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Discussions

A system dynamic model to quantify the impacts of water resources allocation on water-energy-food-society (WEFS) nexus

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Abstract: Sustainable management of water-energy-food (WEF) nexus remains an urgent challenge, as interactions between WEF and community sensitivity and reservoir operation in water system are often neglected. This paper aims to provide a new approach for modeling WEF nexus by incorporating community sensitivity and reservoirs operation into the system. The co-evolution behaviors of the nexus across water, energy, food and society (WEFS) were simulated by the system dynamic model. The reservoirs operation was simulated to determine water supply for energy and food systems by the Interactive River-Aquifer Simulation water resources allocations model. Shortage rates for water, energy and food resulted from the simulations were used to qualify their impacts on WEFS nexus through environmental awareness (EA) in society system. Community sensitivity indicated by EA can adjust the co-evolution behaviors of WEFS nexus through feedback loops. The proposed approach was applied to the mid-lower reaches of Hanjiang river basin in China as a case study. Results show that EA accumulation is mainly from shortages of water and energy, and the available water and energy are the vital resources to sustain WEFS nexus. Feedback driven by EA effectively keeps the system from collapsing and contributes to the concordant development of WEFS nexus. Water resources allocation can remarkably ensure water supply through reservoirs operation, decreasing water shortage rate from 16.60% to 7.53%. The resource constraining the WEFS nexus is transferred from water to energy. This paper therefore contributes to the understanding of interactions across WEFS system and helps the efficiency improving of resources management.

Key words: water-energy-food-society nexus; system dynamic; water resources allocation; community sensitivity

1. Introduction

Water, energy and food are indispensable resources to sustain the development of society. With the growing population, urbanization, globalization and economy, the expected global demands for water, food and energy in 2030 are going to increase by 40%, 50% and 50% respectively in respect to 2010 levels (Alexandratos and Bruinsma, 2012; Mckinsey & Company, 2009; International Energy Agency, 2012). The resources scarcity will be exacerbated with the single-sector strategy in traditional water, energy and food management (El Gafy et al., 2017). To increase the resource use efficiencies and benefits in production and consumption, taking the inextricable interactions among sectors across water, energy and food into rational resources management has become an important strategy (Hsiao et al., 2007; Vörösmarty et al., 2000). Considering the interactions, the water-energy-food (WEF) nexus concept was firstly presented at the Bonn Conference in 2011 as an approach to determine synergies and trade-offs between WEF sectors so as to support the sustainable development goals (Hoff, 2011).

To quantify the interaction in WEF nexus, various methods have been proposed for integrated systems. There are mainly three types of methods: system of systems model (Eusgeld et al., 2011; Housh et al., 2015), agent-based model (Bonabeau, 2002; Dawson et al., 2011) and system dynamics model (El Gafy, 2014; Swanson, 2002).

System of systems model couples several subsystems as a holistic system to addresses the nexus by optimizing the behaviors of systems. Agent-based model simulates the interactions between agents and environments as well as different agents based on the pre-defined rules obtained from long-term observations. These two methods have been proved to be capable to simulate the behaviors of the integrated system. However, neither of them has emphasized the feedback within the integrated systems, which is considered as an important driving force for nexus system (Chiang et al., 2004; Kleinmuntz, 1993; Makindeodusola and Marino, 1989). The results of these two methods on WEF security remain under risk. System dynamics model focuses explicitly on feedback connections between key elements in model to determine the co-evolution process and the long-term characteristics of integrated systems (Liu, 2019; Simonovic, 2002). Therefore, system dynamics model is adopted in this study to simulate the co-evolution process of the nexus system.

System dynamics model has been widely used to analyze WEF nexus around the world at different spatial scales, such as global (Davies and Simonovic, 2010; Susnik, 2018), national (Laspidou et al., 2020; Linderhof et al., 2020) and basin-scale (Purwanto et al., 2021; Ravar et al., 2020). Most of them perform the accounting and analyzing WEF nexus only focusing on the physical process, while rarely taking the social process which indicates human responses to WEF nexus (Elshafei et al., 2014). As the connection between WEF nexus and society is being intensified under rapid socioeconomic development, both physical and social processes should be taken into account for the sustainability of the integrated system in the foreseen future

(Baldassarre et al., 2015).

To simultaneously capture the physical and social process of the integrated system, community sensitivity was taken as a conceptual social state variable to identify environment deterioration (Elshafei et al., 2014; Van Emmerik et al., 2014). Van Emmerik et al. (2014) developed a socio-hydrologic model to understand the competition for water resources between agricultural development and environmental health in Murrumbidgee River basin (Australia). Li et al. (2019) developed an urban socio-hydrologic model to investigate the future water sustainability from a holistic and dynamic perspective in Beijing (China). Feng et al. (2016) used environmental awareness to indicate community's attitude so as to influence the co-evolution behaviors of water-power-environment nexus in Hehuang region (China). These researches have contributed to the effective resources management by incorporating both the physical and social processes. However, potential threats on WEF security still exist, as few of current studies have simultaneously considered the impacts of reservoirs operation in water system on the integrated system.

Reservoir can adjust the uneven temporal and spatial distribution of available water resources and can ensure water supply for reducing the water shortage (Khare et al., 2007; Liu et al., 2019; Zeng et al., 2021; He et al., 2022). However, the available water resources is often adopted under historical natural water flow scenarios, while reservoir is seldom taken into account or its operational rules are significantly simplified in WEF nexus. The assessment of water supply security based on WEF nexus should be improved. Thus, more details of the reservoirs operation should be incorporated in simulation of WEF nexus.

Water resources allocation model can simultaneously incorporate reservoirs operation as well as water acquisition and it has become an effective tool to quantitatively assess the impacts of reservoirs operation on water supply security, and further the impacts on WEF security (Si et al., 2019; Zhou et al., 2019). Our study aims to establish a system dynamic model for the water-energy-food-society (WEFS) nexus and assess the impacts of reservoirs operation on WEFS nexus through integrating water resources allocation model into the integrated system. The reminder of this paper is organized as follows: Section 2 introduces the framework for modelling WEFS nexus and assessing the impacts of water resources allocation on WEFS nexus. Section 3 describes the methodologies applied in the mid-lower reaches of Hanjiang river basin in China that is study area. Section 4 represents the results of co-evolution process and sensitivity analysis of WEFS nexus. The impacts of water resources allocation on WEFS nexus have also been discussed. Section 5 gives the conclusions.

2 Method

System dynamics modelling (SDM) simulates the dynamics among different systems by using nonlinear ordinary differential equations and dynamic feedback loops (Wolstenholme and Coyle, 1983; Swanson, 2002). SDM has become an efficient approach to facilitate the integrated analysis of sectors, processes and interrelations among different system variables (Baldassarre et al., 2015; Simonovic, 2002). SDM for assessing WEFS nexus is composed of four modules (shown in Figure 1): (1) water system module, (2) energy system module, (3) food system module and (4) society system module.

In water system module, socioeconomic and in-stream water demand are projected by quota method and Tennant method (Tennant, 1976), respectively. The water demands and available water resources are further inputted into water resources allocation model to determine water supply and water shortage in every water use sector. The water supply and water shortage rates as outputs from the water system module are taken as inputs to drive energy system module and food system module, respectively. Taking the outputs of the energy and food system modules, the energy and food shortages can be estimated comparing to the planning productions of energy and food. The function of society module is to capture community sensitivity to the degradation in WEF nexus (Elshafei et al., 2014). Environmental awareness is taken as conceptual social state variable to indicate community sensitivity (Van Emmerik et al., 2014). Environmental awareness is composed of water shortage awareness, energy shortage awareness and food shortage awareness that are determined by shortages of water, energy and food, respectively. And these four modules are linked by feedback loops.

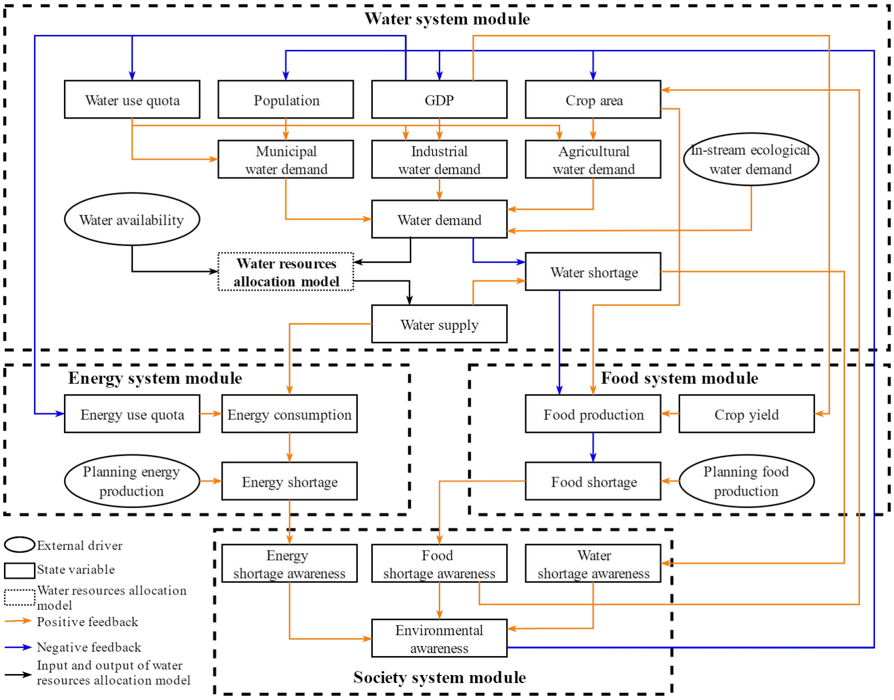

Figure 1. Structure of WEFS nexus model and its feedbacks.

2.1 Water System Module

2.1.1 Water Demand Projection

Water user consists of socioeconomic (also called off-stream) user and in-stream user. Socioeconomic water user can be classified into municipal, rural, industrial and agricultural sectors. Quota method has been taken as an efficient approach to project the annual socioeconomic water demand in the future (Brekke et al., 2002). The amount of water demand for the socioeconomic users can be estimated by equation (1).

$$WD_{i,j}^{t} = WQ_{i,j}^{t} * A_{i,j}^{t} / U_{i,j}^{t} \quad (1)$$

where $WD_{i,j}^{t}$ is the amount of water demand for the *j*th user in the *i*th operational

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zone at the *t*th time step; $WQ_{i,j}^t$ is the water quota unit of water user; $A_{i,j}^t$ is the amount of water units of water user; $U_{i,j}^t$ is the utilization rate of water user. The water quota units are the amount of water consumption per capita in municipal and rural users, the amount of water consumption per ten thousand Yuan in industrial user and the amount of net irrigation water per unit area in agricultural user, respectively; the amount of water units are the projected population in municipal and rural users, the projected GDP in industrial user and the projected irrigated area in agricultural user.

