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Multidimensional critical regulation model for sustainable water resources regulation in a typical arid area of the Manas River watershed

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ABSTRACT

Multidimensional critical regulation of water resources in a typical arid area, such as in the Manas River Watershed in China, is an important way to solve the contradiction between water supply and demand and realize sustainable development. Typically, water managers do not take into account the coordinated development of various water sources and water sectors. To solve this problem, we used a system dynamics model to analyze the supply and demand of water resources in the planning year, and establish a critical control model with four dimensions (water resources, economy, society and ecology) to optimally regulate water resources. The results show that (1) the water resources system entropy was reduced to 0.1506 after several iterations in the planning year; (2) the water resources subsystem, economic subsystem and social subsystem were negatively correlated with system entropy, while the ecosystem subsystem was positively correlated with it; and (3) the reduced water shortage will increase from 2.27×10^8 m^3 in 2020 to 3.76×10^8 m^3 in 2030, which indicates that the water resources system will develop in an orderly and coordinated way.

Keywords: Manas River watershed; System dynamics model; Multidimensional critical regulation; System entropy

1. Introduction

The contradiction between water supply and demand in a typical arid area becomes more and more prominent because of increased water consumption and scarce rainfall [1]. Water resources shortages have become an important bottleneck restricting regional development around the area. The rational distribution of water resources needs to be further improved due to the fragile ecological environment and lower ecological water consumption in an arid area. To solve the contradiction between water supply and demand, as well as ensure the sustainable development, supply and demand analyses and optimal allocation of water resources are particularly important [2]. Analysis of water supply and demand involves studying water supply and demand and the relationship between them in certain areas, laying the foundation for water resources regulation [3]. Water resources regulation refers to the scientific and rational distribution of water resources in a particular river watershed or region by using a combination of engineering measures and non-engineering measures. These achieve the sustainable use of water resources and ensure the coordinated development of the social economy, resources and the ecological environment [4].

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Water supply and demand analysis models mainly include traditional forecasting model and improved multivariable grey model. Traditional forecasting models mainly include a multiple linear regression model (which cannot highlight the influence of recent information on the forecasting results) and a grey prediction model GM(1,1), which can only analyze and forecast the law of water demand history data among all data [5]. Furthermore, an improved multivariable grey model requires careful selection of variables because improper selection will lead to lower prediction accuracy, matrix errors and inverse matrix errors [6]. The system dynamics (SD) model is based on the feedback characteristics of the internal factors of the system. Structure, function and history are combined to quantitatively study high-order, nonlinear and multiple-feedback complex time-varying problems using computer simulations. A SD model not only highlights the influence of new information on prediction results, but also require fewer variables. In recent years, many scholars have used a SD model to analyze the supply and demand of water resources, such as in Zhongshan and Handan [7,8].

International scholars use a variety of water resources analysis and management tools: single reservoir optimization scheduling, multiuser interactive models, and combinations of game theory and Pareto optimal conceptualization and configuration [9–11]. Chinese scholars use a similar array of tools: the "artificial-natural" dual water cycle, whole-attribute water resources allocation, and water resources optimization based on uncertainty analysis [12–14]. These techniques have improved understanding of the relationship between the economy, society and the ecological environment. However, a water resources system is a complex system of "natural-artificial" dual water cycles involving not only water resources [15], but also economy, society, ecology and other subsystems.

There are few studies on the comprehensive analysis of the interrelationship among subsystems. The application of multidimensional critical regulation to the optimal allocation of water resources provides a new way to solve this problem. This paper establishes the SD model of the water supply and demand system of the Shihezi Irrigation District, Mosuowan Irrigation District and Xiayedi Irrigation District, which are components of the Manas River Watershed. Based on Vensim® software (http://vensim.com/vensim-software/), the model combines the ecological water demand inside and outside the Manas River and analyzes the water supply and demand in the Manas River Watershed in a planning year. Based on multidimensional critical regulation theory, we propose the critical regulation of water resources in four subsystems of water resources, economy, society and ecology. Furthermore, we optimally regulate the water consumption between each irrigation area and water users to realize coordinated development and the virtuous circle of water resources management. The study provides a reference for solving the contradiction between water supply and demand in a watershed and realizing the sustainable development of water resources.

2. Materials and methods

2.1. Study area and materials

The Manas River Watershed (E85°01′–E86°32′, N43°27′–N45°21′) is located in the heart of the northern slope of the Tianshan Mountains in Xinjiang, east of the Manas River, and west of the Bayingou River [16] (Fig. 1). Away from the ocean, the climate is a dry typical continental arid climate, with a mean annual precipitation of nearly 200 mm and an average annual evaporation exceeding 1500 mm [17]. Diurnal flow data (1956–2014) for the Manas River at the Hongshanzui hydrological station was analyzed using the hydrological frequency analysis method. Accordingly, the 75% guaranteed rate of annual surface water runoff in the Manas River Watershed was determined to be 11.92×10^8 m^3. The underground water resource is 3.96×10^8 m^3, and the available water resources total is 10.91×10^8 m^3.

The Manas River Watershed mainly includes the Shihezi Irrigation District, Mosuowan Irrigation District and Xiayedi Irrigation District. At the end of 2010, the total population of the Manas River Watershed was 630,000, of which 88,000 comprised the agricultural population. The Manas River Watershed achieved 18.85 billion yuan of gross production, the primary industry added a value of 5.53 billion yuan, the second industry added 7.27 billion yuan, and the third industry added 6.59 million yuan in 2010. The ecological environment water consumption in the Manas River Watershed was 297.9×10^6 m^3, and the ecological water consumption was nil in the river.

2.2. SD model

The SD concept was introduced by Forrester in 1956 through the integrated used of the theories and methods such as system theory, control theory, information theory and computer simulation technology [18]. It is an effective tool for modern scientific decision-making and forecasting, and is widely used in the decision-making research on regional macro-development strategy, which is a combination of qualitative and quantitative research system problems [8].

2.2.1. Model boundary

The model simulates the spatial boundary of the Manas River Watershed, which includes the Shihezi Irrigation District, the Xiayedi Irrigation District and the Mosuowan Irrigation District. The time boundary is 2010–2030, 2010 is the base year, and the time step is 1 year. Domestic life, agriculture, industry, the construction and tertiary industry, and the ecological environment, together with other water requirements, have a great impact on the entire system, so these were included in the content boundary.

