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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 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 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 coupled to stream discharge through irrigation water consumption. In a similar way, the 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.

1 Introduction

In the emergent Anthropocene, the competition for water between humans and the environment plays a fundamental role in how the two coupled systems, human/social and natural, have co-evolved in the past and possible future trajectories of their co-evolution. The interactions between the hydrologic and social subsystems are always changing, generating new connections and, in particular, more significant feedbacks which 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). In fact, these 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,

HESSD
11, 3911–3966, 2014

possible future trajectories of the human–water system could not be fully explored or predicted.

The explicit and detailed description of the interactions between hydrology and society is really 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, 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 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 ecohydrology, Levins and Culver (1971) introduced the logistic function to describe the vegetation dynamics, adapting similar approaches used to describe population dynamics (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: 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, the dynamics involving the interactions and feedbacks between human populations and natural resources have been intensively studied by many researchers 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

HESSD
11, 3911–3966, 2014

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 interaction 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, b). 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.

HESSD
11, 3911–3966, 2014

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 only 34.1 mm and mean annual pan evaporation from 1957 to 2010 is 2630.0 mm at Tieganlike in the lower reach of the Tarim River. Almost all water consumption 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 for a start) 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 on "study area and data", details of the study area and the data used in the modeling are presented, followed by the details and justification of the modeling framework adopted for the Tarim River Basin. Results of model calibration and validation are presented next, along with the results of sensitivity analysis. 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 Fig. 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 modeling effort on the mainstream part of the Tarim River, i.e. from Aral to Taitema Lake which, for computational reasons, is divided into 2

HESSD
11, 3911–3966, 2014

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 Fig. 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 derived from the data set of SURF_CLI_CHN_MUL_DAY_V3 of the China Meteorological Data Sharing Service System. Streamflow data at Aral and Yingbazha hydrological stations were collected from the local hydrological agency. 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, 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 250 m 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 Fig. 2. The vegetation *typical* point (VPL) in the middle and lower reach is at (41°1′10″ N, 86°14′0″ E) near Qiala.

HESSD
11, 3911–3966, 2014

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 land use types contain irrigated crop fields, natural vegetation and bare desert;
2. the water requirement of natural vegetation growth in the lower reach mainly comes from streamflow released from the upper reach;
3. the released discharge from the upper reach is determined by inflow into the upper reach, 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 Tarim River Basin 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. 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 industries are neglected in the present modeling effort.

The state variables of each unit are described as follows:

1. water storage (W), in m^3. W represents assignable 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 ecological water, and it is defined

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
HESSD
11, 3911–3966, 2014
Coupled modeling framework for co-evolution of humans and water
D. Liu et al.
Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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 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 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 hydrology of the system in terms of the water balance equation. The water balance equation for the upper reach is given by:

$$\frac{\mathrm{d}W_\mathrm{U}}{\mathrm{d}t} = P_\mathrm{U}A_\mathrm{U} - E_\mathrm{tU}A_\mathrm{U}V_\mathrm{CU} - E_\mathrm{cU}A_\mathrm{U}R_\mathrm{IU} - E_\mathrm{bU}A_\mathrm{U}(1 - V_\mathrm{CU} - R_\mathrm{IU}) + Q_\mathrm{inU} - Q_\mathrm{outU} \tag{1}$$

where, P is the annual precipitation, E_t is the annual evaporation from natural vegetation area, E_c is the annual evaporation from irrigated crop area, and E_b is the annual evaporation from the bare desert, all expressed in $\mathrm{mm\,yr^{-1}}$. The precipitation falling on the bare desert is assumed to be completely evaporated.

$$\begin{aligned} E_\mathrm{t} &= k_\mathrm{t}E_\mathrm{p} \\ E_\mathrm{c} &= k_\mathrm{c}E_\mathrm{p} \\ E_\mathrm{b} &= P \end{aligned} \tag{2}$$

where E_p is the annual potential evaporation, also in $\mathrm{mm\,yr^{-1}}$, k_t and k_c are empirical coefficients. Q_{inU} is the inflow to the upper reach, in $\mathrm{m^3\,yr^{-1}}$, which is taken as the observed discharge at Aral. Q_{outU} is the outflow from the upper reach, in $\mathrm{m^3\,yr^{-1}}$, and is determined by Q_{inU}, W_U, V_{CL} and other variables. In principle, Q_{outU} could be calculated as

$$Q_{outU} = q_1(Q_{inU}) + q_2(W_U) + q_3(V_{CL}). \quad (3)$$

The first term on the right hand side of Eq. (3), q_1, will increase with upper reach inflow, q_2 will increase with W, i.e. assignable water resource, and $q_3$will increase with vegetation cover of the lower reach, accounting for the vegetation restoration 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.

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. $k_Q Q_{inU}$, 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. Q_{outU} is then given by:

$$Q_{outU} = \max\{P_U A_U - E_{tU} A_U V_{CU} - E_{cU} A_U R_{IU} - E_{bU} A_U (1 - V_{CU} - R_{IU}) + Q_{inU}, k_Q Q_{inU}\}. \quad (4)$$

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

$$E_{tU} = \max\left\{\frac{P_U A_U - E_{cU} A_U R_{IU} - E_{bU} A_U (1 - V_{CU} - R_{IU}) + Q_{inU} - Q_{outU}}{A_U V_{CU}}, P_U\right\}. \quad (5)$$

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

$$E_{cU} = \frac{P_U A_U - E_{tU} A_U V_{CU} - E_{bU} A_U (1 - V_{CU} - R_{IU}) + Q_{inU} - Q_{outU}}{A_U R_{IU}}. \quad (6)$$

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

$$\frac{dW_L}{dt} = P_L A_L - E_{tL} A_L V_{CL} - E_{cL} A_L R_{IL} - E_{bL} A_L (1 - V_{CL} - R_{IL}) + Q_{inL} \quad (7)$$

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

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

If the water in the lower reach is sufficient, all of the assignable 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

$$E_{bL} = \max\left\{\frac{P_L A_L - E_{tL} A_L V_{CL} - E_{cL} A_L R_{IL} + Q_{inL}}{A_L (1 - V_{CL} - R_{IL})}, P_L\right\}. \quad (9)$$

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 evaporation of the natural vegetation, i.e. E_{tL}, is given by:

$$E_{tL} = \max\left\{\frac{P_L A_L - E_{cL} A_L R_{IL} - E_{bL} A_L (1 - V_{CL} - R_{IL}) + Q_{inL}}{A_L V_{CL}}, P_L\right\}. \quad (10)$$

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

$$E_{cL} = \frac{P_L A_L - E_{tL} A_L V_{CL} - E_{bL} A_L (1 - V_{CL} - R_{IL}) + Q_{inL}}{A_L R_{IL}}. \quad (11)$$

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).

