A Water Resources Collaborative Allocation Model for the Composite Water Resources-Socioeconomic-Eco-Environment System

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A Water Resources Collaborative Allocation Model for the Composite Water Resources-Socioeconomic-Eco-environment System

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Abstract: In consideration of the strong mutual exclusion of urban development and ecological environment protection, the coupling relationship of the composite water resources-socioeconomic-eco-environment system is overall recognized on the base, and the key control parameters and order parameters in the collaborative allocation model for the composite system are quantitative characterized. Then, aiming at the coordinated and orderly development of the composite system, the water resources collaborative allocation model is proposed by means of multiple loop iteration technique. At last, the proposed model is successfully applied in the Tarim River in northwest China. The results reveals that when the water frequency is less than or equal to 50%, through an accumulated new water saving irrigation area of 12.76 million mu, an accumulated reduced agricultural irrigation area of 6.22 million mu, as well as an accumulated reduced water usage quantity at 7.5 billion m^3 in national economy, which can realize the orderly benign evolution and efficient and balanced development of the water resources, economic society and ecosystem composite system, and verify the feasibility of the method.

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1. Introduction

Water resources are increasingly being recognized as a strategic resource for human survival and development, as well as a major driving force for ecological stability and evolution. Currently, China is facing a severe conflict over water supply among various competing users in economic, social and ecological areas, which makes the problem of water scarcity more complicated than ever before. Overall, an integrated effort is needed to ensure the sustainable utilization of water resources and especially to bring more benefits to the eco-environment. The South-to-North Water Diversion Project is intended to alleviate water scarcity in North and Northwest China, but the long-term overexploitation of water resources in these regions leads to a series of ecological problems such as groundwater recession, vegetation degradation and desertification, which in turn can exacerbate the conflict over water supply among economic, social and ecological users. Thus, the first problem to be solved in water resources allocation is to maintain the dynamic equilibrium of water resources, economy, society, eco-environment systems in order to prevent further deterioration of eco-environment and ensure sustainable utilization of water resources.

To this end, some attempts have been made to couple the water resources system with the socioeconomic system (Feng 1991; Liu et al.1993; Xu et al. 1997；Gan et al.

1998; Yin et al. 2003). Multi-objective risk analysis, complex adaptive systems and intelligent algorithms are introduced to water resources allocation, and a number of models are established with the objective of maximizing the economic benefit of the dynamically coupled water resources-socioeconomic system. However, such models are subject to criticism for their neglect of the ecological system. The frequent occurrence of water pollution and water crisis in recent years as a result of rapid social development has prompted the researchers to consider the environmental and ecological consequences and the joint allocation of water quantity and quality in water resources allocation. Now, the focus has shifted from considering only water quantity into thoroughly considering the economic, environmental and ecological demands, and much theoretical and practical progress has been made in this field (Afzal et al. 1992; Fleming et al. 1995; Rmcwmb 1997; River Murray Catchment Water Management Board.1997; Percia et al.1997; Wang et al. 1998; Xie et al. 2000; Tewei et al. 2001; Xie et al. 2002; Wang et al. 2003; Yang et al. 2003; Zhao et al. 2007; Jiang et al. 2008; Zhou et al. 2009). It is noted that, despite the recognition of the need to consider the economic, environmental and ecological water demand and supply in water resources allocation, previous studies have focused specifically on the optimization algorithms for water resources allocation and the water demand of the eco-environment system and, more importantly, the water resources, economy, society, and eco-environment systems are considered in isolation without integrating them into a composite system (Zhou 2015; Wang et al. 2017&2019; Shen et al. 2021) .

In this study, a composite water resources-socioeconomic-eco-environment system (hereafter referred to as “composite system” for short) is proposed, in which the coordinated control and optimized allocation are combined to quantify the key control parameters and order parameters of the composite systems considering the coupling relationships among the subsystems, and a coordinated water resource allocation model is established for the composite system using the multiple coupling and cyclic iterative method. The proposed model has been successfully applied to the Tarim River basin in northwestern China.

2. Methodology

2.1 Generalization and equilibrium of the composite system

2.1.1 Generalization of the composite system

The composite system is composed of three closely interconnected systems, including the water resources system that consists of natural and social water cycle subsystems, economic and social system that consists of population, national economy, land use and agriculture subsystems, and eco-environment system that consists of ecology and environment subsystems. Given their important natural, social, economic, eco-environment attributes, water resources constitute an important link in the coupling of the three systems, through which the three systems and their respective subsystems interact and compete with each other in a complex manner, as schematically shown in Fig. 1. The essence of the coordinated development of the composite system is the regulation of the water resources system, economic and social system, and eco-environment system as a whole. It is clear that due to water scarcity, environmental vulnerability and limited environmental capacity, an appropriate regulation should ensure good dynamic balance and development of the three systems and their respective subsystems, so that the composite system can better adapt to environmental challenges and the subsystems can operate more coordinately and effectively. This makes it possible for the subsystems to respond quickly and effectively to external changes, and for the composite system to realize structural, functional, temporal and spatial coordination.

2.1.2 Balance of the three systems

The purpose of the water resources allocation in a composite system is to ensure the dynamic balance among the water resources system, economic and social system and eco-environment system, which is expected to contribute to efficient utilization of water resources, sound economic and social development, reasonable population growth, equitable social welfare, and good ecological environment. Specifically, the quantitative indicators considered in this study include the total water consumption balance and groundwater extraction and recharge balance for the water resources system, water demand-supply balance and and water-soil balance for the economic and social system, and ecological balance and water-salt balance for the eco-environment system, which are described as follows.

(1) Water resources system

The total water consumption balance: based on the relationships among the total inflow (precipitation and water flowed into the basin), evapotranspiration (net water consumption), and outflow (water flowed out of the basin), the total maximum allowable water consumption for economic and ecological purposes is analyzed under the assumption of no eco-environment deterioration. Thus, the purpose here is to ensure the dynamic balance among inflow (local water production, influx and water diverted into the basin), water consumption (water consumption in the basin and water diverted out of the basin), and outflow (water flowed out of the basin).

$$W_{bf} + W_{in} + D_{in} - W_{enc} - W_{elc} \quad R \quad D_{ou} \quad W \tag{1}$$

$$W_{elc} = W_{elcm} + W + W_{selc} \tag{2}$$

where W_{elc} is the total ecological water consumption, D_{in} and D_{ou} are the quantity of water diverted into and out of the basin, W_{in} is the influx of surface water and groundwater, R is the local water production of surface water and groundwater, W_{elcm} is the ecological water consumption for national economy, W_{selc} is the ecological water consumption for the river, and W_{gelc} is the evaporation of phreatic water, respectively.

Groundwater extraction and recharge balance: The exploitable quantity of groundwater in a region is obtained according to the relationships among groundwater discharge, recharge and storage changes in a given period. Under the premise that overexploitation of groundwater should not be exceeded on average, the exploitable groundwater is taken as the upper limit of the exploitation quantity of groundwater. The surface water and groundwater allocation model is linked to realize the dynamic groundwater extraction and recharge balance, which can be expressed as follows:

$$Q_r - Q_d = \pm \mu F \frac{\Delta S}{\Delta t} \text{ (phreatic water),}$$

$$Q_r - Q_d = \pm \mu^* F \frac{\Delta S}{\Delta t} \quad \text{(confined water)} \tag{3}$$

where Q_r mainly includes rainfall infiltration, lateral groundwater recharge (including piedmont lateral recharge and lateral inflow in the flat region), pipeline leakage, river infiltration, canal infiltration, irrigation and farmland infiltration, leakage recharge, and well irrigation regression and infiltration from projects such as reservoirs and ponds; Q_d mainly includes the lateral discharge, spring discharge, phreatic water evaporation and artificial exploitation. The formulas for calculating these terms are not given here for simplicity. ΔS refers to the change in groundwater level; μ and μ^* are the elastic storativity of unconfind and confined aquifers; F is the area of the balance area; and Δt is the duration of the balance period, respectively.

(2) Socioeconomic system

Water demand-supply balance: the water demand-supply balance inside and outsider the river is regulated based on the water resources allocation model.