As population, GDP, crop area and water use quota are the prerequisites for water demand projection, the dynamic equations for these socioeconomic variables should be pre-determined. Malthus growth model is a succinct approach and it has been widely applied in socioeconomic projection (Bertalanffy, 1976; Malthus, 1798). However, the limited environmental capacity hasn't been considered in the original Malthus growth model. The socioeconomic factors may explode to infinity in a long-time evolution. Thus, feedback functions should be adopted to constrain the infinity evolution of socioeconomic variables through equation (2)-(5).

$$\frac{dN_t}{dt} = N_0 * r_P * \exp(-\varphi_P t) * f_1(E) \tag{2}$$

$$\frac{dG_t}{dt} = G_0 * r_G * \exp(-\varphi_G t) * f_2(E) \tag{3}$$

$$\frac{dA_t}{dt} = A_0 * r_A * \exp(-\varphi_A t) * f_3(E, FA) \tag{4}$$

$$\frac{dWQ_t}{dt} = -WQ_0 * r_{qwu} * \exp(-\varphi_{qwu} t) * f_4(r_G^t) \tag{5}$$

where N_t, G_t, A_t and WQ_t are the population, GDP, crop area and water use quota in *t*th year; N_0, G_0, A_0 and WQ_0 are the of population, GDP, crop area and water use quota in baseline year; r_P, r_G, r_A and r_{qwu} are the observed changing rates from history data of population, GDP, crop area and water use quota; exp(-$\varphi_P t$), exp(-$\varphi_G t$), exp(-$\varphi_A t$) and exp(-$\varphi_{qwu} t$) are used to depict the impacts of technology development on evolution of population, GDP, crop area and water use quota; E is environmental awareness; FA is food shortage awareness; f_1, f_2, f_3 and f_4 are the feedback functions; r_G^t is the annual changing rate of GDP in tth year. The equations for E, FA and feedback functions will be described in detail in Section 2.4 and 2.5.

2.1.2 Water Resources Allocation

Based on water availability and projected water demand, available water resources can be deployed to every water use sector and in-stream water flow by water resources allocation model. Interactive River-Aquifer Simulation (IRAS) model is a rule based water system simulation model, which is developed by Cornell University (Loucks, 2002; Zeng et al., 2021). The IRAS model was adopted for water resources allocation due to its flexibility and accuracy in water system simulation.

As water system consists of water transfer, consumption and loss components, it is often sketched by node network topology for the application of water resources allocation model. Reservoir node and demand node are the most important elements in the node network topology, as they are directly corresponding to the processes of water supply, acquisition and consumption. Specifically, the water release from reservoir node can be determined by reservoir operation rules and the water shortage at demand node can be estimated by equation (6) and (7).

$$W_e^{st} = \sum_1^{st} W_{in}^{st} - \sum_1^{st} W_d^{st} * \frac{(tst - st + 1)}{(st - 1)} \tag{6}$$

$$WS^{st} = \frac{W_{dem}^{t} - WD_{dem}^{t} * f_{red} - \sum_1^{st} W_{in}^{st} - W_e^{st}}{tst - st + 1} \tag{7}$$

where t is the current time step; tst is the total number of the sub-time-step; st is the current sub-time-step; W_e^{st} is the amount of natural water inflow; W_{in}^{t} is the total amount of water inflow; W_{dem}^{t} is the water demand of the water user; f_{red} is the demand reduction factor; WS^{st} is the water shortage.

2.2 Energy System Module

Energy consumption is determined by energy use quota and water supply for socioeconomic sectors (Cheng, 2002). As energy use efficiency will be gradually improved with the advancing technology, energy use quota is assumed to be decreased with decreasing rate. Considering the expansion economy can boost energy-use effect, positive feedback of GDP on improving energy use efficiency is deployed. Trajectory of energy use is formulated in equation (8). As water supply for socioeconomic sectors derived from water system module, energy consumption can be estimated by equation (9). Energy shortage rate will be further determined with planning energy production by equation (10).

$$\frac{dEQ_t^{i,j}}{dt} = -EQ_0^{i,j} * r_e * \exp(-\varphi_e t) * f_5(r_G^t) \tag{8}$$

$$EC_t = \sum_{i,j} WSup_t^{i,j} * EQ_t^{i,j} \tag{9}$$

$$ESR_t = \frac{ES_t}{EC_t} = \frac{EC_t - PEP_t}{EC_t} \tag{10}$$

where $EQ_0^{i,j}$, $EQ_t^{i,j}$ are the energy use quotas of jth water user in ith operational zone in baseline year and tth year; r_e is the observed changing rate of energy use quota from historic data; exp(-$\varphi_e t$) is used to depict the energy-saving effect of technology development; f_5 is the feedback function, which will be elaborated in Section 2.5; EC_t is the total energy consumption; $WSup_t^{i,j}$ is the water supply of *j*th water user in *i*th operational zone; ES_t and ESR_t are the energy shortage and energy shortage rate; PEP_t is the planning energy production.

2.3 Food System Module

The food system module focuses on estimating the amount of food production. As water is an important factor for crop yield, water shortage rate can constrain the potential crop yield (French and Schultz, 1984; Lobell et al., 2009). Due to the advancement of technology for irrigation, the amount of potential crop yield is assumed to be increased with decreasing rate, as equation (11) indicates. With the planning food production, food shortage rate can then be estimated by equation (12) and (13).

$$\frac{dCY_t^{i,j}}{dt} = CY_0^{i,j} * r_{pro} * \exp(-\varphi_{pro} t) * f_6(r_G^t) \tag{11}$$

$$FP_t = \sum_{i,j} CY_t^{i,j} * CA_t^{i,j} * (1 - WSR_t^{i,j}) \tag{12}$$

$$FSR_t = \frac{FS_t}{PFP_t} = \frac{PFP_t - FP_t}{PFP_t} \tag{13}$$

where $CY_0^{i,j}$, $CY_t^{i,j}$ are the potential crop yields of *j*th crop in *i*th operational zone in baseline year and *t*th year; r_{pro} is the observed changing rate of crop yield from historic data; exp(-$\varphi_{pro} t$) is used to depict the impacts of technology development on evolution of crop yield; f_6 is the feedback function, which will be elaborated in Section 2.5; FP_t is the total food production; $CA_t^{i,j}$ is the crop area; $WSR_t^{i,j}$ is the water shortage rate; FS_t and FSR_t are the food shortage and food shortage rate; PFP_t is the planning food production.

2.4 Society System Module

Society system module is deployed to simulate the social process of the integrated system. Environmental awareness and community sensitivity are two primary terms of social state variable in sociohydrological modelling used to indicate the perceived level of threat to a community's quality of life (Roobavannan et al., 2018). Environmental awareness describes societal perceptions of the environmental degradation within the prevailing value systems (Feng et al., 2019; Feng et al., 2016; Roobavannan et al., 2018; Van Emmerik et al., 2014). Community sensitivity indicates people's attitudes towards human activity and environmental restoration (Chen et al., 2016; Elshafei et al., 2014; Roobavannan et al., 2018). As environmental awareness is considered to be more specific than community sensitivity (Feng et al., 2019), the term of environmental awareness in this study is on base of the concept in the work of Van Emmerik et al. (2014). The environmental awareness is assumed to be determined by the shortage rates from water, energy and food. The environmental awareness is going to accumulate when shortage rates of water, energy and food are over the given critical values, but decrease otherwise. The dynamics of environmental awareness can be described by equations (14)-(17).

$$\frac{dE}{dt} = \frac{dWA}{dt} + \frac{dEA}{dt} + \frac{dFA}{dt} \tag{14}$$

$$\frac{dWA}{dt} = \begin{cases} \eta_W * (\exp(\theta_W * (WSR - WSR_{crit})) - 1) & WSR > WSR_{crit} \\ -\omega_W * WA & WSR \le WSR_{crit} \end{cases} \tag{15}$$

$$\frac{dEA}{dt} = \begin{cases} \eta_E * (\exp(\theta_E * (ESR - ESR_{crit})) - 1) & ESR \geq ESR_{crit} \\ - \omega_E * EA & ESR < ESR_{crit} \end{cases} \tag{16}$$

$$\frac{dFA}{dt} = \begin{cases} \eta_F * (\exp(\theta_F * (FSR - FSR_{crit})) - 1) & FDR \geq FDR_{crit} \\ - \omega_F * FA & FDR < FDR_{crit} \end{cases} \tag{17}$$

where *E*, *WA*, *EA* and *FA* are environmental awareness, water shortage awareness, energy shortage awareness and food shortage awareness; *WSR*, *ESR* and *FSR* are the shortage rates of water, energy and food; WSR_{crit}, ESR_{crit} and FSR_{crit} are the corresponding critical values of shortage rates, above which environmental deterioration can be perceived; η_W, η_E and η_F are the perception factors describing the community's ability to identify threats of degradation; θ_W, θ_E, θ_F, are the auxiliary factors for environmental awareness accumulation; ω_W, ω_E, ω_F, are the lapse factors, representing the decreasing rate of the shortage awareness for water, energy and food.

2.5 Respond Links

Respond links are the primary feedback loops among the different variables in WEFS nexus. There are mainly two types of respond links. One is driven by the environmental awareness and the other one is driven by community wealth. The terms of feedback functions are based on the work of (Feng et al., 2019).

The environmental awareness is prone to increase with the constant shortages in water, energy and food. As the environmental awareness accumulates above its critical value, negative feedback on socioeconomic factors will be triggered (shown in Figure 1). The growth of population, GDP and crop area will be constrained to alleviate the stress on the integrated system. It's worth noting that, positive feedback on expansion of crop area will be triggered to fill food shortage as the food shortage awareness exceeds its critical value (shown in Figure 1). Despite food shortage awareness is part of environmental awareness, the negative feedback driven by environmental awareness on crop area can only triggered with prerequisite that food shortage awareness is below its threshold value, as food production should firstly be assured. The respond links deployed by the assuming feedback functions as equations (18)-(20) show.

$$f_1(E) = \delta^E_{rp} * (1 - \exp(\zeta_1 * (E - E_{crit})) \tag{18}$$

$$f_2(E) = \delta^E_{rg} * (1 - \exp(\zeta_2 * (E - E_{crit})) \tag{19}$$

$$f_3(E, FA) = \begin{cases} \delta^E_{ra} * (1 - \exp(\zeta^E_3 * (E - E_{crit})) - \delta^F_{ra} * (1 - \exp(\zeta^F_3 * (FA - FA_{crit})) & FA > FA_{crit} \\ \delta^E_{ra} * (1 - \exp(\zeta^E_3 * (E - E_{crit})) & Else \end{cases} \tag{20}$$

where r_P, r_G, and r_A are the changing rates of population, GDP and crop area; E_{crit} and FA_{crit} are the critical values for environmental awareness and food shortage awareness; δ^E_{rp}, δ^E_{rg} and δ^E_{ra} are the factors describing feedback capability from environmental awareness; δ^F_{ra} is the factor describing feedback capability from food shortage awareness; ζ_1, ζ_2 and ζ^E_3 are the auxiliary factors for feedback functions driven by environmental awareness; ζ^F_3 is the auxiliary factor for feedback functions driven by food shortage awareness.