HESSD
11, 3911–3966, 2014
Coupled modeling framework for co-evolution of humans and water
D. Liu et al.

The vegetation dynamical equation has already been applied and validated in the Tarim River (Liu et al., 2012a, b). The dynamical equation of vegetation cover of the upper reach is given by:

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

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:

$$V_{CMU} = \frac{\text{available environmental water/water requirement per unit area}}{A_U}. \tag{13}$$

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

$$g_{VU} = \frac{g_{VU0}}{1 + \exp((r_{EWSUC} - r_{EWSU})/\lambda_{gVU})}$$
$$m_{VU} = \frac{m_{VU2} - m_{VU1}}{1 + \exp((r_{EWSU} - r_{EWSUC})/\lambda_{mVU})} + m_{VU1} \tag{14}$$

where, g_{VU}, m_{VU1}, m_{VU2}, $\lambda_{g_{VU}}$, $\lambda_{m_{VU}}$ and r_{EWSUC} are the empirical parameters. r_{EWS} is 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:

$$r_{EWSU} = \frac{E_{tU}A_UV_{CU}T}{W_{ERU}} \tag{15}$$

HESSD
11, 3911–3966, 2014

where, T is 1 year and is equal to the time step of environmental water requirement, W_{ERU} is environmental water requirement. Similarly, the dynamical equations of vegetation coverage of the lower reach are

$$\frac{\mathrm{d}V_{\mathrm{CL}}}{\mathrm{d}t} = g_{\mathrm{VL}} V_{\mathrm{CL}} (V_{\mathrm{CML}} - V_{\mathrm{CL}}) - m_{\mathrm{VL}} V_{\mathrm{CL}} \tag{16}$$

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

$$\begin{aligned} g_{\mathrm{VL}} &= \frac{g_{\mathrm{VL0}}}{1+\exp((r_{\mathrm{EWSLC}} - r_{\mathrm{EWSL}})/\lambda_{\mathrm{gVL}})} \\ m_{\mathrm{VL}} &= \frac{m_{\mathrm{VL2}} - m_{\mathrm{VL1}}}{1+\exp((r_{\mathrm{EWSL}} - r_{\mathrm{EWSLC}})/\lambda_{\mathrm{mVL}})} + m_{\mathrm{VL1}} \end{aligned} \tag{18}$$

$$r_{\mathrm{EWSL}} = \frac{E_{\mathrm{tL}} A_{\mathrm{L}} V_{\mathrm{CL}} T}{W_{\mathrm{ERL}}}. \tag{19}$$

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 evolution of the irrigated crop area is caused 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. The dynamical equation of irrigated crop area ratio of the upper reach is

$$\frac{\mathrm{d}R_{\mathrm{IU}}}{\mathrm{d}t} = g_{\mathrm{RU}} g_{\mathrm{R2U}} g_{\mathrm{R3U}} R_{\mathrm{IU}} (R_{\mathrm{IMU}} - R_{\mathrm{IU}}) - m_{\mathrm{RU}} m_{\mathrm{R2U}} m_{\mathrm{R3U}} R_{\mathrm{IU}} \tag{20}$$

HESSD
11, 3911–3966, 2014

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

$$R_{IMU} = \frac{\text{available irrigation water/water requirement per unit area}}{A_U}. \quad (21)$$

The terms g_{RU} and m_{RU} represent the impact of available water to the area of irrigated field. The dependent relationships are similar as shown in Fig. 3, which are described by the following equations.

$$g_{RU} = \frac{g_{RU0}}{1 + \exp((r_{WUC} - r_{WU})/\lambda_{gRU})}$$
$$m_{RU} = \frac{m_{RU2} - m_{RU1}}{1 + \exp((r_{WU} - r_{WUC})/\lambda_{mRU})} + m_{RU1} \quad (22)$$

where, g_{RU}, 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:

$$r_{WU} = \frac{E_{cU} A_U R_{IU} T}{W_{IRU}} \quad (23)$$

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 Fig. 3 and described by the following equations.

$$g_{R2U} = \frac{g_{R2U0}}{1 + \exp((V_{CUC} - V_{CU})/\lambda_{gR2U})}$$
$$m_{R2U} = \frac{m_{R2U2} - m_{R2U1}}{1 + \exp((V_{CU} - V_{CUC})/\lambda_{mR2U})} + m_{R2U1} \quad (24)$$

HESSD
11, 3911–3966, 2014

Coupled modeling framework for co-evolution of humans and water

D. Liu et al.

where, g_{R2U}, 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 Fig. 3 and described by the following equations.

$$g_{R3U} = \frac{g_{R3U0}}{1+\exp((V_{CLC}-V_{CL})/\lambda_{gR3U})}$$
$$m_{R3U} = \frac{m_{R3U2}-m_{R3U1}}{1+\exp((V_{CL}-V_{CLC})/\lambda_{mR3U})} + m_{R3U1} \tag{25}$$

where, g_{R3U}, 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

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

$$R_{IML} = \frac{\text{available irrigation water/water requirement per unit area}}{A_L} \tag{27}$$

$$g_{RL} = \frac{g_{RL0}}{1+\exp((r_{WLC}-r_{WL})/\lambda_{gRL})} \tag{28}$$
$$m_{RL} = \frac{m_{RL2}-m_{RL1}}{1+\exp((r_{WL}-r_{WLC})/\lambda_{mRL})} + m_{RL1}$$

$$r_{WL} = \frac{E_{cL} A_L R_{IL} T}{W_{IRL}} \tag{29}$$

$$g_{R2L} = \frac{g_{R2L0}}{1+\exp((V_{CLCL}-V_{CL})/\lambda_{gR2L})}$$
$$m_{R2L} = \frac{m_{R2L2}-m_{R2L1}}{1+\exp((V_{CL}-V_{CLCL})/\lambda_{mR2L})} + m_{R2L1}. \tag{30}$$

HESSD
11, 3911–3966, 2014

Coupled modeling framework for co-evolution of humans and water

D. Liu et al.

The 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

$$\frac{\mathrm{d}N_{\mathrm{U}}}{\mathrm{d}t} = g_{\mathrm{NU}} g_{\mathrm{N2U}} N_{\mathrm{U}} (N_{\mathrm{MU}} - N_{\mathrm{U}}) - m_{\mathrm{NU}} m_{\mathrm{N2U}} N_{\mathrm{U}} \tag{31}$$

