in the two time periods of 2007–2008 and 2009–2010, with a change of 10.9% and 9.7% respectively. The comprehensive co-evolutionary model method has a larger change, and overall, the change from 0.34 in 2004 to 0.58 in 2016 is 0.22, which is much larger than the change value of 0.11 for the harmony theory method. Among them, the comprehensive co-evolutionary model method has the largest change before and after 2010, and the change before and after is 48.8% and 22.6%, respectively. Continuing to analyze the calculation results of the two methods in each region of the TRB, the mean values calculated by the comprehensive co-evolution model method are both higher than those calculated by the harmony theory, but the calculations are closer and the differences are not significant. While the fluctuation ranges are both larger than those calculated by the harmony theory method.

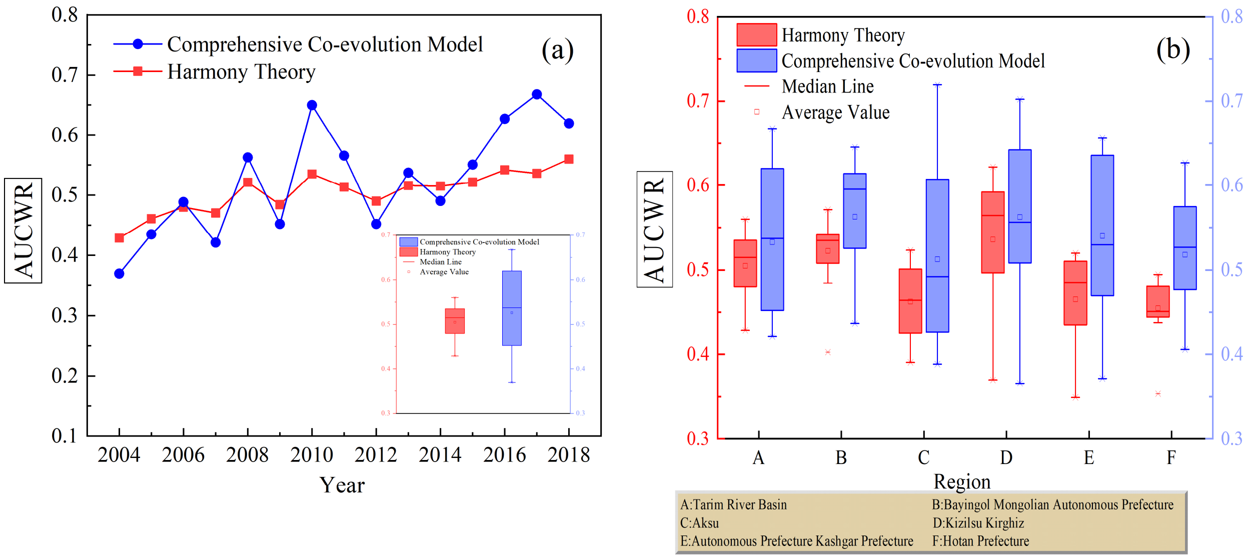

Figure 9. Comparative analysis of AUCWR in the TRB. (**a**): trend comparison of calculation results. (**b**): box-plot of calculation results in different regions.