The other respond link is driven by community wealth that is indicated by the increasing rate of GDP here. With the accumulation of community wealth, more attention is going to be devoted for improving the efficiency in water and energy use as well as food production. The feedbacks on water use quota, energy use quota and crop yield will be triggered as the changing rate of GDP exceeds its critical value as equation (21)-(23) show.

$$f_4(r_G) = \delta_{rwu}^{GDP} * (1 - \exp(\zeta_4 * (r_G - r_{Gcrit}))) \tag{21}$$

$$f_5(r_G) = \delta_{reu}^{GDP} * (1 - \exp(\zeta_5 * (r_G - r_{Gcrit}))) \tag{22}$$

$$f_6(r_G) = \delta_{rcy}^{GDP} * (\exp(\zeta_6 * (r_G - r_{Gcrit})) - 1) \tag{23}$$

where r_G is the changing rate of GDP; r_{Gcrit} is the critical value for changing rate of GDP; δ_{rws}^{GDP}, δ_{reu}^{GDP} and δ_{rcy}^{GDP} are the factors describing feedback capability from community wealth; ζ_4, ζ_5 and ζ_6 are the auxiliary factors for feedback functions driven by economy expansion.

3 Case Study

3.1 Study Area

Hanjiang river is the longest tributary for Yangtze river. The total area of the Hanjiang river basin is 159,000 km^2, the upper and mid-lower reaches of which are 95,200 km^2 and 63,800 km^2 respectively (shown in Figure 2). The Danjiangkou reservoir is located at the upper boundary of the mid-lower reaches of Hanjiang river basin and serves as the water source for the middle route of South-North water transfer project in China. Thus, the water availability in the mid-lower reaches of Hanjiang river basin is remarkably impacted by reservoirs operation. In terms of energy, there are many important steel and petrochemical bases. As the industrial cities Wuhan and Xiangyang locate along the main stream of mid-lower reaches of Hanjiang river, the industrial products as well as the energy consumption are significant. For agriculture, as the land is flat and fertile, the mid-lower reaches of

Hanjiang river basin is considered as an important grain producing area, occupying one of the nine major commodity grain bases in China (i.e., Jianghan plain) (Xu et al., 2019).

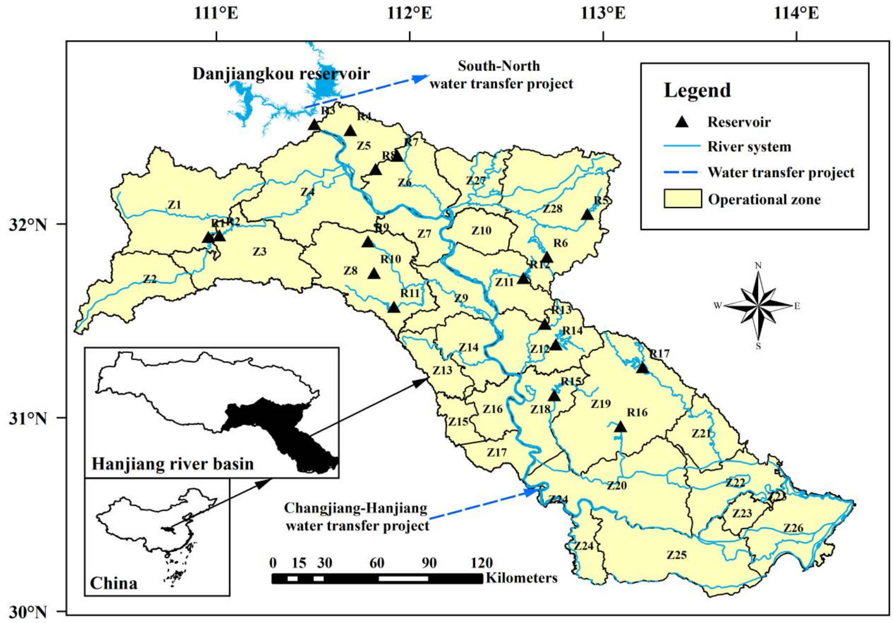


Figure 2. Location of mid-lower reaches of Hanjiang river basin.

However, due to population expansion, fast urbanization and rapid economic development, the local demands for water, energy and food are going to increase enormously. The contradictions between the increasing demands and limited resources will be aggravated. Therefore, impacts of human activities on WEF nexus should be accessed to sustain the collaborative development of the integrated system.

According to the distribution of administrative countries and rivers, the study area can be divided into 28 operational zones. Seventeen exiting medium or large size reservoirs (the total storage volume is 37.3 billion m^3) are taken to regulate water flows. The water connections between operational zones and river systems in IRAS model are sketched in Figure 3.

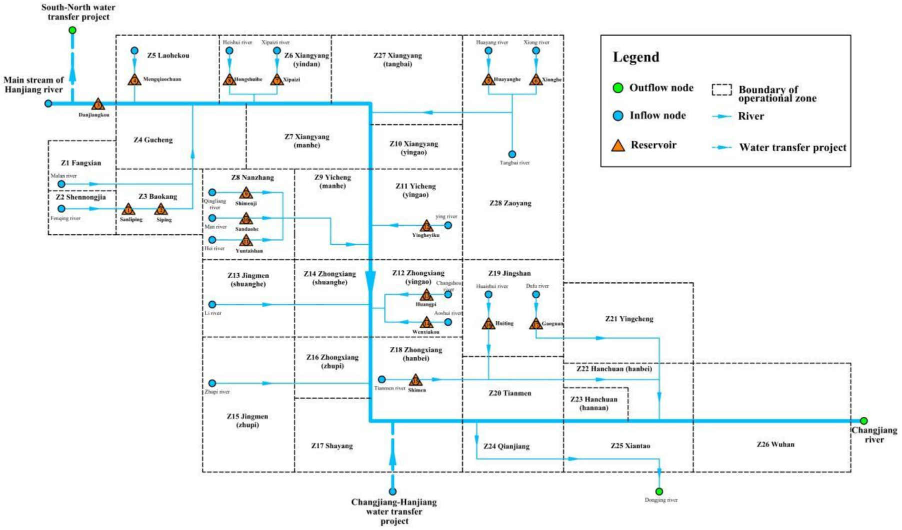


Figure 3. Sketch of water system for the mid-lower reaches of Hanjiang river basin.

3.2 Data sources

There are mainly two types of data: hydrological data and socioeconomic data. The monthly historical discharge series of each operational zone and inflow of reservoirs from 1956 to 2016 were provided by Changjiang Water Resources Commission (Cwrc, 2016). The characteristics and operational rules of the seventeen reservoirs listed in Table 1 were provided by Hubei Provincial Department of Water Resources (Hpdwr, 2014). The socioeconomic data including population, GDP, crop area, water use quota, energy use quota and crop yield during 2010-2019 were collected from the yearbooks of Hubei province, which can be obtained through the Statistical Database of China's Economic and Social Development (http://data.cnki.net/). It's worth noting that, the agricultural water use quota is related to the annual effective precipitation frequency. Four typical exceedance frequencies defined as P = 50%, 75%, 90% and 95% are adopted to determine agricultural water demand. These historical data are further used to predict future trajectories of the WEFS nexus.

Table 1 Characteristics of the seventeen reservoirs (million m^3).

No.	Name	Total storage	Storage at normal water level	Dead storage	Storage at flood limiting water level
R1	Sanliping	510.0	211.0	261.0	389.0/468.5
R2	Siping	269.0	247.0	10.2	127.0
R3	Danjiangkou	33,910.0	27,781.0	12,690.0	22,910.0/25,790.0
R4	Mengqiaochuan	110.3	88.2	2.7	90.9
R5	Huayanghe	107.0	70.8	1.4	72.2
R6	Xionghe	195.9	115.9	20.0	135.9
R7	Xipaizihe	220.4	122.0	2.2	124.2
R8	Hongshuihe	103.6	58.9	5.4	64.3
R9	Shimenji	154.0	114.7	1.9	99.0
R10	Sandaohe	154.6	127.4	0.0	127.4
R11	Yuntaishan	123.0	89.0	5.0	89.0
R12	Yinghe	121.6	76.3	3.6	79.9
R13	Huangpi	125.6	70.3	10.1	63.6
R14	Wenxiakou	520.0	269.0	176.0	388.0
R15	Shimen	159.1	68.6	13.0	81.6
R16	Gaoguan	201.1	154.3	30.9	145.9

R17	Huiting	313.4	173.5	32.50	206.0

4 Results and Discussion

The SDM is applied to the mid-lower reaches of Hanjiang river basin. Table 2 shows the initial conditions of external variables for the integrated system. The model is then be calibrated by fitting the observed data and the calibrated parameters are presented in Table 3. The co-evolutionary behaviors of the WEFS nexus are analyzed: (1) the system dynamic model is validated by observed data, (2) the co-evolution of WEFS nexus is then interpreted and analyzed, (3) parameter sensitivity is tested to identify the most important parameters for the model and (4) the impacts of water resources allocation on WEFS nexus are discussed.

Table 2 Model initial condition setup.

Parameter	Initial value	Unit	Parameter	Initial value	Unit
r_P	0.003	[-]	r_e	-0.004	[-]
r_G	0.04	[-]	r_{pro}	0.018	[-]
r_A	0.003	[-]	PEP	60	[Million t standard coal]
r_{qwu}	-0.02	[-]	PFP	6,000	[Million t]

Table 3 Calibrated parameters for the WEFS model.

