Response to the comment of hessd-11-C3414-2014

Title: A coupled modeling framework of the co-evolution of humans and water: case study of Tarim River Basin, western China
Authors: Dengfeng LIU, Fuqiang TIAN, Mu LIN and Murugesu SIVAPALAN
Manuscript ID: hess-2014-100
Comment: hessd-11-C3414-2014

First of all, we greatly appreciate the valuable and constructive comments from the editor. The following lists our point-to-point replies to the comments.

This is an interesting paper on the coupling between hydrology and society in western China. The second review by Salvatore Manfreda made some substantial and constructive points on improving the manuscript, including a better presentation of the model and about the number of model parameters. I fully agree with his assessment that the manuscript requires a revision to address these issues.
Response: Thanks for the positive comments.

Specifically, when you revise the manuscript, I suggest that in addition to the reviews you:

1. move the detailed model description and tables of parameter values to an appendix and only focus on the essential model components and linkages in the main text. This will make the manuscript more readable to the readers.
Response: Done. The detailed dependent relationships are moved to the Appendix A. The table of parameter values is moved into the nomenclature.

2. reduce the number of model parameters. If you set some parameters to 1, throw them out of the documentation because you do not need them (unless you demonstrate and discuss their importance, but I did not see this in the manuscript).
Response: Done. The parameters, λ, whose values are set to 1.0, are removed from the manuscript.

3. evaluate the sensitivity of the model to some of the parameters. This is important to do so that one can understand which of the many parameters critically affect your model results, and which ones do not.
Response: The sensitivity of the parameters in the model is an important approach to identify the critical parameters which affect the performance of the model. In the hydrological sub-system, the crop coefficient of evapotranspiration (k_c) is an important parameter for system behavior. The crop coefficient of evapotranspiration (k_c) is

decreased or increased by 10%, respectively, to assess the effect on the system quasi-steady state and the results are listed in Table 5 and Table 6. k_c *has significant effects on the vegetation cover of the lower reach (*V_{CL}*) and slight effects on the other quasi-steady states. In the ecological sub-system, economic sub-system and social sub-system, the state variables are governed by logistic type equation, whose characteristics have been investigated by many scholars (Levins and Culver, 1971; Tilman, 1994; Tsoularis and Wallace, 2002). Because the interactions between the sub-systems will affect the colonization rate and mortality rate, the colonization rate only changes in the range from 0 to* g_{VU0} *and mortality rate change in the range from* m_{VU1} *to* m_{VU2}*, taking the vegetation cover of the upper reach as an example. The evolution process and quasi-steady states are determined by the colonization rate, mortality rate and carrying capacity (i.e. the maximum of the variable, such as* V_{CMU}*). The parameters of the vegetation cover of the upper reach(*V_{CU}*) are decreased or increased by 10% to assess the effects on the quasi-steady states of the system and the results are shown in Table 5 and Table 6.* V_{CMU} *and* g_{VU0} *have marked effect on the quasi-steady states of* V_{CU} *and* V_{CL} *because the change of the* V_{CU} *induces the change of the outflow from the upper reach. The quasi-steady states are not sensitive to the other parameters. The results are consistent with the performance of the parameters in the modeling calibration. These two types of parameters, i.e. growth rate (such as* g_{VU0}*) and maximum of the variable (such as* V_{CMU}*), have important effect of the quasi-steady states. The parameters of the other state variables have similar performance and will be quantitatively analyzed in the future work.*

4. the results associated with Fig. 12 and 13 should be moved to the results section. For these scenarios, it would also be important to find out how robust the simulations are and which parameters are the most important to affect the result.

Response: Done. The analysis of the quasi-steady states of the baseline model and revised model are moved to the results section. Some of the parameters are analyzed. The evolution process and quasi-steady states are determined by the colonization rate, mortality rate and carrying capacity (i.e. the maximum of the variable, such as V_{CMU}*). The colonization rate (*g_0*) and carrying capacity (the maximum of the variable) are the most important to affect the result. It is discussed in the section of "Sensitivity analysis".*

I think that these points need to be addressed and will, obviously, require some work. However, I believe that these revisions will improve the manuscript and make the insights more accessible to the reader. I look forward to seeing the revised version of the manuscript.

Response: Thanks.

The list of the main changes in the revised manuscript

1. The detailed dependent relationships are moved to the Appendix A.

2. The table of parameter values is moved into the nomenclature.

3. The parameters, λ, whose values are set to 1.0, are removed from the manuscript.

4. The analysis of the quasi-steady states of the baseline model and revised model are moved to the results section. (Section 4.3)

5. The sensitivity of the parameters in the model is discussed in Section 4.4.

6. Highlight the motivation of the study in the Introduction. Co-evolution of the hydrological and associated systems (including society, economy and ecology) needs to be recognized and incorporated within a suitable modeling approach, in order to predict their reaction to future human or environmental changes (Montanari et al., 2013), which is the aim of this study.

7. Highlight the insights of the study in the Conclusions.

All of the main changes are shown as the following.

A Coupled Modeling Framework of the Co-evolution of Humans and Water: Case Study of Tarim River Basin, Western China

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Abstract

The complex interactions and feedbacks between humans and water are very essential issues but are poorly understood in the newly proposed discipline of socio-hydrology (Sivapalan et al., 2012). An exploratory model with the appropriate level of simplification can be valuable to improve our understanding of the co-evolution and self-organization of socio-hydrological systems driven by interactions and feedbacks operating at different scales. In this study, a simple coupled modeling framework for socio-hydrology co-evolution is developed for the Tarim River Basin in Western China, and is used to illustrate the explanatory power of such a model. The study area is the mainstream of the Tarim River, which is divided into two modeling units. The socio-hydrological system is composed of four parts, i.e., social sub-system, economic sub-system, ecological sub-system, and hydrological sub-system. In each modeling unit, four coupled ordinary differential equations are used to simulate the dynamics of the social sub-system represented by human population, the economic sub-system represented by irrigated crop area, the ecological sub-system represented by natural vegetation cover and the hydrological sub-system represented by water storage~~stream discharge~~. The coupling and feedback processes of the four dominant sub-systems (and correspondingly four state variables) are integrated into several internal system characteristics interactively and jointly determined by themselves and by other coupled systems. For example, the ~~stream discharge~~water storage is coupled to the irrigated crop area by the colonization rate and mortality rate of the irrigated crop area in the upper reach and the irrigated area is reversely coupled to water storage~~stream discharge~~ through irrigation water consumption. In a similar way, the water storage~~stream discharge~~ and natural vegetation cover are coupled together. The irrigated crop area is coupled to human population by the colonization rate and mortality rate of the population. The inflow of the lower reach is determined by the outflow from the upper reach. The natural vegetation cover in the lower reach is coupled to the outflow from the upper reach and governed by regional water resources management policy. The co-evolution of the Tarim socio-hydrological system is then analyzed within this modeling framework to gain insights into the overall system dynamics and its sensitivity to the external drivers and internal system variables. In the modeling framework, the state of each subsystem is holistically described by one state variable and the framework is flexible enough to comprise more processes and constitutive relationships if they are needed to illustrate the interaction and feedback mechanisms of the human-water system.

Keywords: socio-hydrology, evolution, socio-hydrological evolution processes, Tarim River

1. Introduction

In the emergent Anthropocene, the competition for water between humans and the environment leads to the complex interactions between hydrologic and social systems. They play~~s~~ a fundamental role in the past co-evolutionary behavior of~~how~~ the ~~two~~ coupled human-nature system~~s, human/social and natural, have co-evolved in the past~~ and its possible future trajectories~~ of their co-evolution~~. Furthermore, the situation of interactions ~~The interactions between the hydrologic and social subsystems are~~is always changing as social and natural conditions change~~, generating~~. It generates new connections and, in particular, more significant ~~feedbacks which~~feedbacks that need to be understood, assessed, modeled and predicted (Montanari et al., 2013). ~~Socio-hydrology is a new trans-disciplinary field aimed at understanding and predicting the dynamics and co-evolution of coupled human-water systems (Sivapalan et al., 2012).~~ Nevertheless ~~In~~in traditional hydrology~~fact~~, ~~these~~ the ~~important~~ feedback mechanisms between the hydrological and social processes are often ignored~~ in traditional hydrology~~. For example, water consumption activities and landscape changes driven by humans are usually prescribed as external forcing in hydrologic models (Sivapalan et al., 2012) under the assumption of stationarity (Milly et al., 2008; Peel and Blöschl, 2011). In reality, especially in the long-term, human actions in respect of water turn out to be internal processes of the coupled socio-hydrologic system that are not static, but are dynamic and constantly evolving. In traditional research on water resources management, on the other hand, they remain static and externally prescribed. For instance, in the science of integrated water resources management (IWRM) the future state(s) of the coupled system are predicted by a "scenario-based" approach that does not account for the co-evolutionary dynamics of the coupled human-water system (Sivapalan et al., 2012). Consequently, possible future trajectories of the human-water system could not be fully explored or predicted. Therefore socio-hydrology is proposed as a new trans-disciplinary field aimed at understanding and predicting the dynamics and co-evolution of coupled human-water systems (Sivapalan et al., 2012). Based on the successful development of hydrological model in the traditional hydrology with the motivation to identify the limitation of our understanding of the hydrological processes, the research method of numerical modeling is introduced into the socio-hydrology. In this paper, a socio-hydrological modeling framework is set up to explore the limitation of our knowledge of the complex interactions between hydrologic and social systems, and investigate potential ability of the simple modeling framework to predict the possible future trajectories of the human-water system.

~~The above paragraph is not clearly organized. Rewrite it by focusing on interactions~~

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~~between human and water.~~

However, ~~T~~the explicit and detailed description of the interactions between hydrology and society is ~~really~~ rather difficult because society itself is a ~~rather~~ complex nonlinear dynamic system. At the current state of development of socio-hydrology, the interactions and associated feedback mechanisms between hydrological and social processes remain largely unexplored and poorly understood (Di Baldassarre et al., 2013a). In a river basin context, we are not yet in a position where the description of social processes in a coupled socio-hydrologic model can match the level of detail in traditional hydrologic models such as, for example, SWAT (~~???~~Arnold et al., 1998) and THREW (Tian et al., 2006, 2008~~; Tian, 2006; Mou et al.,2008~~). However, there is considerable value in the development and use of simpler, coupled models to improve our understanding of such complex systems. The simplification will be aimed at capturing the most important ~~coupling~~ inter-dependent relationships, and leaves out much of the perhaps unnecessary detail. This is a practice widely adopted in many other inter-disciplinary fields. For example in eco~~hydro~~logy, Levins and Culver (1971) introduced the logistic function to describe the vegetation dynamics, which borrowed ~~adapting~~from ~~similar approaches used to describe~~ population ~~dynamics~~ models (Tsoularis and Wallace, 2002). Baudena et al. (2007) introduced the role of soil moisture into the colonization and extinction rates of vegetation also in the form of a logistic function: in this way soil moisture dynamics is coupled to vegetation dynamics. Lin et al. (2013) developed a simplified but still comprehensive ecohydrological model with pulsed atmospheric forcing to analyze their non-trivial dynamic behaviors both qualitatively and numerically, and confirmed the existence of multiple stationary states. In the case of ~~the~~ social ~~system~~science, ~~the dynamics involving the interactions and feedbacks between human populations and natural resources have been intensively studied by many researchers~~many researchers have intensively studied the interactions and feedbacks between human society and natural resources by using simple constitutive relations. For example, Brander and Taylor (1998) presented a model of renewable resource and population dynamics in the form of a predator-prey model, with humans as the predator and resources as the prey. They applied this model to the historical situation in Easter Island to show that plausible parameter values generate a “feast and famine” pattern of cyclical adjustment in population and resource stocks that may have occurred there. D'Alessandro (2007) studied the long-term dynamic interactions between the exploitation of natural resources and population growth by the Schaefer harvesting production function and found a multiplicity of steady states, which made it possible to consider the effects of technological advances, and cultural and climate changes on the resilience of the existing development pathways. Good and Reuveny (2009) coupled an ecological-economic model of human-resource interaction with endogenous population growth to economic growth theory. Good and Reuveny (2009) used this model to study the abrupt collapse of the Sumerian, Maya, Rapanui and Anasazi peoples and attributed the breakdown to anthropogenic environmental degradation: however, in this case resource use was not explicitly incorporated in their model.