2.2.2. Model structure

The SD model of water resources can be divided into a water supply system and a water demand system, as shown in Fig. 2. The water supply system includes the conventional water system and the sewage treatment system; the water demand system mainly includes the five subsystems of domestic life, agriculture, industry, the construction industry and tertiary industry and the ecological environment. The various subsystems are interrelated, and a change in water in one subsystem will affect water changes in other subsystems. Through a variety of feedback channels, the various subsystems are connected to form a complex whole. The supply and

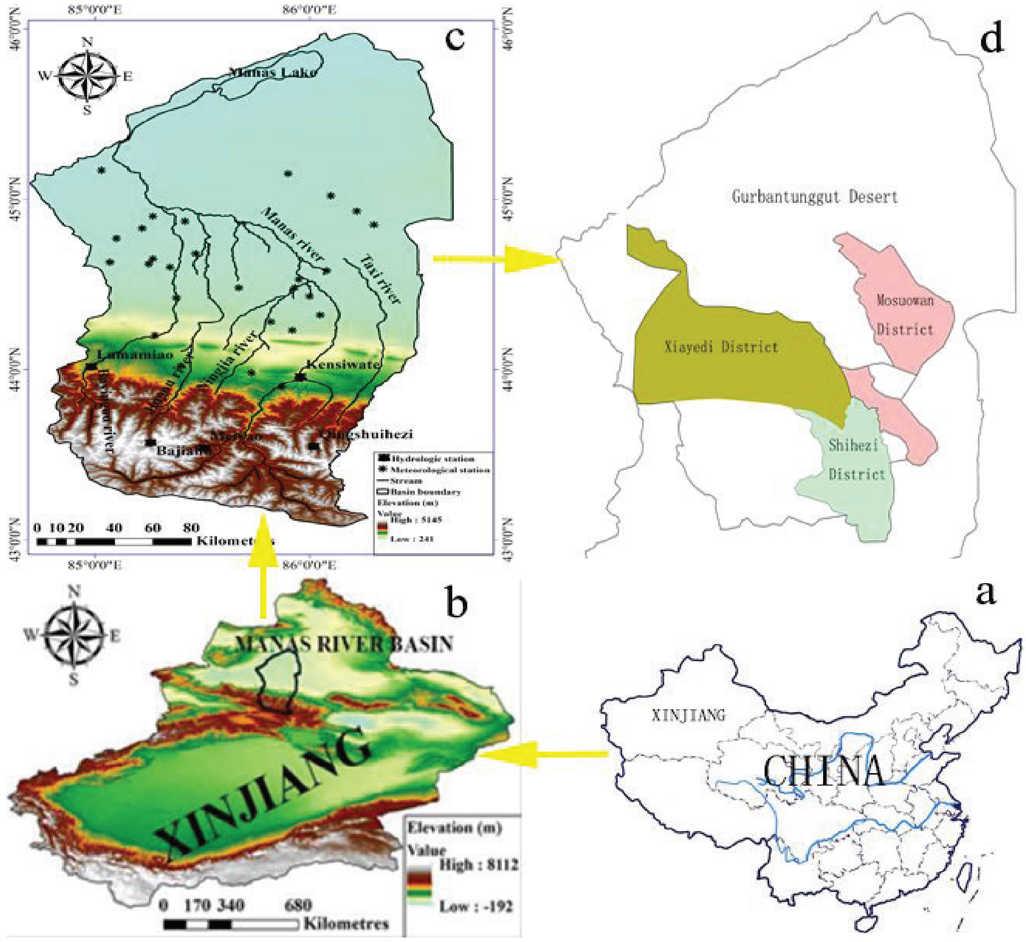

Fig. 1. (a) Xinjiang's position in China, (b) the Manas River Watershed in Xinjiang, (c) the Manas River Watershed, and (d) the three irrigation districts of the Manas River Watershed: Shihezi Irrigation District, Mosuowan Irrigation District and Xiayedi Irrigation District.

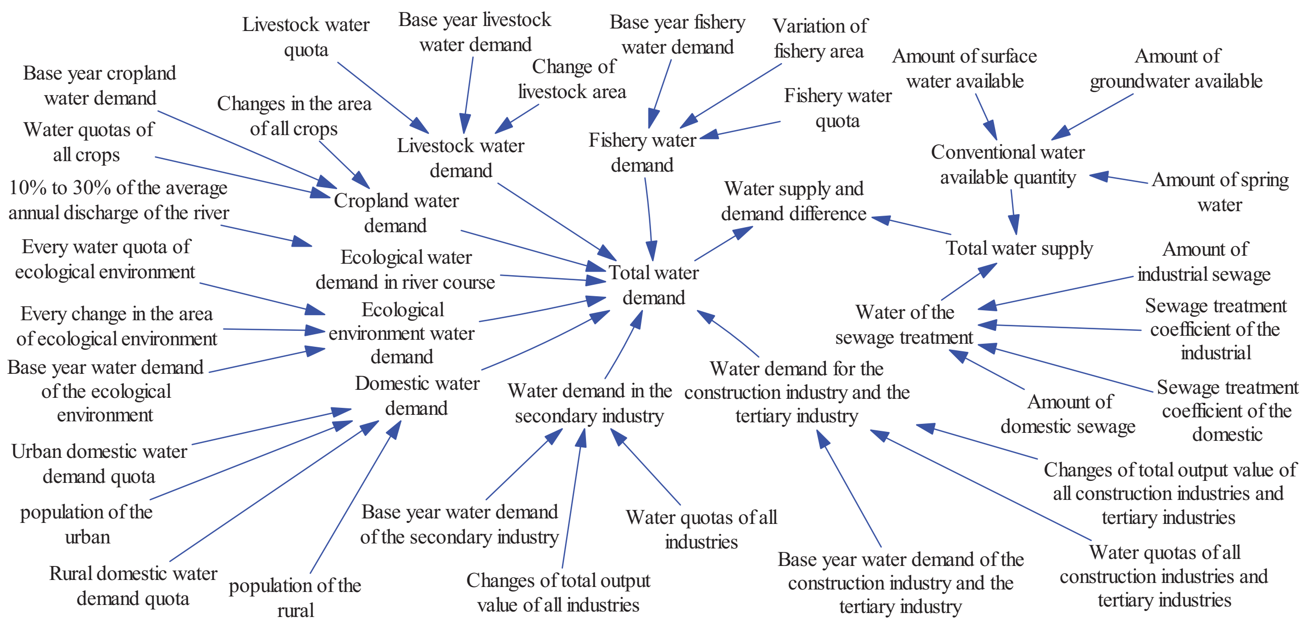

Fig. 2. Conceptual diagram of factors influencing water supply and demand in a watershed.

demand difference reflects the relationship between the total supply and the total demand of water resources.

2.2.3. Main equations of the SD model

Many equations are used in the water resources supply and demand simulation system of the Manas River Watershed.

Water Supply and Demand Difference

Eq. (1) is used in the model to calculate the water supply and demand difference.

$$Q_{Dif} = Q_S - Q_D \quad (1)$$

In Eq. (1), Q_{Dif} is the water supply and demand difference, Q_S is the total water supply, and Q_D is the total water demand.

Total Water Supply

Eq. (2) calculates the total water supply as the sum of conventional water availability and the water diverted through sewage treatment.

$$Q_S = Q_C + Q_T \quad (2)$$

In Eq. (2), Q_C is the conventional water availability, and Q_T is the water diverted through sewage treatment. Conventional water availability includes the amount of surface water available, the amount of groundwater available and the amount of spring water. Sewage refers to industrial and domestic sewage. The amount of sewage treatment can be calculated by Eq. (3).

$$Q_T = Q_{I-Sew} \times m + Q_{D-Sew} \times n \quad (3)$$

In Eq. (3), $Q_{I\text{-}Sew}$ and $Q_{D\text{-}Sew}$, respectively, are the amount of industrial sewage and domestic sewage, and m and n, respectively, are the sewage treatment coefficients of the industrial and domestic wastewater.