Water-soil balance: water resources are regulated temporally and spatially according to irrigation area in order to prevent desertification due to overdevelopment of land in case of water scarcity and soil salinization due to overdevelopment of local water resources.

$$G = 1 - \sum_{i=1}^{n} \left(X_i - X_{i-1}\right)\left(Y_i + Y_{i-1}\right) \tag{4}$$

where X_i (i=1, 2, ……, n) is the cumulative percentage of the farmland irrigation area in each calculation unit, %; Y_i (i=1, 2, ……, n) is the cumulative percentage of the available quantity of water resources in each calculation unit, %. Thus, when i=1, (X_{i-1}, Y_{i-1})=(0, 0).

(3) Eco-environment system

The ecological regulation is to improve the adaption and self-restoration capacities of the eco-environment system by rationally regulating the water quantity for eco-environment at control cross sections under the dual development model of the water resources and society.

The water-salt regulation is to regulate the water-salt balance based on salt production, transfer and deposition laws. In this regard, rational exploitation of groundwater, the irrigation and drainage ratio in the irrigation area, and the irrigation ratio of canals and wells are important to maintain salt payment balance in the irrigation area.

2.2 Water Resources Collaborative Allocation Model

2.2.1 Objective function

(1) The objective of the economic system

The objective of the economic system is to satisfy the off-stream water demand. Thus, the water supply should be maximized in order to regulate the order parameter of the economic system.

$$F_1 = MAX \left\{ \begin{array}{l} \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\alpha_{sur}\left(XCSC_{ijt} + XCSI_{ijt} + XCSE_{ijt} + XCSA_{ijt} + XCSR_{ijt} + XCSV_{ijt}\right) \\ +\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\alpha_{div}\left(XCDC_{ijt} + XCDI_{ijt} + XCDE_{ijt} + XCDA_{ijt} + XCDR_{ijt} + XCDV_{ijt}\right) \\ +\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\alpha_{grd}\left(XZGC_{ijt} + XZGI_{ijt} + XZGE_{ijt} + XZGA_{ijt} + XZGR_{ijt} + XCGV_{ijt}\right) \\ +\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\alpha_{rec}\left(XZTI_{ijt} + XZTE_{ijt} + XZTA_{ijt} + XZTV_{ijt}\right) \end{array} \right\} \quad (5)$$

where F_1 is the total water supply of the basin, and the higher the F_1 value is, the higher the economic benefit of the water resources optimization allocation will be; α_{sur}, α_{div}, α_{grd} and α_{rec} are the weight coefficients of the supply of surface water, diverted water, groundwater and reclaimed water; $XCSC_{ijt}$, $XCSI_{ijt}$, $XCSE_{ijt}$, $XCSA_{ijt}$, $XCSR_{ijt}$ and $XCSV_{ijt}$ are the surface water supply for urban household, industry, urban ecology, agriculture, rural household and rural ecology in the administrative district j of the sub-basin i at period t, respectively. The supply of diverted water, groundwater and reclaimed water for different water users can be derived in a similar way. Note that reclaimed water should only be supplied for industrial and ecological use; T is the total time period, month; I is the number of sub-basins; and J is the number of administrative districts.

(2) The objective of the social system

The ultimate goal of the social system is to ensure water supply equity for different industries and regions. Here, the concept of the water supply Gini coefficient (Hu 2004; Shao et al. 2005) is used to optimize the water resources allocation model in different industries and basins, and the order parameters of the social system is determined by minimizing the water supply Gini coefficient.

$$F_2 = MIN\left\{\sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{k'=2,k'>k}^{K}\left(\frac{\alpha^k W_{ijt}^k / D_{ijt}^k - \alpha^{k'} W_{ijt}^{k'} / D_{ijt}^{k'}}{T*K*M_{ijt}}\right)\right\}$$

$$F_3 = MIN\left\{\sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{j'=2,j'>j}^{J}\left(\frac{W_{it}^j / D_{it}^j - W_{it}^{j'} / D_{it}^{j'}}{T*J*M_{it}}\right)\right\}$$

$$M_{ijt} = \sum_{k=1}^{K}\frac{\alpha^k W_{ijt}^k}{D_{ijt}^k}; M_{it} = \sum_{j=1}^{J}\sum_{k=1}^{K}\frac{W_{ikt}^j}{D_{ikt}^j}; W_{it}^j = \sum_{k=1}^{K} W_{ikt}^j; D_{it}^j = \sum_{k=1}^{K} D_{ikt}^j \tag{6}$$

where F_2 and F_3 are the water supply Gini coefficients for the industry and administrative district, and the smaller the F_2 and F_3 values are, the more equitable the water resources allocation in different industries and administrative districts will be; W_{ijt}^{k} and D_{ijt}^{k} are the water supply and demand of the industry k in the administrative district j of the sub-basin i at period t; k and k' are the industry k and k', including urban household, industry, urban ecology, agriculture, rural household and rural ecology; K is the number of industries; α^{k} is the water supply priority order parameter of industry k; $W_{ijt}^{k'}$, $D_{ijt}^{k'}$ and $\alpha^{k'}$ are the same as above; M_{ijt} is the total of the ratio of water supply to water demand of each industry in the administrative district j of the sub-basin i at period t; M_{it} is the total of the ratio of the water supply to water demand in the administrative district j of the sub-basin i at period t; W_{it}^{j} is the total water supply in the administrative district j of the sub-basin i at period t; and D_{it}^{j} is the water demand in the administrative district j of the sub-basin i at period t.

(3) The objective of the eco-environment system

Given the coupled response of the evolution of the ecological system to water cycle, the key measure to ensure good evolution of the ecological system is to ensure the minimum discharge at the control cross section. Thus, the order parameter of the ecological system is determined to maximize the minimum ecological water supply at the control cross section.

$$F_{4} = MAX\sum_{t=1}^{T}\sum_{l=1}^{L}\left\{\alpha_{t}\frac{W_{lt}^{e}}{D_{lt}^{e}}\right\} \tag{7}$$

where F_4 is the satisfaction degree of ecological water demand, and the higher the F_4 vale is, the more satisfied the ecological water demand will be; W_{lt}^{e} and D_{lt}^{e} are the ecological discharge and demand of the river at the cross section l at period t;

α_t is the sensitivity coefficient of the discharge at period t, which is dependent on the discharge time and the period of seed maturation and germination.

(4) Overall objective

According to the hierarchical principle, appropriate weight coefficients should be assigned to the water supply objectives of the economic, social, eco-environment systems considering the quantity of water resources and the tolerance capacity of the eco-environment in order to optimize the overall water resource allocation.

$$Z = \lambda_1 F_1 - \lambda_2 F_2 - \lambda_3 F_3 + \lambda F_4 \tag{8}$$

where λ_1, λ_2 and λ_3 are the weight parameters of the water resources system, economic and social system, and eco-environment system, respectively.

2.2.2 Constraints

The constraints considered in this study include available water quantity constraint, river ecological constraint, reservoir storage capacity constraint and channel conveyance capacity constraint, which are described in supplementary Table 1 and Table 2.

(1) Available water quantity constraints

Local available water quantity constraints in the calculation unit:

$$XZSFC_{tm}^{j} + XZSFI_{tm}^{j} + XZSFA_{tm}^{j} + XZSFE_{tm}^{j} + XZSFR_{tm}^{j} \le PWSFC^{j} \bullet PWSF_{tm}^{j} \tag{9}$$

Groundwater water supply constraint in the calculation unit:

$$XZGC_{tm}^{j} + XZGI_{tm}^{j} + XZGA_{tm}^{j} + XZGE_{tm}^{j} + XZGR_{tm}^{j} \le PZGTU^{j} \bullet PZGW_{tm}^{j} \tag{10}$$

Diverted water supply constraint in the calculation unit:

$$XCDRC_{tm}^{j} + XCDRI_{tm}^{j} + XCDRA_{tm}^{j} + XCDRE_{tm}^{j} + XCDRR_{tm}^{j} \le PQD_{tm}^{j} \tag{11}$$

Reclaimed water supply constraint in the calculation unit:

$$XZTI_{tm}^{j} + XZTA_{tm}^{j} + XZTE_{tm}^{j} \le PQT_{tm}^{j} \quad (12)$$

Sewage reuse constraint in the calculation unit:

$$\sum_{j=1}^{n} XZTR_{tm}^{j} \ge \lambda^{j} \bullet XQTS_{tm}^{j} \quad (13)$$

where $XQTS_{tm}^{j}$ is the sewage treatment capacity in the calculation unit j, and λ^{j} is the planned reuse rate of the reclaimed water in the calculation unit j:

$$\begin{aligned} XZTR_{tm}^{j} &= (PZWC_{tm}^{j} - XZMC_{tm}^{j}) \bullet PCSCC_{tm}^{j} \bullet PZTCD_{tm}^{j} \bullet PZTCT_{tm}^{j} \bullet PZTCR_{tm}^{j} \\ &+ (PZWI_{tm}^{j} - XZMI_{tm}^{j}) \bullet PCSCI_{tm}^{j} \bullet PZTID_{tm}^{j} \bullet PZTIT_{tm}^{j} \bullet PZTIR_{tm}^{j} \end{aligned} \quad (14)$$

(2) River channel ecological constraint

$$XRQ_{max}^{l} \ge XRQ^{l} \ge XRQ_{min}^{l} \quad (15)$$

where XRQ_{max}^{l} is the maximum conveyance capacity of the river l, XRQ^{l} is the actual conveyance capacity of the river l, and XRQ_{min}^{l} is the minimal ecological water demand of the river 1.