A comparative analysis of the calculation results for the two algorithms can verify the reliability of the calculation results. From the calculation process of the two methods, in which the establishment of an evaluation index system, the determination of index weights, and the determination of evaluation index thresholds are the basic contents of the two methods. The indicator system proposed in the paper takes into account the indicators of the three dimensions of water resources, economy and society, and ecological environment. There are many types of indicators selected, which are more representative [46]. Among them, the harmony theory method uses the index quantification and criterion integration method to calculate the AUCWR, and the algorithm is relatively simple and easy to calculate; the coevolutionary model method has clear ideas, but the calculation formula is more complicated compared with the harmony theory, in which the whole calculation process involves the gray correlation method and the calculation of Hemming distance, which increases its calculation volume [50]. The evaluation index system and index weights are consistent in the two methods, and the evaluation index threshold method is used to a different extent in the two methods. In the harmony theory method, as long as the quantification of each index relies on the index threshold, the final weighting is integrated to obtain the final results, so the division of the index threshold has a greater impact on the calculation results of the harmony theory to a certain extent; the comprehensive co-evolutionary model method in which only the optimal value of the index threshold is used. Therefore, the division of indicator thresholds has relatively less influence on the calculation results of the comprehensive co-evolutionary model. Through comprehensive comparison and analysis, the two calculation results are basically reliable, and each calculation method has its own advantages. This paper evaluates the AUCWR in the TRB based on the two methods, and the evaluation results are also basically in line with the reality.

6. Conclusions

The AUCWR in the TRB and its five prefectures is assessed using the harmony theory method and the comprehensive co-evolutionary model method, and the key factors affecting the AUCWR are analyzed, finally, the applicability of the two assessment methods are discussed at the end. The following conclusions were drawn:

(1) The AUCWR in the TRB demonstrates a fluctuating upward trend from 2004 to 2018 (the harmony theory method assessment results: from 0.43 in 2004 to 0.56 in 2018, with a growth rate of 30.23%; the comprehensive co-evolutionary model method assessment results: from 0.37 in 2004 to 0.62 in 2018, with a significant increase of

67.57%). The development trend is good, but the current level of AUCWR in the TRB is still not high, and there is a lot of room for improvement.

(2) There are differences in the adaptability of subsystems in the TRB, mainly in that the adaptability of the water resources subsystem changes less, the economic and social subsystem increases significantly, and the ecological environment subsystem indicates a decreasing and then increasing trend. The trend of subsystem adaptations in BMAP, Aksu, KP, and HP is consistent with that of TRB, the adaptations of water resources and economic and social subsystems are increasing, while the adaptations of ecological environment subsystems are decreasing. While the adaptations of water resources, economic and social subsystems, and ecological environment subsystems in KP are increasing.

(3) By analyzing the factors, the change characteristics of each factor and the degree of influence on the AUCWR are obtained. Among them, the indicators with large changes from 2004 to 2018 are mainly: water consumption per 10,000 yuan of industrial added value (I_7), per capita domestic water consumption (I_9), water consumption of 10,000 yuan of GDP (I_6), per capita net income of rural residents (I_{14}), per capita GDP (I_{10}), per capita disposable income of urban residents (I_{13}), ecological environment water consumption rate (I_{21}), and fertilizer application intensity (I_{25}). While the analysis of the barrier degree model obtained that the economic and social subsystem had the largest barrier degree with a mean value of 51.45% at subsystem level. From the perspective of indicators, indicators such as per capita GDP (I_{10}), the proportion of non-agricultural output value in GDP (I_{11}), per capita net income of rural residents (I_{14}), population density (I_{16}), and water popularization rate of urban population (I_{18}).

Author Contributions: Conceptualization, Q.Z. and X.L.; methodology, Q.Z. and X.L.; formal analysis, X.L. and Q.Z.; investigation, Q.Z., Y.Z. and X.L.; resources, X.L., Y.W. and S.H.; data curation, X.L.; writing—original draft preparation, Q.Z. and X.L.; writing—review and editing, Q.Z., Y.Z. and J.Z.; visualization, X.L. and S.H.; supervision, Q.Z. and J.Z.; project administration, J.Z.; funding acquisition, Q.Z., Y.Z., J.Z. and Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported by the National Key Research and Development Program of China (Grant No. 2021YFC3200205) and The Natural Sciences Foundation of China (No. U1803241, 52025093, 51979284, and 52109044).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the finding of this study are available from the corresponding author upon reasonable request.

Acknowledgments: We are very grateful to the editor's comments and suggestions. The provided comments have contributed substantially to improve the paper.

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

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