Total Water Demand

Eq. (4) shows the eight components considered in the model. Water demand for each of the eight components is forecasted initially. The total water demand is then estimated by summing the eight demands.

$$Q_D = Q_{Dom} + Q_{Fis} + Q_{Liv} + Q_{Cro} + Q_I + Q_{Con} + Q_E + Q_{Ins} \quad (4)$$

In Eq. (4), Q_{Dom} is the domestic water demand. Q_{Fis} the fishery water demand, Q_{Liv} the livestock water demand, Q_{Cro} the cropland water demand, Q_I the water demand in the secondary industry, Q_{Con} the water demand of the construction industry and the tertiary industry, Q_E the ecological environment water demand, and Q_{Ins} the ecological water demand in the river course.

$$Q_{Dom} = P_U \times Q_{U-Dom} + P_R \times Q_{R-Dom} \quad (5)$$

In Eq. (5), $Q_{U\text{-}Dom}$ and $Q_{R\text{-}Dom}$, respectively, are the urban domestic water demand quota and the rural domestic water demand quota, and P_U and P_R, respectively, are the urban and rural population.

$$Q_{Fis} = Q_{B-Fis} + A_{C-Fis} \times Q_{Q-Fis} \quad (6)$$

In Eq. (6), $Q_{B\text{-}Fis}$ is the base year fishery water demand, $A_{C\text{-}Fis}$ is the variation of fishery area, and $Q_{Q\text{-}Fis}$ is the fishery water quota.

$$Q_{Liv} = Q_{B-Liv} + A_{C-Liv} \times Q_{Q-Liv} \quad (7)$$

In Eq. (7), $Q_{B\text{-}Liv}$ is the base year livestock water demand, $A_{C\text{-}Liv}$ is the change of livestock area, and $Q_{Q\text{-}Liv}$ is the livestock water quota.

$$Q_{Cro} = Q_{B-Cro} + \sum_{i=1}^{n} A_{iC-Cro} \times Q_{iQ-Cro} \quad (8)$$

In Eq. (8), $Q_{B\text{-}Cro}$ is the base year cropland water demand, $A_{iC\text{-}Cro}$ is the change in the area of crop i, and $Q_{iQ\text{-}Cro}$ is the water quota of crop i.

$$Q_I = Q_{B-I} + \sum_{j=1}^{n} V_{jC-I} \times Q_{jQ-I} \quad (9)$$

In Eq. (9), $Q_{B\text{-}I}$ is the base year water demand of the secondary industry, $V_{jC\text{-}I}$ is the change of total output value of industry j, and $Q_{jQ\text{-}I}$ is the water quota of industry j.

$$Q_{Con} = Q_{B-Con} + \sum_{k=1}^{n} V_{kC-Con} \times Q_{kQ-Con} \quad (10)$$

In Eq. (10), $Q_{B\text{-}Con}$ is the base year water demand of the construction industry and the tertiary industry, $V_{kC\text{-}Con}$ is the change of total output value of the construction industry and the tertiary industry k, and $V_{kQ\text{-}Con}$ is the water quota of the construction industry and the tertiary industry k.

$$Q_E = Q_{B-E} + \sum_{l=1}^{n} A_{lC-E} \times Q_{lQ-E} \quad (11)$$

In Eq. (11), $Q_{B\text{-}E}$ is the base year water demand of the ecological environment, $A_{lC\text{-}E}$ is the change in the area of ecological environment l, and $Q_{lQ\text{-}E}$ is the water quota of ecological environment l.

The Tennant method was used to predict the ecological water demand in river courses, and a value of 10% to 30% of the average annual discharge of the river was used to represent this demand [19].

2.2.4. Model parameter determination

Data such as the population change rate, industrial gross domestic production (GDP) change rate and conventional water resources utilization rate were obtained from the Statistical Yearbook of Xinjiang Production and Construction Corps (2011–2016) and the Xinjiang Production and Construction Corps Eighth Division water long-term supply and demand planning report (2013) [20–26], or obtained using mathematical and statistical analyses. Some of the parameters and their initial values are shown in Table 1.

2.2.5. Model calibration

2.2.5.1. Equation and dimensional consistency test

In the model, the process of constructing equations is not necessarily consistent because of the large number of parameters in the model and the independence of each parameter. Therefore, it is necessary to assure consistency among different units. Using the "Start Synthesim" tool in Vensim®, the consistency of the model itself and the units within it were tested. The test results showed that the SD model of water resources supply and demand in the Man as River Watershed, as well as the units within it, was consistent.

Table 1
Partial list of model parameters and their initial values

Parameter	Value
Urban domestic water demand	0.24×10^8 m^3
Rural domestic water demand	0.02×10^8 m^3
Domestic water demand	0.26×10^8 m^3
Agricultural water consumption	10.59×10^8 m^3
Domestic sewage treatment capacity	78%
Industrial water consumption	0.49×10^8 m^3
Water consumption in ecological environment	2.97×10^2 m^3
Construction industry and tertiary industry GDP	7.05 billion yuan
Unit construction industry and tertiary industry water consumption	20 m^3/10,000 yuan
Water consumption in construction industry and tertiary industry	0.14×10^8 m^3
Industrial GDP	5.88 billion yuan
Water consumption per unit industrial GDP	20 m^3/10,000 yuan
Industrial wastewater treatment capacity	78%
Total wastewater treatment	0.39×10^8 m^3
Water supply and demand difference	–0.19×10^8 m^3
Conventional water availability	10.91×10^8 m^3
Total water consumption	11.5×10^8 m^3
Total water supply	11.31×10^8 m^3

GPS = gross domestic production

2.2.5.2. Model calibration

The model used the year 2010 as the starting year, and the period 2014–2015 for model calibration. Table 2 lists the simulation results for some of the main parameters of the supply and demand system model for 2014 and 2015. Comparing these results with the historical data of the actual system showed that the relative error of most parameters was less than 5% and the maximum error was 18.96%. Thus, we concluded that the SD model was basically consistent with the actual system and could be used for future system simulations.

2.2.6. Measures to reduce the difference between water supply and demand

According to the actual situation of the Manas River Watershed and future development planning, by 2030 the regulation of water resources in the Manas River through combined pollution control and water saving irrigation scenarios will increase the sewage treatment rate to 90% and decrease the cropland area by 24.47%. Furthermore, industrial output units will reduce their water quota by 42.9%, and the cropland water quota will be reduced by 11%. Additionally, the construction industry and the tertiary industry water quota will be reduced by 50% [26].