(3) Reservoir storage constraints

$$PRSL_{tm}^{ir} \le XRSV_{tm}^{ir} \le PRSU_{tm}^{ir} \quad (16)$$

where $PRSU_{tm}^{ir} = \begin{cases} PRSU1_{tm}^{ir}, (non-flood\ season) \\ PRSU2_{tm}^{ir}, (flood\ season) \end{cases} \quad (17)$

(4) River channel conveyance capacity constraint

$$XCSRC_{tm}^{ls(u(n),j)} + XCSRI_{tm}^{ls(u(n),j)} + XCSRA_{tm}^{ls(u(n),j)} + XCSRE_{tm}^{ls(u(n),j)} + XCSRR_{tm}^{ls(u(n),j)} = XCSRL_{tm}^{ls(u(n),j)} \quad (18)$$

$$XCDRC_{tm}^{ld(u(n),j)} + XCDRI_{tm}^{ld(u(n),j)} + XCDRA_{tm}^{ld(u(n),j)} + XCDRE_{tm}^{ld(u(n),j)} + XCDRR_{tm}^{ld(u(n),j)} = XCDRL_{tm}^{ld(u(n),j)} \quad (19)$$

$$XCPRC_{tm}^{lp(u(n),j)} + XCPRI_{tm}^{lp(u(n),j)} + XCPRA_{tm}^{lp(u(n),j)} + XCPRE_{tm}^{lp(u(n),j)} + XCPRR_{tm}^{lp(u(n),j)} = XCPRL_{tm}^{lp(u(n),j)} \quad (20)$$

$$PCSL_{tm}^{ls} \le XCSRL_{tm}^{ls} \le PCSU_{tm}^{ls} \quad (21)$$

$$PCSL_{tm}^{ld} \le XCDRL_{tm}^{ld} \le PCSU_{tm}^{ld} \quad (22)$$

$$PCSL_{tm}^{lp} \leq XCPRL_{tm}^{lp} \leq PCSU_{tm}^{lp}$$

2.3 Parameter calibration

Model parameters are calibrated by analysing the water consumption of the water resources system in the reference year, which takes into account the surface water supply, groundwater supply, available surface water quantity, economic water consumption coefficient in different regions, discharge at the control cross sections, ratio of economic and ecological water consumption.

The main steps involved in model parameter calibration are:

(1) The ratio of economic and ecological water consumption is determined and adjusted according to the water consumption balance in different regions, and the unit water storage of the basin is controlled in a given balanced error and should not exceed the available surface water quantity and the exploitable quantity of groundwater;

(2) The surface water and groundwater supply quantities, as well as the economical development and water consumption, are adjusted in different administrative districts in order to realize the water supply-demand balance and the water-soil balance in the region;

(3) The discharge at control cross sections is determined. At a given inflow, the inflow time can have a substantial effect on the downstream ecology. For instance, the growth of natural vegetation in natural oases or the oasis-desert transitional zones in the arid northwestern China is closely associated with the inflow time, and the maximum ecological benefit is obtained when the inflow time coincides with seed

maturity or germination that occurs generally in August or September;

(4) The water-salt balance is achieved by rationally adjusting the quantity and process of water demand and discharge, drainage to irrigation ratio, irrigation ratio of canals and wells, and water-saving irrigation in the irrigation areas.

2.4 Multiple-loop iteration technique

In this study, the evolution direction of the system is determined by the order parameters and the optimal solution is obtained by means of successive iteration. As a result, the total water consumption balance, groundwater extraction and recharge balance, water demand-supply balance, water-soil balance, ecological balance, and water-soil balance of the composite system consisting of different water resources and industries can evolve coordinately at different temporal and spatial scales. The calculation steps are summarized as follows (Fig. 2):

Step 1: Initialize the parameters and input the key control parameters of the water resources system (e.g., surface runoff, initial exploitable quantity of groundwater W_j, j=0) and the economic and social system. The jth water resources allocation is obtained by successive iteration of the composite system;

Step 2: The total water consumption balance and the groundwater extraction and recharge balance at the basin level are determined based on the iterative calculation of the water resources model. Step 2-1: The total water consumption balance at the basin level is determined. Specifically, whether the water allocation scheme in different parts of the basin (upstream, midstream and downstream) is reasonable or not and whether the downstream economic, social, eco-environment water demand could be satisfied or not are determined based on the quantity of water flowed out of the basin. If not satisfied, measures would be taken such as increasing water diversion and water supply from unconventional water sources, and then the key control parameters are input again into the composite system in Step 1 and let j=j+1; if satisfied, go to Step 2-2. Step2-2: The groundwater extraction and recharge balance at the basin level is determined. The parameters associated with the water supply from different sources and the water use in different industries are input to obtain the exploitable quantity of groundwater W_j, where j is the number of iterations, j=1,2,…,n. If satisfied, go to Step; otherwise, measures are taken such as adjusting the ratio of irrigation water in the irrigation area, and then go to Step 1 to input the key control parameters into the composite system and let j=j+1. The previous iteration is repeated until the conditions are satisfied;

Step 3: The water demand-supply balance and the water-soil balance at the administrative district level are determined based on the iterative calculation of the economic and social system. Step 3-1: Determine whether the water demand-supply balance is at the administrative district level, such as total water consumption, water demand and supply, and economic water consumption, is met. If not, measures are taken such as adjusting the development scales of different industries, plantation structure, irrigation area, water saving level, and allowable damage depth, then go to Step 1 to input the key control parameters into the composite system and let j=j+1; otherwise go to Step 3-2: Determine whether the water-soil balance at the administrative district level is met. In other words, determine whether Gini coefficient is within the threshold. If met, go to Step 4; otherwise measures should be taken such as adjusting the structure of water and soil resources, and the irrigation area could be reduced if it is larger than the farmland area or water-saving irrigation mode can be used, then then go to Step 1 to input the key control parameters into the composite system and let j=j+1. The previous iteration is repeated until the conditions are satisfied;

Step 4: The ecological balance at key control cross sections and the water-salt balance in the irrigation area are determined based on the iterative calculation of the eco-environment system. Step 4-1: Determine whether the ecological water guarantee rate is met at key control cross sections. If not met, measures are taken to slightly adjust the economic water consumption norm, development scale and river inflow time. Then, go to Step 1 to input the key control parameters into the composite system and let j=j+1; otherwise go to Step 4-2. Step 4-2: Determine whether the water-salt balance in the irrigation area is met. If not met, measures are taken to adjust the drainage to irrigation ratio in the irrigation area, then go to Step 1 to input the key control parameters into the composite system and let j=j+1; and if it is still not met, go to Step 1 again and let j=j+1. The previous iteration is repeated until the conditions are satisfied;

Step 5: Output the water resources allocation model.

3. Case Study

3.1 Study Area and Data

The Tarim River (E73°39'～93°45'; N34°20'～43°39') is the fifth largest inland river in the world with a total basin area of 1.027 million km^2, which are presented in Fig. 3. (Thevs et al. 2015)However, the precipitation in the Tarim Basin is extremely scanty with an annual average precipitation of only 116.8 mm, and most precipitation occurs in the period from June to October that accounts for approximately 70～80% of the total annual precipitation. The Tarim River is formed by the confluence of the Yarkant River, Hotan River and Aksu River. Despite an increase in the flow rate of the Tarim River in recent years due to climate change, the water demand of the basin could not be fully met as in the economic and social system, the water consumption due to considerable expansion of cultivated land far exceeds the quantity of water saved by the water-saving irrigation and, as a consequence, the water supply originally for the eco-environment system has to be reduced, thus leading to ecological imbalance and malignant evolution of the eco-environment system.

