A Conceptual Socio-hydrological Model of the Co-evolution of Humans and Water: Case Study of the Tarim River Basin, Western China

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Running Head: Conceptual Socio-hydrological Model of Co-evolution of Humans and Water

Manuscript submitted to *Hydrology and Earth System Sciences*

Special issue: *Predictions under Change: Water, Earth and Biota in the Anthropocene*

November 22, 2014

Abstract

The complex interactions and feedbacks between humans and water are critically important issues but remain 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 simplified conceptual socio-hydrological model based on logistic growth curve is developed for the Tarim River Basin in Western China, and is used to illustrate the explanatory power of such a co-evolutionary model. The study area is the main stream of the Tarim River, which is divided into two modeling units. The socio-hydrological system is composed of four sub-systems, i.e., hydrological, ecological, economic, and social sub-systems. In each modeling unit, the hydrological equation focusing on water balance is coupled to the other three evolutionary equations to represent the dynamics of the social sub-system (denoted by population), the economic sub-system (denoted by irrigated crop area ratio), and the ecological sub-system (denoted by natural vegetation cover), each of which is expressed in terms of a logistic growth curve. Four feedback loops are identified to represent the complex interactions among different sub-systems and different spatial units, of which two are inner loops occurring within each separate unit and the other two are outer loops linking the two modeling units. The feedback mechanisms are incorporated into the constitutive relations for model parameters, i.e., the colonization and mortality rates in the logistic growth curves that are jointly determined by the state variables of all sub-systems. The co-evolution of the Tarim socio-hydrological system is then analyzed with this conceptual model to gain insights into the overall system dynamics and its sensitivity to the external drivers and internal system variables. The results show a costly pendulum swing between a balanced distribution of socio-economic and natural ecologic resources among the upper and lower reaches and a highly skewed distribution towards the upper reach. This evolution is principally driven by the attitudinal changes occurring within water resources management policy that reflect the evolving community awareness of society to concerns regarding the ecology and environment.

Keywords: socio-hydrology, co-evolution, conceptual model, growth curve, Tarim River

1. Introduction

In the emergent Anthropocene, the competition for water between humans and ecosystems leads to complex interactions between hydrologic and social systems. They play fundamental roles in the co-evolutionary history of coupled human-nature systems as well as their possible future trajectories. Furthermore, the nature of such interactions is always changing as social and natural conditions change. Over time, they generate new connections and, in particular, additional significant feedbacks that need to be understood, assessed, modeled and predicted (Montanari et al., 2013). These feedback mechanisms between the hydrological and social systems are often ignored in traditional hydrology. For example, water consumption activities and landscape changes driven by humans are usually prescribed as external forcings in hydrologic models. The underlying assumption here is stationarity (Milly et al., 2008; Peel and Blöschl, 2011) in spite of the fact that water related human actions turn out to be internal (endogenous) processes of the coupled socio-hydrologic system and evolve constantly. Also, human actions tend to be treated as static and externally prescribed in traditional water resources planning and management. A prominent example is the “scenario-based” approach used to represent future state(s) of the coupled socio-hydrological system in the science of integrated water resources management. Consequently, possible evolutionary trajectories of human-water systems cannot be fully explored or predicted. To address this deficiency, a new trans-disciplinary science of socio-hydrology has been proposed which aims at understanding and predicting the dynamics and co-evolution of coupled human-water systems (Sivapalan et al., 2012).

There are three avenues through which socio-hydrology can advance (Sivapalan et al, 2012), i.e., historical socio-hydrology, comparative socio-hydrology, and process socio-hydrology. Besides, motivated by the success of hydrological modeling in traditional hydrology towards recognizing the limits of our understanding of hydrological processes, the research method of numerical modeling should be introduced into socio-hydrology as well to light up the three avenues of socio-hydrologic inquiry mentioned above. Models could be used to explore new knowledge and to test the limits of existing knowledge (as included in models) about the complex interactions between hydrologic and social systems. We acknowledge that the interactions and associated feedback mechanisms between hydrological and social processes remain largely unexplored and poorly understood (Di Baldassarre et al., 2013a) at the current state of development of socio-hydrology. 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 SWAT (Arnold et al., 1998) and THREW (Tian et al., 2006, 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 is aimed at capturing the most important 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 the case of ecology, Levins and Culver (1971) introduced the logistic growth function to describe vegetation dynamics, which is an idea borrowed from population growth models (Tsoularis and Wallace, 2002). Baudena et al. (2007) introduced the role of soil moisture into the colonization and extinction rates of vegetation in the form of a logistic function, and in this way the soil moisture dynamics was coupled to vegetation dynamics. Lin et al. (2013) developed a simplified ecohydrological model with pulsed atmospheric forcing to analyze non-trivial dynamic behaviors both qualitatively and numerically, and confirmed the existence of multiple stationary states. In the case of social sciences, 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 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 existing development pathways. Good and Reuveny (2009) coupled an ecological-economic model of human-resource interaction with endogenous coupling of population growth to economic growth. Good and Reuveny (2009) used this model to study the abrupt collapse of the Sumerian, Maya, Rapanui and Anasazi peoples and attributed their breakdown to anthropogenic environmental degradation: however, in this case resource use was not explicitly incorporated in their model. In the area of socio-hydrology itself, there have been a couple of pioneering studies that have shown considerable potential in this direction. For example, Di Baldassarre et al. (2013a, b) developed a simple dynamic model to represent the interactions and feedbacks 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. Along with the simple conceptual model, several researchers have focused on the human response to environmental change. For example, Elshafei et al. (2014) proposed a prototype framework for models of socio-hydrology with the concept of community sensitivity as a core for feedback between environmental and socio-economic systems, and van Emmerik et al. (2014) simulated the co-evolution of humans and water and adopted the concept of environmental awareness to explain dominant features of the pendulum swing observed in the Murrumbidgee River Basin in Australia.

In this study we attempt to develop a simple conceptual model of the co-evolution of the socio-hydrological system in an arid inland oasis area. The Tarim River Basin in the western part of China is chosen for this study. The mainstream of the Tarim River is located in an inland hyper-arid area, with runoff principally from the headwaters (Zhou et al., 2012). In this area, humans are heavily engaged in agricultural production (other industries will be ignored here because their scales are small compared to agriculture). In the long history of Tarim, human populations and their agricultural activities have depended exclusively on water from the Tarim River, and constantly moved with the River as it migrated 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 degradation of the riverine ecosystem. In order to restore the downstream ecological system, the water reallocation policy was introduced and more water has been increasingly released into the lower reach since 2000 (Chen et al., 2010; Liu et al., 2012b). This adjustment of the water allocation policy can be seen as a response of the social system to the change of ecohydrological system and thus represents a negative feedback. On the longer time scale, streamflow, vegetation cover, human population and irrigated 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 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.