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 dependent relationships of the population on the environment, i.e. V_{CU}, are similar as shown in Fig. 3, which are described by the following equations.

$$\begin{aligned} g_{\mathrm{NU}} &= \frac{g_{\mathrm{NU0}}}{1 + \exp((V_{\mathrm{CUCNU}} - V_{\mathrm{CU}})/\lambda_{\mathrm{gNU}})} \\ m_{\mathrm{NU}} &= \frac{m_{\mathrm{NU2}} - m_{\mathrm{NU1}}}{1 + \exp((V_{\mathrm{CU}} - V_{\mathrm{CUCNU}})/\lambda_{\mathrm{mNU}})} + m_{\mathrm{NU1}} \end{aligned} \tag{32}$$

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 Fig. 3, which are described as:

$$\begin{aligned} g_{\mathrm{N2U}} &= \frac{g_{\mathrm{N2U0}}}{1 + \exp((R_{\mathrm{IUCNU}} - R_{\mathrm{IU}})/\lambda_{\mathrm{gN2U}})} \\ m_{\mathrm{N2U}} &= \frac{m_{\mathrm{N2U2}} - m_{\mathrm{N2U1}}}{1 + \exp((R_{\mathrm{IU}} - R_{\mathrm{IUCNU}})/\lambda_{\mathrm{mN2U}})} + m_{\mathrm{N2U1}} \end{aligned} \tag{33}$$

HESSD
11, 3911–3966, 2014

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

$$\frac{dN_L}{dt} = g_{NL}g_{N2L}N_L(N_{ML} - N_L) - m_{NL}m_{N2L}N_L \tag{34}$$

$$g_{NL} = \frac{g_{NL0}}{1 + \exp((V_{CLCNL} - V_{CL})/\lambda_{gNL})}$$
$$m_{NL} = \frac{m_{NL2} - m_{NL1}}{1 + \exp((V_{CL} - V_{CLCNL})/\lambda_{mNL})} + m_{NL1} \tag{35}$$

$$g_{N2L} = \frac{g_{N2L0}}{1 + \exp((R_{ILCNL} - R_{IL})/\lambda_{gN2L})}$$
$$m_{N2L} = \frac{m_{N2L2} - m_{N2L1}}{1 + \exp((R_{IL} - R_{ILCNL})/\lambda_{mN2L})} + m_{N2L1}. \tag{36}$$

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 Fig. 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 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 assignable water resources (W_U) will decrease and the 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 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 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 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

HESSD
11, 3911–3966, 2014

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.

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 3. The assignable 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.

4.3 Simulation results

The simulation results of discharge, vegetation cover, ratio of irrigated area and population of two modeling units are shown in Figs. 5–11, 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 Fig. 5. For comparison, the observed inflow of the upper reach is also shown in Fig. 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 dynamics of evolution of vegetation cover are shown in Figs. 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 Figs. 6 and 7, the simulated vegetation cover decreases from 1951 to 2010 and holds at the similar level with the

HESSD
11, 3911–3966, 2014

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 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 Figs. 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 Figs. 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.

HESSD
11, 3911–3966, 2014

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 Figs. 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 %, 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.

HESSD
11, 3911–3966, 2014

5 Discussion

In order to study the evolution of the socio-hydrological system, precipitation, evaporation and inflow are repeated 4 times 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 Fig. 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 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 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 Table 2.

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 Eq. (4) could be calculated as

$$k_Q = k_{qc} \exp(-k_{qa} V_{CL}) + k_{qb} \tag{37}$$

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 Eq. (4) is

$$Q_{outU} = (k_{qc} \exp(-k_{qa} V_{CL}) + k_{qb}) Q_{inU}. \tag{38}$$

The resulting model is denoted here as the *revised model*. The dynamics of co-evolution governed by the inclusion of the Eq. (38) and using the 300 years forcing

HESSD
11, 3911–3966, 2014

data are shown in Fig. 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 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. Eq. (38), which is the driver for water release from the upstream to the downstream. In Eq. (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 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 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.

HESSD
11, 3911–3966, 2014

D. Liu et al.

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 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.

In order to analyze the sensitivity of system behaviors to initial values and boundary conditions, i.e. the precipitation, potential evaporation and inflow of the upper reach, the baseline model 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 5, where the initial values, precipitation, potential evaporation, inflow of the upper reach and k_c are decreased or increased by 10 %, respectively. The results show that all the tested

HESSD
11, 3911–3966, 2014

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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 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, 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 co-evolution.

6 Conclusions

Because water plays an important role in the socio-hydrological system in Tarim River Basin, the hydrological process, ecological process and socioeconomic process are coupled together by water and water allocation policy within the river basin. The socio-hydrologic co-evolution model, a simple coupled modeling framework, is developed for the Tarim River Basin in Western China, and is used to illustrate the explanatory power of such models. In the Tarim River, humans depend heavily on agricultural production, and the social 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 stream discharge.

In each modeling unit, four ordinary differential equations are used to simulate the dynamics of the hydrological system represented by 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

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD
11, 3911–3966, 2014

Coupled modeling framework for co-evolution of humans and water

D. Liu et al.

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.

The simulated evolution processes of the socio-hydrological evolution model are consistent with observed behaviors. The simulated average annual runoff of the outflow in the upper reach is 2.312×10^9 m^3, which is 51.0 % of the inflow, and is 16.2 % less than the observed outflow. The average absolute value of the relative error of the simulated irrigated crop area ratio (R_I) in upper reach is 5.2 % and that is 12.3 % in the lower reach. The average absolute of relative error of the simulated population in the upper reach is 3.9 % and is 2.7 % in the lower reach.

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 unconsciously and usually is the

HESSD
11, 3911–3966, 2014

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.