3.2 Coordinated water resources allocation network

According to the inherent characteristics and present situation of the Tarim River, the planning of water conservancy projects in the basin and the requirement of water resources allocation, the physical elements of the water resources system (e.g., important water conservancy projects, calculation units, and river or channel confluences) are taken as nodes that are collected by lines representing the water transfer network of the Tarim River basin. Finally, the network is generalized into 39 Three-level counties or cities, 45 nodes for hydrological control stations, water diversion, discharge and cross sections, 34 constructed and planned reservoirs, 66 surface water supply channels, 140 river segments, and 42 discharge channels. In this study, the Aksu basin is studied as an example, as shown in Fig. 4.

3.3 Parameter calibration and verification

Because a large number of parameters are involved in the network, only some key parameters are calibrated and verified as an example. The discharge processes at control cross sections at the sluices of the Aksu River, the Heniyaz section of the Yarkant River, the Shawta section of the Hotan River, and the No. 66 division gate of the Kaidu-Kongque River are simulated based on the analysis of the water demand-supply balance and the water consumption balance in the reference year and compared with the measurement data (Fig. 5).

The results show that the Nash coefficients are over 0.62 for all cross sections with an average of 0.67, indicating that the simulation accuracy is acceptable. The fitting results of water discharge at control cross sections are presented in Table 3.

4. Results Analysis and Discussion

4.1 Balance of the water resources system

4.1.1 Total water consumption balance

As illustrated in Fig. 6, At P=50%, the inflow at the Arael section is projected to be 4.85 billion m^3 in 2030, and the corresponding discharge is 3.55 billion m^3 at the Aksu and Bavutolac sluice of the Aksu River, 0. 35 billion m^3 at the Heniyaz section of the Yarkant River, and 0.95 billion m^3 at the Shawta section of the Hotan River, respectively. In this case, the total water consumption balance can be achieved, which allows sufficient water supply from the water sources to the Tarim main stream and thus causes no ecological problems as the ecological water demand is satisfied in the lower reaches of the Tarim main stream. It is also projected that the discharge is 3.55 billion m³ at the Aksu and Bavutolac sluice, 0.88 billion m³ at Erikta section of the Yarkant River, and 1.95 billion m³ at the Lianghe canal head of the Hotan River in 2030, respectively, which can meet the ecological water demand of the downstream woodland and meadow of the Aksu River, Hotan River, and Yarkant River.

4.1.2 Groundwater extraction and recharge balance

The groundwater of the Tarim River basin is recharged mainly by surface water infiltration, 38.6% of which is derived from river channel leakage; 53.7% of which is derived from surface water infiltration in the irrigation area (e.g., canal leakage, farmland infiltration, well irrigation regression, reservoir and pond leakage); and only 7.7% of which is derived from piedmont lateral recharge and rainfall infiltration. However, it is important to note that the measures taken in the planning level year, such as construction of mountainous reservoirs in the upstream regions of the basin, modification of industrial structure, changes in irrigation regime and the policy of returning farmland to water, can lead to a substantial increase in river channel leakage but a substantial decrease in surface water infiltration in the irrigation area. However, the piedmont lateral recharge and rainfall infiltration remain largely unchanged. On the whole, although the exploitable quantity of groundwater in the Tarim River basin shows a decreasing trend, its available quantity and actual water supply are still within reasonable ranges, as shown in Table 4.

4.2 Balance of the economic and social system

4.2.1 Water demand-supply balance

The Tarim River basin faces many problems in the reference year, such as water scarcity, low water use efficiency, unreasonable water use structure and environmental degradation, which pose a great threat to the water safety of the basin. In the planning level year, a number of measures are taken to address these problems, such as adjusting the water use structure, returning farmland to water, water-saving irrigation, sewage treatment and reuse, construction of mountainous reservoirs, and water reclamation. As a result, the efficiency of the multi-source water supply system of the Tarim River basin is greatly increased. In terms of water supply, the water resources allocation scheme has put much emphasis on water recycling; in terms of water use, the scheme takes into account the coordination of different industries by optimizing the water use structure, reducing the ratio of agricultural water, and increasing the ratio of industrial and domestic water; while in terms of water supply benefit, the water demand of the Tarim River basin at different probabilities can be met by returning farmland to water to support the industrial development and implementing the water-saving policy to save more water for ecological use. In addition, the reclaimed water is supplied for agricultural, industrial and ecological use, which can not only reduce the water supply from conventional water sources, but can also minimize the impact of sewage on the eco-environment. Thus, the proposal scheme takes into account of social, economic and ecological benefits and thus coordinates the water demand and supply of the water resources system, social and economic system, and the eco-environment system, as shown in Table 5.

4.2.2 Water-soil balance

In 2030, the irrigated farmland area is reduced by 2440000 Mu in the Aksu River basin, 830000 Mu in the Yarkant River basin, 50000 Mu in the Hotan River basin, 840000 Mu in the Kaidu-Kongque River basin, and 300000 Mu in the mainstream, and the area in which water-saving irrigation scheme is used is increased by 2580000 Mu, 4410000 Mu, 2140000 Mu, 1260000 Mu and 670000 Mu, respectively, with a total decrease of 6.9 billion m^3 of economic water. It is noted that the agricultural water-soil balance is gradually increased with the implementation of the policies of returning farmland to water and water-saving irrigation, which are presented in Fig. 7.

4.3 Balance of the eco-environment system

4.3.1 Ecological balance

As shown in Fig. 8, the ratio of ecological water supply of the Tarim River basin is increased from 44% in the reference year to 54% in 2030. Specifically, it is increased from 46% to 50% in the Aksu River basin, from 27% to 43% in the Yarkant River basin, from 48% to 53% in the Hotan River basin, from 39% to 41% in the Kaidu-Kongque River basin, and from 73% to 83% in the mainstream, respectively, indicating sustainable development of the water resources and river eco-environment of the Tarim River basin.

In 2030, large discharge at control cross sections of the Tarim River basin (P=50%) mainly occurs in the period from June to October, which coincide approximately with the period of seed maturity and germination (generally in August and September), and thus the ecological profit can be maximized.

4.3.2 Water-salt balance

As shown in Fig. 9, in the reference year, serious soil salinization occurs mainly in the First Agricultural Division irrigation area of the Aksu River basin, the Second Agricultural Division irrigation area of the Kaidu-Kongque River basin, and the Yuli County in the Tarim River basin. In the planning level year, some effective measures have been taken to optimize irrigation and drainage and improve groundwater utilization, and as a result the ratio of drainage to irrigation in the irrigation area of the Tarim River basin is decreased to 5-30%, and the saline and alkaline land is improved by 69% in 2020 and by 96% in 2030, respectively.

5. Conclusions

In this study, the coupled relationships among the water resources system, the economic and social system, and the eco-environment system are considered, and the order and control parameters are used to establish a multidimensional composite system, which can realize the total water consumption balance and groundwater extraction and recharge balance for the water resources system, water demand-supply balance and water-soil balance for the economic and social system, and ecological balance and water-salt balance for the eco-environment system.

Then, a case study is performed with the Tarim River basin, and the results show that under the conditions of conserved inflow series (1956-2000), the annual average water demand in 2030 is estimated to be 17.086 billion m^3, the annual average water supply is 16.916 billion m^3 (where the supply of surface water, groundwater and reclaimed water is 14.952 billion m^3, 1.617 billion m^3 and 0.347 billion m^3, respectively), the annual average water consumption is 16.916 billion m^3 (where the domestic, industrial and agricultural water consumption is 0.687 billion m^3, 1.246 billion m^3 and 14.983 billion m^3, respectively). Thus, the total water deficiency is 0.17 billion m^3 with a water deficiency rate of 0.99%. In 2030, water-saving irrigation is adopted in 12.757 million Mu of new farmland in the Tarim River basin. It is noted that the irrigation area is reduced by 6.217 million Mu and the economic water consumption is reduced by 7.462 billion m^3, thus resulting in coordinated evolution and development of the composite system.