In a socio-hydrologic context, water is the key limited resource that is at the center of ~~the~~ system dynamics. An important part in the understanding of socio-hydrologic processes is to know which way the water is flowing and why this is so (Sivapalan et al., 2012). Kallis (2010) studied the co-evolution of water resource development in Athens, Greece, and found that water supply appears as the response to an insatiable demand, exogenous to the water system, and that water supply and demand in fact co-evolve, new supply generating higher demands, and in turn, higher demands favoring supply expansion over other alternatives. While socio-hydrology is a new scientific discipline, one of its three areas of enquiry, process socio-hydrology, is aimed at gaining more detailed insights into causal constitutive relationships relating to human-water system exchanges (Sivapalan et al., 2012). There have been several pioneering studies that have shown considerable potential in this direction (Di Baldassarre et al., 2013a; Di Baldassarre et al., 2013b; van Emmerik et al., 2014). For example, Di Baldassarre et al. (2013b) developed a simple dynamic model to represent the interactions and feedback loops between hydrological and social processes in the case of flooding, and found that a simple conceptual model is able to reproduce reciprocal effects between floods and people and the generation of emergent patterns from the coupled system dynamics. van Emmerik et al.(2014) presented a parsimonious, stylized, quasi-distributed coupled socio-hydrologic system model, that simulates the two-way coupling between human and hydrological systems, to mimic and explain dominant features of the pendulum swing in the Murrumbidgee River basin.

To show the coupled co-evolution of a socio-hydrological system over a long time frame, ~~The~~the Tarim River Basin in Western China is an excellent example ~~to show the coupled co-evolution of a socio-hydrological system over a long time frame~~ (Liu et al., 2014). The mainstream of the Tarim River is located in an inland arid area. The mean annual precipitation from 1957 to 2010 ~~is~~ was only 34.1 mm and mean annual pan evaporation ~~from 1957 to 2010~~during the same period ~~is~~ was 2630.0 mm at Tieganlike, located in the lower reach of the Tarim River. Because of the extreme dry climate, ~~A~~almost all water consumption in~~from~~ the mainstream of the Tarim River is dependent on the runoff from the headwaters

(Zhou et al., 2012). In the Tarim River Basin, humans are heavily engaged in agricultural production (other industries will be ignored here because almost no other major industry exists in the Tarim River Basin apart from agriculture~~for a start~~~~) which~~), which is highly dependent on the use of water from the Tarim River. In the long history of the Tarim Basin, human populations and their agricultural activities depended exclusively on the water from the Tarim River, and constantly moved with the river as it migrated periodically in response to climatic variations (Liu et al., 2014). In the last 60 years, due to the dramatic increase of irrigated agriculture, the lower reach of the Tarim River has nearly dried up (Deng, 2009), causing the riverine ecosystem to degrade. In order to restore the ecology of the lower reach of the Tarim River, the water allocation policy of river basin management for the Tarim Basin was revised and increasingly more water has been released into the lower reach since 2000 (Chen et al., 2010; Liu et al., 2012b). The adjustment of the water allocation policy can be seen as a response of the social system back to the ecohydrological system and represents a negative feedback in response to the ecologic degradation of the lower reach. In this way, for example, vegetation cover of the lower reach is coupled to the streamflow from the upper reach, thus closing the socio-hydrological feedback loop. At the river basin scale, and on long time scales, the streamflow, vegetation cover, human population and the irrigated crop area could be exchanged between the upper and lower reaches, which are the key co-evolutionary processes associated with the socio-hydrologic system. Co-evolution of hydrological and associated systems (including society, economics and ecology) needs to be recognized and incorporated within a suitable modeling approach, in order to predict their reaction to future human or environmental changes (Montanari et al., 2013). This paper is aimed at developing such a simple coupled model of the co-evolution of the coupled socio-hydrologic system for the Tarim River Basin. The coupled model is then employed to explore the co-evolution of the coupled social, economic, ecological and hydrological sub-systems with the use of chosen constitutive relationships, which are then calibrated with the use of historic data.

The remainder of the paper is organized as follows. In the ~~next section~~Sect. 2~~ on “study area and data”~~, details of the study area and the data used in the modeling are presented, which is followed by the details and justification of the modeling framework adopted for the Tarim River Basin in Sect. 3. Results of model calibration and validation are presented ~~next,~~ along with the ~~results of~~ sensitivity analysis in Sect. 4. The paper concludes with ~~a discussion of~~ the main results and recommendations for future research.

2. Study area and data

2.1. Study area

Tarim River Basin (TRB) is located in Western China and experiences a hyper-arid climate with annual precipitation of 50-100 mm only. It is the largest inland basin of China with an area of 1,100,000 km^2, most of which is covered by the Taklimakan desert. There are four tributaries of the Tarim River, namely Aksu River, Yarkand River, Hotan River, and Kongqi River. The four tributaries serve as main source of water for the mainstream Tarim River, which originates from the point of union of Aksu, Yarkand and Hotan Rivers (near Aral city in western Xinjiang) and empties into a terminal lake (Taitema Lake). The overview of Tarim River Basin and its river system are shown in Figure 1. For more details about TRB, including especially the historical development of the coupled socio-hydrological system within the TRB, please refer to Chen et al. (2010) and ~~the paper by~~ Liu et al. (2013).

In this study, we focus ~~the~~ our modeling efforts on the mainstream part of the Tarim River, i.e., from Aral to Taitema Lake which ~~, for computational reasons,~~ is divided into 2 modeling units, i.e., the upper reach, from Aral (40°31'41"N, 81°16'12"E) to Yingbazha (41°10'28"N, 84°13'45"E), and the “middle and lower” reach (although shortened as the *lower reach* hereafter in the paper), from Yingbazha to Taitema Lake. See Figure 2 for more details about the discretization of the mainstream of the Tarim River into these two units.

2.2. Data

In this study the modeling period is from 1951 to 2010. Daily precipitation and pan evaporation data from Aral and Tikanlik (40°38'N, 87°42'E) ~~are~~ were ~~derived~~ obtained from the data~~-~~set of SURF_CLI_CHN_MUL_DAY_V3.0 of the China Meteorological Data Sharing Service System. Streamflow data at Aral and Yingbazha hydrological stations were collected from the local hydrological ~~agency~~bureau. Data on irrigated area and human population size, which are supported by the mainstream of the Tarim River, have come from several statistics yearbooks, including the Xinjiang Statistical Yearbook, Xinjiang Production & Construction Group Statistical Yearbook, ~~and the~~ Tarim Petroleum Annual, and Xinjiang Fifty Years (1955-2005).

The NDVI (Normalized Difference Vegetation Index) time series data of *typical* (or representative) points near the main channel of the Tarim River are employed as the reference values to the simulated regional vegetation cover. The NDVI data are extracted from MODIS products, "MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V005" (MOD13Q1), with quality control. The vegetation *typical* point in the upper reach (VPU) is located at (40°57'40" N, 82°25'0" E) near Aral as shown in Figure 2. The vegetation *typical* point (VPL) in the middle and lower reach is at (41°1'10" N, 86°14'0" E) near Qiala.

3. Modeling framework for socio-hydrology co-evolution

3.1. General description of the socio-hydrological system

The socio-hydrological system associated with the Tarim River Basin is a complex network of multiple inter-connected processes, and in order to undertake the modeling with the-state-of-the-art understanding of the system, we assume that:

(1) ~~due to the limited water resources of Tarim River, the~~The land use types ~~contain~~ are composed of irrigated crop field~~s~~, naturally vegetated land~~ion~~ and bare desert;

(2) T~~t~~he water requirement of natural vegetation ~~growth~~ in the lower reach is mainly ~~satisfied~~fed by~~mainly comes from~~ the streamflow released from the upper reach;

(3) ~~the~~The released discharge from the upper reach is determined by inflow into the upper reach, degradation of natural vegetation ~~status~~ in the lower reach, and the regional water resources management policy.

~~For more detailed description of the historical evolution of coupled socio-hydrological processes within the TRB, the readers are referred to Liu et al. (2013).~~ The modeling framework for co-evolution of the T~~arim River Basin~~RB socio-hydrological system is shown in Table 1~~Table 1~~. Each modeling unit includes a hydrological system, an ecological system, a social system, and an economic system. Principally TRB is an agricultural society and ~~State variables are employed to describe each system quantitatively. Almost no other major industry exists in the Tarim River Basin, apart from agriculture, and consequently~~ other economic ~~industries~~ sectors (e.g., industrial sector) are neglected in ~~the present modeling effort~~our economic system.

The state variables of each unit are described as follows:

(1) ~~water~~ Water storage (W), in m^3. W represents allocatable ~~assignable~~ water resources of the modeling unit.

(2) ~~vegetation~~ Vegetation cover (V_C), dimensionless, in [0, 1]. V_C represents the natural vegetation cover, which is determined by the available ~~ecological~~ water, and it is defined as the ratio of the area covered by natural vegetation to the area of the modeling unit.

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(3) ~~irrigated~~ Irrigated crop area ratio (R_I), dimensionless, in [0, 1]. R_I is defined as the ratio of irrigated crop area to area of the modeling unit.

(4) Human population (N), in units of 10^4 persons.

In each modeling unit, four ordinary differential equations are used to describe the dynamics of: the hydrological sub-system represented by water storage~~stream discharge~~, ecological sub-system represented by natural vegetation cover, economic sub-system represented by irrigated crop area, and social sub-system represented by human population. The area of modeling unit is noted as A. The subscript U of the symbol represents the upper reach, and the subscript L of the symbol represents the lower reach.