The remainder of the paper is organized as follows. In Section 2, the study area and the data used in the modeling are introduced, which is followed by the details and justification of the conceptual model adopted for the Tarim River Basin, which are presented in Section 3. Results of the model calibration and validation are presented in Section 4, along with the results of sensitivity analysis with the model. The paper concludes with 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 an annual precipitation of 50-100 mm only. It is the largest inland basin in 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 the main source of water for the mainstream of 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 Liu et al. (2014).

In this study, we focus our modeling efforts on the mainstream of the Tarim River, i.e., from Aral to Taitema Lake which 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) were obtained from the dataset 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 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, Tarim Petroleum Annual, and Xinjiang Fifty Years (1955-2005).

The NDVI (Normalized Difference Vegetation Index) time series data of reference 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 reference 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 reference point (VPL) in the middle and lower reach is at (41°1'10" N, 86°14'0" E) near Qiala.

3. Conceptual model 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) The land use types are composed of irrigated crop field, naturally vegetated land and bare desert;

(2) The water requirement of natural vegetation in the lower reach is mainly fed by the streamflow released from the upper reach;

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

The modeling framework for the co-evolution of the TRB socio-hydrological system is shown in 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 other economic sectors (e.g., industrial) are neglected in the economic system. The state variables of each unit are as follows:

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

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

(3) Irrigated crop area ratio (R_I), dimensionless, in [0, 1]. R_I is defined as the ratio of irrigated crop area to the 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: hydrological sub-system represented by water storage, 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 the modeling unit is noted as *A*. The subscript *U* in the notation represents the upper reach, and the subscript *L* represents the lower reach.

3.2. Water balance of the hydrological sub-system

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

$$\frac{dW_{\mathrm{U}}}{dt} = P_{\mathrm{U}}A_{\mathrm{U}} - E_{\mathrm{tU}}A_{\mathrm{U}}V_{\mathrm{CU}} - E_{\mathrm{cU}}A_{\mathrm{U}}R_{\mathrm{IU}} - E_{\mathrm{bU}}A_{\mathrm{U}}(1 - V_{\mathrm{CU}} - R_{\mathrm{IU}}) + Q_{\mathrm{inU}} - Q_{\mathrm{outU}} \quad (1)$$

where, P is the annual precipitation, E_{t} is the annual evapotranspiration from natural vegetation, E_{c} is the annual evapotranspiration from irrigated crop, and E_{b} is the annual evaporation from the bare desert, all expressed in mm/yr. We assume that the precipitation falling on the bare desert is completely evaporated. The evapotranspiration terms are calculated by the following equations if there is sufficient water supply:

$$\begin{aligned} E_t &= k_t E_p \\ E_c &= k_c E_p \\ E_b &= P \end{aligned} \quad (2)$$

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

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

where q_1, q_2, q_3 are the corresponding release functions of Q_{inU}, W_{U}, V_{CL}, of which q_1 increases with upper reach inflow (Q_{inU}), q_2 increases with *W*, i.e., allocatable water resource, and q_3 increases with vegetation cover of the lower reach, accounting for the government environment protection policy. Q_{outU} is calculated using the following procedure according to present water allocation practice in Tarim, which could be generalized in a future study.

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 (see Eqn (2)). Otherwise, the outflow will be equal to the minimum outflow, i.e., $k_Q Q_{inU}$, 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. The outflow, water consumptions from natural vegetation and irrigated drop are determined in the following procedure. 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. If this is the case, the annual evapotranspiration 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 evapotranspiration 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 symbols are similar to those in the upper reach equation (1), and Q_{inL} is equal to outflow from upper reach.

$$Q_{\mathrm{inL}} = Q_{\mathrm{outU}} \quad (8)$$

If the water in the lower reach is sufficient, all of the allocatable water will be evaporated on the desert after water requirement of irrigated agriculture and natural vegetation are satisfied, which can be similarly calculated by Eqn (2). Otherwise, the water consumptions in the lower reach are determined in the following procedure and the evaporation on the bare soil only comes from the precipitation. E_{bL} is thus calculated as

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

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

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

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

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

3.3. Natural vegetation dynamics of ecological sub-system

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

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

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 human planning or by the following equation, in which V_{CMU} is the ratio of the vegetated area that the available environmental water could feed to the modeling unit area.

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

Adopted from Liu et al. (2012a, b), the colonization and mortality rates of natural vegetation depend on the environmental water supply, which basically come from groundwater reservoir recharged by streamflow in the river. The readers are referred to Liu et al. (2012a) for details about the hydrological situation in the mainstream of Tarim River. The dependent relationships are shown in Figure 3, which are described by the following equations.

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

where, g_{VU}, m_{VU1}, m_{VU2} and r_{EWSUC} are the empirical parameters. r_{EWS} 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 threshold value of r_{EWSU}, where r_{EWSU} is defined as:

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

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 cover of the lower reach are

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

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

The dependent relationships of g_{VL} and m_{VL} are similar, which are presented in Appendix A for readability. The meanings of all the symbols used above are reported in the separate nomenclature presented at the end of the paper.

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

The dynamics of the irrigated crop area is balanced by wasteland cultivation and farmland abandonment. The process of its evolution 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) have also presented this kind of conceptualization. In their work they also used the similar equation to describe the resource stock in the ecological-economic model of human-resource interaction. Originally, the logistic growth model is introduced to simulate the growth of biological systems. Subsequently there have been several applications of the logistic growth model outside the field of biology also. As summarized by Tsoularis and Wallace (2002), the logistic growth model has been used to describe the market penetration of many new products and technologies, world energy usage and source substitution, as 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 corresponds to the colonization and mortality in our vegetation dynamic equation. We assume that this evolution can be roughly described by the logistic growth model. The dynamical equation of irrigated crop area ratio of the upper reach is

$$\frac{dR_{\mathrm{IU}}}{dt} = g_{\mathrm{RU}} g_{\mathrm{R2U}} g_{\mathrm{R3U}} R_{\mathrm{IU}} (R_{\mathrm{IMU}} - R_{\mathrm{IU}}) - m_{\mathrm{RU}} m_{\mathrm{R2U}} m_{\mathrm{R3U}} R_{\mathrm{IU}} \tag{18}$$

where, g_{RU}, g_{R2U} and g_{R3U} represent the cultivation rate of new irrigated field. m_{RU}, m_{R2U} and m_{R3U} represent the abandonment rate of current irrigated field. R_{IMU} represents the maximum of R_{IU}. It could be determined by planning or by the available irrigation water as the following:

$$R_{\mathrm{IMU}} = \frac{\text{available irrigation water / water requirement per unit area}}{A_{\mathrm{U}}} \tag{19}$$

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 adopted are similar as shown in Figure 3, which are also listed in the Appendix A.