Parameter	Calibrated value	Parameter	Calibrated value
φ_P	0.0856	ζ_6	0.0856
φ_G	0.0856	$WSRcrit$	0.07
φ_A	0.0856	$ESRcrit$	0.05

φ_{qwu}	0.0856	$FSRcrit$	0.05
φ_e	0.0856	ω_W	0.1
φ_{pro}	0.0856	ω_E	0.1
η_W	300	ω_F	0.1
η_E	35	r_{Gcrit}	0.01
η_F	200	FA_{crit}	1.5
θ_W	0.0856	E_{crit}	10
θ_E	0.0856	δ_{rp}^{E}	0.001
θ_F	0.0856	δ_{rg}^{E}	0.05
ζ_1	0.0856	δ_{ra}^{E}	0.01
ζ_2	0.0856	δ_{ra}^{F}	0.05
ζ_3^E	0.0856	δ_{rws}^{GDP}	3
ζ_3^F	0.0856	δ_{reu}^{GDP}	1.5
ζ_4	0.0856	δ_{rcy}^{GDP}	3
ζ_5	0.0856		

4.1 Model Validation

The Nash-Sutcliffe Efficiency (NSE) coefficient and percentage bias (PBIAS) (Krause et al., 2005; Nash and Sutcliffe, 1970) are used to validate the model. The simulated state variables including water demand, energy consumption, food production, population, GDP and crop area are compared with their observed values during 2010-2019. As is shown in Table 4, the NSEs (i.e., 0.75, 0.89, 0.83, 0.96, 0.93

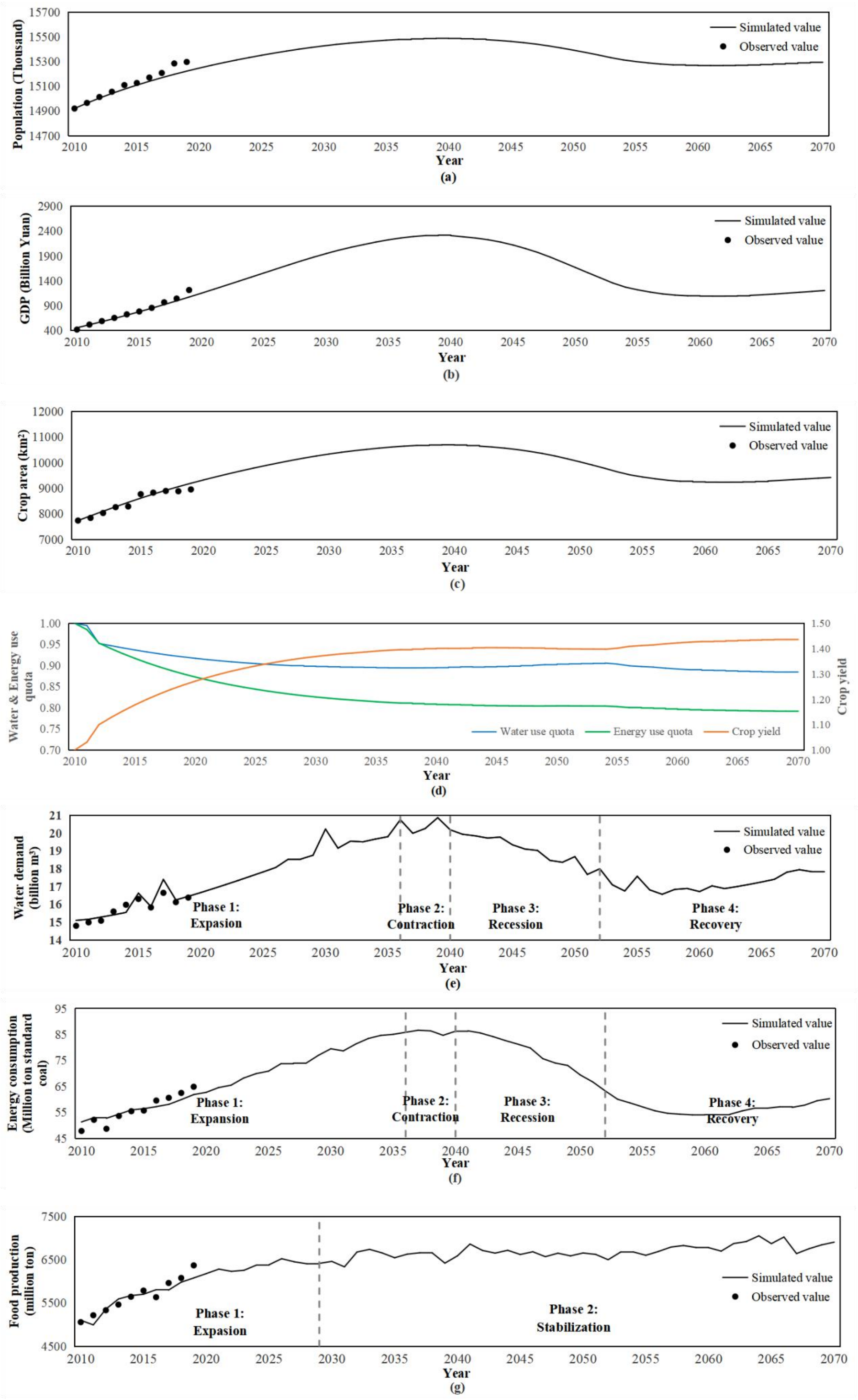
and 0.68, respectively) range from 0.68 to 0.96 and the corresponding PBIASs (i.e., -0.2%, -1.6%, -0.6%, -3.8%, -0.2% and -2.4%, respectively) are within -15% to 15%, suggesting that the established model is reliable to simulate co-evolution of the WEFS nexus.

Table 4 NSE and PBIAS of state variables.

	Water demand	**Energy consumption**	**Food production**	**Population**	**GDP**	**Crop area**
NSE	0.75	0.89	0.83	0.96	0.93	0.68
PBIAS (%)	-0.2	-1.6	-0.6	-3.8	-0.2	-2.4

4.2 Co-evolution of WEFS nexus

The validated system dynamic model can be used to examine the property of the integrated system by simulating the co-evolution of state variables in WEFS nexus. Figure 4 shows the trajectories of population, GDP, crop area, water demand, energy consumption, food production, shortage rates for water, energy and food, awareness for water shortage, energy shortage and food shortage as well as environmental awareness during 2010-2070. According to the trajectory of environmental awareness, the co-evolution processes of water demand and energy consumption can be divided into four phases: expansion, contraction, recession and recovery. Food production can be divided into two phases based on the trajectory of food shortage awareness: expansion and stabilization.


Population (Thousand)
15700
15500
15300
15100
14900
14700
Simulated value
Observed value
2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070
Year
(a)
GDP (Billion Yuan)
2900
2400
1900
1400
900
400
Simulated value
Observed value
Year
(b)
Crop area (km²)
12000
11000
10000
9000
8000
7000
Simulated value
Observed value
Year
(c)
Water & Energy use quota
1.00
0.95
0.90
0.85
0.80
0.75
0.70
Crop yield
1.50
1.40
1.30
1.20
1.10
1.00
Water use quota
Energy use quota
Crop yield
Year
(d)
Water demand (billion m³)
21
20
19
18
17
16
15
14
Phase 1: Expasion
Phase 2: Contraction
Phase 3: Recession
Phase 4: Recovery
Simulated value
Observed value
Year
(e)
Energy consumption (Million ton standard coal)
95
85
75
65
55
45
Phase 1: Expansion
Phase 2: Contraction
Phase 3: Recession
Phase 4: Recovery
Simulated value
Observed value
Year
(f)
Food production (million ton)
7500
6500
5500
4500
Phase 1: Expasion
Phase 2: Stabilization
Simulated value
Observed value
Year
(g)

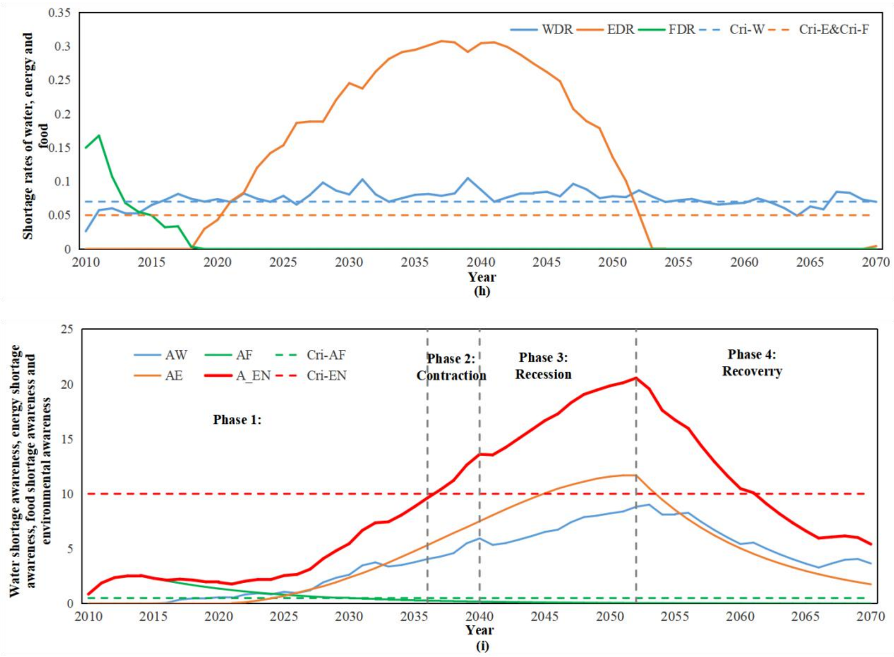


Figure 4. The trajectories of state variables in WEFS nexus: (a) population; (b) GDP; (c) crop area; (d) percentage variations (compared with initial values) of water use quota, energy use quota and crop yield; (e) water demand; (f) energy consumption; (g) food production; (h) shortage rates of water, energy and food; (i) water shortage awareness, energy shortage awareness, food shortage awareness and environmental awareness.

For water demand and energy consumption, the four phases in co-evolution process can be interpreted as follows:

In expansion phases (2010-2036): with environmental awareness below its critical value, the negative feedback on socioeconomic sectors isn't triggered and water demand as well as energy consumption increases rapidly. In the beginning of co-evolution, the water demand from socioeconomic sectors can be almost satisfied due to abundant water availability. Water shortage rate is often less than 0.07 and

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below its critical value (Figure 4 (h)), thus water shortage awareness stays at a low level which is less than 5.0 as is shown in Figure 4 (i). As water use is increased with the increasing water demand (Figure 4 (e)), energy consumption is increased but still within its planning value. Little energy shortage can be found and thus no energy shortage awareness is accumulated as Figure 4 (h) and (i) presented. Energy shortage awareness has just accumulated gradually as the energy shortage rate begins to exceed its critical value slightly since 2018. Food production is less than its planning value in the beginning of co-evolution. The initial food shortage rate is 0.15 and more than its critical value 0.05, accounting for the rapid increase of food shortage awareness shown in Figure 4 (i). With food shortage awareness increasing over its critical value 1.5 (but less than critical environmental awareness 10.0), positive feedback on facilitating the increase of crop area is triggered. Meanwhile, the crop yield has also increased with the advancement of technology under the fast economy expansion (Figure 4 (d)). The food production is then increased and the planning food production can be ensured. The food shortage awareness is resilient below its critical value and often keeps at a low level henceforth shown in Figure 4 (i). Therefore, as environmental awareness stays below its critical value, negative feedback to constrain the expansion of socioeconomic sectors isn't triggered and water demand as well as energy consumption increases remarkably in expansion phase.

In contraction phase (2037-2040): as environmental awareness exceeds its critical value, negative feedback on socioeconomic sectors is triggered and the increases of water demand and energy consumption are constrained. With the technology advancement, the quotas for water use and energy use have been decreasing as Figure 4 (d) presented. However, there are still minor increases of water demand and energy consumption due to the continuous expansion of population, GDP and crop area (Figure 4 (a), (b) and (c)), which can exceed the local water and energy carry capacities. Thus, water shortage awareness and energy shortage awareness keep increasing, as their shortage rates stay over corresponding critical values as shown in Figure 4 (h) and (i). The environmental awareness thereby exceeds its critical value in 2037 and keeps increasing. The negative feedback on socioeconomic sectors is triggered and keeps strengthening. The water demand and energy consumption increase gradually with decreasing rate and reach their maximum values, 20.9 billion m^3 and 86.4 million tons standard coal respectively, at the end of contraction phase.