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HESSD
11, 3911–3966, 2014

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HESSD
11, 3911–3966, 2014

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HESSD
11, 3911–3966, 2014

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 (V_C)	–
upper reach	Economic system	Industry product	–	–	Nearly none
		Irrigated crop area	Water supply and vegetation coverage	Irrigated crop area Ratio (R_I)	–
	Social system	Population	Irrigated crop area and vegetation coverage	Population (N)	–
	Hydrological system	Water storage	Water consumption and policy	Water storage (W)	–
	Ecological system	Natural vegetation area	Water supply	Vegetation coverage (V_C)	–
middle and lower reach	Economic system	Industry product	–	–	Nearly none
		Irrigated crop area	Water supply and vegetation coverage	Irrigated crop area Ratio (R_I)	–
	Social system	Population	Irrigated crop area and vegetation coverage	Population (N)	–

HESSD
11, 3911–3966, 2014

Coupled modeling framework for co-evolution of humans and water

D. Liu et al.

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_{VU}	$year^{-1}$	0.8	(14)
m_{VU1}	$year^{-1}$	0.1	(14)
m_{VU2}	$year^{-1}$	0.3	(14)
λ_{gVU}	–	1.0	(14)
λ_{mVU}	–	1.0	(14)
V_{CML}	–	0.5	(16)
r_{EWSLC}	–	0.3	(18)
g_{VL}	$year^{-1}$	0.8	(18)
m_{VL1}	$year^{-1}$	0.1	(18)
m_{VL2}	$year^{-1}$	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}	$year^{-1}$	0.62	(22)
m_{RU1}	$year^{-1}$	0.02	(22)
m_{RU2}	$year^{-1}$	0.1	(22)
λ_{gRU}	–	1.0	(22)
λ_{mRU}	–	1.0	(22)

HESSD
11, 3911–3966, 2014

Table 2. Continued.

Variable	Unit	Value	Equation
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}	year^{-1}	0.59	(28)
m_{RL1}	year^{-1}	0.02	(28)
m_{RL2}	year^{-1}	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)

HESSD
11, 3911–3966, 2014

Table 2. Continued.

Variable	Unit	Value	Equation
V_{CUCNU}	–	0.4	(32)
g_{NU0}	year^{-1}	0.0019	(32)
m_{NU1}	year^{-1}	0.01	(32)
m_{NU2}	year^{-1}	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}	year^{-1}	0.002	(35)
m_{NL1}	year^{-1}	0.01	(35)
m_{NL2}	year^{-1}	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)

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD
11, 3911–3966, 2014

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 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

HESSD
11, 3911–3966, 2014

Coupled modeling framework for co-evolution of humans and water

D. Liu et al.

Table 4. 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}	$10^9 m^3 year^{-1}$	4.544	4.544	–
Q_{outU}	$10^9 m^3 year^{-1}$	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 %

HESSD
11, 3911–3966, 2014

Coupled modeling framework for co-evolution of humans and water

D. Liu et al.

Table 5. Mean values of state variables during last 60 years of system evolution for sensitivity tests.

Conditions	Q_{outU}/ 10^9 m^3 year^{-1}	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

HESSD
11, 3911–3966, 2014

Table 6. 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
$0.9 \times P$	−0.32	−0.45	0.00	−0.33	−0.87	0.00	0.00
$1.1 \times P$	0.38	0.91	0.00	0.00	0.00	0.09	0.00
$0.9 \times E_{\mathrm{p}}$	4.83	10.45	160.00	2.01	6.09	0.82	0.99
$1.1 \times E_{\mathrm{p}}$	−3.24	−10.00	−80.00	−2.34	−5.22	−0.73	−0.59
$0.9 \times Q_{\mathrm{inU}}$	−12.91	−10.00	−60.00	−2.34	−6.09	−0.73	−0.59
$1.1 \times Q_{\mathrm{inU}}$	14.12	9.09	100.00	1.67	5.22	0.64	0.59
$0.9 \times k_{\mathrm{c}}$	2.35	7.73	60.00	1.34	5.22	0.55	0.59
$1.1 \times k_{\mathrm{c}}$	−1.84	−7.73	−60.00	−2.01	−5.22	−0.55	−0.59

HESSD
11, 3911–3966, 2014

Table A1. Nomenclature: the subscript U of the symbol represents the upper reach, and the subscript L of the symbol represents the lower reach.

Symbol	Unit	Description	Equation
W_U	m^3	Water storage	(1)
P_U	mm $year^{-1}$	Annual precipitation	(1)
A_U	km^2	Area of modeling unit	(1)
E_{tU}	mm $year^{-1}$	Annual evapotranspiration of the natural vegetation	(1)
E_{cU}	mm $year^{-1}$	Annual evapotranspiration of the irrigated crop area	(1)
E_{bU}	mm $year^{-1}$	Annual evapotranspiration of the bare desert	(1)
V_{CU}	–	Vegetation coverage	(1)
R_{IU}	–	Irrigated crop area ratio	(1)
Q_{inU}	m^3 $year^{-1}$	Inflow of upper reach	(1)
Q_{outU}	m^3 $year^{-1}$	Outflow of upper reach	(1)
k_{tU}	–	Coefficient	(2)
k_{cU}	–	Coefficient	(2)
E_p	mm $year^{-1}$	Annual potential evaporation	(2)
k_Q	–	Coefficient	(4)
k_{tL}	–	Coefficient	(7)
k_{cL}	–	Coefficient	(7)
W_L	m^3	Water storage	(7)
P_L	mm $year^{-1}$	Annual precipitation	(7)
A_L	km^2	Area of modeling unit	(7)
E_{tL}	mm $year^{-1}$	Annual evapotranspiration of the natural vegetation	(7)
E_{cL}	mm $year^{-1}$	Annual evapotranspiration of the irrigated crop area	(7)
E_{bL}	mm $year^{-1}$	Annual evapotranspiration of the bare desert	(7)
V_{CL}	–	Vegetation coverage	(7)
R_{IL}	–	Irrigated crop area ratio	(7)
Q_{inL}	m^3 $year^{-1}$	Inflow of lower reach	(7)

HESSD
11, 3911–3966, 2014

Table A1. Continued.

Symbol	Unit	Description	Equation
V_{CMU}	–	Maximum of vegetation coverage	(12)
g_{VU}	year^{-1}	Colonization rate	(12)
m_{VU}	year^{-1}	Mortality rate	(12)
r_{EWSUC}	–	Parameter	(14)
g_{VU}	year^{-1}	Parameter	(14)
m_{VU1}	year^{-1}	Parameter	(14)
m_{VU2}	year^{-1}	Parameter	(14)
λ_{gVU}	–	Parameter	(14)
$\lambda_{m\mathrm{VU}}$	–	Parameter	(14)
r_{EWSU}	–	Environmental water supply ratio	(15)
W_{ERU}	m^3	Environmental water requirement	(15)
T	year	Time step, 1 year	(15)
g_{VL}	year^{-1}	Colonization rate	(16)
m_{VL}	year^{-1}	Mortality rate	(16)
V_{CML}	–	Maximum of vegetation coverage	(16)
r_{EWSLC}	–	Parameter	(18)
g_{VL}	year^{-1}	Parameter	(18)
m_{VL1}	year^{-1}	Parameter	(18)
m_{VL2}	year^{-1}	Parameter	(18)
λ_{gVL}	–	Parameter	(18)
λ_{mVL}	–	Parameter	(18)
r_{EWSL}	–	Environmental water supply ratio	(19)
W_{ERL}	m^3	Environmental water requirement	(19)
g_{RU}	year^{-1}	Colonization rate of new irrigated field	(20)
g_{R2U}	–	Colonization rate of new irrigated field	(20)
g_{R3U}	–	Colonization rate of new irrigated field	(20)
m_{RU}	year^{-1}	Desolation rate of current irrigated field	(20)

HESSD
11, 3911–3966, 2014

Table A1. Continued.