2.3. Multidimensional critical regulation theory

The object of multidimensional critical regulation is a natural and human system composed of a complex giant system [15]. The theory of multidimensional critical regulation is composed of critical cybernetics, ordered principle, dissipative structure theory and synergetic principles. It is applied to study the optimal allocation of water resources, and can enable scientific analysis of many contradictory goals, so that the complex giant system is coordinated and order direction to run [27]. Multidimensional critical regulation has three layers. The first layer is coordination in which the relationships between water resources, economy, society, and ecology and water departments are coordinated, so that the system as a whole and the various subsystems can give full play to best effect. The second layer is optimi-

Table 2
Simulation results for selected parameters for the Manas River Watershed in 2014 and 2015

Year	Cropland area (10^4 ha)			Fishery (ha)			Total water supply/10^{8}m^3		
	Actual value	Simulation value	Error/%	Actual value	Simulation value	Error/%	Actual value	Simulation value	Error/%
2014	18	17.9	–0.37	743.8	743.6	–0.03	11.71	11.63	–0.68
2015	18.87	18.8	–0.14	773.7	773.5	–0.03	11.84	11.64	–1.69
Year	Construction industry and tertiary industry gross domestic production, (GDP, 10^{10} yuan)			Industrial GDP (10^{10} yuan)			Total water consumption (10^8 m^3)		
	Actual value	Simulation value	Error (%)	Actual value	Simulation value	Error (%)	Actual value	Simulation value	Error (%)
2014	1.68	1.67	–0.59	1.351	1.35	–0.07	13.2	15.3	–15.92
2015	1.98	1.97	–0.51	1.382	1.38	–0.14	13.4	15.9	–18.96

zation, which is the necessary means of multidimensional critical regulation to achieve overall, coordinated, orderly and efficient analysis. The third layer is a virtuous circle. A virtuous circle is the ultimate goal of sustaining water resources systems [28]. To ensure the coordinated, orderly and virtuous circle of water resources system, it is necessary to study how the four subsystems of water resources, economy, society and ecology can be coordinated to achieve rational allocation of water resources and avoid the critical threshold of system collapse. The order parameter is used to describe the order degree of the system. The order parameter has a slower effect than the other variables of the system state, so it is also called the "slow" variable. That means it can dominate the evolution of the system and the behavior of "fast" variables [29]. Therefore, the coordination of the system can be controlled by the coordination of order parameters.

However, due to the complexity and uncertainty of the water resources system in the Manas River Watershed, it is impossible to distinguish the speed of the order parameter from time to time, so the determination of the order parameter can only be determined according to a representative metric, such as economic growth. The indicators of economic development in economic subsystems include per capita GDP, GDP growth rate, industrial output modulus, per capita grain output, and total industrial output value as a percentage of GDP. However, any change in the value of one indicator cannot simultaneously determine the trend of other indicators (i.e., cannot control the behavior of other indicators).

Therefore, the choice of economic subsystems is based on the analysis of economic benefits. The economic benefits of water resources systems mainly accrue from the water supply efficiency to various agricultural, industrial and domestic sectors of the national economy. Benefits include agricultural irrigation water and industrial and domestic water supply. Water supply efficiency and water supply quantity have a proportional relationship. Therefore, the economic subsystem of the order parameters was chosen for domestic life, industry and agricultural water supply. After study, the subsystem parameters were determined as shown in Table 3.

2.3.1. Order degree of order parameters and subsystems

A water system is a dissipative structure, and the system's phase transition results do not necessarily follow a logical order. Rather, the system may go into disorder [30]. Therefore, to grasp the degree of system coordination, the concept of order is introduced to measure the coordination effect. Consider the subsystem SS_i, for which the evolutionary process of the order parameter variable is $e_{ij} = (e_{i1}, e_{i2},...,e_{in})$, where $n \geq 1$. The value of e_{ij} should be in the critical threshold interval, such that $U_{ij} \leq e_{ij} \leq T_{ij}$, $j \in [1,n]$ where U_{ij} and T_{ij} are, respectively, the minimum and maximum values for e_{ij}. The following order is calculated for the Manas River Watershed water resources system. The ordering degree of the order parameter e_{ij} of the subsystem SS_i is:

$$u_i\left(e_{ij}\right) = \left(e_{ij} - U_{ij}\right) / \left(T_{ij} - U_{ij}\right) \tag{12}$$

In Eq. (12), $u_i(e_{ij})$ is the order degree of the order parameter e_{ij}, and U_{ij} and T_{ij}, respectively, are the minimum and maximum critical thresholds of e_{ij}. The critical thresholds of the order parameters are the basis of system regulation. Therefore, the thresholds should be clear from the method of knowledge acquisition for the purpose of regulation. The thresholds used in the systems dynamic model of the Manas River Watershed included those for surface water supply, groundwater exploitation, reservoir fulfillment, and non-flood season ecological base flow. The minimum value of water supply to surface water resources is the amount of water in a dry water year, and the maximum value of water supply is the amount of water in a normal water year. The amount of groundwater exploitation is maintained within the allowable scope to prevent the groundwater level from falling. To ensure the safety and stability of society and achieve the largest economic benefit, the water level of the Jiahezi reservoir should be maintained between the minimum water level and the normal water level. According to the Tennant method, an amount that is 10%–30% of the Manas River's annual mean runoff is used as the ecological base flow in the river [19]. The calculated thresholds are shown in Table 4.

From Eq. (12), if an initial value is given to the order parameter, the corresponding order degree can be determined. Therefore, if the order parameter $u_i(e_{ij}) \in [0, 1]$ of the order parameter e_{ij} is in the critical threshold interval, the larger the e_{ij} value is, the greater is the contribution of the subsystem SS_i. On the contrary, if $e_{ij} \notin [0,1]$, the description of e_{ij} is not a reasonable threshold interval, so the interval needs to be adjusted. On the whole, the "total contribution" of the order parameter variable e_{ij} to the degree of subsystem SS_i ordering can be achieved by $u_i(e_{ij})$ integration, as shown in Eq. (13):

$$u_i(e_i) = \sum_{j=1}^{n} \lambda_j u_i(e_{ij}),\ \lambda_j \geq 0,\ \sum_{j=1}^{n} \lambda_j = 1 \tag{13}$$

In Eq. (13), λ_j is weight coefficient of the ordered parameter variable e_{ij}, $u_j(e_{ij})$ is the same as defined previously, and

Table 3
Determination of order parameters for multidimensional critical regulation of water resources in the Manas River watershed

Subsystem name	Control objectives	Order parameter
Water resources subsystem	Reduce water resources consumption	Groundwater use
Economic subsystem	Water supply	Domestic, industrial, and agricultural water supply
Social subsystem	Prevent floods and protect water resources	Operation of Jiahezi Reservoir
Ecological subsystem	Prevent deterioration due to low flow	Non-flood season ecological base flow

Table 4
Sequential component thresholds of the Manas River watershed

	Surface water supply (10^4 m^3)	Groundwater exploitation (10^4 m^3)	Water level of Jiahezi reservoir (m)	Ecological base flow in non-flood season (10^4 m^3)
Minimum	74727.94	0	394	13160
Maximum	88369.21	26800	399.4	39480

$u_i(e_i)$ is the order degree of the subsystem. The λ_j of each order parameter was determined to be 1. The order degree of the subsystem can be obtained by weighting and summing the order degree of the order parameter.