In recession phase (2041-2052): the environmental awareness accumulates to the maximum value and water demand as well as energy consumption goes to depress significantly. With the negative feedback driven by environmental awareness, the population, GDP and crop area are constrained to decrease as shown in Figure 4 (a), (b) and (c). The water demand and energy consumption are thereby decreased but still over the local water and energy carry capacities. Therefore, as the shortage rates of water and energy are decreased but still more than corresponding critical values (Figure 4 (h)), environmental awareness keeps accumulating with a decreasing rate and reaches the maximum value 20.5 at the end of recession phase, which facilitates the decreases of water demand and energy consumption.

In recovery phase (2053-2070): as environmental awareness gradually decreases below its critical value, water demand and energy consumption decrease slightly and then tend to stabilization. With the continuous depression of socioeconomic sectors, water demand and energy consumption rapidly decrease within their carry capabilities. The shortage rates of water and energy have then been resilient back to below corresponding critical values since 2054, resulting in the decreases of water shortage awareness and energy shortage awareness as shown in Figure 4 (h) and (i). As the environmental awareness decreases below its critical value, negative feedback is removed and the integrated system tends to stabilization.

For food production, the co-evolution process consists of expansion and stabilization phases. In expansion phase (2010-2029): with the food shortage awareness over its critical value, positive feedback on crop area is triggered to increase food production. The detailed analysis is demonstrated in the expansion phase during the co-evolution of water demand and energy consumption. In stabilization phase (2030-2070): food shortage awareness decreases below its critical value and food production tends to stabilization. The increasing crop area and crop yield (Figure 4 (c) and (d)) has significantly alleviated food shortage. Food shortage awareness keeps decreasing and stays below its critical value after 2030. The increase of environmental awareness is mainly from water shortage awareness and energy shortage awareness. As environmental awareness increases over its critical value in 2037, the negative feedback on crop area is triggered and the crop area is further decreased. But as the crop yield keeps increasing continuously, the variation of food production is insignificant. With environmental awareness below its critical value since 2053, the negative feedback on crop area has been removed. Food production can always cover its planning value and tends to stabilization.

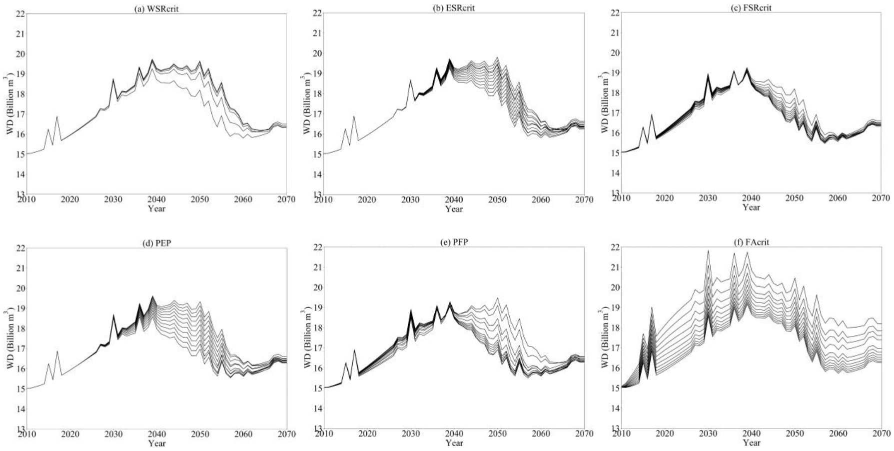
According to the analysis on the co-evolution process of WEFS nexus, available water and energy are the vital resources constraining the long-term concordant development of the integrated system. Specifically, the recession phase for water demand and energy consumption is accompanied by the most violent deterioration. It means severe socioeconomic degeneration will probably happen after the rapid development in expansion phase, which will block the sustainable develop of the integrated system. Moreover, time lag exists in contraction phase when community responds to the deterioration of the WEFS nexus system. Although the water demand and energy consumption have reached their maximum values and begun to decrease, environmental awareness can still gradually increase. As the water demand and energy consumption can’t be resilient back within the local water and energy carry capacities immediately, environmental awareness will keep increasing in a short time. Therefore, more attention should be paid to the time lag of community’s response to the deterioration WEFS nexus to prevent the integrated system from collapsing, especially after the fast expansion of water demand and energy consumption.

4.3 Sensitivity analysis for WEFS nexus

Sensitivity analysis is conducted to assess the impacts of parameters on WEFS nexus co-evolution process. As the critical values and boundary conditions of WEFS nexus are considered as vital factors for policy makers to sustain the concordant development of the integrated system, seven parameters are selected for sensitivity analysis (shown in Table 5). Each parameter was varied by the given increment with other parameters remaining unchanged. The maximum and minimum values as well as the increments for the seven parameters are listed in Table 5. Parameter sensitivity is then conducted by analyzing the trajectories of water demand, energy consumption, food production and environmental awareness shown in Figure 5, 6, 7 and 8.

Table 5 Parameter set for sensitivity analysis.

No.	Parameter	Description	Min.	Max.	Increment
1	*WSRcrit*	Critical water shortage rate	0.05	0.15	0.01
2	*ESRcrit*	Critical energy shortage rate	0.05	0.15	0.01
3	*FSRcrit*	Critical food shortage rate	0.05	0.15	0.01
4	*PEP*	Planning energy production	55	65	1
5	*PFP*	Planning food production	5,500	6,500	100
6	*FAcrit*	Critical food shortage awareness	1	8	0.7
7	*EAcrit*	Critical environmental awareness	3	12	0.9



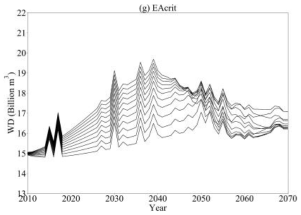


Figure 5. Trajectories of water demand with varied parameters.

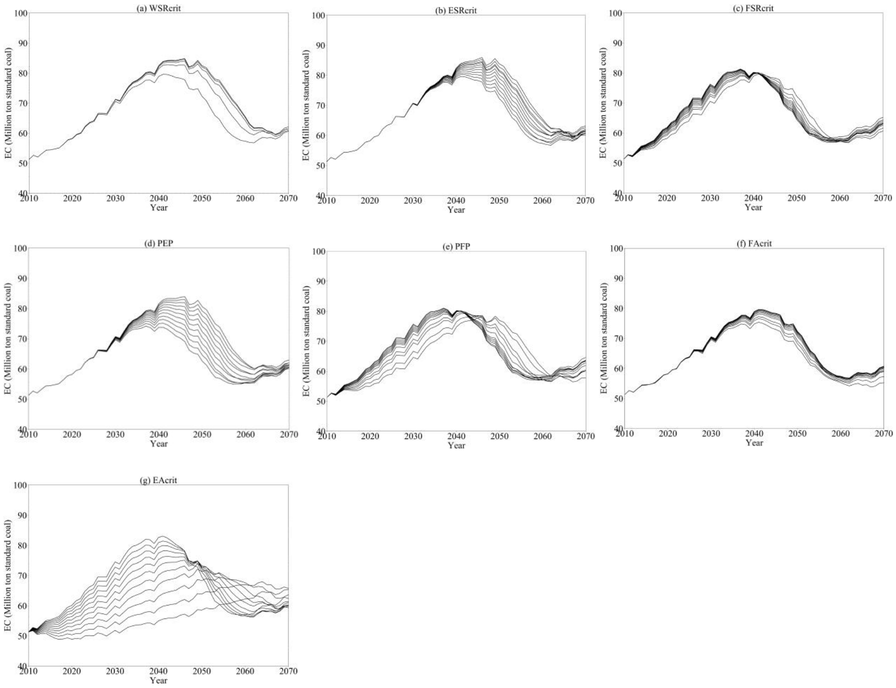
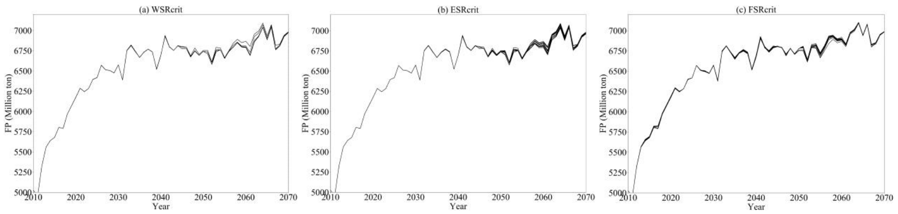


Figure 6. Trajectories of energy consumption with varied parameters.



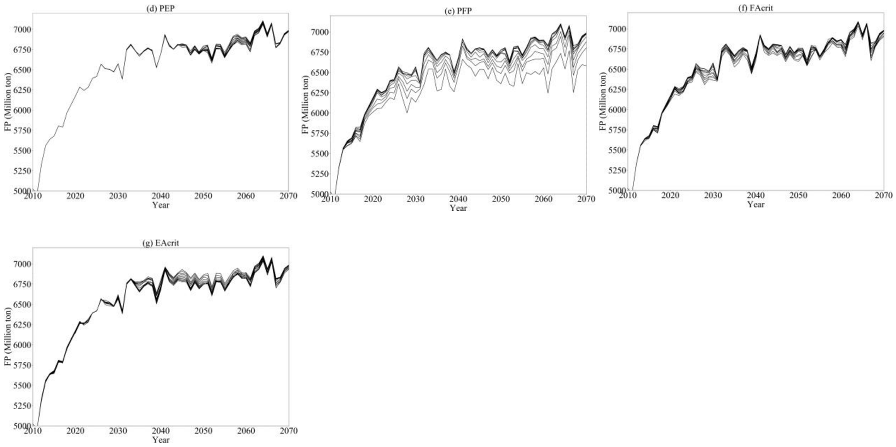


Figure 7. Trajectories of food production with varied parameters.

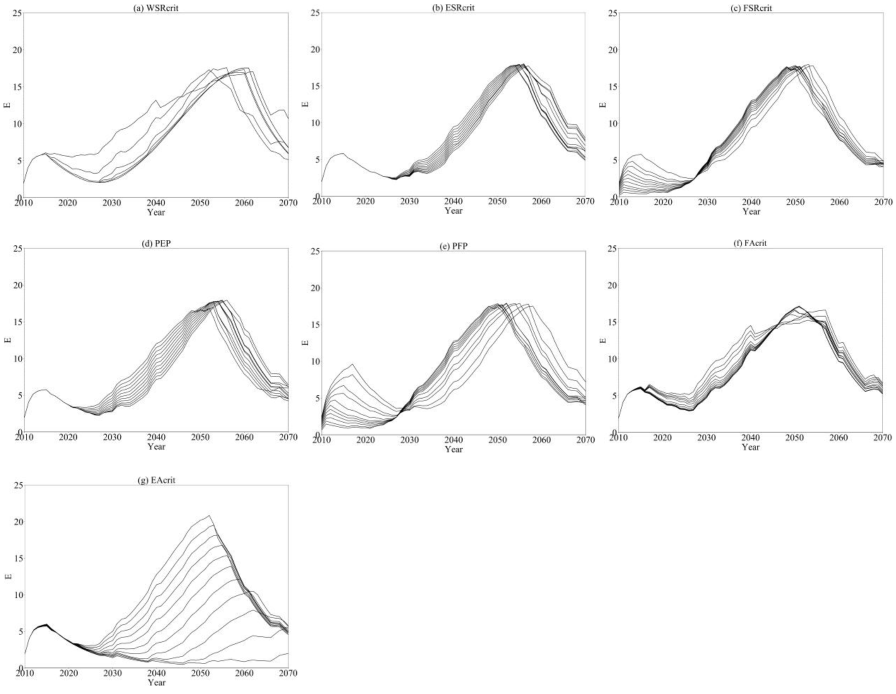


Figure 8. Trajectories of environmental awareness with varied parameters.