3.2. Water balance of the hydrological sub-system

At the annual scale, we represent the dominant hydrological process~~y~~ of the system in terms of the water balance equation. The water balance equation for the upper reach is given by:

$$\frac{dW_U}{dt} = P_U A_U - E_{tU} A_U V_{CU} - E_{cU} A_U R_{IU} - E_{bU} A_U (1 - V_{CU} - R_{IU}) + Q_{inU} - Q_{outU} \qquad (1)$$

where, P is the annual precipitation, E_t is the annual evapotranspiration~~evaporation~~ from natural vegetation~~ area~~, E_c is the annual evapotranspiration~~evaporation~~ from irrigated crop ~~area~~, and E_b is the annual evaporation from the bare desert, all expressed in mm/yr. We assume that ~~T~~the precipitation falling on the bare desert is ~~assumed to be~~ completely evaporated, i.e.,

$$E_t = k_t E_p$$
$$E_c = k_c E_p \qquad (2)$$
$$E_b = P$$

where E_p is the annual potential evaporation, also in mm/yr, k_t and k_c are the empirical coefficients to calculate the actual evaporation from natural vegetation and crop, respectively. Q_{inU} is the inflow to the upper reach, in m^3/ yr, which is taken as the observed discharge at Aral. Q_{outU} is the outflow from the upper reach, in m^3/ yr, and is determined by Q_{inU}, W_U, V_{CL} and other variables. In principle, Q_{outU} could be calculated as

$$Q_{\mathrm{outU}} = q_1(Q_{\mathrm{inU}}) + q_2(W_{\mathrm{U}}) + q_3(V_{\mathrm{CL}}) \quad (3)$$

The first term on the right hand side of Equation (3)(3), q_1, will increase with upper reach inflow (Q_{inU}), q_2 will increase with W, i.e., assignable allocatable water resource, and q_3 will increase with vegetation cover of the lower reach, accounting for the vegetation restorationgovernment environment protection policy of river basin management. As we do not have the specific constitutive relationships for all three terms (i.e., q_1, q_2, and q_3), Q_{outU} is calculated using the following simplified procedure, which could be refined in a future study.

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If there is sufficient inflow from the headwaters, the streamflow will be released to the lower reach after the water requirement for agriculture and natural vegetation are satisfied. Otherwise, the outflow will be equal to the minimum outflow, i.e., $k_{\mathrm{Q}}Q_{\mathrm{inU}}$, in line with the water allocation policy adopted in this region, and therefore the water requirement for agriculture and natural vegetation will not be fully satisfied. Q_{outU} is then given by:

$$Q_{\mathrm{out\,U}} = \max\left\{P_{\mathrm{U}}A_{\mathrm{U}} - E_{\mathrm{tU}}A_{\mathrm{U}}V_{\mathrm{CU}} - E_{\mathrm{cU}}A_{\mathrm{U}}R_{\mathrm{IU}} - E_{\mathrm{bU}}A_{\mathrm{U}}(1 - V_{\mathrm{CU}} - R_{\mathrm{IU}}) + Q_{\mathrm{in\,U}},\ \ k_{\mathrm{Q}}Q_{\mathrm{in\,U}}\right\} \quad (4)$$

After the Q_{outU} is determined, natural vegetation water requirement may not be fully met and the annual evapotranspirationevaporation of the natural vegetation, i.e. E_{tU}, is given by:

$$E_{\mathrm{tU}} = \max\left\{\frac{P_{\mathrm{U}}A_{\mathrm{U}} - E_{\mathrm{cU}}A_{\mathrm{U}}R_{\mathrm{IU}} - E_{\mathrm{bU}}A_{\mathrm{U}}(1 - V_{\mathrm{CU}} - R_{\mathrm{IU}}) + Q_{\mathrm{in\,U}} - Q_{\mathrm{out\,U}}}{A_{\mathrm{U}}V_{\mathrm{CU}}},\ \ P_{\mathrm{U}}\right\} \quad (5)$$

Finally, the annual evapotranspirationevaporation of the irrigated crop area, E_{cU}, is

$$E_{\mathrm{cU}} = \frac{P_{\mathrm{U}}A_{\mathrm{U}} - E_{\mathrm{tU}}A_{\mathrm{U}}V_{\mathrm{CU}} - E_{\mathrm{bU}}A_{\mathrm{U}}(1 - V_{\mathrm{CU}} - R_{\mathrm{IU}}) + Q_{\mathrm{in\,U}} - Q_{\mathrm{out\,U}}}{A_{\mathrm{U}}R_{\mathrm{IU}}} \quad (6)$$

In a similar way as above, the water balance equation of the lower reach is given by:

$$\frac{dW_{\mathrm{L}}}{dt} = P_{\mathrm{L}}A_{\mathrm{L}} - E_{\mathrm{tL}}A_{\mathrm{L}}V_{\mathrm{CL}} - E_{\mathrm{cL}}A_{\mathrm{L}}R_{\mathrm{IL}} - E_{\mathrm{bL}}A_{\mathrm{L}}(1 - V_{\mathrm{CL}} - R_{\mathrm{IL}}) + Q_{\mathrm{inL}} \quad (7)$$

where, the definitions of the variables are similar to those in the upper reach in Equation (1)~~(1)~~, and Q_{inL} is equal to outflow from upper reach.

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$$Q_{\text{inL}} = Q_{\text{outU}} \tag{8}$$

If the water in the lower reach is sufficient, all of the ~~assignable~~ allocatable water will be evaporated on the bare desert after irrigated agriculture and natural vegetation are satisfied. Otherwise, only the precipitation on the bare soil evaporates. E_{bL} is thus calculated as

$$E_{\text{bL}} = \max\left\{ \frac{P_{\text{L}} A_{\text{L}} - E_{\text{tL}} A_{\text{L}} V_{\text{CL}} - E_{\text{cL}} A_{\text{L}} R_{\text{IL}} + Q_{\text{inL}}}{A_{\text{L}}(1 - V_{\text{CL}} - R_{\text{IL}})},\quad P_{\text{L}} \right\} \tag{9}$$

If the inflow cannot fully meet the water requirement, natural vegetation water requirement will not be fully satisfied and the minimum is the local precipitation. The annual evapotranspiration~~evaporation~~ of the natural vegetation, i.e., E_{tL}, is given by:

$$E_{\text{tL}} = \max\left\{ \frac{P_{\text{L}} A_{\text{L}} - E_{\text{cL}} A_{\text{L}} R_{\text{IL}} - E_{\text{bL}} A_{\text{L}}(1 - V_{\text{CL}} - R_{\text{IL}}) + Q_{\text{inL}}}{A_{\text{L}} V_{\text{CL}}},\quad P_{\text{L}} \right\} \tag{10}$$

Finally, the annual evapotranspiration~~evaporation~~ of the irrigated crop area, E_{cL}, is given by:

$$E_{\text{cL}} = \frac{P_{\text{L}} A_{\text{L}} - E_{\text{tL}} A_{\text{L}} V_{\text{CL}} - E_{\text{bL}} A_{\text{L}}(1 - V_{\text{CL}} - R_{\text{IL}}) + Q_{\text{inL}}}{A_{\text{L}} R_{\text{IL}}} \tag{11}$$

3.3. Natural vegetation dynamics of ecological sub-system

The dynamics of natural vegetation cover is described by Levins' model (Levins and Culver, 1971; Tilman, 1994), which is a logistic type equation (Baudena et al., 2007). The vegetation dynamical equation has ~~already~~ been applied and validated in the Tarim River in ~~(~~Liu et al. (~~,~~ 2012a, b)~~; Liu et al., 2012b)~~. The dynamical equation of vegetation cover of the upper reach is given by:

$$\frac{dV_{\text{CU}}}{dt} = g_{\text{VU}} V_{\text{CU}} (V_{\text{CMU}} - V_{\text{CU}}) - m_{\text{VU}} V_{\text{CU}} \tag{12}$$

where, g_{V} represents the colonization rate and m_{V} represents the mortality rate. V_{CM}

represents the maximum of V_C. It could be determined by planning or by the following equation:

$$V_{CMU} = \frac{\text{available environmental water / water requirement per unit area}}{A_U} \quad (13)$$

The colonization and mortality rates of natural vegetation depend on the environmental water supply. The dependent relationships are shown in Figure 3, which are described by the following equations.

$$g_{VU} = \frac{g_{VU0}}{1+\exp\left(r_{EWSUC} - r_{EWSU}\right)}$$
$$m_{VU} = \frac{m_{VU2} - m_{VU1}}{1+\exp\left(r_{EWSU} - r_{EWSUC}\right)} + m_{VU1} \quad (14)$$

where, g_{VU}, m_{VU1}, m_{VU2}~~,~~ ~~λ_{gVU}, λ_{mVU}~~ and r_{EWSUC} are the empirical parameters. r_{EWS} ~~is~~ can be considered as environmental water supply ratio, i.e., the ratio of available environmental water to environmental water requirement, and dimensionless, in [0, 1]. r_{EWSUC} is the critical value of r_{EWSU}, where r_{EWSU} is defined as:

$$r_{EWSU} = \frac{E_{tU} A_U V_{CU} T}{W_{ERU}} \quad (15)$$

where, T is 1 yr and is equal to the time step of environmental water requirement, W_{ERU} is environmental water requirement.

Similarly, the dynamical equations of vegetation ~~coverage~~cover of the lower reach are

$$\frac{dV_{CL}}{dt} = g_{VL} V_{CL} (V_{CML} - V_{CL}) - m_{VL} V_{CL} \quad (16)$$

$$V_{CML} = \frac{\text{available environmental water / water requirement per unit area}}{A_L} \quad (17)$$

$$g_{VL} = \frac{g_{VL0}}{1+\exp\left(r_{EWSLC} - r_{EWSL}\right)}$$
$$m_{VL} = \frac{m_{VL2} - m_{VL1}}{1+\exp\left(r_{EWSL} - r_{EWSLC}\right)} + m_{VL1} \quad (18)$$

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$$r_{\mathrm{EWSL}} = \frac{E_{\mathrm{tL}} A_{\mathrm{L}} V_{\mathrm{CL}} T}{W_{\mathrm{ERL}}} \quad (19)$$

The dependent relationships of g_{VL} and m_{VL} are presented in Appendix A. The meanings of all the symbols used above are reported in the separate Nomenclature presented at the end of the paper.

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3.4. Dynamic equations of economic sub-system and social sub-system

The evolution of the irrigated crop area is caused balanced by wasteland cultivation and farmland abandonment. So the evolution process of the irrigated crop area can also be described by the logistic type equation, whose form is similar to the vegetation dynamical equation (Levins and Culver, 1971; Tilman, 1994). Good and Reuveny (2006, 2009) also used the similar equation to describe the resource stock in the ecological-economic model of human-resource interaction. Originally, the logistic type equation is introduced to simulate the growth of biological systems. Subsequently there have been a lot of applications of the logistic model outside the field of bBiology also. As summarized by Tsoularis and Wallace (2002), the logistic type equation has been used to describe the market penetration of many new products and technologies, world energy usage and source substitution, an evolutionary process of the industrial revolution. For this case, the evolution of the irrigated crop area is driven by wasteland cultivation and farmland abandonment, which is correspondings to the colonization and mortality. We assume that this evolution , and can be roughly described by the logistic type equation. The dynamical equation of irrigated crop area ratio of the upper reach is

$$\frac{dR_{\mathrm{IU}}}{dt} = g_{\mathrm{RU}} g_{\mathrm{R2U}} g_{\mathrm{R3U}} R_{\mathrm{IU}} (R_{\mathrm{IMU}} - R_{\mathrm{IU}}) - m_{\mathrm{RU}} m_{\mathrm{R2U}} m_{\mathrm{R3U}} R_{\mathrm{IU}} \quad (1820)$$

where, g_{RU}, g_{R2U} and g_{R3U} represent the colonization cultivation rate of new irrigated field. m_{RU}, m_{R2U} and m_{R3U} represent the desolation abondonment rate of current irrigated field. R_{IMU} represents the maximum of R_{IU}. It could be determined by planning or by

$$R_{\mathrm{IMU}} = \frac{\text{available irrigation water / water requirement per unit area}}{A_{\mathrm{U}}} \quad (1921)$$

The terms g_{RU} and m_{RU} represent the impact of available water to the area of irrigated field. The terms g_{R2U} and m_{R2U} represent the impact of natural vegetation cover of the upper reach to the area of irrigated field through the environment protection policy. The terms g_{R3U} and

m_{R3U} represent the impact of natural vegetation cover of the lower reach to the irrigated field area of the upper reach through the environment protection policy. The dependent relationships are similar as shown in Figure 3, which are also ~~described~~ listed in the Appendix A.