2.3.2. Qualitative reasoning of evolution direction of water resources system

A water resources system is a complex system of water resources, economy, society and ecology. The four subsystems are interrelated and interact, and the change of order degree for one subsystem will cause an order change in other subsystems. However, the order of the whole system (from disorder to orderly changes) is the critical regulation of the water resources system that needs to be resolved. The entropy theory of a dissipative structure refers to the qualitative analysis of the evolution direction of a system using the entropy to reduce the order enhancement and reduce the entropy increase order. According to the meaning of entropy, the system entropy function of determining the evolution direction of water resources system is established using the order degree of subsystems, as described by Eq. (14) [31]:

$$S_Y = -\sum_{i=1}^{4} \frac{1-u_i(e_i)}{4} \log \frac{1-u_i(e_i)}{4} \tag{14}$$

In Eq. (14), $u_1(e_1)$, $u_2(e_2)$, $u_3(e_3)$, and $u_4(e_4)$, represent the order degree of water, economic, social and ecological subsystems, respectively. Each regulation can determine a system entropy function.

According to the order degree and entropy change theory, the following theorem applies: If the order of the subsystem changes $\Delta u_i(e_{ij})$ in the entropy function S_Y decreases, and the order of the entire system will increase, indicating that the subsystems can coordinate the development of the system to an orderly or benign direction. On the contrary, if the order of the subsystem does not change, the system tends to disorder or there is a vicious direction of evolution. Eq. (15) describes these rules:

$$\Delta S_Y = S_Y(n+1) - S_Y(n) \tag{15}$$

In Eq. (15), $S_Y(n+1)$ is the final state entropy of system "n+1", $S_Y(n)$ is the n^{th} regulation of entropy, and ΔS_Y is the entropy change caused by the $(n+1)^{\text{th}}$ regulation. According to the size of the entropy variable ΔS_Y, the evolution direction of the system can be judged. When continuous control of the entropy variable causes $\Delta S_Y = 0$, indicating that after the control system entropy does not change, the system state entropy reaches convergence to achieve optimization. We believe that this regulation scenario achieves the optimal regulation results. The four subsystems of the water resources system have been coordinated, and the system has evolved to the direction of sustainable development.

2.3.3. Control scenarios

For planning, the water demand for 2020 was projected to be 14.86×10^8 m^3 and for 2030 the demand was projected to be 16.71×10^8 m^3. Thus, the water supply and demand contradiction is predicted to further intensify over time. A variety of controls must be implemented to solve the projected shortage of water resources.

Agricultural and industrial water-saving control methods should be used to reduce the projected agricultural and industrial water demands. Enhanced agricultural water-saving control techniques should be implemented to improve the irrigation utilization coefficient and reduce the irrigation quota of agriculture [26]. Such measures would reduce the projected water demand of agricultural production by 17.95% (by 2020) and 7.64% (by 2030). Furthermore, the use of industrial water conservation controls (such as reducing the growth rate of industrial water use, adopting water-saving processes, and increasing the rate of reuse) should be implemented to improve the water utilization efficiency. These means can reduce the projected industrial water demand by 8.4% (by 2020) and 15.02% (by 2030). Sewage treatment technology to further improve the reuse of urban industrial and domestic sewage resources should be implemented. By 2020 and 2030, these actions could make available 1.51×10^8 m^3 and 2.48×10^8 m^3, respectively, of treated sewage resources. Regulatory plans for 2020 and 2030 are shown in Tables 5 and 6.

3. Results

3.1. Projection of water supply and demand

Using the SD model, the water supply and demand and the water resources supply and demand difference in different years can be obtained. Projections of the water supply and demand in the Manas River Watershed are shown in Fig. 3.

The inflection point in 2016 shown in Fig. 3 occurred in response to the large population in 2015, the cropland area increased. Furthermore, the ecological environment of water managed by the government departments resulted in increased water allocation. In addition, fisheries, animal husbandry, industry, the construction industry and the tertiary industry developed rapidly, resulting in increased demand for water. Yet, the total amount of water resources experienced a smaller increase than the increase in demand, which increased the gap between water supply and demand.

Table 5
Multidimensional critical control scenarios for water resources in 2020 (10^4 m^3, unless otherwise stated)

Scenarios name	Initial scenario	Scenario I	Scenario II	Scenario III	Scenario IV
Industrial water saving			8.40%		8.40%
Agricultural water saving				17.95%	17.95%
Sewage reclamation		15100	15100	15100	15100
Industrial water demand	28876.5	28876.5	26450.9	28876.5	26450.9
Agricultural water demand	99991.4	84891.4	84891.4	69653.4	69653.4
Domestic water demand	5560.8	5560.8	5560.8	5560.8	5560.8
Ecological water demand	14204.6	14204.6	14204.6	14204.6	14204.6
Total water demand	148633.2	133533.2	131107.6	118295.2	115869.6

Table 6
Multidimensional critical control scenarios for water resources in 2030 (10^4 m^3, unless otherwise stated)

Scenarios name	Initial scenario	Scenario I	Scenario II	Scenario III	Scenario IV
Industrial water saving			15.02%		15.02%
Agricultural water saving				7.64%	7.64%
Sewage reclamation		24800	24800	24800	24800
Industrial water demand	49616.6	49616.6	42164.2	49616.6	42164.2
Agricultural water demand	94954.6	70154.6	70154.6	64794.8	64794.8
Domestic water demand	7901.3	7901.3	7901.3	7901.3	7901.3
Ecological water demand	14656	14656	14656	14656	14656
Total water demand	167128.4	142328.4	134876	136968.6	129516.2

In addition, the level of water resources development and utilization was not high, and the waste of water resources was serious. Demands for water environment protection coupled with water pollution control deficiencies meant that the supply of water resources could not meet the needs of social and economic development. Since 2016, the pollution control capability has been gradually strengthened, and the implementation of water-saving programs has been strengthened. The water supply and demand situation has been improved, and the water resources supply and demand gap has gradually decreased. Thus, by 2020 the water resources supply and demand difference is projected to be -1.23×10^8 m^3. After 2020, all sewage treatment would be completed, and the total water supply is projected to increase slowly, while industry was forecast to continue developing at a high speed. These changes are predicted to result in a gradual decrease in the gap between water resources supply and demand to -1.98×10^8 m^3 by 2030.

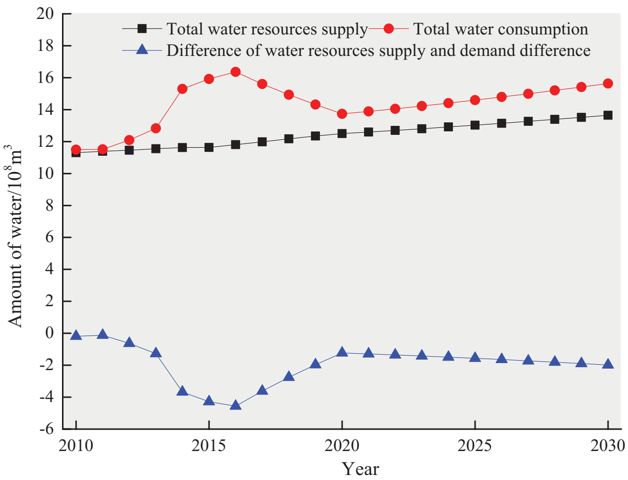

Fig. 3. Projection of water supply and demand in the Manas River watershed.