The variations of the seven parameters can remarkably change the trajectory of water demand as shown in Figure 5, indicating that water demand is sensitive to the seven parameters. Specifically, the sensitive responses to the first five parameters listed in Table 5 mainly occur in contraction and recession phases of the co-evolution process for water demand (Figure 5 (a), (b), (c), (d) and (e)), while parameters *FAcrit* and *EAcrit* are always sensitive in the whole co-evolution process (Figure 5 (f) and (g)). *WSRcrit*, *ESRcrit* and *FSRcrit* are the critical values that determine the awareness of water, energy and food shortages to accumulate. *PEP* and *PFP* indicate the amounts of the planning energy and food productions, which directly determine their shortage rates. Although water demand and energy consumption will increase in expansion phase, they will not exceed their carry capacities. The environmental awareness is accumulated mainly from food shortage awareness but remains below its critical value (Figure 4 (i)). As the feedback driven by environmental awareness is not strong enough, the impacts on the co-evolution are ignorable, and are taken as the insensitivity of water demand in expansion phase. After the socioeconomic expansion, water shortage and energy shortage occur and become serious gradually in contraction phase, leading the increase of environmental awareness. As environmental awareness accumulation can be accelerated with smaller critical shortage rates or larger shortage rates, negative feedback to constrain the increase of water demand will be advanced and strengthened. Water demand evolution in contraction and recession phases thereby performs sensitivity. In recovery phase, water demand will be decreased to adapt to local water and energy carry capacities as discussed in Section 4.2, and thus performs insensitivity. *FAcrit* and *EAcrit* indicate the community sensitivity to determine the feedback triggering driven by food shortage awareness and environmental awareness, respectively. The smaller *FAcrit* and *EAcrit* mean that it will be easier to capture the deterioration of the integrated system. Even the environmental awareness stays at a low level in expansion phase, feedback can still be triggered as long as the critical environmental awareness is small enough. Hence, water demand is sensitive to *FAcrit* and *EAcrit* in the whole process.

Sensitivity analysis for energy consumption and environmental awareness (Figure 6 and 8) can be interpreted in a similar way. It's worth noting that environmental awareness is also sensitive to *FSRcrit* and *PFP* in the beginning of the evolution (Figure 8 (c) and (e)). *FSRcrit* indicates the community sensitivity to food shortage rate. Smaller *FSRcrit* can lower the threshold and accelerate the food shortage awareness accumulation. While *PFP* can directly determine the food shortage rate, larger *PFP* will consequently lead larger food shortage rate and further larger food shortage awareness. The environmental awareness thereby increases.

PFP is the only parameter that can remarkably change the trajectory of food production shown in Figure 7, which is considered as the sensitive parameter for food production. The food production is less than its planning value in the beginning of the co-evolution. As the food shortage rate is over its critical value as shown in Figure 4 (i), food shortage awareness accumulates rapidly in expansion phase. Strong positive feedback for increasing crop area is thereby triggered to increase food production. Food production is then increased due to the increasing crop area and crop yield, and further tends to stabilization near its planning value as discussed in Section 4.2. *PFP* is thereby the sensitive parameter for food production in stabilization phase.

Therefore, water demand, energy consumption and environmental awareness are sensitive to the seven parameters listed in Table 5. Specifically, *WSRcrit*, *ESRcrit* and *FSRcrit* determine environmental awareness accumulation, while *PEP* and *PFP* directly determine shortage rates of energy and food. The environmental awareness accumulation can be advanced and accelerated by constraining these five parameters to further impact the co-evolution process, especially in contraction and recession phases. *FAcrit* and *EAcrit* can be used to evaluate the community sensitivity to the deterioration of the integrated system. These two parameters determine the threshold for feedback triggering, which can be capable to impact the trajectory in the whole co-evolution process. As food production tends to stabilization near the planning food production, the planning value *PFP* is considered as an important parameter to regulate the co-evolution of food production in stabilization phase.

4.4 WEFS Nexus Response to Water Resources Allocation

Water is the main driven factor for WEFS nexus. Rational water resources management plays an important role for the sustainable development of WEFS nexus. Water resources allocation can regulate water flow by reservoirs operation, which has been considered one of most effective tools for water resources management. To study the impacts of water resources allocation on WEFS nexus, two scenarios are set: scenario I indicates the scenario considering water resources allocation, while scenario II hasn't taken water resources allocation into account.

4.4.1 Results of Water Resources Allocation

Based on the Integrated Water Resources Planning of Hanjiang River Basin

(Cwrc, 2016), the domesticity and ecology water uses should be firstly ensured. The priorities for water use from high to low are municipal and rural domesticities, in-stream ecology, industrial and agricultural sectors, respectively. Water resources allocation is then simulated by IRAS model at monthly time step. The average annual water demand, supply and shortage are listed in Table 6.

Table 6 Water resources allocation results for the five water use sectors (million m^3).

Scenario	**Variables**	**Municipal**	**Rural**	**Industry**	**Agriculture**	**In-stream ecology**	**Total**
I	Demand	326	151	8,156	5,522	3,779	17,933
	Supply	325	151	7,265	5,184	3,659	16,583
	Shortage	1	0	891	338	120	1,350
	Shortage rate	0.24%	0.23%	10.93%	6.12%	3.16%	7.53 %
II	Demand	322	151	4,124	8,266	3,779	16,642
	Supply	294	138	3,263	6,871	3,313	13,879
	Shortage	28	13	861	1,395	465	2,763
	Shortage rate	8.70%	8.72%	20.87%	16.88%	12.31%	16.60%

Despite the water demand has increased from 16,642 million m^3 to 17,933 m^3 under scenario I, the water supply is increased from 13,879 million m^3 to 16,583 million m^3. The total water shortage rate decreases from 16.60% to 7.53% due to properly water resources allocation. As more available water resources can be stored in flood season and then released in dry season through reservoirs operation, the uneven temporal and spatial distribution of available water resources is remarkably

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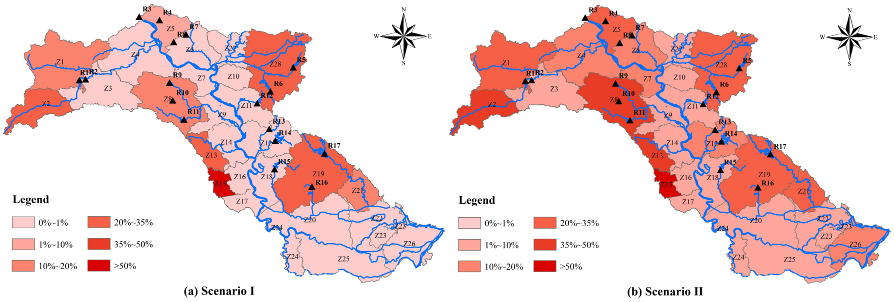
relived and the insurance of water supply is thereby increased. For water use sectors, water shortages are mainly found in industrial and agricultural sectors (891 million m^3 and 338 million m^3, respectively), while other sectors can be satisfied under scenario I. Water shortage becomes more serious under scenario II, as water shortage rates of the five sectors increase significantly, from 0.24%, 0.23%, 10.93%, 6.12% and 3.16% to 8.70%, 8.72%, 20.87%, 16.88% and 12.31%, respectively. To analyze the spatial distribution of water shortage rates, Figure 9 shows the water shortage rate in each operational zone. Water shortage rates of study area under scenario I are obviously higher than those under scenario II, especially for the operational zones located at the boundaries of basin (e.g., operational zone Z1, Z2, Z8, Z13, etc.). The boundary zones are far away from the main stream of Hanjiang river and their local water availability is unevenly distributed without much resilience, the regulating capacity of water system is not strong enough to ensure the water supply.



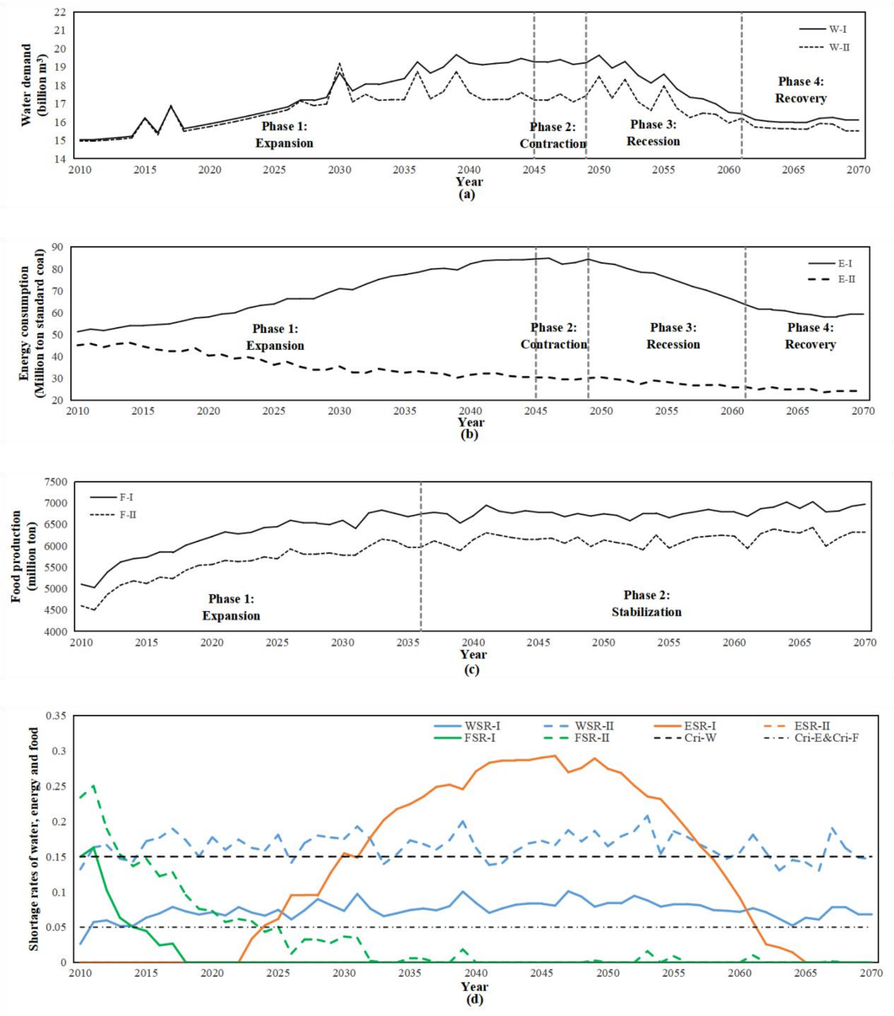
(a) Scenario I

(b) Scenario II

Figure 9. Distribution of water shortage rates.