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

$$\frac{dR_{\text{IL}}}{dt} = g_{\text{RL}} g_{\text{R2L}} R_{\text{IL}} (R_{\text{IML}} - R_{\text{IL}}) - m_{\text{RL}} m_{\text{R2L}} R_{\text{IL}} \tag{20}$$

$$R_{\text{IML}} = \frac{\text{available irrigation water / water requirement per unit area}}{A_{\text{L}}} \tag{21}$$

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

In the socio-economic system, the dynamic evolution of the population is traditionally simulated by the logistic growth model (Tsoularis and Wallace, 2002) although it is usually complicated by human migration and other factors. Both the colonization and mortality terms are dependent on the environment and agriculture. The dynamical equation of the population of upper reach is

$$\frac{dN_{\text{U}}}{dt} = g_{\text{NU}} g_{\text{N2U}} N_{\text{U}} (N_{\text{MU}} - N_{\text{U}}) - m_{\text{NU}} m_{\text{N2U}} N_{\text{U}} \tag{22}$$

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 arrangement.

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 are similar as shown in Figure 3, which are described in the Appendix A.

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

$$\frac{dN_{\text{L}}}{dt} = g_{\text{NL}} g_{\text{N2L}} N_{\text{L}} (N_{\text{ML}} - N_{\text{L}}) - m_{\text{NL}} m_{\text{N2L}} N_{\text{L}} \tag{23}$$

The descriptions for the dependent relationships and symbols are referred to the Appendix A and Nomenclature.

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 four main feedback loops in the socio-hydrological system of Tarim River, as shown in Figure 4.

The first feedback loop, W_{U}-V_{CU}-R_{IU}-W_{U}, is an inner loop occurring within the upper reach. This is a negative feedback. If the inflow to the upper reach increases, the allocatable 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 environmental conditions become better, and thus the irrigated crop area will expand and the irrigation water consumption will increase correspondingly. As a result, the allocatable water resources (W_U) will decrease and the allocatable water resource (W_U) receives a negative feedback. The second feedback loop, W_L-V_{CL}-R_{IL}-W_L, is the corresponding inner loop occurring in the lower reach. It is also a negative feedback.

The third loop, V_{CL}-W_U-W_L-V_{CL}, is the outer loop linking the upper and lower reaches. If the natural vegetation in the lower reach (V_{CL}) decreases (degrades), the allocation of the water resources in upper reach (W_U) will be inclined to increase discharge to lower reach (Q_{outU}), which depends on water resources management and vegetation protection policy. 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. Obviously, this is also a negative feedback. It is primarily controlled by policies and laws, which are driven by the community awareness discussed in Elshafei et al. (2014). In the baseline model, this feedback is not in effect. Its role will be analyzed later in a subsequent section.

The fourth loop, R_{IU} -W_U-W_L-V_{CL}-R_{IU}, is a related outer loop linking the two modeling units. This is a negative feedback also. 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 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 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 the Tarim River Basin

The conceptual model 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. The estimation of the parameter values is important for model application. A total of 58 parameters arise from the constitutive relationships presented in the model description above, almost all of which are not measurable directly, at least with the state-of-the-art understanding of associated socio-hydrological processes. To reduce the equifinality problem in the parameter estimation, 44 parameters from the 11 dependent relations refer to the corresponding values in Baudena et al. (2007) and Liu et al. (2012b), which are also subject to certain adjustment 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 summarized in 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. The initial allocatable water volumes of both modeling units are 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 the statistic book and expert knowledge.

4.3. 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 the 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 evolutionary dynamics of vegetation cover are shown in Figures 6 and 7. Due to the scarcity of the long-term areal vegetation cover, remote sensing 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 reference point of the upper reach and lower reach, respectively. The vegetation cover evolution should be validated in future based on 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 (Song 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 throughout the simulation period 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 status.

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), and the productive and restorative actions of humans (van 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 water’s economic value and ecological value. At different stages of the socio-hydrological system, the dominant driving forces may be different. During the study period the dominant driving force was indeed the productive force, i.e., expanding agricultural production within the Tarim River Basin. The realization of 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 consumed 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, 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% 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. For the model, it means that the negative feedback, outer loop "V_{CL}–W_U–W_L–V_{CL}", should be switched on to analyze the long-term evolutionary dynamics.

In order to study the evolution of the socio-hydrological system, precipitation, evapotranspiration and inflow are repeated another 4 times after 1951-2010 to obtain a synthetic time 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. 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 and is 50.5×10^4 in the lower reach. All of the above 6 variables are much smaller than the maximum values shown in the Nomenclature.

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, after 2000 the outflow of upper reach has been now regulated through changes to the river basin management policy 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) could be calculated as

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

where, k_{qa}, k_{qb} and k_{qc} are parameters, as shown in the Nomenclature. The negative feedback "V_{CL}-W_U-W_L-V_{CL}" is quantitatively described through the constitutive relationship of V_{CL} and k_Q. 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. After the decrease of V_{CL}, k_Q will increase and then more water will be released into the lower reach. As a result of increase of water in the lower reach, V_{CL} will increase. So the outflow of upper reach (Q_{outU}) in Equation (4) is

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

The resulting model is denoted here as the *revised model*. The dynamics of the Tarim socio-hydrological system governed by the inclusion of the Equation (25) 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 3. 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, while the vegetation cover, irrigated crop area ratio and population in the lower reach in the 60 years modeled by the revised model are larger.

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, the environmental feedback forces 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 3. The state to which the vegetation cover could be restored is determined by the water resources allocation, i.e., the relative preference by humans between 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. Considering the whole simulation, we can find a costly pendulum swing between a balanced distribution of socio-economic resources and natural ecologic resources among upper and lower reaches and a centered distribution in the upper reach. This pendulum swing of spatial distribution of resources is very similar to the pendulum swing of values between agricultural socio-economic benefits and ecosystem services found in Murrumbidge River Basin by Kandasamy et al. (2014). In fact, the first pendulum swing is driven by the second one.

In both the baseline model and the revised model, the socio-hydrological system reaches a quasi-steady state after 2100. The rate at which the quasi-steady state is reached turned out to be faster than our intuition suggested, which could be ascribed to the absence of technology improvement in the co-evolution model. As irrigation technology advances, crop coefficient of evapotranspiration (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, also following the example of van Emmerik et al. (2014).

4.4. Sensitivity analysis

In order to assess the effect of the initial values and boundary conditions to system quasi-steady state, the sensitivity of system behaviors to initial values and boundary conditions, i.e. the precipitation, potential evaporation and inflow of the upper reach, was analyzed with the baseline model. By increasing and decreasing the initial values, precipitation, potential evaporation, and inflow of the upper reach by 10%, the model is re-run under different combinations of initial and boundary conditions, and the results are listed in Table 4. 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, which indicates that the changes of the precipitation have a slight effect with the range of -1%~1%, which can be attributed to the absolutely small precipitation amount in this area. Otherwise, the potential evaporation (very high compared to precipitation) and inflow of the upper reach 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 co-evolution.