~~by the following equations.~~

$$\text{U} = \frac{g_{RU0}}{1+\exp\left(r_{WUC}-r_{WU}\right)}$$

$$\text{U} = \frac{m_{RU2}-m_{RU1}}{1+\exp\left(r_{WU}-r_{WUC}\right)} + m_{RU1}$$

~~where, g_{RU0}, m_{RU1}, m_{RU2}, λ_{gRU}, λ_{mRU} and r_{WUC} are parameters. The term r_{WU} is irrigation water supply ratio and is dimensionless, in [0, 1]. r_{WUC} is the critical value of r_{WU}, which is defined as:~~

$$\text{U} = \frac{E_{cU} A_{U} R_{IU} T}{W_{IRU}}$$

~~where, W_{IRU} is irrigation water requirement. The terms g_{R2U} and m_{R2U} represent the impact of natural vegetation cover of the upper reach to the area of irrigated field through the environment protection policy. The dependent relationships are similar as shown in Figure 3 and described by the following equations.~~

$$\text{2U} = \frac{g_{R2U0}}{1+\exp\left(V_{CUC}-V_{CU}\right)}$$

$$\text{2U} = \frac{m_{R2U2}-m_{R2U1}}{1+\exp\left(V_{CU}-V_{CUC}\right)} + m_{R2U1}$$

~~where, g_{R2U0}, m_{R2U1}, m_{R2U2}, λ_{gR2U}, λ_{mR2U} and V_{CUC} are parameters.~~

~~The terms g_{R3U} and m_{R3U} represent the impact of natural vegetation cover of the lower reach to the irrigated field area of the upper reach through the environment protection policy.~~

~~The dependent relationships are similar as shown in Figure 3 and described by the following equations.~~

$$\text{3U} = \frac{g_{R3U0}}{1+\exp\left(V_{CLC}-V_{CL}\right)}$$

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$$\sim_{R3U} = \frac{m_{R3U2} - m_{R3U1}}{1+\exp\left(V_{CL} - V_{CLC}\right)} + m_{R3U1}$$

~~where, g_{R3U0}, m_{R3U1}, m_{R3U2}, λ_{gR3U}, λ_{mR3U} and V_{CLC} are parameters.~~

Similarly, the dynamical equations of irrigated crop area ratio of the lower reach are

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$$\frac{dR_{IL}}{dt} = g_{RL} g_{R2L} R_{IL} (R_{IML} - R_{IL}) - m_{RL} m_{R2L} R_{IL} \qquad (20~~26~~)$$

$$R_{IML} = \frac{\text{available irrigation water / water requirement per unit area}}{A_L} \qquad (21~~27~~)$$

$$g_{RL} = \frac{g_{RL0}}{1+\exp\left(r_{WLC} - r_{WL}\right)}$$

~~(28)~~

$$m_{RL} = \frac{m_{RL2} - m_{RL1}}{1+\exp\left(r_{WL} - r_{WLC}\right)} + m_{RL1}$$

$$r_{WL} = \frac{E_{cL} A_L R_{IL} T}{W_{IRL}}$$

~~(29)~~

$$g_{R2L} = \frac{g_{R2L0}}{1+\exp\left(V_{CLCL} - V_{CL}\right)}$$

~~(30)~~

$$m_{R2L} = \frac{m_{R2L2} - m_{R2L1}}{1+\exp\left(V_{CL} - V_{CLCL}\right)} + m_{R2L1}$$

Again, ~~T~~the dependent relationships of g_{RL}, m_{RL}, g_{R2L}, and m_{R2L} are described in the Appendix A, and t~~. T~~he meanings of symbols are presented in the Nomenclature section later in the paper.

In the socio-economic system, the dynamic evolution of the population is traditionally simulated by the logistic type equation (Tsoularis and Wallace, 2002). Both of the growth term and mortality term are dependent on the environment and agriculture. The dynamical equation of the population of upper reach is

$$\frac{dN_U}{dt} = g_{NU} g_{N2U} N_U (N_{MU} - N_U) - m_{NU} m_{N2U} N_U \qquad (22~~31~~)$$

where, g_{NU} and g_{N2U} represent the colonization and migration rate of the human population. m_{NU} and m_{N2U} represent the mortality and emigration rate. N_M represents the maximum of N.

It could be assigned depending on the planning arrangements.

The terms g_{NU} and m_{NU} represent the impact of the environment, i.e. V_{CU} to the population of the upper reach. The terms g_{N2U} and m_{N2U} represent the impact of the agriculture, i.e. R_{IU} to the population of the upper reach. The dependent relationships of the population on the environment, i.e. V_{CU}, are similar as shown in Figure 3, which are described in the Appendix A.by the following equations.

$$g_{NU} = \frac{g_{NU0}}{1+\exp\left(V_{CUCNU} - V_{CU}\right)}$$

$$m_{NU} = \frac{m_{NU2} - m_{NU1}}{1+\exp\left(V_{CU} - V_{CUCNU}\right)} + m_{NU1}$$

)

where, g_{NU0}, m_{NU1}, m_{NU2}, λ_{gNU}, λ_{mNU} and V_{CUCNU} are parameters.

The dependent relationships of the population on agriculture, i.e. R_{IU}, are similar as shown in Figure 3, which are described as:

$$g_{N2U} = \frac{g_{N2U0}}{1+\exp\left(R_{IUCNU} - R_{IU}\right)}$$

(33)

$$m_{N2U} = \frac{m_{N2U2} - m_{N2U1}}{1+\exp\left(R_{IU} - R_{IUCNU}\right)} + m_{N2U1}$$

where, g_{N2U0}, m_{N2U1}, m_{N2U2}, λ_{gN2U}, λ_{mN2U} and R_{IUCNU} are parameters.

Similarly, the dynamical equations of the population of the lower reach are,

$$\frac{dN_L}{dt} = g_{NL} g_{N2L} N_L (N_{ML} - N_L) - m_{NL} m_{N2L} N_L \qquad (2334)$$

$$g_{NL} = \frac{g_{NL0}}{1+\exp\left(V_{CLCNL} - V_{CL}\right)}$$

(35)

$$m_{NL} = \frac{m_{NL2} - m_{NL1}}{1+\exp\left(V_{CL} - V_{CLCNL}\right)} + m_{NL1}$$

$$g_{N2L} = \frac{g_{N2L0}}{1+\exp\left(R_{ILCNL} - R_{IL}\right)} \qquad (36)$$

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$$~~m_{N2L} = \frac{m_{N2L2} - m_{N2L1}}{1+\exp\left(R_{IL} - R_{ILCNL}\right)} + m_{N2L1}~~$$

The descriptions for the dependent relations and sybmbos are refered to the Appendix A and Nomenclature.~~The dependent relationships of g_{NL}, m_{NL}, g_{N2L}, and m_{N2L} are described in the Appendix A. The meanings of symbols are presented in the Nomenclature section later in the paper.~~

3.5. Feedback loops in the socio-hydrological system

The socio-hydrological processes are coupled by dependent relationships and feedbacks generated in the socio-hydrological system. There are 4 main feedback loops in the socio-hydrological system of Tarim River as shown in Figure 4.

The first feedback loop is W_U-V_{CU}-R_{IU}-W_U. This is a negative feedback. If the inflow to the upper reach increases the allocatable~~assignable~~ water resources (W_U) will increase and then there will be more water to foster natural vegetation (V_{CU}). With the increase of V_{CU}, the irrigated crop area will expand and the irrigation water consumption will increase correspondingly. As a result, the allocatable~~assignable~~ water resources (W_U) will decrease and the allocatable~~assignable~~ water resource (W_U) receives a negative feedback. The second feedback loop is W_L-V_{CL}-R_{IL}-W_L. This is a negative feedback. The processes underlying the negative feedback, W_L-V_{CL}-R_{IL}-W_L, in the lower reach is the same as that in the upper reach.

The third loop is V_{CL}-W_U-W_L-V_{CL}. This is a negative feedback. If the natural vegetation in the lower reach (V_{CL}) decreases, the partition of the water resources in upper reach (W_U) will change to increase outflow of the upper reach (Q_{outU}), which depends on water resources management and vegetation protection policies. So the inflow of lower reach will increase and there will be more water to allocate in the lower reach (W_L). With more water supplied to natural vegetation, the natural vegetation in the lower reach (V_{CL}) will recover and thus receives a negative feedback. In the current model, this feedback is not in effect. Its role will be analyzed later in the discussion section.

The fourth loop is R_{IU} -W_U-W_L-V_{CL}-R_{IU}. This is a negative feedback. If the irrigated crop area in the upper reach (R_{IU}) increases, more water (W_U) will be used by irrigation in the upper reach and less water will be released to the lower reach. So the allocatable~~assignable~~ water resources (W_L) will decrease and there will be less water for the natural vegetation in the lower reach (V_{CL}). It may lead to decrease of the natural vegetation (V_{CL}) and then the

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irrigated crop area in the upper reach (R_{IU}) may decrease because of environment protection policy. In the equations, g_{R3U} will decrease and m_{R3U} will increase with the decrease of V_{CL}. As a result, R_{IU} receives a negative feedback. The dependent relationship of the irrigated field area of upper reach (R_{IU}) to the natural vegetation coverage of lower reach (V_{CL}) is the key chain of the feedback loop.

4. Socio-hydrologic evolution processes within Tarim River Basin

The modeling framework for socio-hydrologic co-evolution is applied to the mainstream of Tarim River at an annual time step from 1951 to 2010.

4.1. Parameters of the model

The parameters of the model are listed in the Nomenclature~~Table 2~~. The estimation of the parameter values is important for model application. A total of 66 parameters arise from the constitutive relationships presented in the model description above, almost all of which are presently unmeasurable directly, at least with the present state-of-the-art understanding of the associated socio-hydrological processes. Based on reference to the parameter values in Baudena et al. (2007) and Liu et al. (2012b), some of the parameter values are semi-quantitatively estimated by fitting the observed co-evolution process. The other parameters are estimated based on the status of the Tarim River. The values of the parameters are presented in ~~Table 2~~ the Nomenclature.

4.2. Initial values of the systems states

The initial values of the system states are obtained from the literature, which are listed in Table 2~~Table 3~~. The ~~assignable~~ allocatable water volume of both modeling units is assumed to be zero. The initial population of the upper reach is 17×10^{4} persons, which refers to the actual population in 1951. The initial population of the lower reach is 21×10^{4} persons. The vegetation cover and irrigated crop area ratio are assigned reasonable initial values referring to what is known about the evolution processes.