4.4.2 Impacts of Water Resources Allocation on Co-evolution of WEFS Nexus

In order to assess the impacts of water resources allocation on WEFS nexus, Figure 10 shows the trajectories of key state variables of the integrated system including water demand, energy consumption, food production, shortage rates for water, energy and food, awareness for water shortage, energy shortage and food shortage as well as environmental awareness. The critical water shortage rate is set as maximum value 0.15 to avoid the explosion of water shortage awareness, while the other parameters are consistent with the corresponding initial values as listed in Table 5. The phases dividing is based on scenario I, as the dividing rules is established under the assumption considering reservoirs operation, which is not applicable in scenario II.



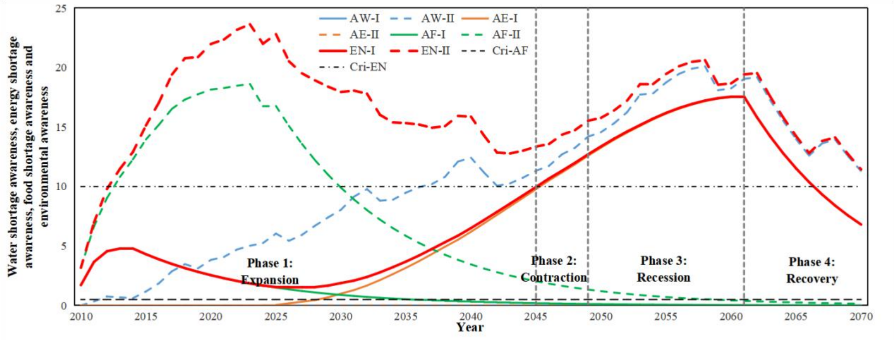


Figure 10. The trajectories of state variables in WEFS nexus under scenario I and II: (a) water demand; (b) energy consumption; (c) food production; (d) shortage rates of water, energy and food; (e) Water shortage awareness, energy shortage awareness, food shortage awareness and environmental awareness (the legends with suffix 'I' indicates scenario I, while the suffix 'II' indicates scenario II).

Under scenario II without considering water resources allocation, the average water shortage rate is 16.60%, exceeding the critical value. The water shortage awareness keeps accumulating shown in Figure 10 (e). As water supply can't be effectively ensured and remains at a low level, the energy consumption is small and always within its planning value. No energy shortage awareness is accumulated in the beginning of the co-evolution shown in Figure 10 (e). The rapid increasing environmental awareness is mainly from the dramatic increases of water shortage awareness and food shortage awareness. As the environmental awareness accumulates over its critical value in 2013 and keeps increasing, negative feedback to constrain the socioeconomic expansion is triggered and keeps strengthening. The energy consumption thereby keeps decreasing in Figure 10 (b), preventing the accumulation of environmental awareness from energy shortage awareness. For water demand, although it shows a slight decrease compared with that under scenario I (from 17,933 million m^3 under scenario I to 16,642 million m^3 under scenario II), the total water shortage still increases (from 1,350 million m^3 under scenario I to 2,763 million m^3 under scenario II). As water shortage rate remains over its critical value in Figure 10 (d), the water shortage awareness keeps increasing and stays at a high level in the whole co-evolution process. The food production rapidly increases over its planning value with the positive feedback to increase crop area driven by the high-level food shortage awareness and the increasing crop yield driven by the advancement of technology. The food shortage awareness then decreases gradually below its critical value in 2059. Therefore, the environmental awareness will keep staying at a high level under scenario II due to the continuously accumulating water shortage awareness.

With water resources allocation taken into account, water shortage is significantly alleviated under scenario I as discussed in Section 4.4.1 (from 16.60% scenario II to 7.53% under scenario I). The water shortage rate keeps below its critical value in the whole co-evolution process (Figure 10 (d)). Thus, there is no accumulation of water shortage awareness in Figure 10 (e). As agricultural water demand is effectively ensured, water availability is no longer the constraining factor for food production. Food production increases remarkably and food shortage awareness further decreases significantly compared with those under scenario II (Figure (c) and (e)). Therefore, the environmental awareness in expansion phase stays at a low level and mainly comes from food shortage awareness. With the positive feedback driven by food shortage awareness, the crop area is increased to increase food production. The food shortage awareness thereby gradually decreases below its critical value in 2036. In terms of energy system, the energy consumption increases continuously and exceeds the planning energy production in 2024. The energy shortage awareness accumulates rapidly and further results in the fast increase of environmental awareness, reaching the maximum value 15.8 at the end of the contraction phases in 2062. With the strengthening negative feedback due to the increasing environmental awareness, the constraints on socioeconomic expansion are thereby intensified. Water demand and energy consumption are then decreased as shown in Figure 10 (a) and (b). Energy shortage keeps decreasing and stays below its critical value after 2062. Environmental awareness from energy shortage awareness decreases rapidly and the integrated system goes into recovery phase.

Overall, water resources allocation can effectively alleviate water shortage to decrease water shortage awareness by increasing water supply. As the agricultural water use is effectively ensured, the food production will increase and further relieve the accumulation of food shortage awareness. The increase of environmental awareness is mainly led by the constant high-level energy shortage rate. Therefore, the planning energy production is the primary boundary condition for sustainable development of WEFS nexus, when water resources allocation is taken into account. While under the scenario without considering water resources allocation, the risk of water shortage is considerable. Water shortage awareness keeps accumulating and stays at a high level under scenario II. Considerable water shortage will

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simultaneously decrease food production and further lead the increase of food shortage awareness. The rapid increasing water shortage awareness and food shortage awareness will result in the fast accumulation of environmental awareness in the beginning of co-evolution process. With the positive feedback on crop area and advancement of technology on crop yield, food productions will rapidly increase and further satisfy its planning value. The food shortage awareness will thereby gradually decrease to a low level. Water availability becomes the vital resource that constraining the concordant development of WEFS nexus under the scenario without considering water resources allocation.

5. Conclusion

The sustainable management of WEF nexus remains an urgent challenge, as community sensitivity and reservoirs operation are seldom taken into account in current studies. This paper used environmental awareness to capture community sensitivity, and simultaneously incorporated reservoirs operation in the form of water resources allocation model (i.e., IRAS model) into water system so as to develop a system dynamic model for WEFS nexus. The proposed model was applied to mid-lower reached of Hanjiang river basin in China. The conclusions are drawn as follows:

The evolution of water demand and energy consumption can be divided into four phases: expansion, contraction, recession and recovery. Specifically, contraction and recession phases are the two important phases which policy makers should pay more attention to. In contraction phase, environmental awareness keeps accumulating due to time lag, despite water demand and energy consumption have reached their maximum values. Violent deterioration of water demand and energy consumption will further be followed in recession phase. Food production increases steadily in expansion phase and then keeps fluctuating near the planning food production in stabilization phase, which brings little threats to the long-term co-evolution of WEFS nexus.

Seven controllable parameters are adopted for sensitivity analysis, including (a) critical water shortage rate, (b) critical energy shortage rate, (c) critical food shortage rate, (d) planning energy production, (e) planning food production, (f) critical food shortage awareness and (g) critical environmental awareness. Results shows the mode of WEFS nexus system functioning strongly depends on the selection of certain parameter values. Specifically, water demand, energy consumption and environmental awareness are sensitive to the seven parameters. As environmental awareness accumulation can be accelerated by constraining parameter (a), (b), (c), (d) and (e), the feedback will further be advanced and strengthened. The co-evolution is thereby impacted, especially when water demand and energy consumption exceed their carry capacities in contraction and recession phases. Parameters (f) and (g) can be used to evaluate the community sensitivity to shortages of water, energy and food, which dominate the whole co-evolution process. Planning food production can determine the food production in stabilization phase and is considered as an important parameter for food production.

Water resources allocation can significantly ensure the sustainable development of WEFS nexus. The relieved water shortage is contributed by the increased water supply through reservoirs operation. And the level environmental awareness driven by water shortage is also effectively alleviated. The primary resource constraining the concordant development of WEFS nexus is transferred from available water to available energy.

As the primary inputs of the proposed WEFS nexus model, water availability is adopted based on historical scenario in this paper. Climate change in the future hasn't been taken into account for the sake of simplicity. In fact, considerable uncertainties of water availability are brought into water system in WEFS nexus due to climate change (Chen et al., 2011). Propagation of the uncertainties can also be quite complicated, with the interactions among water, energy, food and society systems during the co-evolution process. Therefore, more attention should be paid to uncertainty analysis on WEFS nexus under climate change. However, the proposed framework and our research results will not only offer useful guidelines for local sustainable development but also demonstrate the potential for effective application in other basins.

Data availability: The socioeconomic data used in producing this paper are available at http://data. cnki.net/

Author contributions: Conceptualization, DL and YZ; Methodology, YZ;

Software, YZ; Data Curation, YZ, ZW and LD; Formal analysis, YZ and DL; Writing-Original Draft preparation, YZ and LD; Writing-Review and Editing, SG, LX, PL, JY and DL; Funding acquisition, DL.

Competing interests: The authors declare that they have no conflict of interest.

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References

Alexandratos, N. and Bruinsma, J.: World agriculture towards 2030/2050, 2012.

Baldassarre, G. D., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., and Bloeschl, G.: DebatesPerspectives on socio-hydrology: Capturing feedbacks between physical and social processes, Water Resour. Res., 51, 4770-4781, 10.1002/2014wr016416, 2015.

Bertalanffy, L. V.: General System Theory: Foundations, Development, Applications, 3, George Braziller, New York, America1976.

Bonabeau, E.: Agent-based modeling: Methods and techniques for simulating human systems, Proc. Natl. Acad. Sci. U. S. A., 99, 7280-7287, 10.1073/pnas.082080899, 2002.

Brekke, L., Larsen, M. D., Ausburn, M., and Takaichi, L.: Suburban water demand modeling using stepwise regression, Journal American Water Works Association, 94, 65-75, 2002.

Chen, J., Brissette, F. P., and Leconte, R.: Uncertainty of downscaling method in quantifying the impact of climate change on hydrology, Journal of Hydrology, 401, 190-202, 10.1016/j.jhydrol.2011.02.020, 2011.

Chen, X., Wang, D., Tian, F., and Sivapalan, M.: From channelization to restoration: Sociohydrologic modeling with changing community preferences in the Kissimmee River Basin, Florida, Water Resour. Res., 52, 1227-1244, 10.1002/2015wr018194, 2016.