The sensitivity of the parameters in the model is an important approach to identify the critical parameters that 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 k_c is decreased or increased by 10%, respectively, to assess its effect on the system quasi-steady state and the results are listed in Table 4 and Table 5. The k_c has significant effects on the vegetation cover of the lower reach (V_{CL}) and slight effects on the other variables. 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}) were decreased or increased by 10% to assess the effects on the quasi-steady states of the system and the results are shown in Table 4 and Table 5. V_{CMU} and g_{VU0} have a 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 effects on the quasi-steady states.

5. Conclusions

For socio-hydrological systems, their hydrological processes, ecological processes and socio-economic processes are coupled together via water consumption activities and water allocation policies. To explore such interactive processes, a conceptual dynamical model is developed by coupling water balance equation for hydrological process and logistic growth equations for evolution of vegetation, irrigation, and population. Four state variables, i.e., water storage, vegetation cover, irrigated crop area ratio, and human population, are adopted to represent the state of hydrological, ecological, economic, and social sub-systems, respectively. Each growth equation contains several colonization terms and mortality terms, which are jointly determined by the state variables of different sub-systems through the corresponding constitutive relations. We recognize that a few previous studies have proposed the concepts of community sensitivity (Elshafei et al. 2014) or environmental awareness (van Emmerik et al., 2014) to explicitly represent the feedback mechanisms between social and environment systems. In our model, the feedback mechanisms are implicitly incorporated into the model through constitutive relations and hidden feedback loops. At the current stage of our understanding of complex socio-hydrological processes, the logistic growth model can reduce the need for an explicit representation of human behavior and also benefit from the vast amount of literature on the growth model in biologic and social sciences.

Forced by the annual precipitation, pan evaporation and streamflow of the headwater basins, the co-evolution model reproduces the past trajectories of the human-water system in the Tarim River Basin. The simulated evolution processes are consistent with observed patterns, such as the outflow of the upper reach, vegetation cover, irrigated crop area ratio and human population, which suggests a reasonably good performance of the model. The long-term simulation results from both baseline and revised model runs show a pendulum swing between a balanced distribution of socio-economic resources and natural ecologic resources among upper and lower reaches and a highly skewed distribution towards the upper reach. The real history of Tarim River Basin discussed in Liu et al. (2014) confirms this simulation result. During the traditional agricultural period with lower level of productive force, the population was distributed relatively uniformly along the Tarim River. When the time came to the industrialized agriculture, the water consumption in the upper reach saw a tremendous increase. As a result, the natural vegetation in the lower reach deteriorated and thus the agriculture and population shrank. The pendulum swung to the opposite end. On the other hand, with the increasing awareness of the environment in human consciousness, the society changed the water allocation policy and more water is now required to be released to the lower reach. Consequently, the natural ecological resources and also socio-economic resources could regain in the lower reach, and the pendulum swung back to the former mode. This costly pendulum swing of the spatial distribution of resources is very similar to the pendulum swing of values between agricultural socio-economic benefits and ecosystem services that was observed in the Murrumbidge River Basin in Australia by Kandasamy et al. (2014). Simulation models of the kind presented here can shed light on the possible future trajectories of similar socio-hydrological systems.

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.

$$g_{\mathrm{VL}} = \frac{g_{\mathrm{VL0}}}{1+\exp\left(r_{\mathrm{EWSLC}} - r_{\mathrm{EWSL}}\right)}$$
$$m_{\mathrm{VL}} = \frac{m_{\mathrm{VL2}} - m_{\mathrm{VL1}}}{1+\exp\left(r_{\mathrm{EWSL}} - r_{\mathrm{EWSLC}}\right)} + m_{\mathrm{VL1}} \tag{26}$$

$$r_{\mathrm{EWSL}} = \frac{E_{\mathrm{tL}} A_{\mathrm{L}} V_{\mathrm{CL}} T}{W_{\mathrm{ERL}}} \tag{27}$$

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

$$g_{\mathrm{RU}} = \frac{g_{\mathrm{RU0}}}{1+\exp\left(r_{\mathrm{WUC}} - r_{\mathrm{WU}}\right)}$$
$$m_{\mathrm{RU}} = \frac{m_{\mathrm{RU2}} - m_{\mathrm{RU1}}}{1+\exp\left(r_{\mathrm{WU}} - r_{\mathrm{WUC}}\right)} + m_{\mathrm{RU1}} \tag{28}$$

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.

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

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

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

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

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

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.

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

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

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.

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

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

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.

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

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

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

$$m_{\mathrm{N2L}} = \frac{m_{\mathrm{N2L2}} - m_{\mathrm{N2L1}}}{1+\exp\left(R_{\mathrm{IL}} - R_{\mathrm{ILCNL}}\right)} + m_{\mathrm{N2L1}} \tag{38}$$

The meanings of symbols are presented in the Nomenclature section.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 51309188, 51179084, 51190092 and 51190093). The funding also comes from SRFDP (20136118120021), Key Innovation Group of Science and Technology of Shaanxi (2012KCT-10) and State Key Laboratory of Hydroscience and Engineering of Tsinghua University (2012-KY-03，2014-KY-01). This financial support is greatly appreciated. The present work was developed partially within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences (IAHS).

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

Modeling unit	System	State variable	Controlling factors	Modeling variable (symbol)
upper reach	Hydrological system	Water storage	Water consumption and policy	Water storage (W)
	Ecological system	Natural vegetation area	Water supply	Vegetation cover (V_C)
	Economic system	Irrigated crop area	Water supply and vegetation cover	Irrigated crop area Ratio (R_I)
	Social system	Population	Irrigated crop area and vegetation cover	Population (N)
middle and lower reach	Hydrological system	Water storage	Water consumption and policy	Water storage (W)
	Ecological system	Natural vegetation area	Water supply	Vegetation cover (V_C)
	Economic system	Irrigated crop area	Water supply and vegetation cover	Irrigated crop area Ratio (R_I)
	Social system	Population	Irrigated crop area and vegetation cover	Population (N)

Table 2 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 3 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}	$10^9 \mathrm{m}^3$/yr	4.544	4.544	-
Q_{outU}	$10^9 \mathrm{m}^3$/yr	1.572	2.149	36.7%
$Q_{\mathrm{outU}}/\mathrm{Q}_{\mathrm{inU}}$	-	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 4 Mean values of state variables during last 60 years of system evolution for sensitivity tests