3.2. Multidimensional critical regulation

The ordering degree and the system entropy of subsystems are the core of multidimensional critical regulation of water resources in the Manas River Watershed. Under the guidance of order degree and system entropy, water resources are allocated to subsystems that have the greatest contribution to the entropy of the system. The system entropy decreases gradually along the direction of the maximum entropy change gradient, until it converges, so that the coordination degree is the largest among the subsystems of the Manas River Watershed. According to different regulation scenarios, water resources in the Manas River Watershed are regulated using specific steps. First, the initial values of the order parameters of the four subsystems are given, the order degree of the order parameter is calculated using Eq. (12), and the order degree of the subsystem is calculated using Eq. (13). Second, the system entropy function of the first regulation is determined using Eq. (14). Finally, the value of an order parameter of a subsystem is changed, and the system entropy function of the second regulation is calculated by following the above steps, and the entropy change is obtained using Eq. (15). According to this procedure, the obtained entropy change tends to 0. At this time, the water resources system of the Manas River Watershed is the most coordinated.

In projections for 2020 (for example), the degree of coordination between subsystems in the system was relatively poor at the initial level of control. The agricultural water supply order parameters and industrial water supply order parameters are negative, $e_{ij} \notin [0,1]$, and not in a reasonable threshold interval. Therefore, e_{ij} needs to be adjusted. Greater coordination is achieved in the water resources subsystem, economic subsystem, social subsystem and ecological subsystem by treating 1.51×10^8 m^3 of sewage, and reducing industrial water use by 8.4% and reducing agricultural water use by 17.95% through implementation of various control measures. These improvements would reduce the system entropy from 0.3163 to 0.1506, indicating that the control measures taken to strengthen the coordination between the subsystems were successful. The subsystem order degrees and the entropy convergence trend of the system in 2020 are shown in Fig. 4.

Similarly, the system entropy would be reduced from 0.3216 to 0.1506 in the Manas River watershed in 2030. This is achieved by treating 2.48×10^8 m^3 of sewage, reducing industrial water use by 15.02%, reducing agricultural water use by 7.64% and implementing various control measures. The subsystem order degrees and the entropy convergence trend of the system in 2030 are shown in Fig. 5.

The effects of the above multidimensional critical regulation control procedures on water resources in the Manas River watershed for 2020 are shown in Fig. 6. Similarly, the effects of multidimensional critical regulation in the Manas River Watershed for 2030 are shown in Fig. 7.

Fig. 6a shows the water supply and water demand of industry in 2020. The industrial water demands of the initial scenario, scenario I and scenario III are the same, both of which are 2.89×10^8 m^3. The industrial water demands of scenario II and scenario IV are both 2.65×10^8 m^3. However, the gap between supply and demand of industrial water is gradually reduced from 0.86×10^8 m^3 in the initial scenario to 0.16×10^8 m^3 in scenario IV. Fig. 6b shows the water supply and water demand of agriculture. Agricultural water consumption gradually decreased from the initial sce-

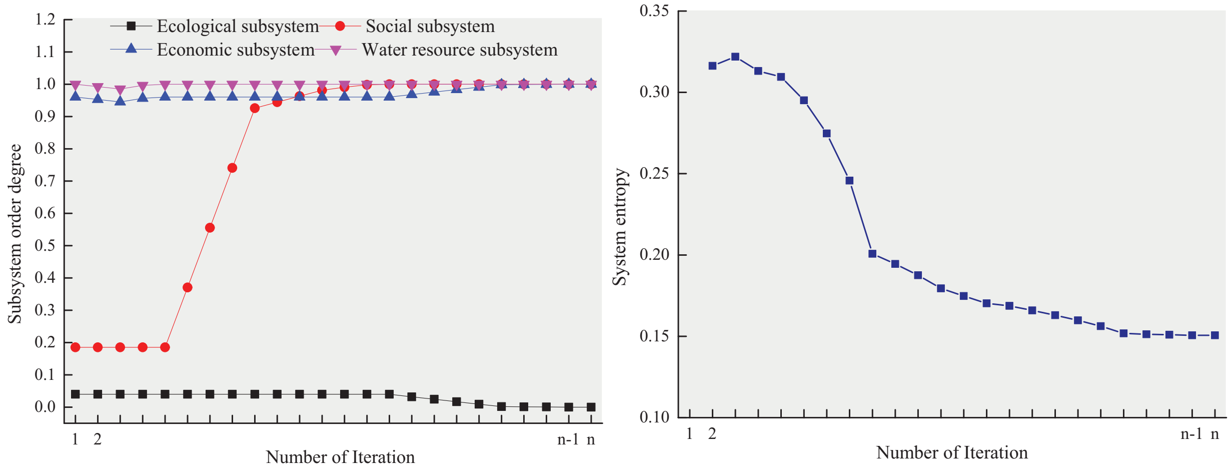

Fig. 4. Subsystem order degrees and entropy convergence trend of the Manas River watershed system in 2020.

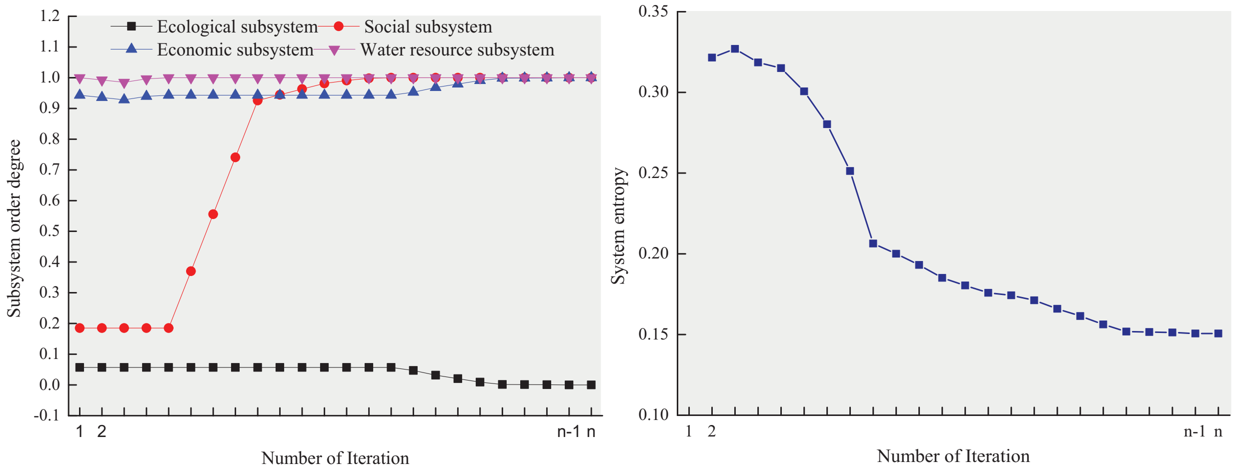

Fig. 5. Subsystem order degrees and entropy convergence trend of the Manas River watershed system in 2030.