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4.3. ~~Simulation results~~ Dynamics of the socio-hydrological system

The simulation results of discharge, vegetation cover, ratio of irrigated area and population of two modeling units are shown in Figures 5, 6, 7, 8, 9, 10 and 11, respectively. Although the water balance equation is at the annual scale, the simulated outflow of upper reach is close to the observed outflow, as shown in Figure 5. For comparison, the observed inflow of the upper reach is also shown in Figure 5 and the simulated outflow shows almost the same trend as the inflow. The average annual runoff of the inflow at Aral from 1957 to 2008 is 4.536×10^{9} m^3 and the average annual runoff of the outflow at Yingbazha is 2.760×10^{9} m^3, which is 60.8% of the inflow. The simulated annual mean runoff of the outflow is 2.312×10^{9} m^3, which is 51.0% of the inflow, and is 16.2% less than the observed value.

The evolution dynamics of ~~evolution of~~ vegetation cover are shown in Figures 6 and 7. Due to the scarcity of the long-term areal vegetation cover, point vegetation cover data from 2000 to 2010 are employed as reference. As shown in Figures 6 and 7, the simulated vegetation cover decreases from 1951 to 2010 and holds at the similar level with the vegetation cover of the vegetation typical point of the upper reach and lower reach, respectively. The vegetation cover evolution should be validated in future based on ~~the~~ more historical data.

Irrigated crop area is one of the critical variables of the socio-economic system in the Tarim River Basin. The catchment area of the main stream of Tarim River is 4.6×10^{4} km^2 and the mainstream is the typical inland river, where no runoff can be generated and all water comes from the headwaters (Sun et al., 2003). In the calculation of the irrigated crop area ratio, the area of the modeling unit represents the area within 10 km of both of the riversides along the river channel. Most of the farmland is located within this area. The simulated values of irrigated crop area ratio are shown in Figures 8 and 9. From 1951 to 2010, the simulated irrigated crop area ratio (R_I) increases all the time and is similar to the observed R_I from 1989 to 2010. The average absolute value of relative error of the simulated R_I in the upper reach is 5.2% and is 12.3% in lower reach. The R_I of the upper reach is much higher than the R_I of lower reach because there is more water in the upper reach than in the lower reach in Tarim River, which is an inland river basin. In contrast, there is more runoff in the lower reach than that in the upper reach, usually in the exorheic rivers.

The human population is another important variable in the socio-economic system, especially in this agriculture-dominant river basin. The simulated population is shown in Figures 10 and 11. In both of the two modeling units, the simulated population numbers are very close to the observed values. Although, the simulated population of the lower reach is higher than the observed after 1990, the dynamical equation describes the evolution of the population quite well. The average absolute value of relative error of the simulated population in the upper reach is 3.9% and is 2.7% in the lower reach. Based on the outcomes of the co-evolution model, it appears that the system has not yet reached a steady state. The inflow of the upper reach and the policy of the river basin management, i.e. water allocation scheme, will influence the future trajectories of the system states.

Although the evolution of the socio-hydrological system is driven by the interactions of humans and water as governed by the Taiji-Tire Model (Liu et al., 2014), the productive and restorative actions of the humans (Emmerik et al., 2014), invoked either actively or passively, and intentionally or unconsciously, are at the core of these interactions. In fact, the observed co-evolution is the consequence of the balancing of the water's economic value and water's ecological value by humans. At different stages of the socio-hydrological system, the dominant driving forces may be different. During the 1951-2010 period the dominant driving force was indeed the productive force, i.e., expanding agricultural production within the Tarim River Basin. The realization of the productive force is the water allocation scheme established as part of the river basin management. From 1951 to 2010, agricultural production increased significantly and contributed to the growth of agricultural productivity. During this period, irrigation water was unconstrained and water that otherwise would have served the ecological system was instead exploited and assigned for agricultural irrigation. The ecological water ratio, i.e. the ratio of ecological water to the total water consumption, decreased from 67.0% (1951-1990) to 35.1% (1991-2010). Consequently, ~~fractional~~ vegetation cover decreased, as shown in Figures 6 and 7.

The degradation of the ecological system since 1990 contributed to a re-evaluation of the original water allocation scheme within the Tarim River Basin. A research project, by Xi'an University of Technology and Tarim River Basin Management Bureau, and funded by the Ministry of Water Resources of the People's Republic of China, studied a more rational water resources allocation scheme for the Tarim River Basin. The results of a scenario analysis suggested that, the ratio of ecological water to the total water consumption could reach 50.2%~~ in 2020 when the runoff frequency at Aral is 50%~~ if the recurrence interval of the annual runoff at Aral in 2020 is 2 years, in the commendatory scenario. With the implementation of the new water resources allocation scheme, the dominant driving force may have been switched to the environmental restorative force. But in the current model, the negative feedback, "V_{CL}–W_U–W_L–V_{CL}", is not in effect. The model should be revised to activate the restorative force to analyze the long-term evolution dynamics.

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~~5. Discussion~~

In order to study the evolution of the socio-hydrological system, precipitation, evapotranspiration~~evaporation~~ and inflow are repeated another 4 times after 1951-2010 to obtain a series of 300-years. In the current modeling framework, denoted as the baseline model, a quasi-steady state of the system is reached in the 300-years simulation. The dynamics of the resulting co-evolution are shown in Figure 12. After 2100, vegetation cover, irrigated crop area ratio and population almost approach quasi-steady states. The average values of system variables in the last 60 years, i.e. from 2191 to 2250, are shown in Table 3~~Table 4~~. It shows that 34.6% of the inflow is released into the lower reach. The average vegetation cover of the upper reach is 0.220 and is 0.005 in the lower reach (much smaller than that in the upper reach). The average irrigated crop area ratio of the upper reach is 0.299 and is 0.115 in the lower reach. The average population number of the upper reach is 109.7×10^4 ~~persons~~ and is 50.5×10^4 ~~persons~~ in the lower reach. All of the above 6 variables are much smaller than the maximum values shown in the Nomenclature~~Table 2~~.

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In the baseline model, the outflow of the upper reach (Q_{outU}) is not connected to the natural vegetation of the lower reach. In fact, the outflow of upper reach has been now regulated through changes to the river basin management policy after 2000 in order to restore the natural vegetation of the lower reach, i.e., the negative feedback "V_{CL}-W_{U}-W_{L}-V_{CL}" is now in effect. So the parameter k_{Q} in Equation (4)~~(4)~~ could be calculated as

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$$k_{\mathrm{Q}} = k_{\mathrm{qc}}\exp(-k_{\mathrm{qa}}V_{\mathrm{CL}}) + k_{\mathrm{qb}} \qquad (24~~37~~)$$

where, k_{qa}, k_{qb} and k_{qc} are parameters, as shown in ~~Table 2~~. When V_{CL} is 0, k_{Q} is 0.50. When V_{CL} is 0.3, k_{Q} is 0.3. When V_{CL} is more than 0.3, k_{Q} is still 0.3. So the outflow of upper reach (Q_{outU}) in Equation (4)~~(4)~~ is

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$$Q_{\mathrm{outU}} = (k_{\mathrm{qc}}\exp(-k_{\mathrm{qa}}V_{\mathrm{CL}}) + k_{\mathrm{qb}})Q_{\mathrm{inU}} \qquad (25~~38~~)$$

The resulting model is denoted here as the *revised model*. The dynamics of co-evolution governed by the inclusion of the Equation (25)~~(38)~~ and using the 300-years forcing data are shown in Figure 13. It shows that the natural vegetation of the lower reach is obviously improved. The average values of system variables in the last 60 years are compared in Table

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3Table 4. In contrast, the vegetation cover, irrigated crop area ratio and the population in upper reach in the last 60 years modeled by the revised model are smaller than those in the baseline model and the vegetation cover, irrigated crop area ratio and population in the lower reach in the 60 years modeled by the revised model are larger than those in the baseline model.

This behavior is attributed to the equation for Q_{outU}, i.e., Equation (38), which is the driver for water release from the upstream to the downstream. In Equation (38), as the vegetation cover in the lower reach decreases, more water will be released to the lower reach from the upper reach. The environmental feedback forcing the system to release more water to the downstream, i.e., the third feedback loop of V_{CL}-W_U-W_L-V_{CL}, is thus activated in the revised model, in this way the restorative force is invoked to restore the vegetation in the lower reach. With water flowing into the lower reach, vegetation cover, irrigated crop area and population also effectively “flow” into the lower reach. The runoff flowing into the lower reach increases by 36.7% and the variable which changes most is the vegetation cover in the lower reach, which increases from 0.005 to 0.017, i.e., an increase of 240.0%, as shown in Table 3Table 4. The state to which the vegetation cover could be restored is determined by the water resources allocation, i.e., in other words the relative preference by humans between the economic value and ecological value. It is exhibited as the relative priority given to water resource allocation between the upper and the lower reaches, and between different sectors within one reach. Although vegetation in the revised model is on the increase, the ecological water ratio is 9.3% in the revised model and is 16.3% in the baseline model, over the last 60 years. These values are far smaller than the 50.2%, which is the ecological water ratio in the new water resources allocation scheme. Therefore, water use priority (expressing the value of society for water) is another driver, which drives the water to be channeled into ecological water consumption. This driver would need to be explicitly considered in the modeling of socio-hydrological systems in the future.

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National water policy also has an important effect on regional land use and ecological co-evolution. After the implementation of the national policies of “returning farmland to forest” and “returning pasture to grassland”, vegetation cover increased from 31% in 2000 to 53% in 2012 (Reported by Ministry of Land and Resources of the People's Republic of China, http://www.mlr.gov.cn/xwdt/chxw/201312/t20131210_1295585.htm). In addition, the Water and Ecology Civilization Establishment was formed in 2013, with water allocation scheme to be optimized by the Ministry of Water Resources of the People's Republic of China. In this way water would be reallocated between the upper and lower reaches, and between different sectors within each reach, in such a way that the restorative force would be dominant.

In both the baseline model and the revised model, the states of the socio-hydrological system reach quasi-steady states after 2100. The rates at which these quasi-steady states are reached are rather fast compared to ~~common~~ the intuition, which could be ascribed to the absence of technology improvement in the co-evolution model. As irrigation technology advances, irrigation coefficient (k_c) will decrease and irrigation water requirement will decrease. As a result, the quasi-steady state may be attained much later. The importance of technology advance was highlighted by Good and Reuveny (2009) who, however, assumed that technology is static in their work. Alvarez and Bilancini (2011) and Bilancini and D'Alessandro (2012) included the development of technology in their social system model. Based on the results presented here, it is clear that the advance of the technology should be incorporated in future efforts at the modeling of socio-hydrological systems.