Symbol	Unit	Description	Equation
m_{R2U}	–	Desolation rate of current irrigated field	(20)
m_{R3U}	–	Desolation rate of current irrigated field	(20)
r_{IMU}	–	Maximum of irrigated crop area ratio	(20)
r_{WUC}	–	Parameter	(22)
g_{RU0}	$year^{-1}$	Parameter	(22)
m_{RU1}	$year^{-1}$	Parameter	(22)
m_{RU2}	$year^{-1}$	Parameter	(22)
λ_{gRU}	–	Parameter	(22)
λ_{mRU}	–	Parameter	(22)
r_{WU}	–	Irrigation water supply ratio	(23)
W_{IRU}	m^3	Irrigation water requirement	(23)
V_{CUC}	–	Parameter	(24)
g_{R2U0}	–	Parameter	(24)
m_{R2U1}	–	Parameter	(24)
m_{R2U2}	–	Parameter	(24)
λ_{gR2U}	–	Parameter	(24)
λ_{mR2U}	–	Parameter	(24)
V_{CLC}	–	Parameter	(25)
g_{R3U0}	–	Parameter	(25)
m_{R3U1}	–	Parameter	(25)
m_{R3U2}	–	Parameter	(25)
λ_{gR3U}	–	Parameter	(25)
λ_{mR3U}	–	Parameter	(25)
g_{RL}	$year^{-1}$	Colonization rate of new irrigated field	(26)
g_{R2L}	–	Colonization rate of new irrigated field	(26)
m_{RL}	$year^{-1}$	Desolation rate of current irrigated field	(26)
m_{R2L}	–	Desolation rate of current irrigated field	(26)
R_{IML}	–	Maximum of irrigated crop area ratio	(26)

HESSD
11, 3911–3966, 2014
Coupled modeling framework for co-evolution of humans and water
D. Liu et al.

Table A1. Continued.

Symbol	Unit	Description	Equation
r_{WLC}	–	Parameter	(28)
g_{RL0}	year^{-1}	Parameter	(28)
m_{RL1}	year^{-1}	Parameter	(28)
m_{RL2}	year^{-1}	Parameter	(28)
λ_{gRL}	–	Parameter	(28)
V_{CLCL}	–	Parameter	(30)
λ_{mRL}	–	Parameter	(28)
r_{WL}	–	Irrigation water supply ratio	(29)
W_{IRL}	m^3	Irrigation water requirement	(29)
g_{R2L0}	–	Parameter	(30)
m_{R2L1}	–	Parameter	(30)
m_{R2L2}	–	Parameter	(30)
λ_{gR2L}	–	Parameter	(30)
λ_{mR2L}	–	Parameter	(30)
g_{NU}	year^{-1}	Colonization and immigration rate of the population	(31)
g_{N2U}	–	Colonization and immigration rate of the population	(31)
m_{NU}	year^{-1}	Mortality and emigration rate of the population	(31)
m_{N2U}	–	Mortality and emigration rate of the population	(31)
N_{MU}	10^4 persons	Maximum of the population	(31)
V_{CUCNU}	–	Parameter	(32)
g_{NU0}	year^{-1}	Parameter	(32)
m_{NU1}	year^{-1}	Parameter	(32)
m_{NU2}	year^{-1}	Parameter	(32)
λ_{gNU}	–	Parameter	(32)
λ_{mNU}	–	Parameter	(32)
R_{IUCNU}	–	Parameter	(33)
g_{N2U0}	–	Parameter	(33)

HESSD
11, 3911–3966, 2014

Table A1. Continued.

Symbol	Unit	Description	Equation
m_{N2U1}	–	Parameter	(33)
m_{N2U2}	–	Parameter	(33)
λ_{gN2U}	–	Parameter	(33)
λ_{mN2U}	–	Parameter	(33)
g_{NL}	year^{-1}	Colonization and immigration rate of the population	(34)
g_{N2L}	–	Colonization and immigration rate of the population	(34)
m_{NL}	year^{-1}	Mortality and emigration rate of the population	(34)
m_{N2L}	–	Mortality and emigration rate of the population	(34)
N_{ML}	10^4 persons	Maximum of the population	(34)
V_{CLCNL}	–	Parameter	(35)
g_{NL0}	year^{-1}	Parameter	(35)
m_{NL1}	year^{-1}	Parameter	(35)
m_{NL2}	year^{-1}	Parameter	(35)
λ_{gNL}	–	Parameter	(35)
λ_{mNL}	–	Parameter	(35)
R_{ILCNL}	–	Parameter	(36)
g_{N2L0}	–	Parameter	(36)
m_{N2L1}	–	Parameter	(36)
m_{N2L2}	–	Parameter	(36)
λ_{gN2L}	–	Parameter	(36)
λ_{mN2L}	–	Parameter	(36)
k_{qa}	–	Parameter	(37)
k_{qb}	–	Parameter	(37)
k_{qc}	–	Parameter	(37)