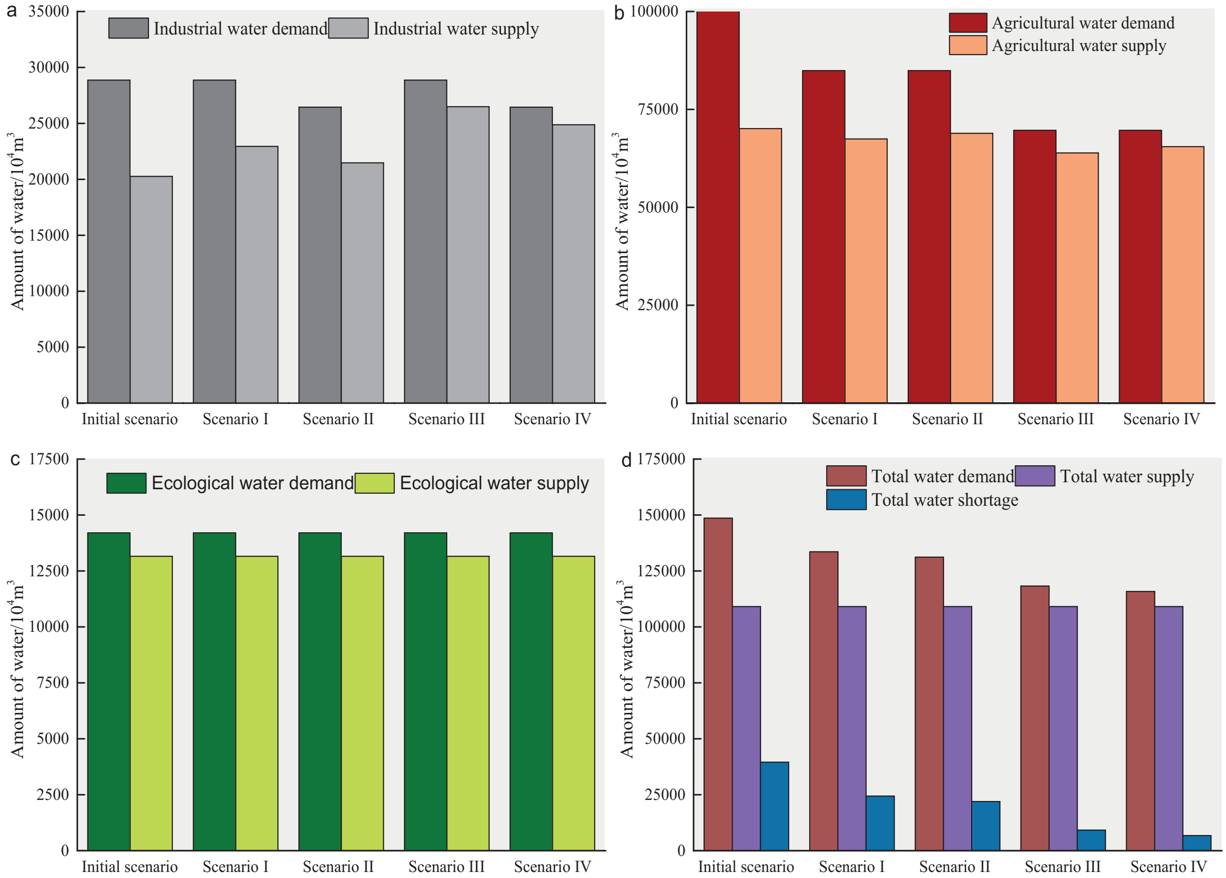

Fig. 6. Multidimensional critical regulation of the Manas River watershed water resources in 2020.

nario to scenario IV, agricultural water supply is gradually decreased, and the gap between supply and demand also gradually decreased. Fig. 6c shows the ecological water supply and demand, and the gap between supply and demand is invariable. Fig. 6d shows that the projected water demand of the Manas River Watershed in 2020 is 14.86×10^8 m^3, the projected water supply is 10.91×10^8 m^3 and the total water shortage is 3.95×10^8 m^3. The total supply of water resources remains unchanged, and the total water demand gradually decreases. Therefore, the gap between supply and demand of water resources is gradually decreasing. The water shortage was reduced from 3.95×10^8 m^3 in the initial scenario to 0.68×10^8 m^3 in scenario IV. Thus, the control effect is obvious because the water deficit is reduced by 2.27×10^8 m^3.

Fig. 7a shows the water supply and water demand of industry in 2030. The industrial water demands in the initial scenario, scenario I and scenario III are 4.96×10^8 m^3. The industrial water demands of scenario II and scenario IV are 4.22×10^8 m^3. However, the gap between supply and demand of industrial water is gradually reduced from 1.94×10^8 m^3 in the initial scenario to 0.75×10^8 m^3 in scenario IV. Fig. 7b shows the water supply and water demand of agriculture. Agricultural water consumption gradually decreased from the initial scenario to scenario IV, agricultural water supply gradually decreased, and the gap between supply and demand is also gradually decreasing. Fig. 7c shows the water supply and water demand of the ecology. Fig. 7d shows that the projected water demand of the Manas River Watershed in 2030 is 16.71×10^8 m^3, the projected water supply is 10.91×10^8 m^3 and the total water shortage is 5.8×10^8 m^3. Furthermore, the gap between supply and demand of water resources is gradually decreased. The water shortage was reduced from 5.8×10^8 m^3 of the initial scenario to 2.04×10^8 m^3 of scenario IV, and the water deficit was reduced by 3.76×10^8 m^3.

4. Discussion

The Manas River Watershed is the largest oasis in Xinjiang, China, and is mainly dedicated to agricultural production. Consequently, the proportion of agricultural water demand is relatively large (approximately 90%) [32]. The long-term water structure in the district has led to a significant reduction in the amount of surface water flowing downstream in the Manas River. In addition, a large amount of groundwater is mined as a supplementary source of water, and the tail lakes are gradually disappearing because the groundwater level has declined. Furthermore, the vegetation is degraded and the natural oasis area is decreasing. The ecological environment has been severely damaged [33]. Liu identified the problem of water pollution in the Manas River Watershed. It was considered that the Moguhu reservoir, the area around which was mainly cultivated and irrigated, was affected by sewage discharged from industry and residents,