4.4. Sensitivity analysis

In order to assess the effect of the initial values and boundary conditions to system quasi-steady state, ~~analyze~~ the sensitivity of system behaviors to initial values and boundary conditions, i.e. the precipitation, potential evaporation and inflow of the upper reach, is analyzed in the baseline model, which is re-run under different combinations of initial and boundary conditions. ~~The irrigation coefficient (k_c) is an important parameter for system behavior and it is also included in the sensitivity analysis.~~ The results are listed in Table 4~~Table 5~~, where the initial values, precipitation, potential evaporation, and inflow of the upper reach ~~and k_c~~ are decreased or increased by 10%, respectively. The results show that all the tested conditions can alter system quasi-steady state except for the initial values. In our tested ranges, the system presents unique quasi-steady states without regard to initial values. The relative change rate of quasi-steady states compared with the baseline results are shown in Table 5~~Table 6~~, which indicates that the changes of the precipitation have a slight effect and the relative change is in the range of -1%~1%. Otherwise, the potential evaporation, and inflow of the upper reach ~~and k_c~~ have significant effects especially on the vegetation cover of the lower reach (V_{CL}). Furthermore, our test results show that initial/boundary conditions have only a slight impact on the population of the upper and the lower reaches, and the relative change is in the range of -1%~1%. Generally, the boundary conditions including potential evaporation and upper reach inflow play an important role in the system

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co-evolution.

The sensitivity of the parameters in the model is an important approach to identify the critical parameters which affect the performance of the model. In the hydrological sub-system, the crop coefficient of evapotranspiration (k_c) is an important parameter for system behavior. The crop coefficient of evapotranspiration (k_c) is decreased or increased by 10%, respectively, to assess the effect on the system quasi-steady state and the results are listed in Table 5 and Table 6. k_c has significant effects on the vegetation cover of the lower reach (V_{CL}) and slight effects on the other quasi-steady states. In the ecological sub-system, economic sub-system and social sub-system, the state variables are governed by logistic type equation, whose characteristics have been investigated by many scholars (Levins and Culver, 1971; Tilman, 1994; Tsoularis and Wallace, 2002). Because the interactions between the sub-systems will affect the colonization rate and mortality rate, the colonization rate only changes in the range from 0 to g_{VU0} and mortality rate change in the range from m_{VU1} to m_{VU2}, taking the vegetation cover of the upper reach as an example. The evolution process and quasi-steady states are determined by the colonization rate, mortality rate and carrying capacity (i.e. the maximum of the variable, such as V_{CMU}). The parameters of the vegetation cover of the upper reach(V_{CU}) are decreased or increased by 10% to assess the effects on the quasi-steady states of the system and the results are shown in Table 5 and Table 6. V_{CMU} and g_{VU0} have marked effect on the quasi-steady states of V_{CU} and V_{CL} because the change of the V_{CU} induces the change of the outflow from the upper reach. The quasi-steady states is not sensitive to the other parameters. The parameters of the other state variables have similar performance and will be quantitatively analyzed in the future work.

6.5.Conclusions

Because water plays an important role in the socio-hydrological system in Tarim River Basin,For socio-hydrological systems, their hydrological process, ecological process and socioeconomic process are coupled together by via water consumption activities and water allocation policiesy within the river basin. The A socio-hydrologic co-evolution model, a simple coupled modeling framework, is developed in this study to illustrate the explanatory power of such modelsfor the Tarim River Basin in Western China, and is appliedused in the Tarim River Basin in Western China to illustrate the explanatory power of such models to reproduce the past trajectories of the human-water system and to predict the possible future trajectories. The socio-hydrological system in the modeling frame work consists of hydrological sub-system, ecological sub-system, economic sub-system and social sub-system, which are represented by water storage, vegetation cover, irrigated crop area ratio and human

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population. The interaction between the sub-systems are actualized via the dependent relationships of the internal variables on the state variables.

~~In the Tarim River, humans depend heavily on agricultural production, and the socioeconomical processes can be described principally by two variables, i.e., irrigated area and human population. The eco-hydrological processes are expressed in terms of area under natural vegetation and water storage~~~~stream discharge~~.

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~~In each modeling unit, four ordinary differential equations are used to simulate the dynamics of the hydrological system represented by water storage~~~~stream discharge~~, ~~ecological system represented by area under natural vegetation, the economic system represented by irrigated area under agriculture and social system represented by human population. The four dominant variables are coupled together by several internal variables. Due to the macro-scale aspect of the socio-hydrological evolution model, the parameterization of the model is an important issue. The annual precipitation, pan evaporation, and streamflow of the headwater are used to drive the model. The discharge of the upper reach, natural vegetation coverage, irrigated area, and human population are employed to assess the performance of the socio-hydrological evolution model.~~

Forced by the annual precipitation, pan evaporation and streamflow of the headwater, the socio-hydrologic co-evolution model reproduces the past trajectories of the human-water system in the Tarim River Basin. The simulated evolution processes of the socio-hydrological evolution model are consistent with observed behaviors, such as the outflow of the upper reach, vegetation cover, irrigated crop area ratio and human population.

The long-term simulation results suggest that the socio-hydrological system of the Tarim River Basin has so far not reached a steady state, and in the “current” dependent constitutive relationships, i.e., river basin management policy, the system will evolve to a state with very low vegetation cover in the lower reach. In order to incorporate ecological protection of the lower reach in the water allocation policy of regional watershed management, a new dependent relationship of the outflow of upper reach is developed in the revised model and the outflow of the upper reach (Q_{outU}) will increase while the natural vegetation cover of lower reach deceases. In contrast, the steady state in the revised model will have higher vegetation cover than that in the baseline model, and the irrigated crop area and population in the lower reach will increase, too. ~~The dependent relationships between the variables should be identified further so as to enhance the utility of the model.~~

The co-evolution of the socio-hydrological system is the consequence of the balancing of the productive force and the restorative force, which are the balance of the water's economic value and water's ecological value by humans, in substance. At different stages of the socio-hydrological system, the dominant driving forces may be different. Before the establishment of the water resources management system of the river basin, human's preference of the water's value is its ~~unconsciously and usually is the~~ economic value. With the river basin management, the preference is intentionally and determined by the managers of the river basin. The preference of the value is explicitly represented by the water use priority in the water resources allocation. In the socio-hydrologic co-evolution model, the water use priority between the upper and the lower reaches is described by the water allocation order and constitutive relationships of the outflow in the upper reach. The water use priority between different sectors within one reach is described by the water allocation order.

To achieve the aim to predict the possible future trajectories of socio-hydrological system based on the socio-hydrologic co-evolution model, the model should be improved in two ways. The first is to identify the feedbacks between the subsystems and especially the dominant feedbacks in the socio-hydrologic system, which forces the co-evolution. The second is to describe the dependent relationships between the variables quantitatively using a proper mathematic formula so as to activate the feedbacks in the model. The improvement of such models depends on the understanding of the socio-hydrologic processes, analysis of the historical co-evolution and comparison of pre-existing socio-hydrologic models.

Appendix A The dependent relationships of the variables

The dependent relationships of g_{VL} and m_{VL} in Section 3.3 are described by the following equations.

$$g_{VL} = \frac{g_{VL0}}{1+\exp\left(r_{EWSLC} - r_{EWSL}\right)}$$

$$m_{VL} = \frac{m_{VL2} - m_{VL1}}{1+\exp\left(r_{EWSL} - r_{EWSLC}\right)} + m_{VL1} \qquad (26~~18~~)$$

$$r_{EWSL} = \frac{E_{tL} A_L V_{CL} T}{W_{ERL}} \qquad (27)$$

The dependent relationships of g_{RU} and m_{RU} in Section 3.4 are described by the following equations.

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$$g_{\mathrm{RU}} = \frac{g_{\mathrm{RU0}}}{1+\exp\left(r_{\mathrm{WUC}} - r_{\mathrm{WU}}\right)}$$

$$m_{\mathrm{RU}} = \frac{m_{\mathrm{RU2}} - m_{\mathrm{RU1}}}{1+\exp\left(r_{\mathrm{WU}} - r_{\mathrm{WUC}}\right)} + m_{\mathrm{RU1}} \tag{28}$$

where, g_{RU0}, m_{RU1}, m_{RU2} and r_{WUC} are parameters. The term r_{WU} is irrigation water supply ratio and is dimensionless, in [0, 1]. r_{WUC} is the critical value of r_{WU}, which is defined as:

$$r_{\mathrm{WU}} = \frac{E_{\mathrm{cU}} A_{\mathrm{U}} R_{\mathrm{IU}} T}{W_{\mathrm{IRU}}} \tag{29}$$

where, W_{IRU} is irrigation water requirement.

The dependent relationships g_{R2U} and m_{R2U} in Section 3.4 are described by the following equations.

$$g_{\mathrm{R2U}} = \frac{g_{\mathrm{R2U0}}}{1+\exp\left(V_{\mathrm{CUC}} - V_{\mathrm{CU}}\right)}$$

$$m_{\mathrm{R2U}} = \frac{m_{\mathrm{R2U2}} - m_{\mathrm{R2U1}}}{1+\exp\left(V_{\mathrm{CU}} - V_{\mathrm{CUC}}\right)} + m_{\mathrm{R2U1}} \tag{30}$$

where, g_{R2U0}, m_{R2U1}, m_{R2U2} and V_{CUC} are parameters.

The dependent relationships of g_{R3U} and m_{R3U} in Section 3.4 are described by the following equations.

$$g_{\mathrm{R3U}} = \frac{g_{\mathrm{R3U0}}}{1+\exp\left(V_{\mathrm{CLC}} - V_{\mathrm{CL}}\right)}$$

$$m_{\mathrm{R3U}} = \frac{m_{\mathrm{R3U2}} - m_{\mathrm{R3U1}}}{1+\exp\left(V_{\mathrm{CL}} - V_{\mathrm{CLC}}\right)} + m_{\mathrm{R3U1}} \tag{31}$$

where, g_{R3U0}, m_{R3U1}, m_{R3U2} and V_{CLC} are parameters.

The dependent relationships of g_{RL}, m_{RL}, g_{R2L}, and m_{R2L} in Section 3.4 are described by the following equations.

$$g_{\mathrm{RL}} = \frac{g_{\mathrm{RL0}}}{1+\exp\left(r_{\mathrm{WLC}} - r_{\mathrm{WL}}\right)}$$

$$m_{\mathrm{RL}} = \frac{m_{\mathrm{RL2}} - m_{\mathrm{RL1}}}{1+\exp\left(r_{\mathrm{WL}} - r_{\mathrm{WLC}}\right)} + m_{\mathrm{RL1}} \tag{32}$$

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$$r_{WL}=\frac{E_{cL}A_{L}R_{IL}T}{W_{IRL}} \tag{33}$$

$$g_{R2L}=\frac{g_{R2L0}}{1+\exp\left(V_{CLCL}-V_{CL}\right)}$$

$$m_{R2L}=\frac{m_{R2L2}-m_{R2L1}}{1+\exp\left(V_{CL}-V_{CLCL}\right)}+m_{R2L1} \tag{34}$$

The meanings of symbols are presented in the Nomenclature section.

The dependent relationships of g_{NU} and m_{NU} in Section 3.4 are described by the following equations.

$$g_{NU}=\frac{g_{NU0}}{1+\exp\left(V_{CUCNU}-V_{CU}\right)}$$

$$m_{NU}=\frac{m_{NU2}-m_{NU1}}{1+\exp\left(V_{CU}-V_{CUCNU}\right)}+m_{NU1} \tag{35}$$

where, g_{NU0}, m_{NU1}, m_{NU2} and V_{CUCNU} are parameters.