However, the limitations of this study should also be noted. For instance, the water supply from multiple water sources and the water demand of different subsystems are investigated in this study without considering carbon emission and capture. Thus, the carbon-water coupling mechanism should be considered in water resources allocation in order to reduce carbon emission and increase carbon capture, which can improve and ecological value and sustainable development of water sources.

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Declarations

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Conflicts of interest/Competing interests The authors declare no conflict of interest.

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Code availability Not applicable.

Authors Contributions All authors contributed to the study conception and design. The formulation of overarching research goals,creation of models were performed by Liqin Li. The first draft of the manuscript was written by Ting Wang. The results was analyzed by Xinmin Xie and Xingyao Pan. All authors commented on previous versions of the manuscript, and authors read and approved the final manuscript.

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Consent to Participate Not applicable.

Consent to Publish The authors confirm that the work described has not been published before, and not under consideration for publication elsewhere. Its publication has been approved by all co-authors, and we agree to publish this article in the journal of WARM by Springer.

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Figures

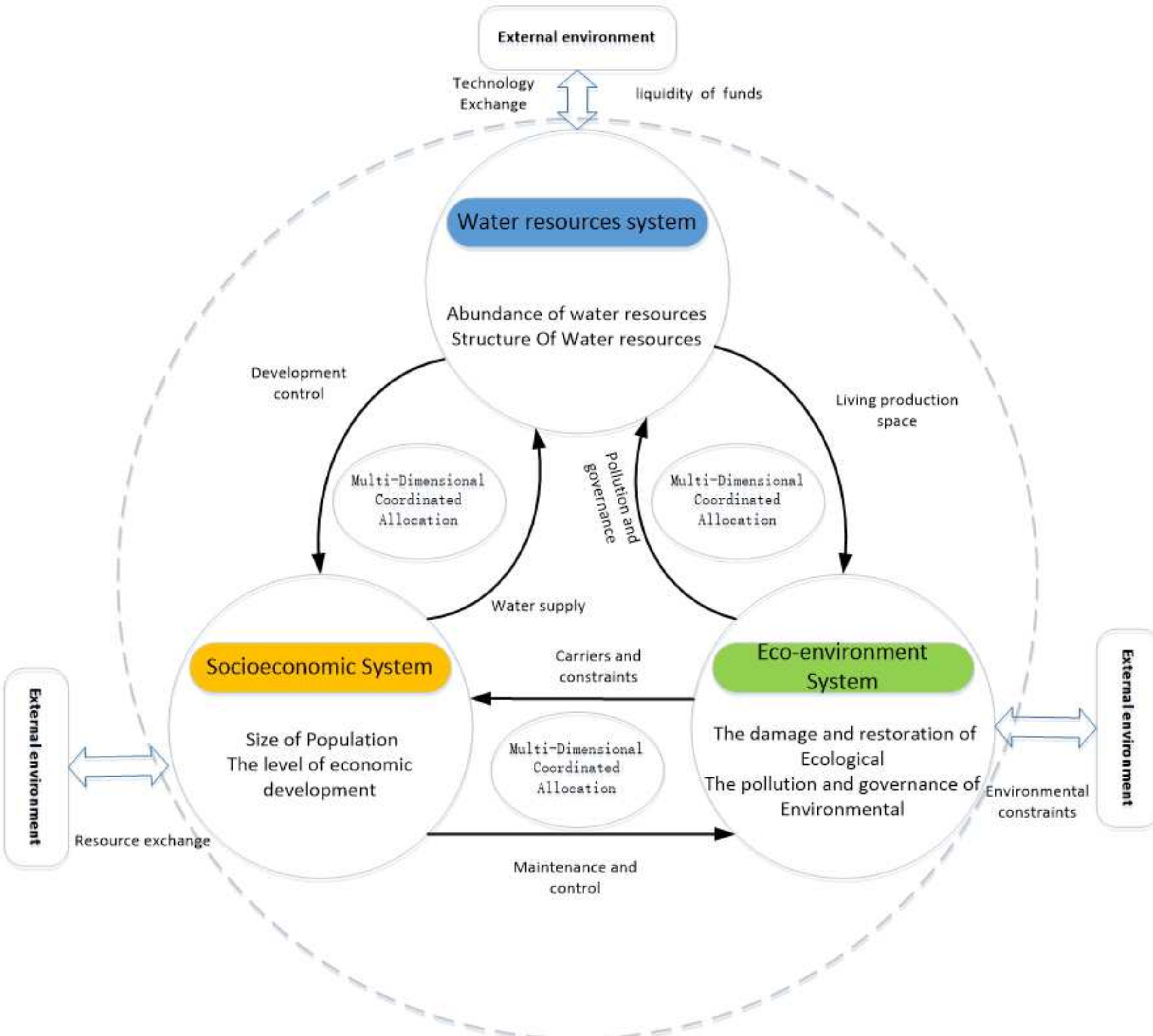

Figure 1

Schematically of composite water resources-socioeconomic-eco-environment system

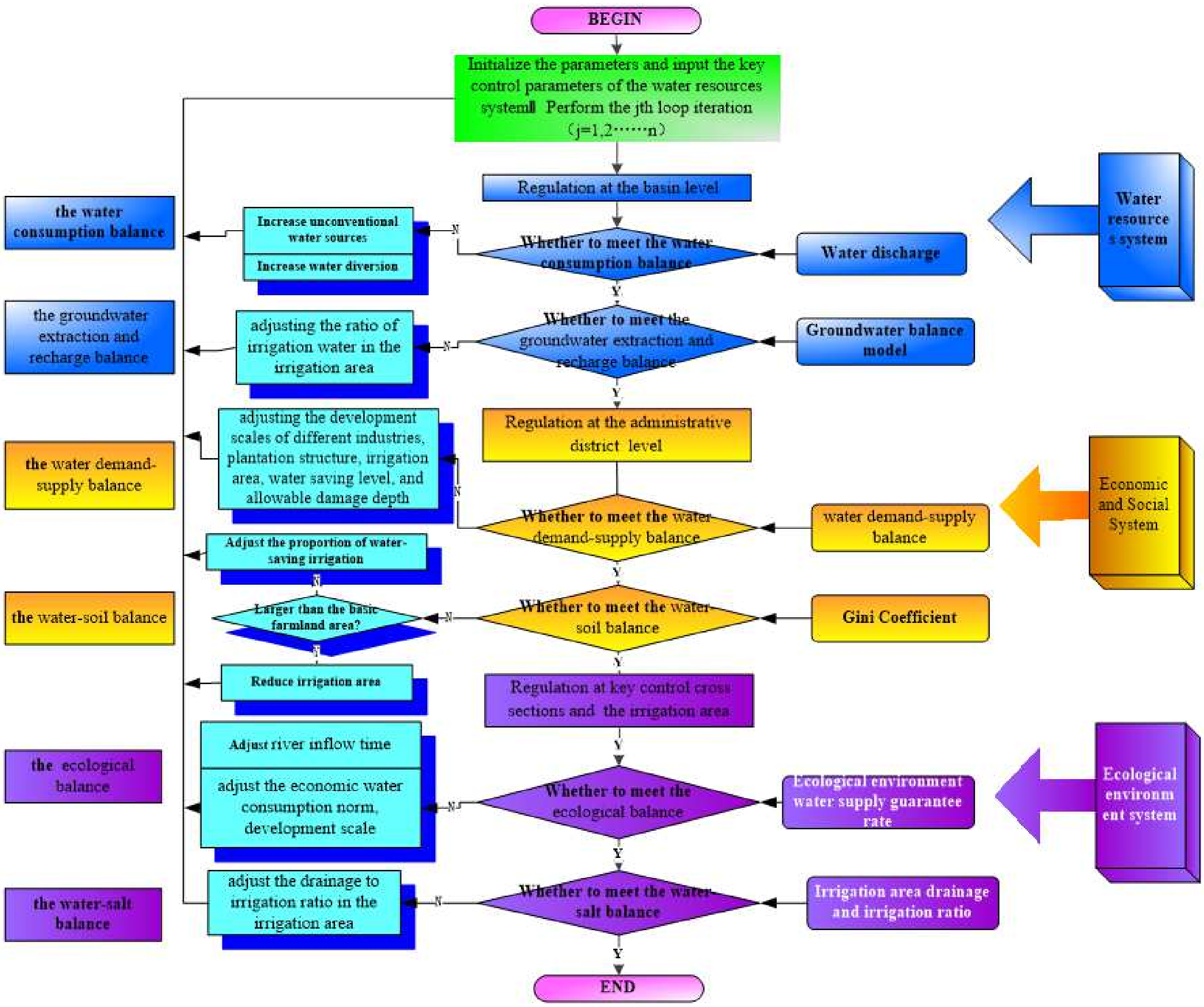

Figure 2

Multi-dimensional collaborative allocation of water resources and multi-cycle iteration process diagram