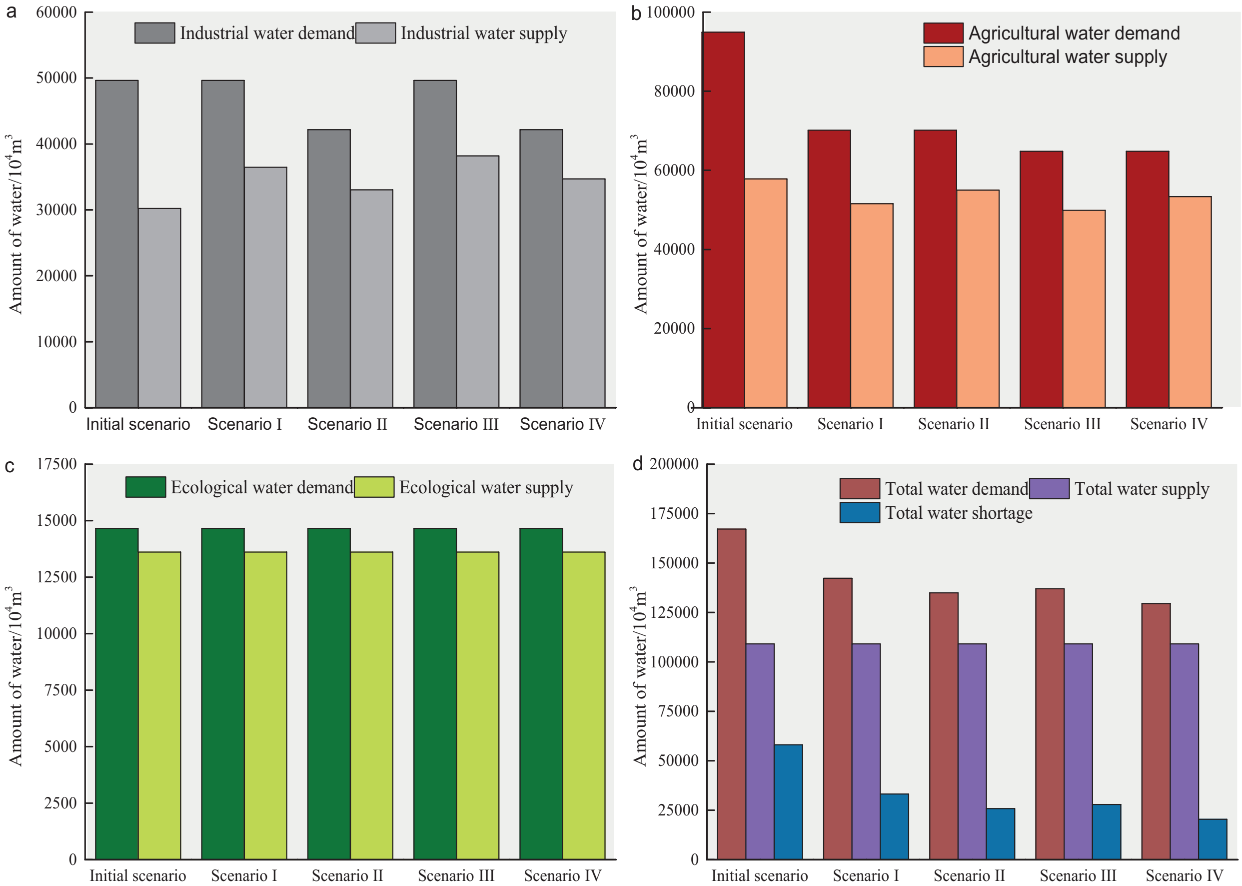

Fig. 7. Multidimensional critical regulation of the Manas River watershed water resources in 2030.

resulting in poor water quality and serious pollution [34]. The unbalanced water use, the decline of the groundwater level and the existence of pollution in the Manas River Watershed will become primary factors restricting the future social and economic development of the region, and bring an unanticipated threat to the social stability.

This study divided the water resources system of the Manas River watershed into four subsystems, taking into account groundwater exploitation, ecological water demand outside the river channel and ecological base flow in the river. Using the concept of system entropy, the coordination degree between the water resources system and the internal subsystems was assessed. The system entropy guided water resources allocation among each subsystem in order to realize the coordination among subsystems and achieve the sustainable development of regional water resources targets.

The results shown in Figs. 4 and 5 suggest that the water resources subsystem, the economic subsystem and the social subsystem are negatively correlated with the system entropy, and the ecosystem subsystem is positively correlated with the system entropy. The system entropy decreased by 1, the order of the water resource subsystem increased by 1.28, the order of the economic subsystem increased by 1.73, the order of the social subsystem increased by 6.38, and the order of the ecological subsystem decreased by 2.38. This indicates that entropy is most sensitive to changes in the water resources subsystem and least sensitive to changes in the social subsystem. Therefore, to make the system entropy converge most rapidly during multidimensional critical control, the water resource subsystem can be adjusted first, followed in order by the economic subsystem, the ecological subsystem, and the social subsystem. The results shown in Figs. 4 and 5 imply that the ordering degree of each subsystem tends to be stable after repeated regulation, and the corresponding system entropy tends to be stable. According to the laws of entropy, when the entropy variable approaches 0 after many times of regulation and control, control reaches the optimal state; that is, the system under this entropy changes to the direction of orderly coordination.

The results shown in Figs. 6 and 7 indicate that the system entropy of water resources can be reduced to a minimum of 0.1506 by means of industrial water saving, agricultural water saving and sewage reclamation. Through regulation, the domestic water supply is 0.56×10^8 m^3, the industrial water supply is 2.49×10^8 m^3, the agricultural water supply is 6.55×10^8 m^3, and the ecological water supply is 1.32×10^8 m^3 in the Manas River Watershed in 2020. Furthermore, the water shortage is reduced from 3.95×10^8 m^3 in the initial scenario to 0.68×10^8 m^3 in scenario IV, and the control effect is obvious. The domestic water supply is 0.79×10^8 m^3, the industrial water supply is 3.47×10^8 m^3, the agricultural water supply is 5.33×10^8 m^3, and the ecological water supply is 1.32×10^8 m^3 in 2030. Furthermore, the water shortage is reduced from 5.8×10^8 m^3 in the initial scenario to 2.04×10^8 m^3 in scenario IV. Thus, the water shortage in 2030 was reduced by 3.76×10^8 m^3, exceeding the reduction in 2020 and indicating that the water resources system is developing in the direction of orderly coordination.

Multidimensional critical regulation can coordinate the relationship between water resources, economy, society and ecology, and ensure that the water demand of each subsystem is maintained within the threshold range, and the magnitude of the water shortage is minimized. It is of great significance to meet the daily needs of people, to promote economic and social development, to improve the ecological environment and to ensure the sustainable development of water resources.

Multidimensional critical regulation based on system entropy guides the allocation of water resources among subsystems, solves the dimensional problem in the dynamic planning of water resources, and provides a new mode of thinking about the optimal allocation of water resources. However, there are still some problems in applying multidimensional critical regulation to water resources management. Multidimensional critical regulation cannot quantitatively represent competition and restriction among factors. Nor is it possible to convert each sub-goal from a qualitative description to quantitative analysis. These issues are deserving of further research.

5. Conclusions

Based on the analysis of water resources in the Manas River Watershed, a dynamic model of the water resources system in the irrigation area was successfully constructed, tested and applied. The model facilitates the quantitative analysis of water supply and demand in combination with long-term water supply and demand planning. Systematic regulation of water resources in the Manas River watershed was accomplished using multidimensional critical control. As a result, between 2020 and 2030 the projected system entropy was reduced to 0.1506. Furthermore, the water shortage was reduced by 2.27×10^8 m^3 in 2020 and by 3.76×10^8 m^3 in 2030. These results provide a reference for the optimal allocation of water resources. Furthermore, the study provides a research method for the sustainable development of water resources.

Acknowledgements

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