HESSD
11, 3911–3966, 2014

Coupled modeling framework for co-evolution of humans and water

D. Liu et al.

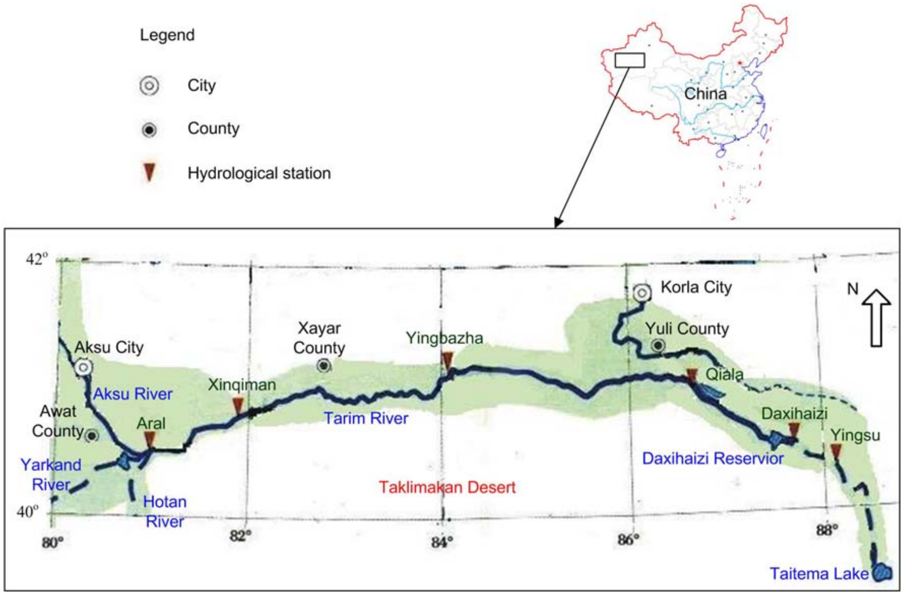

Fig. 1. Location of main stream of Tarim River.

HESSD
11, 3911–3966, 2014

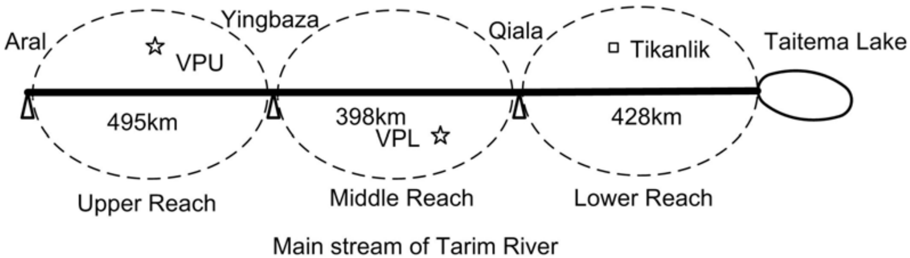

Fig. 2. Sketch map of main stream of Tarim River.

HESSD
11, 3911–3966, 2014

Coupled modeling framework for co-evolution of humans and water

D. Liu et al.

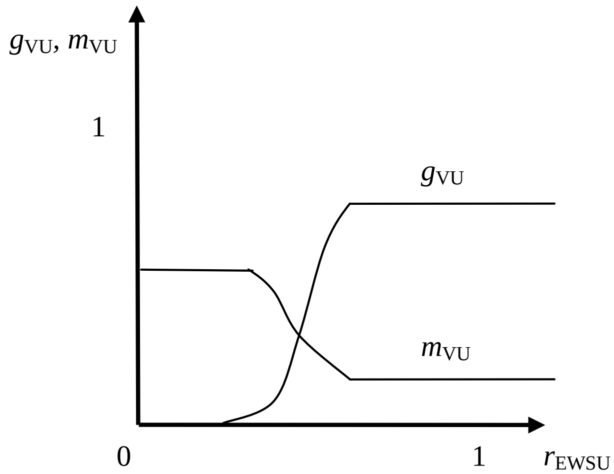

Fig. 3. Dependent relationships of the colonization and mortality of natural vegetation depending on the environmental water supply.

HESSD
11, 3911–3966, 2014

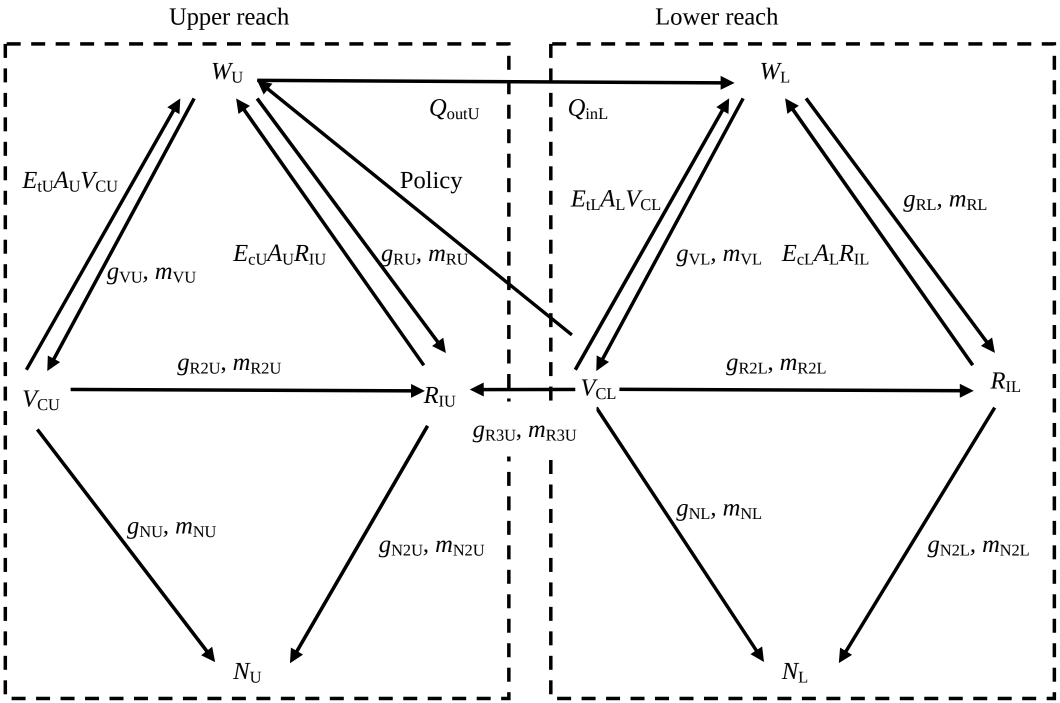

Fig. 4. Feedbacks in the socio-hydrological system of Tarim River.