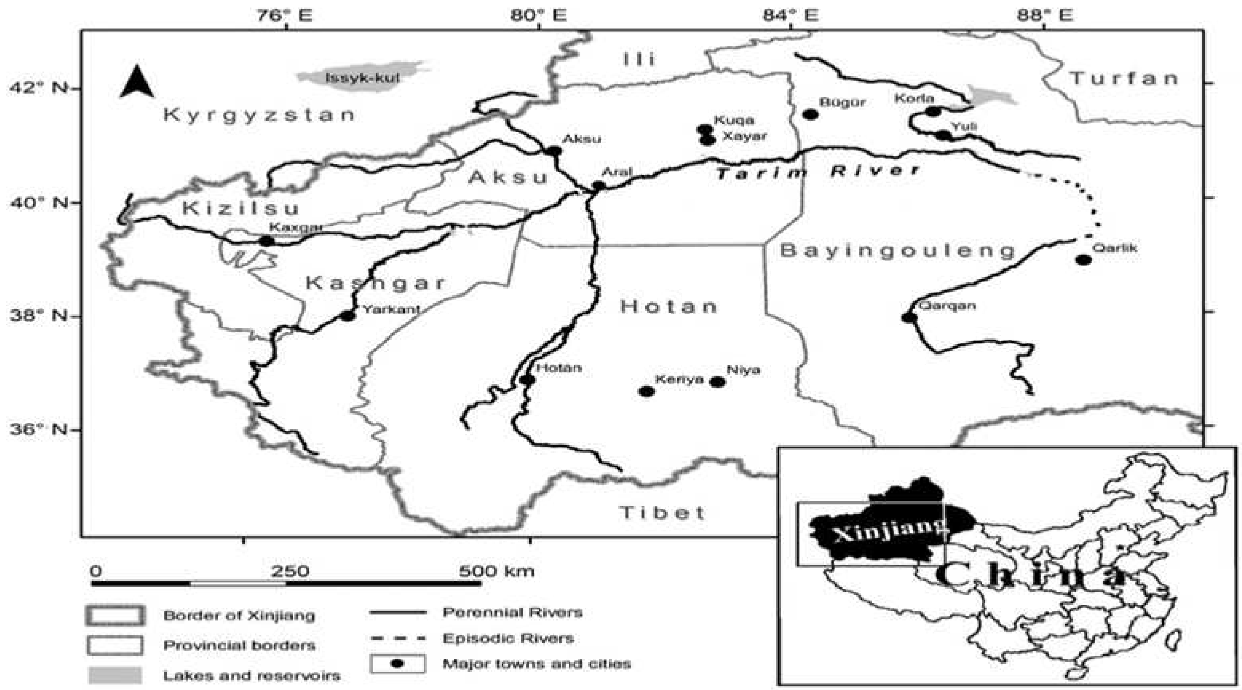

Figure 3

Location of Tarim River in northwest China

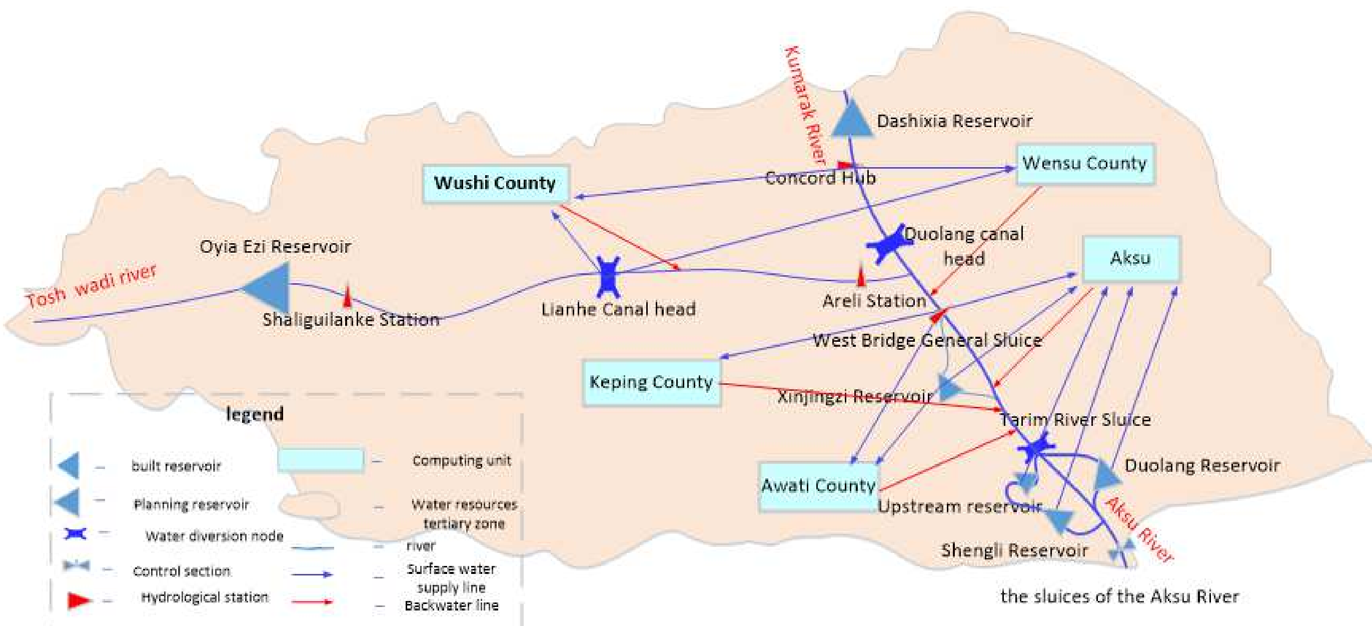

Figure 4

Water resource deployment network chart of Aksu basin

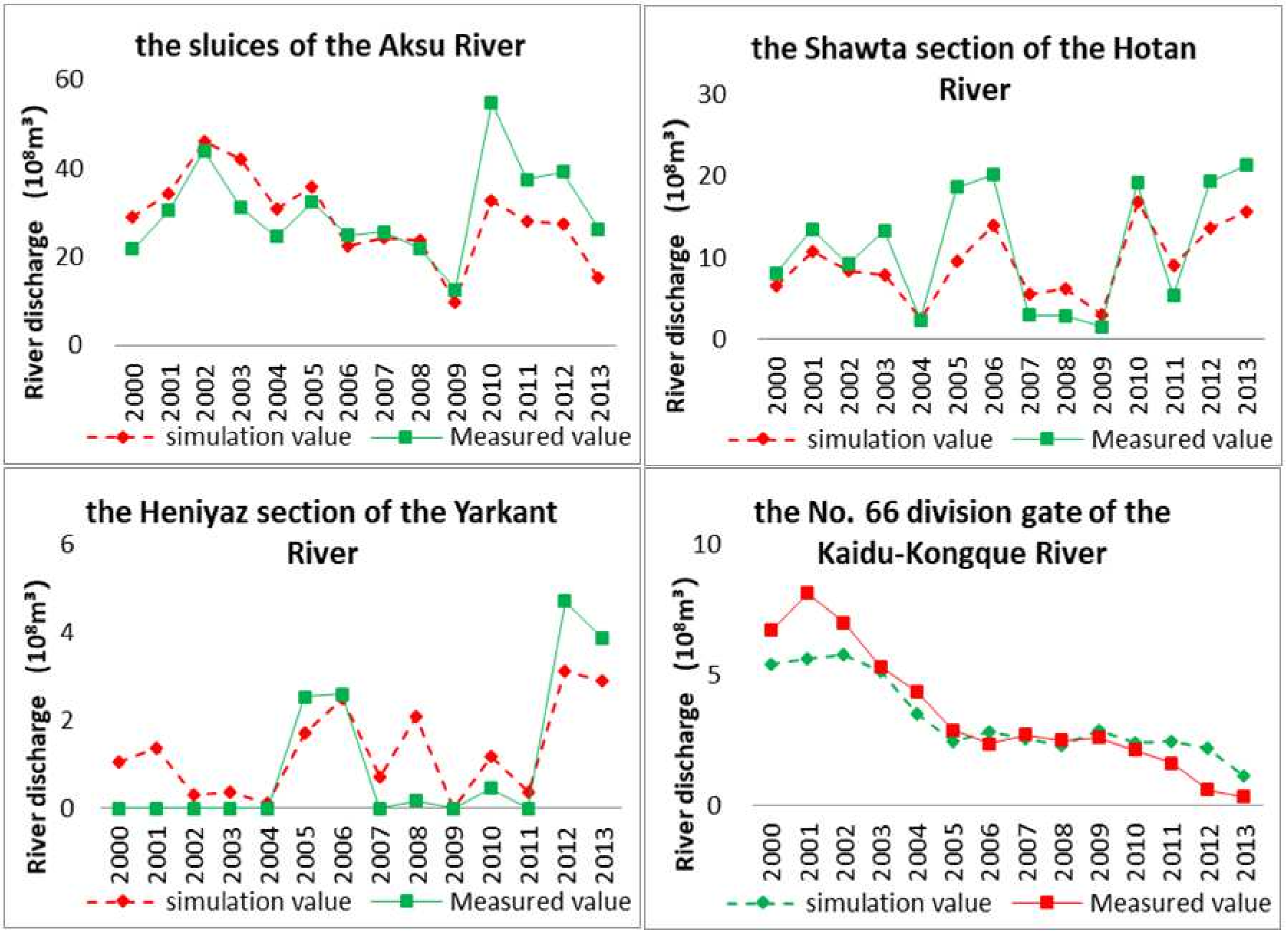

Figure 5

Fitting results of water discharge at control cross sections

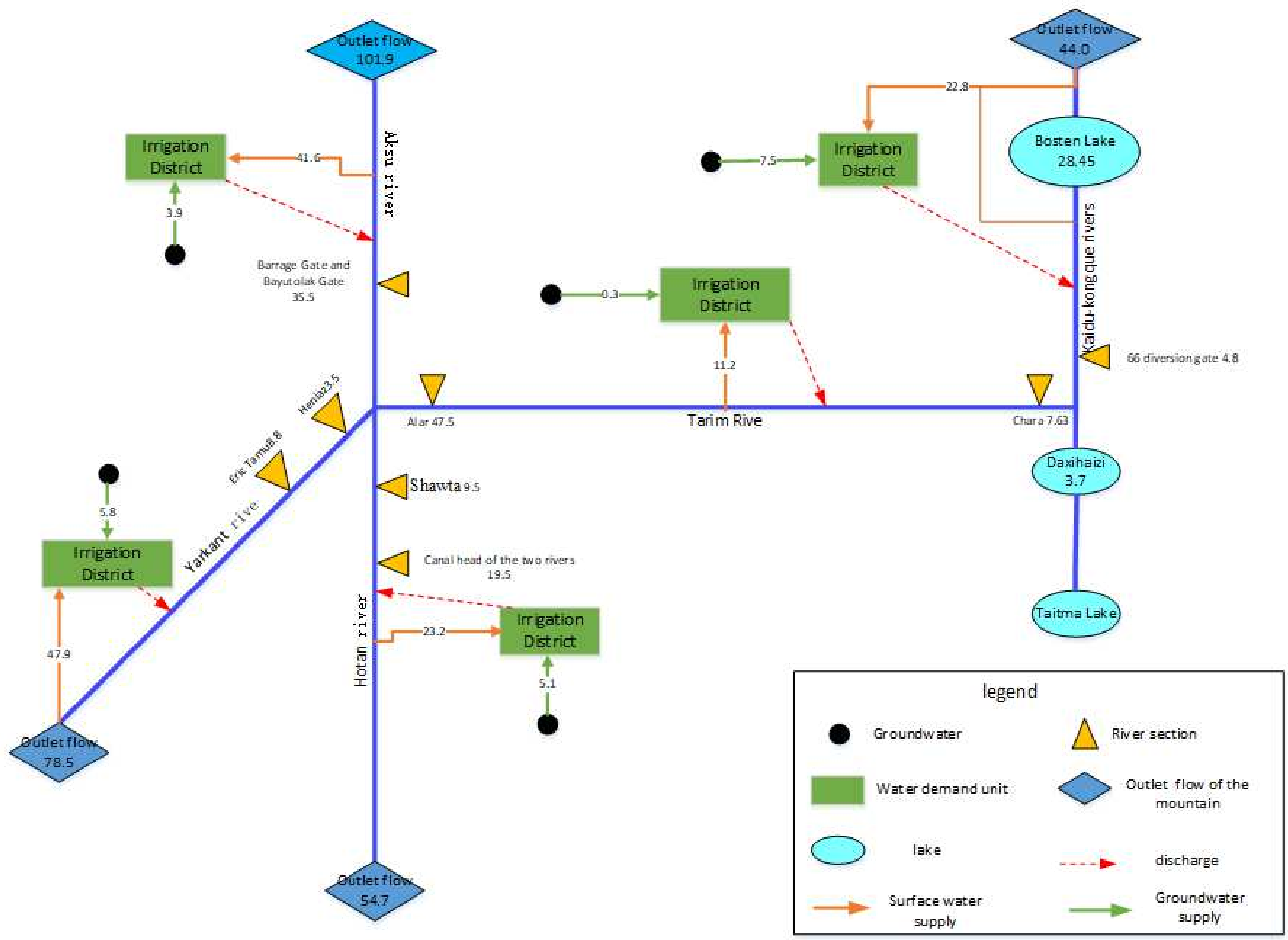

Figure 6

The balance of total water consumption control in 2030 (P=50%)