The dependent relationships of g_{N2U} and m_{N2U} in Section 3.4 are described by the following equations.

$$g_{N2U}=\frac{g_{N2U0}}{1+\exp\left(R_{IUCNU}-R_{IU}\right)}$$

$$m_{N2U}=\frac{m_{N2U2}-m_{N2U1}}{1+\exp\left(R_{IU}-R_{IUCNU}\right)}+m_{N2U1} \tag{36}$$

where, g_{N2U0}, m_{N2U1}, m_{N2U2} and R_{IUCNU} are parameters.

The dependent relationships of g_{NL}, m_{NL}, g_{N2L}, and m_{N2L} in Section 3.4 are described by the following equations.

$$g_{NL}=\frac{g_{NL0}}{1+\exp\left(V_{CLCNL}-V_{CL}\right)}$$

$$m_{NL}=\frac{m_{NL2}-m_{NL1}}{1+\exp\left(V_{CL}-V_{CLCNL}\right)}+m_{NL1} \tag{37}$$

$$g_{N2L}=\frac{g_{N2L0}}{1+\exp\left(R_{ILCNL}-R_{IL}\right)} \tag{38}$$

$$m_{\mathrm{N2L}} = \frac{m_{\mathrm{N2L2}} - m_{\mathrm{N2L1}}}{1 + \exp\left(R_{\mathrm{IL}} - R_{\mathrm{ILCNL}}\right)} + m_{\mathrm{N2L1}}$$

The meanings of symbols are presented in the Nomenclature section.

Acknowledgements

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Table 1 Modeling framework for socio-hydrology co-evolution of Tarim River

Modeling unit	System	State variable	Dependent factor	Modeling variable	Reason to neglect
	Hydrological system	Water storage	Water consumption and policy	Water storage (W)	-
	Ecological system	Natural vegetation area	Water supply	Vegetation ~~coverage~~cover (V_C)	-
upper reach	Economic system	Industry product	-	-	Nearly none
		Irrigated crop area	Water supply and vegetation ~~coverage~~cover	Irrigated crop area Ratio (R_I)	-
	Social system	Population	Irrigated crop area and vegetation ~~coverage~~cover	Population (N)	-
	Hydrological system	Water storage	Water consumption and policy	Water storage (W)	-
	Ecological system	Natural vegetation area	Water supply	Vegetation ~~coverage~~cover (V_C)	-
middle and lower reach	Economic system	Industry product	-	-	Nearly none
		Irrigated crop area	Water supply and vegetation ~~coverage~~cover	Irrigated crop area Ratio (R_I)	-
	Social system	Population	Irrigated crop area and vegetation ~~coverage~~cover	Population (N)	-

Table 2 Parameter values of the model

Variable	Unit	Value	Equation
k_{tU}	-	0.3	(2)
k_{cU}	-	0.4	(2)
k_{Q}	-	0.3	(4)
k_{tL}	-	0.28	(7)
k_{cL}	-	0.38	(7)
V_{CMU}	-	0.6	(12)
r_{EWSUC}	-	0.3	(14)
g_{VU0}	1/yr	0.8	(14)
m_{VU1}	1/yr	0.1	(14)
m_{VU2}	1/yr	0.3	(14)
λ_{gVU}	-	1.0	(14)
λ_{mVU}	-	1.0	(14)
V_{CML}	-	0.5	(16)
r_{EWSLC}	-	0.3	(18)
g_{VL0}	1/yr	0.8	(18)
m_{VL1}	1/yr	0.1	(18)
m_{VL2}	1/yr	0.3	(18)
λ_{gVL}	-	1.0	(18)
λ_{mVL}	-	1.0	(18)
r_{IMU}	-	0.6	(20)
r_{WUC}	-	0.3	(22)
g_{RU0}	1/yr	0.62	(22)
m_{RU1}	1/yr	0.02	(22)
m_{RU2}	1/yr	0.1	(22)
λ_{gRU}	-	1.0	(22)
λ_{mRU}	-	1.0	(22)
V_{CUC}	-	0.2	(24)
g_{R2U0}	-	1.5	(24)
m_{R2U1}	-	1.1	(24)
m_{R2U2}	-	1.3	(24)
λ_{gR2U}	-	1.0	(24)
λ_{mR2U}	-	1.0	(24)
V_{CLC}	-	0.1	(25)

g_{R3U0}	-	1.5	(25)
m_{R3U1}	-	1.1	(25)
m_{R3U2}	-	1.3	(25)
λ_{gR3U}	-	1.0	(25)
λ_{mR3U}	-	1.0	(25)
R_{IML}	-	0.35	(26)
r_{WLC}	-	0.3	(28)
g_{RL0}	1/yr	0.59	(28)
m_{RL1}	1/yr	0.02	(28)
m_{RL2}	1/yr	0.1	(28)
λ_{gRL}	-	1.0	(28)
λ_{mRL}	-	1.0	(28)
V_{CLCL}	-	0.1	(30)
g_{R2L0}	-	1.5	(30)
m_{R2L1}	-	1.1	(30)
m_{R2L2}	-	1.4	(30)
λ_{gR2L}	-	1.0	(30)
λ_{mR2L}	-	1.0	(30)
N_{MU}	10^4 persons	150.0	(31)
V_{CUCNU}	-	0.4	(32)
g_{NU0}	1/yr	0.0019	(32)
m_{NU1}	1/yr	0.01	(32)
m_{NU2}	1/yr	0.03	(32)
λ_{gNU}	-	1.0	(32)
λ_{mNU}	-	1.0	(32)
R_{IUCNU}	-	0.01	(33)
g_{N2U0}	-	1.2	(33)
m_{N2U1}	-	1.1	(33)
m_{N2U2}	-	1.2	(33)
λ_{gN2U}	-	1.0	(33)
λ_{mN2U}	-	1.0	(33)
N_{ML}	10^4 persons	100.0	(34)
V_{CLCNL}	-	0.4	(35)
g_{NL0}	1/yr	0.002	(35)

m_{NL1}	1/yr	0.01	(35)
m_{NL2}	1/yr	0.03	(35)
λ_{gNL}	-	1.0	(35)
λ_{mNL}	-	1.0	(35)
R_{ILCNL}	-	0.01	(36)
g_{N2L0}	-	1.2	(36)
m_{N2L1}	-	1.1	(36)
m_{N2L2}	-	1.2	(36)
λ_{gN2L}	-	1.0	(36)
λ_{mN2L}	-	1.0	(36)
k_{qa}	-	15	(37)
k_{qb}	-	0.3	(37)
k_{qc}	-	0.2	(37)

Table 2~~3~~ Initial values of system state variables

Variable	Unit	Value
W_U	m^3	0.0
V_{CU}	-	0.4
R_{IU}	-	0.008
N_U	10^4 persons	17
W_L	m^3	0.0
V_{CL}	-	0.35
R_{IL}	-	0.008
N_L	10^4 persons	21

Table 34 Mean values of state variables during last 60 years of system evolution

Variable	Unit	Baseline model	Revised model	Relative change comparing with Baseline model
Q_{inU}	$10^9 m^3/yr$	4.544	4.544	-
Q_{outU}	$10^9 m^3/yr$	1.572	2.149	36.7%
Q_{outU}/Q_{inU}	-	0.346	0.473	-
V_{CU}	-	0.220	0.161	-26.8%
V_{CL}	-	0.005	0.017	240.0%
R_{IU}	-	0.299	0.285	-4.7%
R_{IL}	-	0.115	0.137	19.1%
N_U	10^4 persons	109.7	107.6	-1.9%
N_L	10^4 persons	50.5	51.4	1.8%

Table 45 Mean values of state variables during last 60 years of system evolution for sensitivity tests

Conditions	Q_{outU}/ $10^9 m^3$/yr	V_{CU}/-	V_{CL}/-	R_{IU}/-	R_{IL}/-	N_U/ 10^4 persons	N_L/ 10^4 persons
0.9× Initial values	1.572	0.220	0.005	0.299	0.115	109.7	50.5
1.1× Initial values	1.572	0.220	0.005	0.299	0.115	109.7	50.5
0.9× P	1.567	0.219	0.005	0.298	0.114	109.7	50.5
1.1× P	1.578	0.222	0.005	0.299	0.115	109.8	50.5
0.9× E_p	1.648	0.243	0.013	0.305	0.122	110.6	51.0
1.1× E_p	1.521	0.198	0.001	0.292	0.109	108.9	50.2
0.9× Q_{inU}	1.369	0.198	0.002	0.292	0.108	108.9	50.2
1.1× Q_{inU}	1.794	0.240	0.010	0.304	0.121	110.4	50.8
0.9× k_c	1.609	0.237	0.008	0.303	0.121	110.3	50.8
1.1× k_c	1.543	0.203	0.002	0.293	0.109	109.1	50.2
0.9×V_{CMU}	1.670	0.180	0.008	0.293	0.117	108.3	50.7
1.1×V_{CMU}	1.502	0.262	0.002	0.304	0.114	111.1	50.3
0.9×g_{VU0}	1.629	0.194	0.006	0.294	0.116	108.8	50.6
1.1×g_{VU0}	1.529	0.244	0.003	0.302	0.114	110.6	50.4
0.9×m_{VU1}	1.557	0.229	0.005	0.300	0.114	110.0	50.5
1.1×m_{VU1}	1.588	0.212	0.005	0.297	0.115	109.5	50.5
0.9×m_{VU2}	1.539	0.238	0.004	0.301	0.114	110.3	50.4
1.1×m_{VU2}	1.605	0.204	0.005	0.296	0.115	109.2	50.5
0.9×r_{EWSUC}	1.563	0.225	0.005	0.299	0.114	109.9	50.5
0.9×r_{EWSUC}	1.582	0.215	0.005	0.298	0.115	109.6	50.5

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Table 56 Changing rate of Mean values of state variables during last 60 years of system evolution for sensitivity tests

Conditions	Q_{outU}/ %	V_{CU}/%	V_{CL}/%	R_{IU}/%	R_{IL}/%	N_U/ %	N_L/ %
0.9×Initial values	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.1×Initial values	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.9×P	-0.32	-0.45	0.00	-0.33	-0.87	0.00	0.00
1.1×P	0.38	0.91	0.00	0.00	0.00	0.09	0.00
0.9×E_p	4.83	10.45	160.00	2.01	6.09	0.82	0.99
1.1×E_p	-3.24	-10.00	-80.00	-2.34	-5.22	-0.73	-0.59
0.9× Q_{inU}	-12.91	-10.00	-60.00	-2.34	-6.09	-0.73	-0.59
1.1× Q_{inU}	14.12	9.09	100.00	1.67	5.22	0.64	0.59
0.9× k_c	2.35	7.73	60.00	1.34	5.22	0.55	0.59
1.1× k_c	-1.84	-7.73	-60.00	-2.01	-5.22	-0.55	-0.59
0.9×V_{CMU}	6.20	-18.18	62.00	-2.11	1.30	-1.24	0.35
1.1×V_{CMU}	-4.46	18.91	-60.00	1.74	-1.22	1.29	-0.34
0.9×g_{VU0}	3.62	-11.95	10.00	-1.54	0.43	-0.80	0.11
1.1×g_{VU0}	-2.73	11.09	-38.00	0.97	-0.96	0.78	-0.22
0.9×m_{VU1}	-0.93	3.91	-8.00	0.27	-0.52	0.30	-0.05
1.1×m_{VU1}	1.02	-3.59	2.00	-0.57	-0.17	-0.21	0.03
0.9×m_{VU2}	-2.07	8.23	-24.00	0.67	-0.78	0.59	-0.15
1.1×m_{VU2}	2.07	-7.18	4.00	-0.97	0.00	-0.46	0.06
0.9×r_{EWSUC}	-0.55	2.36	-6.00	0.10	-0.52	0.20	-0.03
0.9×r_{EWSUC}	0.62	-2.09	0.00	-0.40	-0.26	-0.11	0.02

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Nomenclature: The subscript U of the symbol represents the upper reach, and the subscript L of the symbol represents the lower reach.

Symbol	Unit	Value of the parameter	Description	Equation
W_U	m^3		Water storage	(1)(1)
P_U	mm/yr		Annual precipitation	(1)(1)
A_U	km^2		Area of modeling unit	(1)(1)
E_{tU}	mm/yr		Annual evapotranspiration of the natural vegetation	(1)(1)
E_{cU}	mm/yr		Annual evapotranspiration of the irrigated crop area	(1)(1)
E_{bU}	mm/yr		Annual evapotranspiration of the bare desert	(1)(1)
V_{CU}	-		Vegetation coveragecover	(1)(1)
R_{IU}	-		Irrigated crop area ratio	(1)(1)
Q_{inU}	m^3/yr		Inflow of upper reach	(1)(1)
Q_{outU}	m^3/yr		Outflow of upper reach	(1)(1)
k_{tU}	-	0.3	Coefficient	(2)(2)
k_{cU}	-	0.4	Coefficient	(2)(2)
E_p	mm/yr		Annual potential evaporation	(2)(2)
k_Q	-	0.3	Coefficient	(4)(4)
k_{tL}	-	0.28	Coefficient	(7)(7)
k_{cL}	-	0.38	Coefficient	(7)(7)
W_L	m^3		Water storage	(7)(7)
P_L	mm/yr		Annual precipitation	(7)(7)
A_L	km^2		Area of modeling unit	(7)(7)
E_{tL}	mm/yr		Annual evapotranspiration of the natural vegetation	(7)(7)
E_{cL}	mm/yr		Annual evapotranspiration of the irrigated crop area	(7)(7)
E_{bL}	mm/yr		Annual evapotranspiration of the bare desert	(7)(7)
V_{CL}	-		Vegetation coveragecover	(7)(7)
R_{IL}	-		Irrigated crop area ratio	(7)(7)
Q_{inL}	m^3/yr		Inflow of lower reach	(7)(7)
V_{CMU}	-	0.6	Maximum of vegetation coveragecover	(12)(12)
g_{VU}	1/yr		Colonization rate	(12)(12)
m_{VU}	1/yr		Mortality rate	(12)(12)
r_{EWSUC}	-	0.3	Parameter	(14)(14)
g_{VU0}	1/yr	0.8	Parameter	(14)(14)
m_{VU1}	1/yr	0.1	Parameter	(14)(14)
m_{VU2}	1/yr	0.3	Parameter	(14)(14)
λ_{gVU}	-	Parameter		(14)
λ_{mVU}	-	Parameter		(14)
r_{EWSU}	-		Environmental water supply ratio	(15)(15)
W_{ERU}	m^3		Environmental water requirement	(15)(15)
T	yr		Time step, 1 year	(15)(15)

g_{VL}	1/yr		Colonization rate	(16)(16)	
m_{VL}	1/yr		Mortality rate	(16)(16)	
V_{CML}	-	0.5	Maximum of vegetation ~~coverage~~cover	(16)(16)	
r_{EWSLC}	-	0.3	Parameter	~~(18)~~	域代码已更改
g_{VL0}	1/yr	0.8	Parameter	~~(18)~~	域代码已更改
m_{VL1}	1/yr	0.1	Parameter	~~(18)~~	域代码已更改
m_{VL2}	1/yr	0.3	Parameter	~~(18)~~	域代码已更改
~~λ_{gVL}~~	~~-~~	~~Parameter~~		~~(18)~~	
~~λ_{mVL}~~	~~-~~	~~Parameter~~		~~(18)~~	
r_{EWSL}	-		Environmental water supply ratio	~~(19)~~	域代码已更改
W_{ERL}	m^3		Environmental water requirement	~~(19)~~	域代码已更改
g_{RU}	1/yr		Colonization rate of new irrigated field	(18)~~(20)~~	
g_{R2U}	-		Colonization rate of new irrigated field	(18)~~(20)~~	
g_{R3U}	-		Colonization rate of new irrigated field	(18)~~(20)~~	
m_{RU}	1/yr		Desolation rate of current irrigated field	(18)~~(20)~~	
m_{R2U}	-		Desolation rate of current irrigated field	(18)~~(20)~~	
m_{R3U}	-		Desolation rate of current irrigated field	(18)~~(20)~~	
r_{IMU}	-	0.6	Maximum of irrigated crop area ratio	(18)~~(20)~~	
r_{WUC}	-	0.3	Parameter	~~(22)~~	域代码已更改
g_{RU0}	1/yr	0.62	Parameter	~~(22)~~	域代码已更改
m_{RU1}	1/yr	0.02	Parameter	~~(22)~~	域代码已更改
m_{RU2}	1/yr	0.1	Parameter	~~(22)~~	域代码已更改
~~λ_{gRU}~~	~~-~~	~~Parameter~~		~~(22)~~	
~~λ_{mRU}~~	~~-~~	~~Parameter~~		~~(22)~~	
r_{WU}	-		Irrigation water supply ratio	~~(23)~~	域代码已更改
W_{IRU}	m^3		Irrigation water requirement	~~(23)~~	域代码已更改
V_{CUC}	-	0.2	Parameter	~~(24)~~	域代码已更改
g_{R2U0}	-	1.5	Parameter	~~(24)~~	域代码已更改
m_{R2U1}	-	1.1	Parameter	~~(24)~~	域代码已更改
m_{R2U2}	-	1.3	Parameter	~~(24)~~	域代码已更改
~~λ_{gR2U}~~	~~-~~	~~Parameter~~		~~(24)~~	
~~λ_{mR2U}~~	~~-~~	~~Parameter~~		~~(24)~~	
V_{CLC}	-	0.1	Parameter	~~(25)~~	域代码已更改
g_{R3U0}	-	1.5	Parameter	~~(25)~~	域代码已更改
m_{R3U1}	-	1.1	Parameter	~~(25)~~	域代码已更改
m_{R3U2}	-	1.3	Parameter	~~(25)~~	域代码已更改
~~λ_{gR3U}~~	~~-~~	~~Parameter~~		~~(25)~~	

~~λ_{mR3U}~~	~~-~~	~~Parameter~~		~~(25)~~
g_{RL}	1/yr		Colonization rate of new irrigated field	(20)~~(26)~~
g_{R2L}	-		Colonization rate of new irrigated field	(20)~~(26)~~
m_{RL}	1/yr		Desolation rate of current irrigated field	(20)~~(26)~~
m_{R2L}	-		Desolation rate of current irrigated field	(20)~~(26)~~
R_{IML}	-	0.35	Maximum of irrigated crop area ratio	(20)~~(26)~~
r_{WLC}	-	0.3	Parameter	~~(28)~~
g_{RL0}	1/yr	0.59	Parameter	~~(28)~~
m_{RL1}	1/yr	0.02	Parameter	~~(28)~~
m_{RL2}	1/yr	0.1	Parameter	~~(28)~~
~~λ_{gRL}~~	~~-~~	~~Parameter~~		~~(28)~~
~~λ_{mRL}~~	~~-~~	~~Parameter~~		~~(28)~~
r_{WL}	-		Irrigation water supply ratio	~~(29)~~
W_{IRL}	m^3		Irrigation water requirement	~~(29)~~
V_{CLCL}	-	0.1	Parameter	~~(30)~~
g_{R2L0}	-	1.5	Parameter	~~(30)~~
m_{R2L1}	-	1.1	Parameter	~~(30)~~
m_{R2L2}	-	1.4	Parameter	~~(30)~~
~~λ_{gR2L}~~	~~-~~	~~Parameter~~		~~(30)~~
~~λ_{mR2L}~~	~~-~~	~~Parameter~~		~~(30)~~
g_{NU}	1/yr		Colonization and immigration rate of the population	(22)~~(31)~~
g_{N2U}	-		Colonization and immigration rate of the population	(22)~~(31)~~
m_{NU}	1/yr		Mortality and emigration rate of the population	(22)~~(31)~~
m_{N2U}	-		Mortality and emigration rate of the population	(22)~~(31)~~
N_{MU}	10^4 persons	150	Maximum of the population	(22)~~(31)~~
V_{CUCNU}	-	0.4	Parameter	~~(32)~~
g_{NU0}	1/yr	0.0019	Parameter	~~(32)~~
m_{NU1}	1/yr	0.01	Parameter	~~(32)~~
m_{NU2}	1/yr	0.03	Parameter	~~(32)~~
~~λ_{gNU}~~	~~-~~	~~Parameter~~		~~(32)~~
~~λ_{mNU}~~	~~-~~	~~Parameter~~		~~(32)~~
R_{IUCNU}	-	0.01	Parameter	~~(33)~~
g_{N2U0}	-	1.2	Parameter	~~(33)~~
m_{N2U1}	-	1.1	Parameter	~~(33)~~
m_{N2U2}	-	1.2	Parameter	~~(33)~~

~~λ_{gN2U}~~	-	~~Parameter~~		~~(33)~~
~~λ_{mN2U}~~	-	~~Parameter~~		~~(33)~~
g_{NL}	1/yr		Colonization and immigration rate of the population	(23)~~(34)~~
g_{N2L}	-		Colonization and immigration rate of the population	(23)~~(34)~~
m_{NL}	1/yr		Mortality and emigration rate of the population	(23)~~(34)~~
m_{N2L}	-		Mortality and emigration rate of the population	(23)~~(34)~~
N_{ML}	10^4 persons	100	Maximum of the population	(23)~~(34)~~
V_{CLCNL}	-	0.4	Parameter	~~(35)~~
g_{NL0}	1/yr	0.002	Parameter	~~(35)~~
m_{NL1}	1/yr	0.01	Parameter	~~(35)~~
m_{NL2}	1/yr	0.03	Parameter	~~(35)~~
~~λ_{gNL}~~	-	~~Parameter~~		~~(35)~~
~~λ_{mNL}~~	-	~~Parameter~~		~~(35)~~
R_{ILCNL}	-	0.01	Parameter	~~(36)~~
g_{N2L0}	-	1.2	Parameter	~~(36)~~
m_{N2L1}	-	1.1	Parameter	~~(36)~~
m_{N2L2}	-	1.2	Parameter	~~(36)~~
~~λ_{gN2L}~~	-	~~Parameter~~		~~(36)~~
~~λ_{mN2L}~~	-	~~Parameter~~		~~(36)~~
k_{qa}	-	15	Parameter	(24)~~(37)~~
k_{qb}	-	0.3	Parameter	(24)~~(37)~~
k_{qc}	-	0.2	Parameter	(24)~~(37)~~

List of figures