Conditions	Q_{outU}/ 10^9m^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

Table 5 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

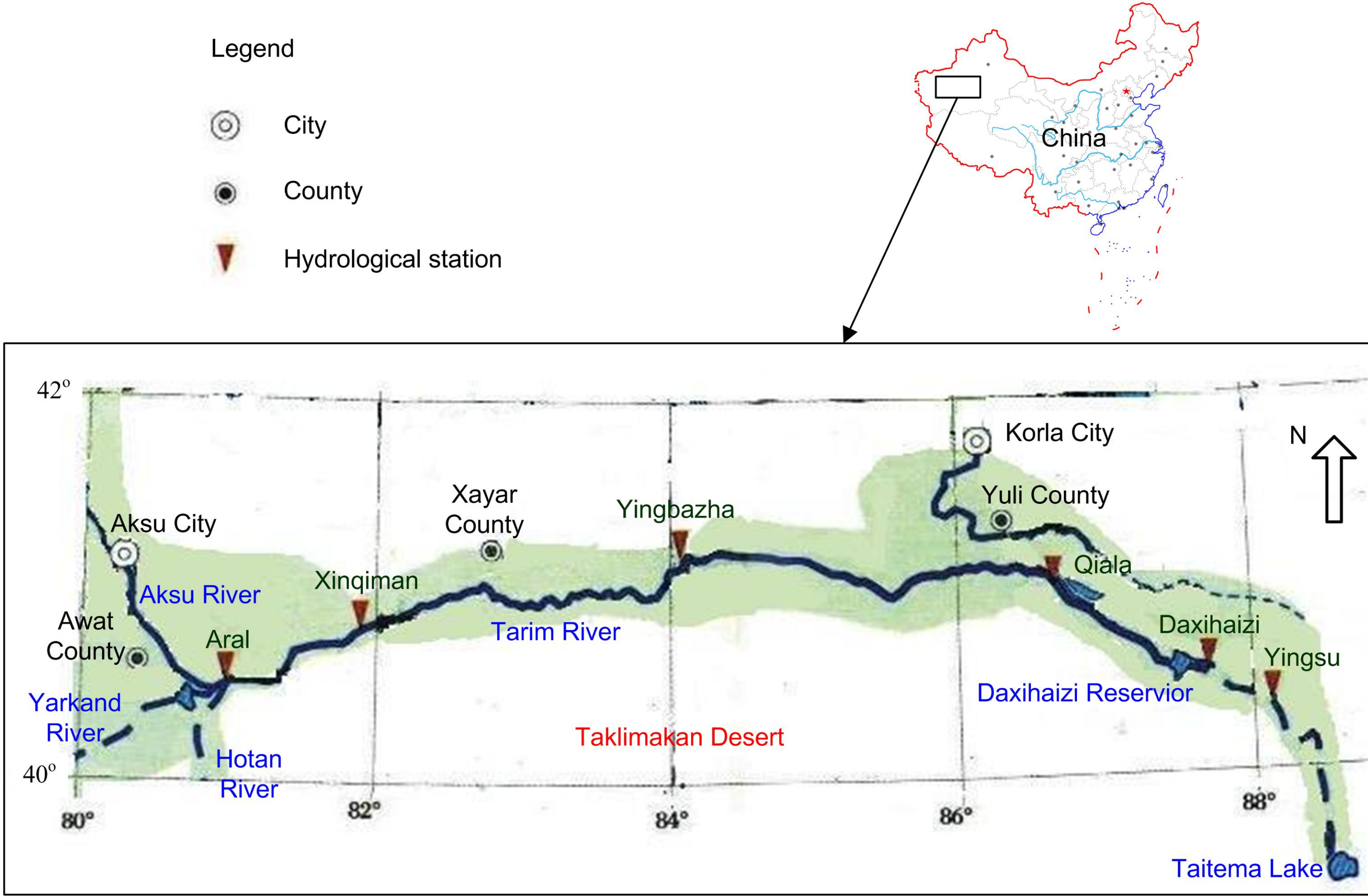
Nomenclature: The subscript *U* of the symbol represents the upper reach, and the subscript *L* of the symbol represents the lower reach.

Symbol	Unit	Value of the parameter	Description	Equation
W_{U}	m^3		Water storage	(1)
P_{U}	mm/yr		Annual precipitation	(1)
A_{U}	km^2		Area of modeling unit	(1)
E_{tU}	mm/yr		Annual evapotranspiration of the natural vegetation	(1)
E_{cU}	mm/yr		Annual evapotranspiration of the irrigated crop area	(1)
E_{bU}	mm/yr		Annual evapotranspiration of the bare desert	(1)
V_{CU}	-		Vegetation cover	(1)
R_{IU}	-		Irrigated crop area ratio	(1)
Q_{inU}	m^3/yr		Inflow of upper reach	(1)
Q_{outU}	m^3/yr		Outflow of upper reach	(1)
k_{tU}	-	0.3	Coefficient	(2)
k_{cU}	-	0.4	Coefficient	(2)
E_{p}	mm/yr		Annual potential evaporation	(2)
k_{Q}	-	0.3	Coefficient	(4)
k_{tL}	-	0.28	Coefficient	(7)
k_{cL}	-	0.38	Coefficient	(7)
W_{L}	m^3		Water storage	(7)
P_{L}	mm/yr		Annual precipitation	(7)
A_{L}	km^2		Area of modeling unit	(7)
E_{tL}	mm/yr		Annual evapotranspiration of the natural vegetation	(7)
E_{cL}	mm/yr		Annual evapotranspiration of the irrigated crop area	(7)
E_{bL}	mm/yr		Annual evapotranspiration of the bare desert	(7)
V_{CL}	-		Vegetation cover	(7)
R_{IL}	-		Irrigated crop area ratio	(7)
Q_{inL}	m^3/yr		Inflow of lower reach	(7)
V_{CMU}	-	0.6	Maximum of vegetation cover	(12)
g_{VU}	1/yr		Colonization rate	(12)
m_{VU}	1/yr		Mortality rate	(12)
r_{EWSUC}	-	0.3	Parameter	(14)
g_{VU0}	1/yr	0.8	Parameter	(14)
m_{VU1}	1/yr	0.1	Parameter	(14)
m_{VU2}	1/yr	0.3	Parameter	(14)
r_{EWSU}	-		Environmental water supply ratio	(15)
W_{ERU}	m^3		Environmental water requirement	(15)
T	yr		Time step, 1 year	(15)
g_{VL}	1/yr		Colonization rate	(16)
m_{VL}	1/yr		Mortality rate	(16)
V_{CML}	-	0.5	Maximum of vegetation cover	(16)
g_{RU}	1/yr		Colonization rate of new irrigated field	(18)

g_{R2U}	-		Colonization rate of new irrigated field	(18)
g_{R3U}	-		Colonization rate of new irrigated field	(18)
m_{RU}	1/yr		Desolation rate of current irrigated field	(18)
m_{R2U}	-		Desolation rate of current irrigated field	(18)
m_{R3U}	-		Desolation rate of current irrigated field	(18)
r_{IMU}	-	0.6	Maximum of irrigated crop area ratio	(18)
g_{RL}	1/yr		Colonization rate of new irrigated field	(20)
g_{R2L}	-		Colonization rate of new irrigated field	(20)
m_{RL}	1/yr		Desolation rate of current irrigated field	(20)
m_{R2L}	-		Desolation rate of current irrigated field	(20)
R_{IML}	-	0.35	Maximum of irrigated crop area ratio	(20)
g_{NU}	1/yr		Colonization and immigration rate of the population	(22)
g_{N2U}	-		Colonization and immigration rate of the population	(22)
m_{NU}	1/yr		Mortality and emigration rate of the population	(22)
m_{N2U}	-		Mortality and emigration rate of the population	(22)
N_{MU}	10^4 persons	150	Maximum of the population	(22)
g_{NL}	1/yr		Colonization and immigration rate of the population	(23)
g_{N2L}	-		Colonization and immigration rate of the population	(23)
m_{NL}	1/yr		Mortality and emigration rate of the population	(23)
m_{N2L}	-		Mortality and emigration rate of the population	(23)
N_{ML}	10^4 persons	100	Maximum of the population	(23)
k_{qa}	-	15	Parameter	(24)
k_{qb}	-	0.3	Parameter	(24)
k_{qc}	-	0.2	Parameter	(24)
r_{EWSLC}	-	0.3	Parameter	(26)
g_{VL0}	1/yr	0.8	Parameter	(26)
m_{VL1}	1/yr	0.1	Parameter	(26)
m_{VL2}	1/yr	0.3	Parameter	(26)
r_{EWSL}	-		Environmental water supply ratio	(26)
W_{ERL}	m^3		Environmental water requirement	(27)
r_{WUC}	-	0.3	Parameter	(28)
g_{RU0}	1/yr	0.62	Parameter	(28)
m_{RU1}	1/yr	0.02	Parameter	(28)
m_{RU2}	1/yr	0.1	Parameter	(28)
r_{WU}	-		Irrigation water supply ratio	(28)
W_{IRU}	m^3		Irrigation water requirement	(29)
V_{CUC}	-	0.2	Parameter	(30)
g_{R2U0}	-	1.5	Parameter	(30)
m_{R2U1}	-	1.1	Parameter	(30)
m_{R2U2}	-	1.3	Parameter	(30)
V_{CLC}	-	0.1	Parameter	(31)
g_{R3U0}	-	1.5	Parameter	(31)

m_{R3U1}	-	1.1	Parameter	(31)
m_{R3U2}	-	1.3	Parameter	(31)
r_{WLC}	-	0.3	Parameter	(32)
g_{RL0}	1/yr	0.59	Parameter	(32)
m_{RL1}	1/yr	0.02	Parameter	(32)
m_{RL2}	1/yr	0.1	Parameter	(32)
r_{WL}	-		Irrigation water supply ratio	(32)
W_{IRL}	m^3		Irrigation water requirement	(33)
V_{CLCL}	-	0.1	Parameter	(34)
g_{R2L0}	-	1.5	Parameter	(34)
m_{R2L1}	-	1.1	Parameter	(34)
m_{R2L2}	-	1.4	Parameter	(34)
V_{CUCNU}	-	0.4	Parameter	(35)
g_{NU0}	1/yr	0.0019	Parameter	(35)
m_{NU1}	1/yr	0.01	Parameter	(35)
m_{NU2}	1/yr	0.03	Parameter	(35)
R_{IUCNU}	-	0.01	Parameter	(36)
g_{N2U0}	-	1.2	Parameter	(36)
m_{N2U1}	-	1.1	Parameter	(36)
m_{N2U2}	-	1.2	Parameter	(36)
V_{CLCNL}	-	0.4	Parameter	(37)
g_{NL0}	1/yr	0.002	Parameter	(37)
m_{NL1}	1/yr	0.01	Parameter	(37)
m_{NL2}	1/yr	0.03	Parameter	(37)
R_{ILCNL}	-	0.01	Parameter	(38)
g_{N2L0}	-	1.2	Parameter	(38)
m_{N2L1}	-	1.1	Parameter	(38)
m_{N2L2}	-	1.2	Parameter	(38)

List of figures


Legend
City
County
Hydrological station
China
42°
40°
80°
82°
84°
86°
88°
N
Korla City
Yuli County
Yingbazha
Xayar County
Aksu City
Aksu River
Xinqiman
Qiala
Awat County
Aral
Tarim River
Daxihaizi
Yingsu
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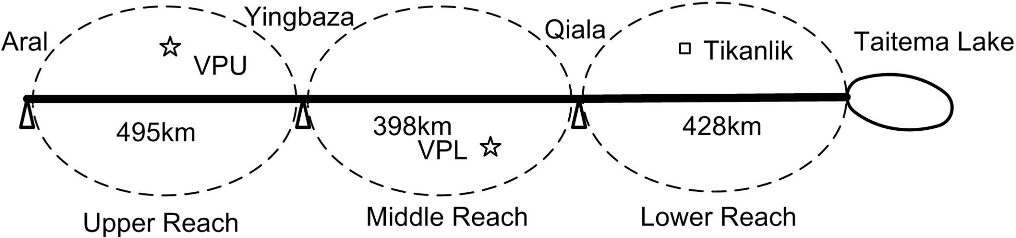
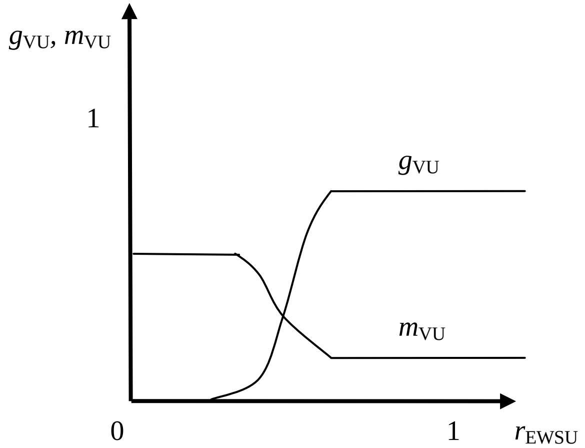
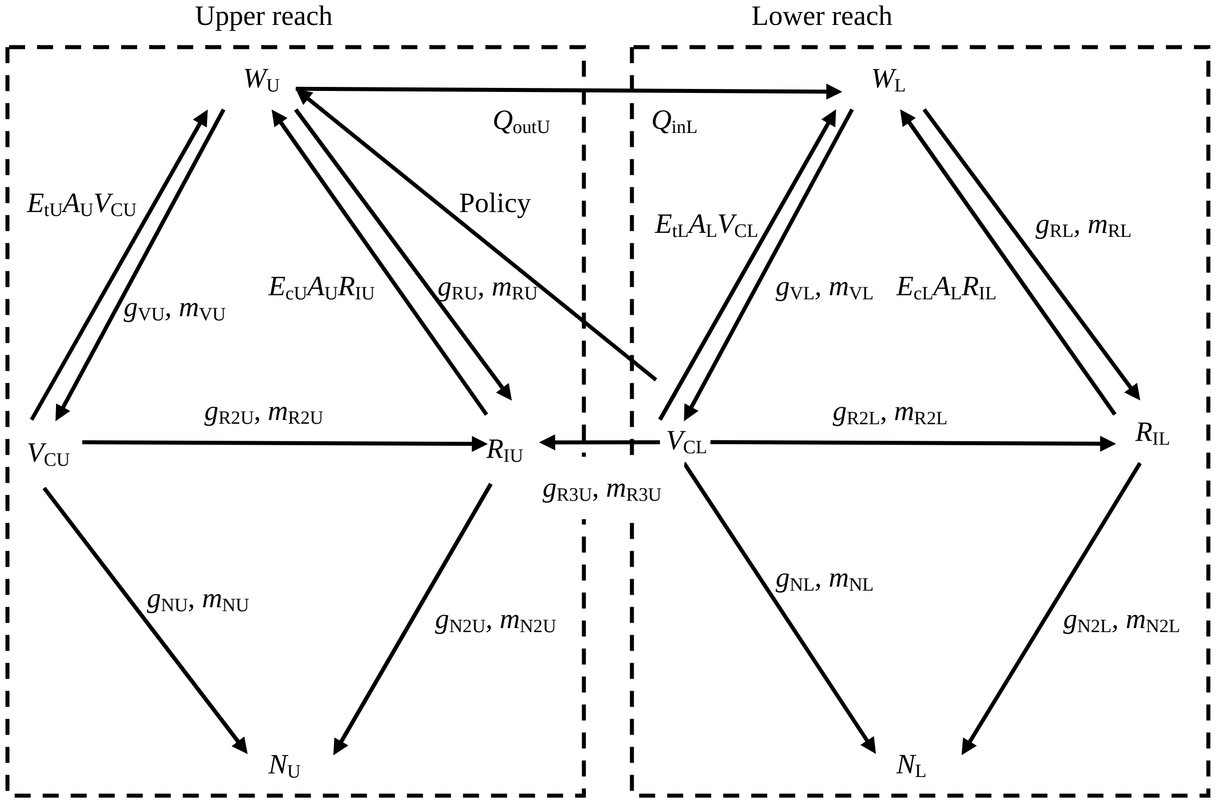
Taklimakan Desert
Hotan River
Taitema Lake



Main stream of Tarim River



g_{VU}, m_{VU}
1
g_{VU}
m_{VU}
0
1
r_{EWSU}


Upper reach
Lower reach
W_U
W_L
Q_{outU}
Q_{inL}
Policy
$E_{tU}A_UV_{CU}$
g_{VU}, m_{VU}
$E_{cU}A_UR_{IU}$
g_{RU}, m_{RU}
$E_{tL}A_LV_{CL}$
g_{VL}, m_{VL}
$E_{cL}A_LR_{IL}$
g_{RL}, m_{RL}
V_{CU}
g_{R2U}, m_{R2U}
R_{IU}
V_{CL}
g_{R2L}, m_{R2L}
R_{IL}
g_{R3U}, m_{R3U}
g_{NU}, m_{NU}
g_{N2U}, m_{N2U}
g_{NL}, m_{NL}
g_{N2L}, m_{N2L}
N_U
N_L

x 10^9
Qin
Sim. Qout
Obs. Qout
Discharge of Upper Reach(m^3/year)
0
1
2
3
4
5
6
7
1950
1960
1970
1980
1990
2000
2010
Year

0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1950
1960
1970
1980
1990
2000
2010
Year
V_c of Upper Reach(-)
Sim.
Obs.

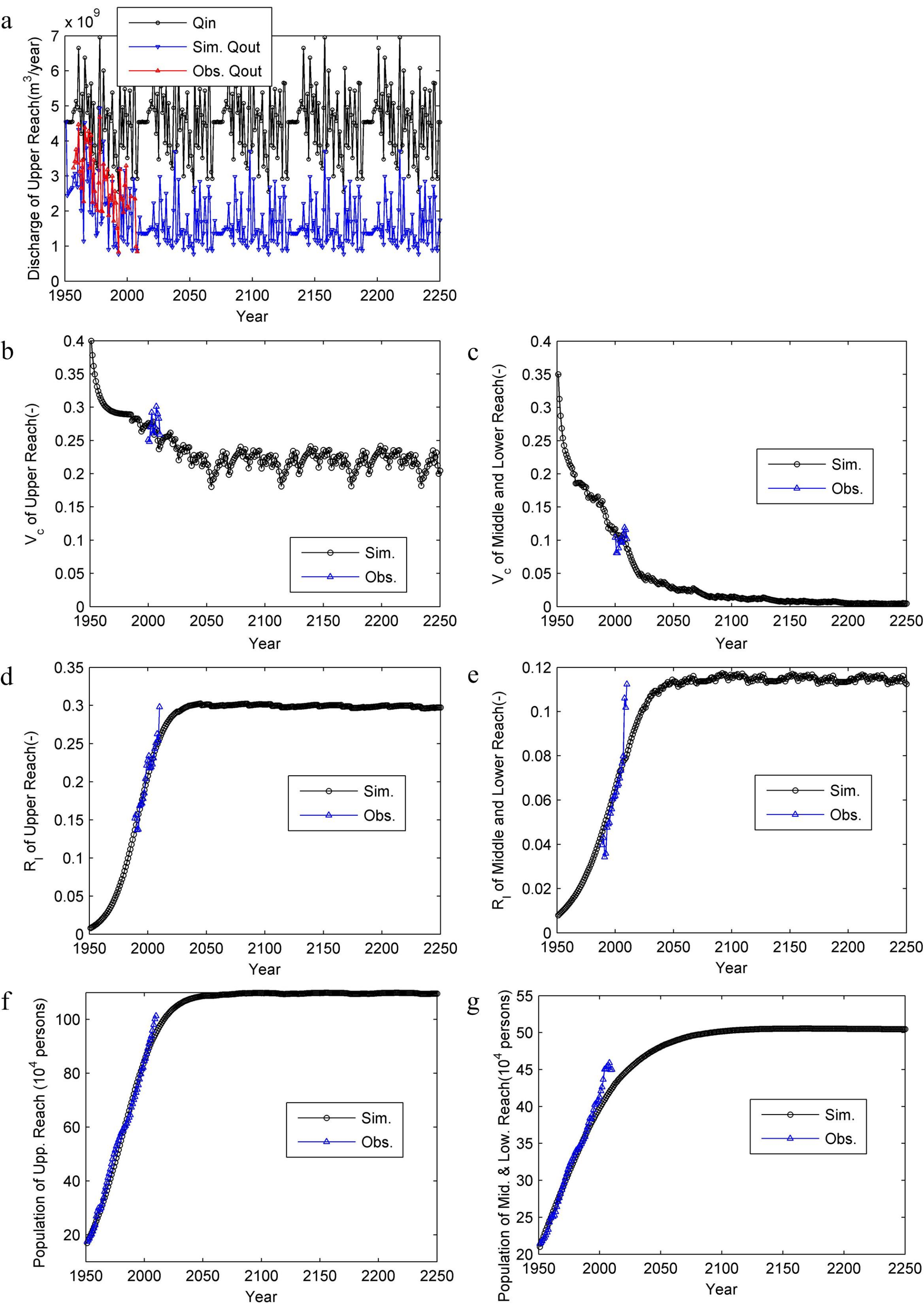
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1950
1960
1970
1980
1990
2000
2010
Year
V_c of Middle and Lower Reach(-)
Sim.
Obs.