Cheng, C. L.: Study of the inter-relationship between water use and energy conservation for a building, Energy and Buildings, 34, 261-266, 10.1016/s0378-7788(01)00097-4, 2002.

Chiang, Y. M., Chang, L. C., and Chang, F. J.: Comparison of static-feedforward and dynamic-feedback neural networks for rainfall-runoff modeling, Journal of Hydrology, 290, 297-311, 10.1016/j.jhydrol.2003.12.033, 2004.

Changjiang Water Resources Commission (CWRC): Integrated Water Resources Planning of Hanjiang River Basin, Wuhan, China, 2016. (in Chinese)

Davies, E. G. R. and Simonovic, S. P.: ANEMI: a new model for integrated assessment of global change, Interdisciplinary Environmental Review, 11, 127, 10.1504/ier.2010.037903, 2010.

Dawson, R. J., Peppe, R., and Wang, M.: An agent-based model for risk-based flood incident management, Natural Hazards, 59, 167-189, 10.1007/s11069-011-9745-4, 2011.

El Gafy, I., Grigg, N., and Reagan, W.: Dynamic Behaviour of the Water-Food-Energy Nexus: Focus on Crop Production and Consumption, Irrigation and Drainage, 66, 19-33, 10.1002/ird.2060, 2017.

El Gafy, I. K.: System Dynamic Model for Crop Production, Water Footprint, and Virtual Water Nexus, Water Resources Management, 28, 4467-4490, 10.1007/s11269-014-0667-2, 2014.

Elshafei, Y., Sivapalan, M., Tonts, M., and Hipsey, M. R.: A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach, Hydrology and Earth System Sciences, 18, 2141-2166, 10.5194/hess-18-2141-2014, 2014.

Eusgeld, I., Nan, C., and Dietz, S.: "System-of-systems" approach for interdependent critical infrastructures, Reliability Engineering & System Safety, 96, 679-686, 10.1016/j.ress.2010.12.010, 2011.

Feng, M., Liu, P., Li, Z., Zhang, J., Liu, D., and Xiong, L.: Modeling the nexus across water supply, power generation and environment systems using the system dynamics approach: Hehuang Region, China, Journal of Hydrology, 543, 344-359, 10.1016/j.jhydrol.2016.10.011, 2016.

Feng, M., Liu, P., Guo, S., Yu, D. J., Cheng, L., Yang, G., and Xie, A.: Adapting reservoir operations to the nexus across water supply, power generation, and environment systems: An explanatory tool for policy makers, Journal of Hydrology, 574, 257-275, 10.1016/j.jhydrol.2019.04.048, 2019.

French, R. J. and Schultz, J. E.: Water-use efficiency of wheat in a mediterranean-type environment. 1. The relation between yield, water-use and climate, Aust. J. Agric. Res., 35, 743-764, 10.1071/ar9840743, 1984.

He, S., Guo, S., Yin, J., Liao, Z., Li, H., and Liu, Z.: A novel impoundment framework for a mega reservoir system in the upper Yangtze River basin, Appl. Energy, 305, 10.1016/j.apenergy.2021.117792, 2022.

Hoff, H.: Understanding the nexus. In: Background Paper for the Bonn 2011 Conference. The Water, Energy and Food Security Nexus., Stockholm Environment Institute, 2011.

Housh, M., Cai, X., Ng, T. L., McIsaac, G. F., Ouyang, Y., Khanna, M., Sivapalan, M., Jain, A. K., Eckhoff, S., Gasteyer, S., Al-Qadi, I., Bai, Y., Yaeger, M. A., Ma, S., and Song, Y.: System of Systems Model for Analysis of Biofuel Development, Journal of Infrastructure Systems, 21, 10.1061/(asce)is.1943-555x.0000238, 2015.

Hubei Provincial Department of Water Resources (HPDWR): Dispatching schedules of Hubei provincial large reservoirs, Wuhan, China, 2014. (in Chinese)

Hsiao, T. C., Steduto, P., and Fereres, E.: A systematic and quantitative approach to improve water use efficiency in agriculture, Irrig. Sci., 25, 209-231, 10.1007/s00271-007-0063-2, 2007.

International Energy Agency: World Energy Outlook 2012, International Energy Agency, Paris, France, 2012.

Khare, D., Jat, M. K., and Sunder, J. D.: Assessment of water resources allocation options:

Conjunctive use planning in a link canal command, Resour. Conserv. Recycl., 51, 487-506, 10.1016/j.resconrec.2006.09.011, 2007.

Kleinmuntz, D. N.: Information-processing and misperceptions of the implications of feedback in dynamic decision-making, System Dynamics Review, 9, 223-237, 10.1002/sdr.4260090302, 1993.

Krause, P., Boyle, D. P., and Bäse, F.: Comparison of different efficiency criteria for hydrological model assessment, Advances in Geosciences, 5, 89-97, 10.5194/adgeo-5-89-2005., 2005.

Laspidou, C. S., Mellios, N. K., Spyropoulou, A. E., Kofinas, D. T., and Papadopoulou, M. P.: Systems thinking on the resource nexus: Modeling and visualisation tools to identify critical interlinkages for resilient and sustainable societies and institutions, Sci. Total Environ., 717, 10.1016/j.scitotenv.2020.137264, 2020.

Li, B., Sivapalan, M., and Xu, X.: An Urban Sociohydrologic Model for Exploration of Beijing's Water Sustainability Challenges and Solution Spaces, Water Resour. Res., 55, 5918-5940, 10.1029/2018wr023816, 2019.

Linderhof, V., Dekkers, K., and Polman, N.: The Role of Mitigation Options for Achieving a Low-Carbon Economy in the Netherlands in 2050 Using a System Dynamics Modelling Approach, Climate, 8, 10.3390/cli8110132, 2020.

Liu, D.: Evaluating the dynamic resilience process of a regional water resource system through the nexus approach and resilience routing analysis, Journal of Hydrology, 578, 10.1016/j.jhydrol.2019.124028, 2019.

Liu, D., Guo, S., Liu, P., Xiong, L., Zou, H., Tian, J., Zeng, Y., Shen, Y., and Zhang, J.: Optimisation of water-energy nexus based on its diagram in cascade reservoir system, Journal of Hydrology, 569, 347-358, 10.1016/j.jhydrol.2018.12.010, 2019.

Lobell, D. B., Cassman, K. G., and Field, C. B.: Crop Yield Gaps: Their Importance, Magnitudes, and Causes, Annual Review of Environment and Resources, 34, 179-204, 10.1146/annurev.environ.041008.093740, 2009.

Loucks, D. P.: Interactive River-Aquifer Simulation and Stochastic Analyses for Predicting and Evaluating the Ecologic Impacts of Alternative Land and Water Management Policies;, Kluwer Academic Publishers, Dordrecht, The Netherlands2002.

Makindeodusola, B. A. and Marino, M. A.: Optimal-control of groundwater by the feedback method of control, Water Resour. Res., 25, 1341-1352, 10.1029/WR025i006p01341, 1989.

Malthus, T.: An Essay on the Principle of Population, Penguin, Harmondsworth, England1798.

McKinsey & Company: Charting our water future: economic frameworks to inform decision-making, 2030 Water Resources Group, 2009.

Nash, J. E. and Sutcliffe, J. V.: River flow forecasting through conceptual models part I — A discussion of principles, Journal of Hydrology, 10, 282-290, 10.1016/0022-1694(70)90255-6., 1970.

Purwanto, A., Susnik, J., Suryadi, F. X., and de Fraiture, C.: Quantitative simulation of the water-energy-food (WEF) security nexus in a local planning context in indonesia, Sustainable Production and Consumption, 25, 198-216, 10.1016/j.spc.2020.08.009, 2021.

Ravar, Z., Zahraie, B., Sharifinejad, A., Gozini, H., and Jafari, S.: System dynamics modeling for assessment of water-food-energy resources security and nexus in Gavkhuni basin in Iran, Ecological Indicators, 108, 10.1016/j.ecolind.2019.105682, 2020.

Roobavannan, M., van Emmerik, T. H. M., Elshafei, Y., Kandasamy, J., Sanderson, M. R., Vigneswaran, S., Pande, S., and Sivapalan, M.: Norms and values in sociohydrological models, Hydrology and Earth System Sciences, 22, 1337-1349, 10.5194/hess-22-1337-2018, 2018.

Si, Y., Li, X., Yin, D., Li, T., Cai, X., Wei, J., and Wang, G.: Revealing the water-energy-food nexus in the Upper Yellow River Basin through multi-objective optimization for reservoir system, Sci. Total Environ., 682, 1-18, 10.1016/j.scitotenv.2019.04.427, 2019.

Simonovic, S. P.: World water dynamics: global modeling of water resources, J. Environ. Manag., 66, 249-267, 10.1006/jema.2002.0585, 2002.

Susnik, J.: Data-driven quantification of the global water-energy-food system, Resour. Conserv. Recycl., 133, 179-190, 10.1016/j.resconrec.2018.02.023, 2018.

Swanson, J.: Business dynamics - Systems thinking and modeling for a complex world, J. Oper. Res. Soc., 53, 472-473, 10.1057/palgrave.jors.2601336, 2002.

Tennant, D. L.: Instream flow regimens for fish, wildlife, recreation and related environmental resources, Fisheries, 1, 6-10, 10.1577/1548-8446(1976)001<0006:ifrffw>2.0.co;2, 1976.

Van Emmerik, T. H. M., Li, Z., Sivapalan, M., Pande, S., Kandasamy, J., Savenije, H. H. G., Chanan, A., and Vigneswaran, S.: Socio-hydrologic modeling to understand and mediate the competition for water between agriculture development and environmental health: Murrumbidgee River basin, Australia, Hydrology and Earth System Sciences, 18, 4239-4259, 10.5194/hess-18-4239-2014, 2014.

Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B.: Global water resources: Vulnerability from climate change and population growth, Science, 289, 284-288, 10.1126/science.289.5477.284, 2000.

Wolstenholme, E. F. and Coyle, R. G.: The development of system dynamics as a methodology for system description and qualitative analysis, J. Oper. Res. Soc., 34, 569-581, 10.1057/jors.1983.137, 1983.

Xu, X. B., Hu, H. Z., Tan, Y., Yang, G. S., Zhu, P., and Jiang, B.: Quantifying the impacts of climate variability and human interventions on crop production and food security in the Yangtze River Basin, China, 1990-2015, Sci. Total Environ., 665, 379-389, 10.1016/j.scitotenv.2019.02.118, 2019.

Zeng, Y., Liu, D., Guo, S., Xiong, L., Liu, P., Yin, J., Tian, J., Deng, L., and Zhang, J.: Impacts of Water Resources Allocation on Water Environmental Capacity under Climate Change, Water, 13, 10.3390/w13091187, 2021.

Zhou, Y., Chang, L., Uen, T., Guo, S., Xu, C., and Chang, F.: Prospect for small-hydropower installation settled upon optimal water allocation: An action to stimulate synergies of water-food-energy nexus, Appl. Energy, 238, 668-682, 10.1016/j.apenergy.2019.01.069, 2019.