HESSD
11, 3911–3966, 2014

HESSD
11, 3911–3966, 2014

D. Liu et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

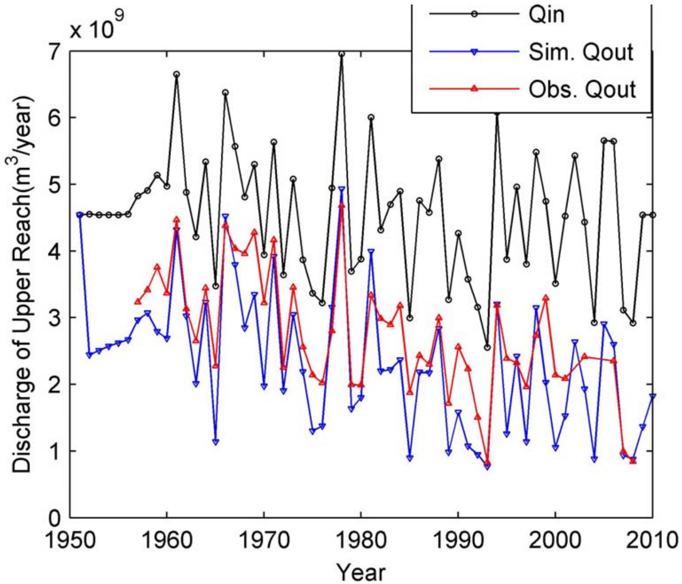

Fig. 5. Discharge of the upper reach of Tarim River. The outflow (Q_{out}) of the upper reach is the inflow of the lower reach.

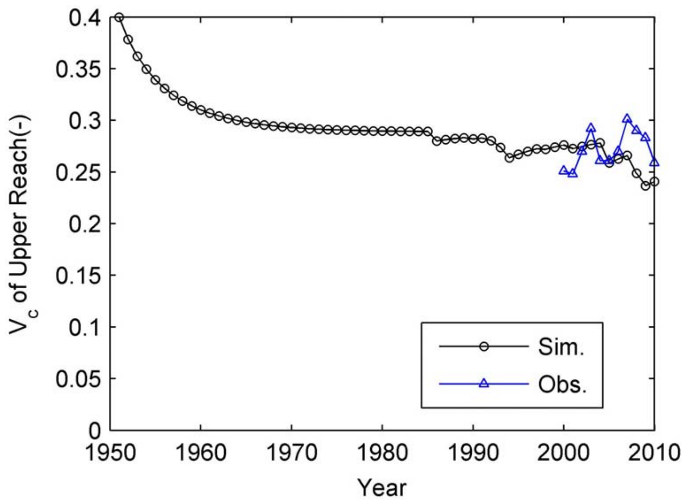

Fig. 6. Vegetation coverage (V_C) of the upper reach of Tarim River.

HESSD
11, 3911–3966, 2014

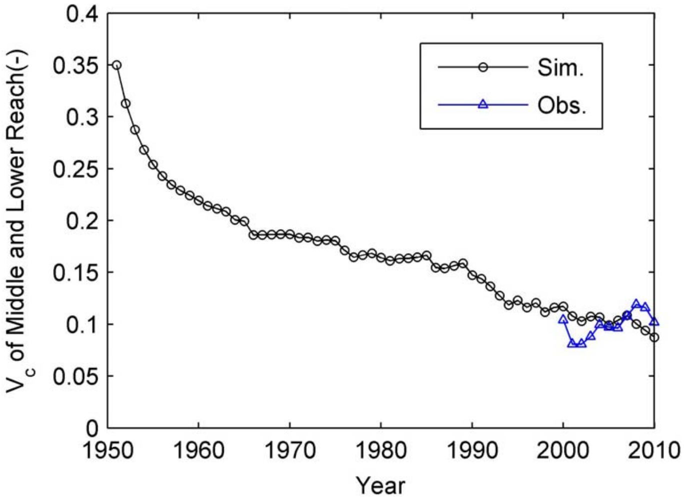

Fig. 7. Vegetation coverage (V_C) of the lower reach of Tarim River.

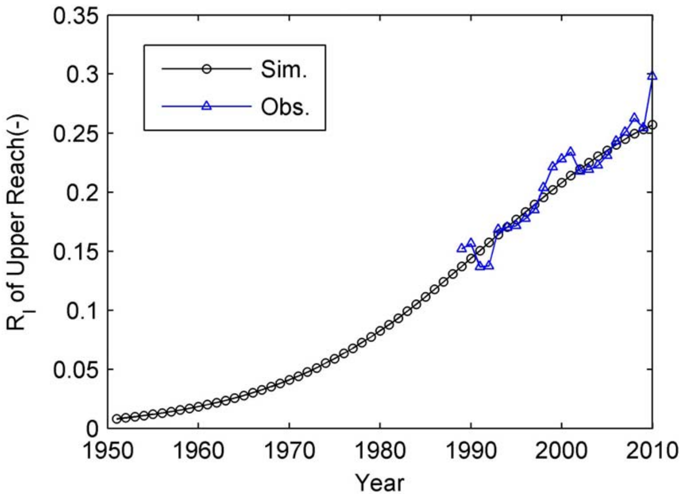

Fig. 8. Ratio of irrigated area (R_I) of the upper reach of Tarim River.

HESSD
11, 3911–3966, 2014

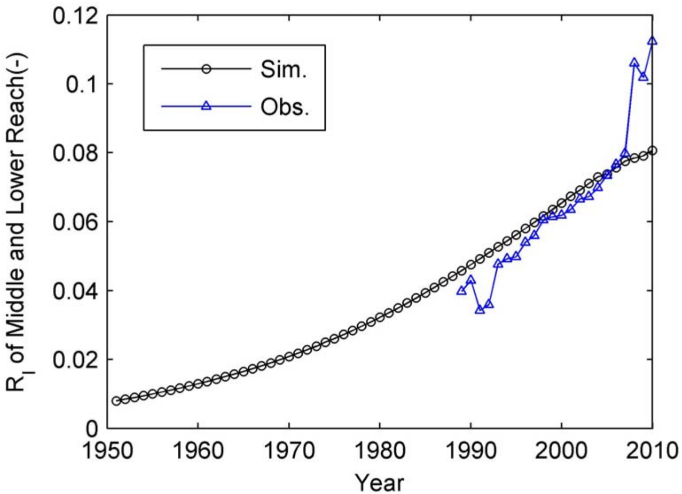

Fig. 9. Ratio of irrigated area (R_l) of the lower reach of Tarim River.