0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1950
1960
1970
1980
1990
2000
2010
Year
R_l of Upper Reach(-)
Sim.
Obs.

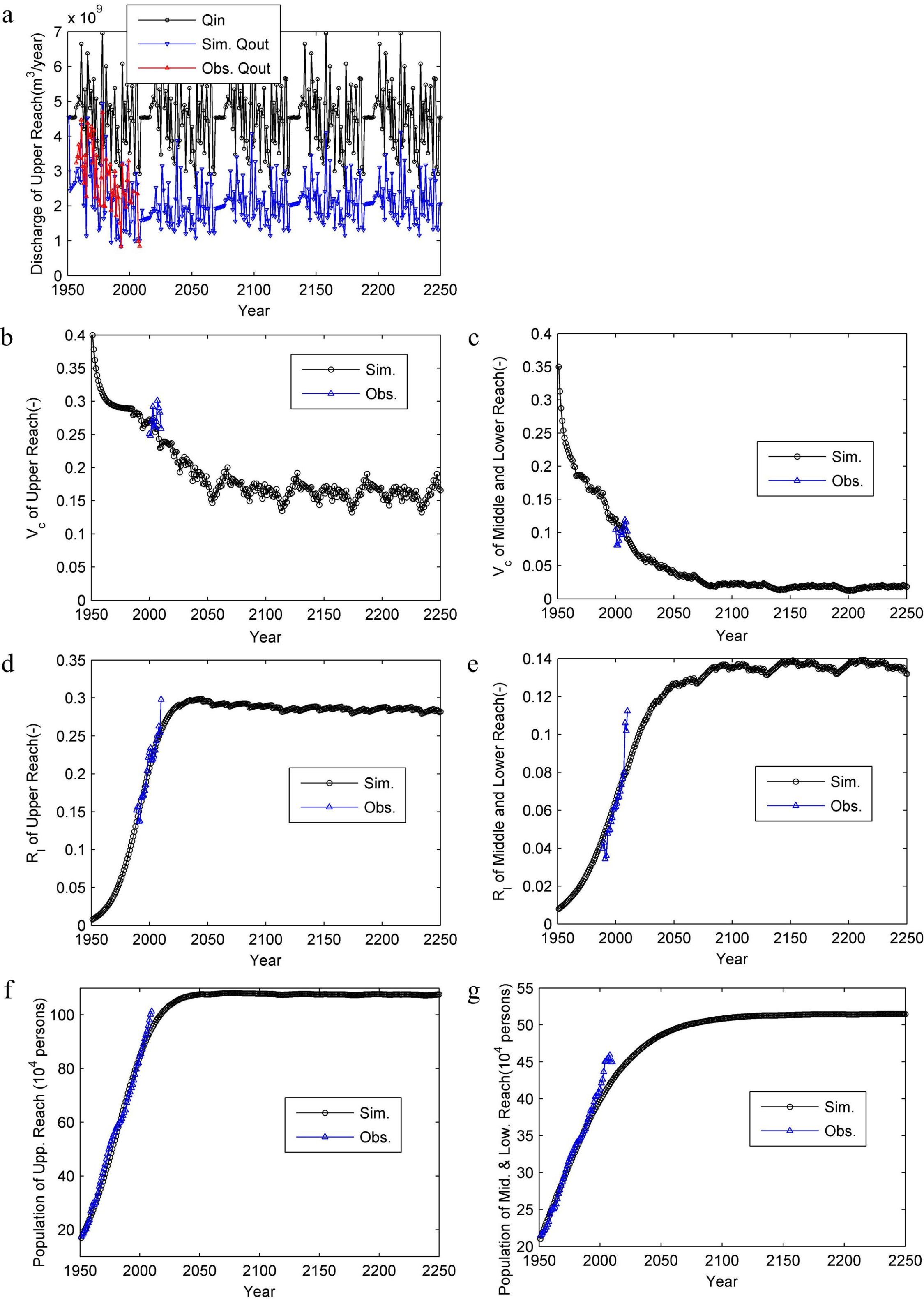
Sim.
Obs.
0.12
0.1
0.08
0.06
0.04
0.02
0
1950
1960
1970
1980
1990
2000
2010
Year
R_l of Middle and Lower Reach(-)

Population of Upp. Reach (10^4 persons)
100
80
60
40
20
1950
1960
1970
1980
1990
2000
2010
Year
Sim.
Obs.

Popu. of Mid.& Low.Reach(10^4persons)
Year
Sim.
Obs.
20
25
30
35
40
45
50
1950
1960
1970
1980
1990
2000
2010



a
x 10^9
Qin
Sim. Qout
Obs. Qout
Discharge of Upper Reach(m^3/year)
Year
b
V_c of Upper Reach(-)
Sim.
Obs.
Year
c
V_c of Middle and Lower Reach(-)
Sim.
Obs.
Year
d
R_I of Upper Reach(-)
Sim.
Obs.
Year
e
R_I of Middle and Lower Reach(-)
Sim.
Obs.
Year
f
Population of Upp. Reach (10^4 persons)
Sim.
Obs.
Year
g
Population of Mid. & Low. Reach(10^4 persons)
Sim.
Obs.
Year



a
x 10^9
Qin
Sim. Qout
Obs. Qout
Discharge of Upper Reach(m^3/year)
Year
b
Sim.
Obs.
V_c of Upper Reach(-)
Year
c
Sim.
Obs.
V_c of Middle and Lower Reach(-)
Year
d
Sim.
Obs.
R_l of Upper Reach(-)
Year
e
Sim.
Obs.
R_l of Middle and Lower Reach(-)
Year
f
Sim.
Obs.
Population of Upp. Reach (10^4 persons)
Year
g
Sim.
Obs.
Population of Mid. & Low. Reach(10^4 persons)
Year