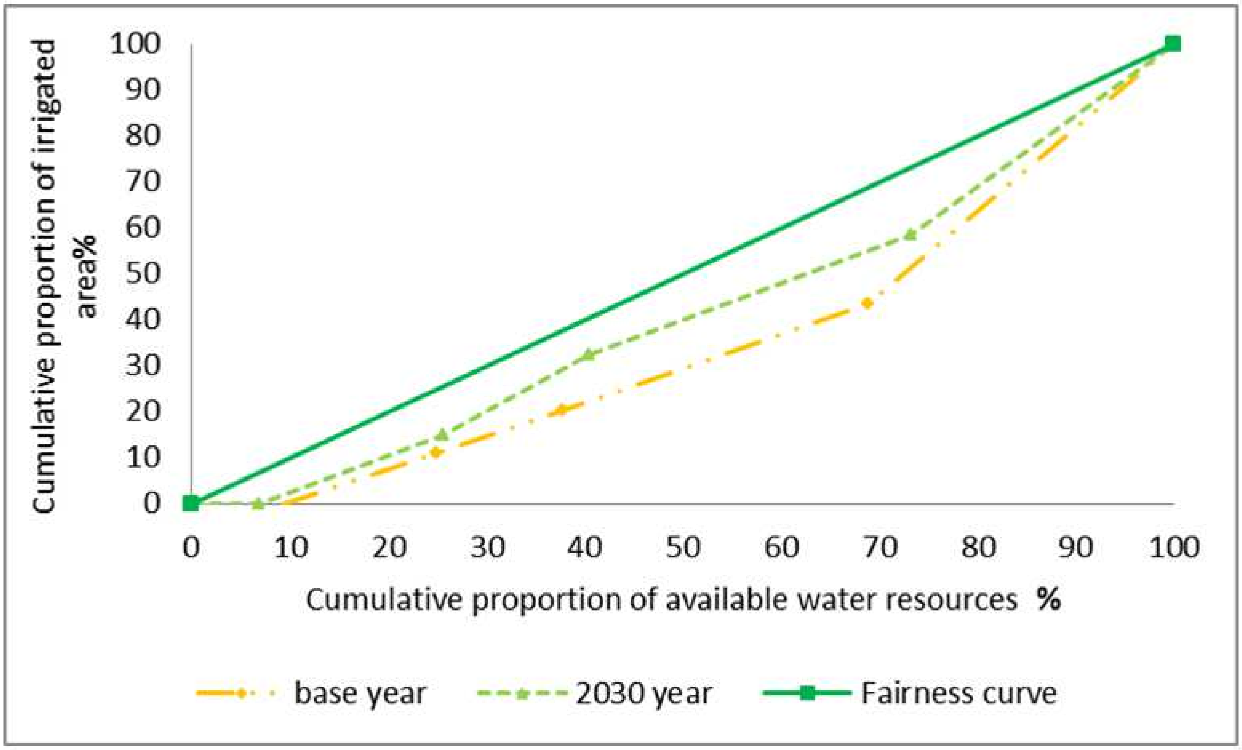

Figure 7

Lorenz Curve of Soil and Water Balance in Tarim River Basin

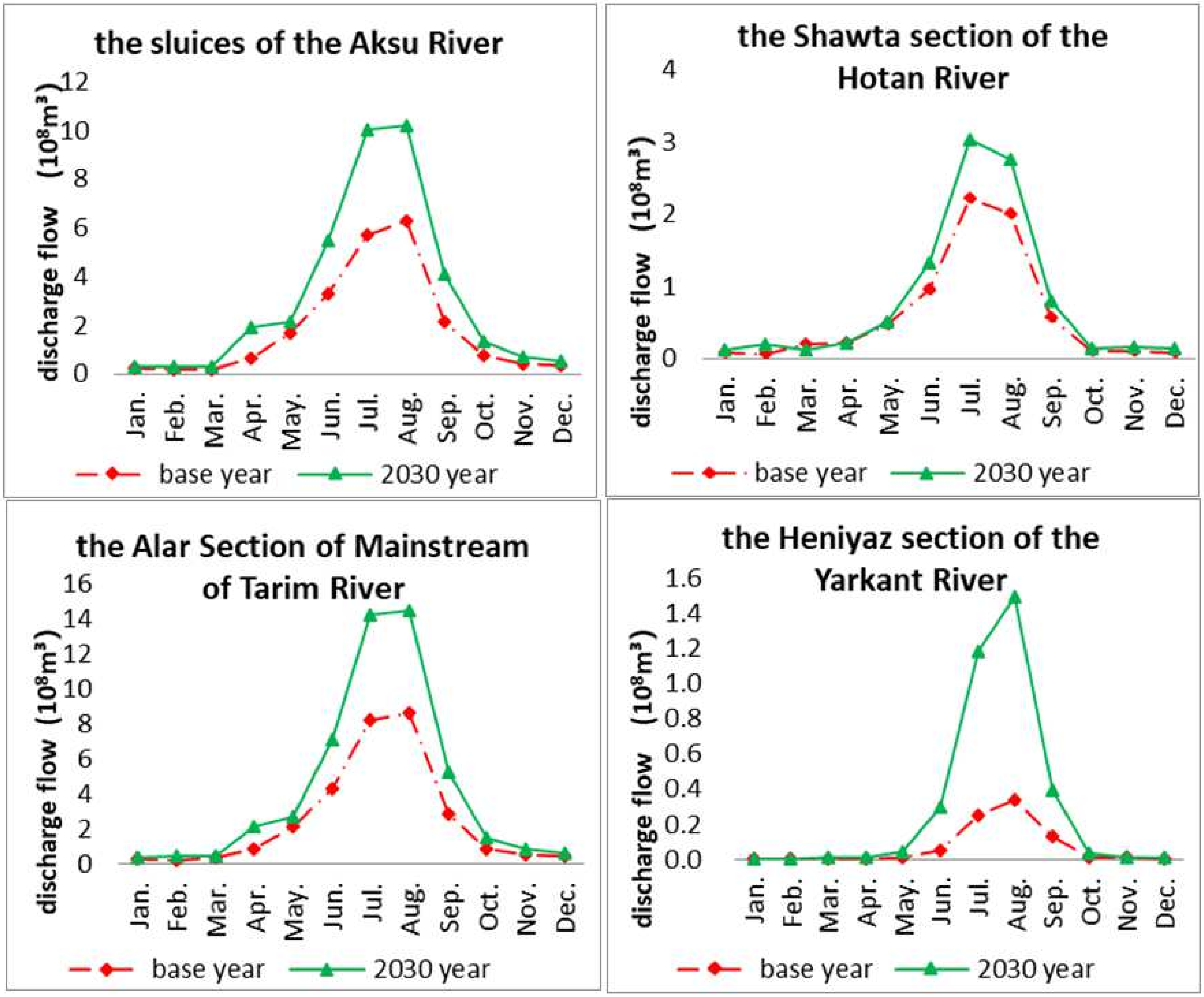

Figure 8

Process line of water discharge under key control sections (P=50%)

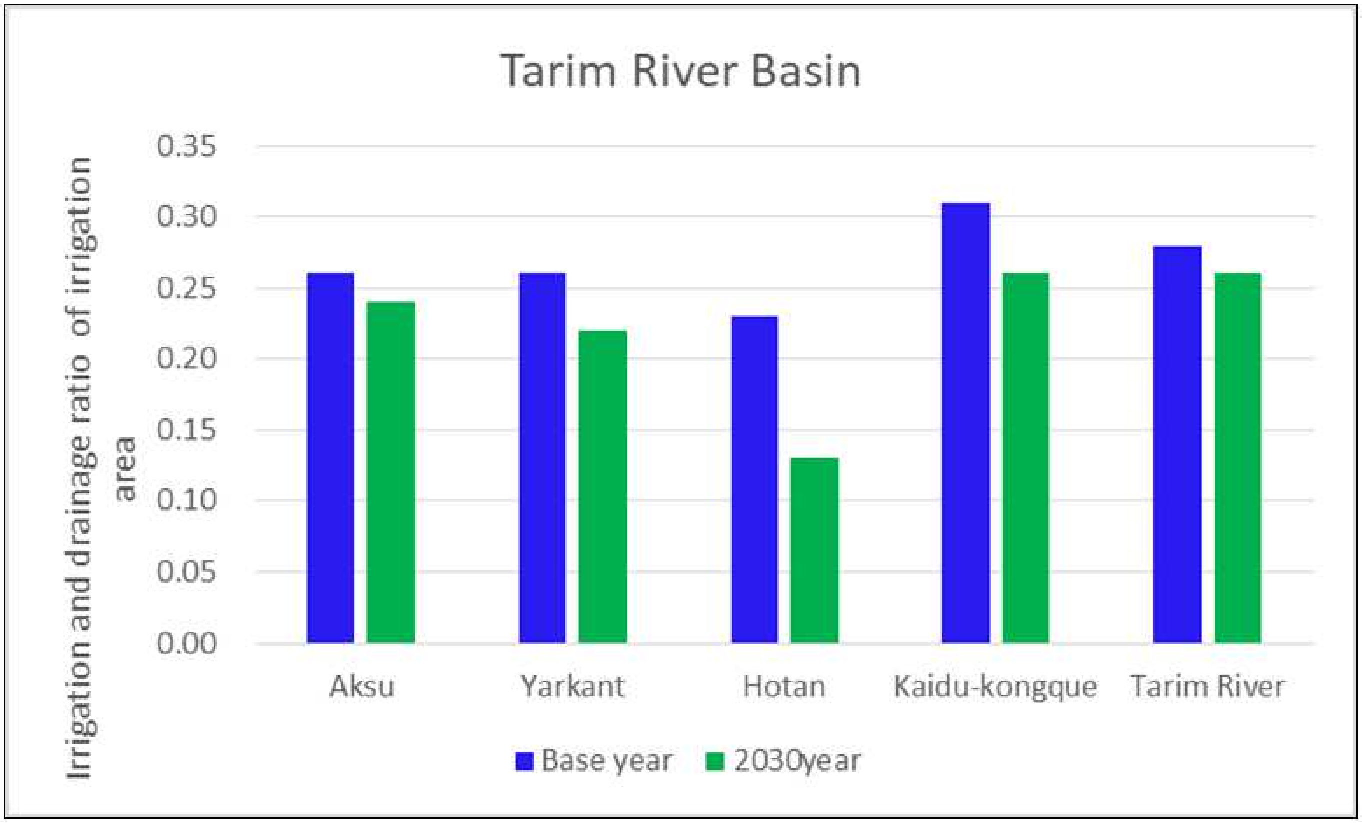

Figure 9

Irrigation and drainage ratio of irrigation area in Tarim River Basin