HESSD
11, 3911–3966, 2014

Coupled modeling framework for co-evolution of humans and water

D. Liu et al.

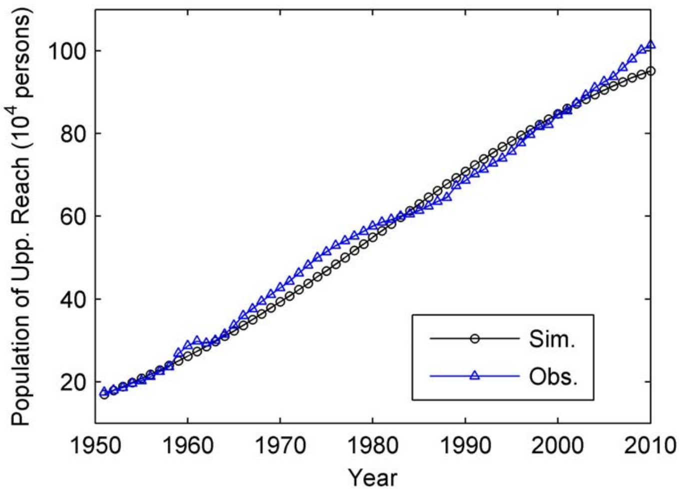

Fig. 10. Population of the upper reach of Tarim River.

HESSD
11, 3911–3966, 2014

Coupled modeling framework for co-evolution of humans and water

D. Liu et al.

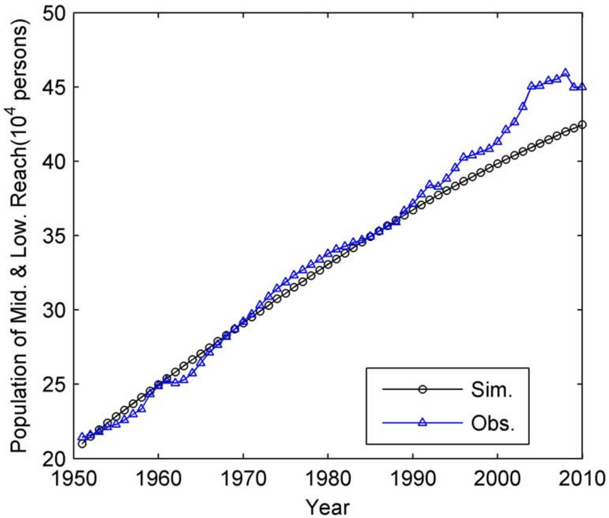

Fig. 11. Population of the lower reach of Tarim River.

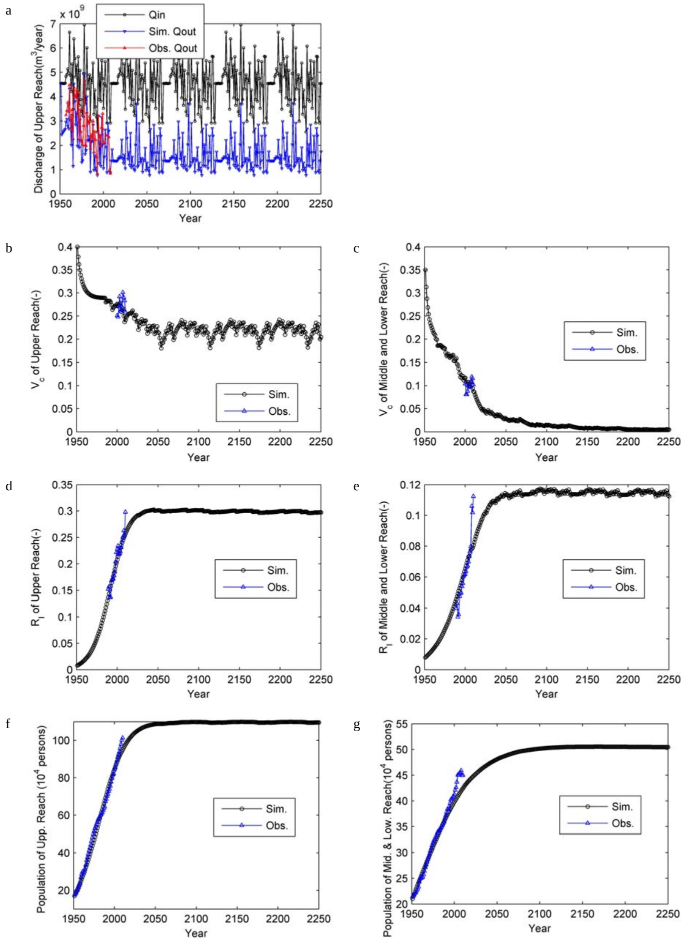

Fig. 12. Quasi-steady state of the socio-hydrological system with the 300 years series (baseline model).

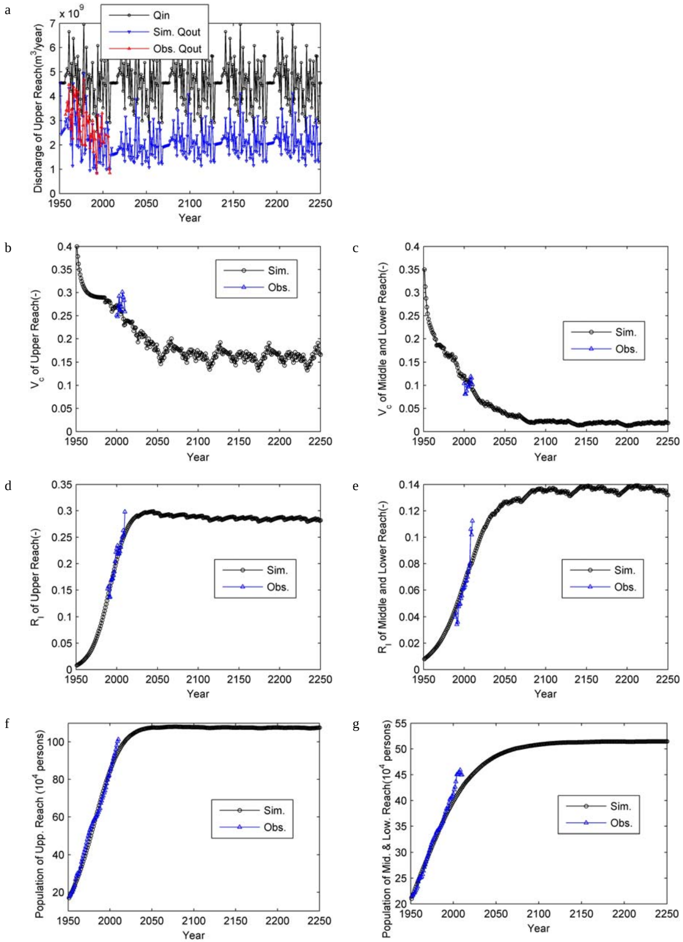

Fig. 13. Quasi-steady state of the socio-hydrological system with improved Q_{outU} equation (revised model).

HESSD

11, 3911–3966, 2014

Coupled modeling framework for co-evolution of humans and water

D. Liu et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion