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 the water-energy-food (WEF) nexus remains an urgent challenge, as interactions between WEF and human sensitivity and reservoir operation in the water system are typically neglected. This study proposes a new approach for modeling the WEF nexus by incorporating human sensitivity and reservoir operation into the system. The co-evolution behaviors of the nexus across the water, energy, food, and society (WEFS) were simulated using the system dynamic model. The reservoir operation was simulated to determine the water supply for energy and food systems by the Interactive River-Aquifer Simulation water resources allocation model. Shortage rates for water, energy, and food resulting from the simulations were used to qualify their impacts on the WEFS nexus through environmental awareness in the society system. The human sensitivity indicated by environmental awareness can adjust the co-evolution behaviors of the WEFS nexus through feedback loops. The proposed approach was applied to the mid-lower reaches of the Hanjiang river basin in China as a case study. The results show that environmental awareness can effectively capture the human sensitivity to shortages from water, energy, and food systems. The feedback driven by environmental awareness regulates the socioeconomic expansion to maintain the integrated system from constant resources shortages, thereby decreasing the energy shortage rate from 17.16% to 5.80% and contributing to the sustainability of the WEFS nexus. Water resources allocation can ensure water supply through reservoir operation, decreasing the water shortage rate from 15.89% to 7.20%. The resource constraining the WEFS nexus is transferred from water to energy. Therefore, this study contributes to the

understanding of interactions across the WEFS systems and helps in improving the efficiency of resources management.

Keywords: water-energy-food-society nexus; system dynamic; water resources allocation; human sensitivity

1. Introduction

Water, energy, and food are indispensable resources for sustainable development of society. With the growing population, urbanization, globalization, and economic development, the expected global demands for water, food, and energy in 2030 will increase by 40%, 50%, and 50%, respectively, compared to the 2010 levels (Alexandratos and Bruinsma, 2012; Mckinsey & Company, 2009; International Energy Agency, 2012). Resource scarcity will be exacerbated by the single-sector strategy in traditional water, energy, and food management (El Gafy et al., 2017). To increase resource use efficiency 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 these interactions, the water-energy-food (WEF) nexus concept was first presented at the Bonn Conference in 2011 as an approach to determine synergies and trade-offs between WEF sectors to support sustainable development goals (Hoff, 2011).

Various methods have been proposed for integrated systems to quantify the interactions in the WEF nexus. There are three main 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 dynamic model (El Gafy, 2014; Swanson, 2002). The system of systems model comprises several subsystems as a holistic system to address the nexus by optimizing system behavior. The agent-based model simulates the interactions between agents and environments as well as different agents based on predefined rules obtained from long-term observations. These two methods have been established to be capable of simulating the behaviors of an integrated system. However, neither of them has emphasized feedback within the integrated systems, which is considered an important driving force for nexus system (Chiang et al., 2004; Kleinmuntz, 1993; Makindeodusola and Marino, 1989). The results of these two methods for WEF security remain at risk. The system dynamic model explicitly focuses on feedback connections between key elements in a model to determine the co-evolution process and long-term characteristics of integrated systems (Liu, 2019; Simonovic, 2002). Therefore, system dynamic model was adopted in this study to simulate the co-evolution process of the nexus system.

System dynamic model has been widely used to analyze the WEF nexus worldwide 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 these models perform the accounting and analysis of the WEF nexus, focusing only on the physical process, while rarely highlighting the social process that indicates human responses to the WEF nexus (Elshafei et al., 2014). As the connection between the WEF nexus and society is intensified under rapid socioeconomic development, both physical and social processes should be considered for the sustainability of the integrated system in the future (Di Baldassarre et al., 2015; Di Baldassarre et al., 2019).

To simultaneously capture the physical and social processes of the integrated system, human sensitivity was considered as a conceptual social state variable to identify environmental 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 the Murrumbidgee river basin (Australia). Li et al. (2019) developed an urban socio-hydrologic model to investigate future water sustainability from a holistic and dynamic perspective in Beijing (China). Feng et al. (2016) used environmental awareness to indicate community's attitude to influence the co-evolution behaviors of the water-power-environment nexus in the Hehuang region (China). These studies have contributed to effective resources management by incorporating both physical and social processes. However, potential threats to WEF security exist, as few of the current studies have simultaneously considered the impacts of reservoir operation in water system on the integrated system.

Reservoirs can adjust the uneven temporal and spatial distribution of available water resources and can ensure water supply to reduce water shortage (Khare et al., 2007; Liu et al., 2019; Zeng et al., 2021; He et al., 2022). However, the available water resources are typically adopted under historical natural water flow scenarios, while reservoirs are seldom considered, or their operational rules are significantly simplified in the WEF nexus. The assessment of water supply security based on the WEF nexus should be improved. Thus, additional details regarding the reservoir operation should be incorporated into the simulation of the WEF nexus.

The water resources allocation model can simultaneously incorporate reservoir operation and water acquisition, and it has become an effective tool to quantitatively assess the impacts of reservoir operation on water supply security, as well as 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 reservoir operation on the WEFS nexus by integrating the water resources allocation model into the integrated system. The reminder of this paper is organized as follows: Section 2 introduces the framework for modeling the WEFS nexus and assessing the impacts of water resources allocation on the WEFS nexus. Section 3 describes the methodologies applied in the mid-lower reaches of the Hanjiang river basin in China, which is the study area. Section 4 presents the results of the co-evolution process and the sensitivity analysis of the WEFS nexus. The impacts of water resources allocation on the WEFS nexus have also been discussed. The conclusions of this study are presented in Section 5.

2 Methods

System dynamic modeling (SDM) simulates the dynamics among different systems 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 (Di Baldassarre et al., 2015; Simonovic, 2002). The SDM for assessing the WEFS nexus comprises four modules (shown in Figure 1): water system module, energy system module, food system module, and society system module.

In the water system module, socioeconomic water demand (i.e., municipal, rural, industrial, and agricultural water demand) and in-stream water demand are projected using the quota method and Tennant method (Tennant, 1976), respectively. The water demands and available water resources are further inputted into the water resources allocation model to determine the water supply and water shortage for every water use sector in each operational zone. The water supply for socioeconomic water use sectors and agricultural water shortage rates as outputs from the water system module are taken as the inputs of the energy system module and food system module to determine the energy consumption and food production, respectively. Considering the outputs of the energy and food system modules, the energy and food shortages can be estimated by comparing the planning energy availability and planning food production, respectively. The function of the society module is to capture human sensitivity to degradation in the WEF nexus (Elshafei et al., 2014). Environmental awareness is considered as the conceptual social state variable to indicate human 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. As environmental awareness accumulates over its critical value, negative feedback on socioeconomic sectors (i.e., population, GDP, and crop area) will be triggered to constrain the increases in water demand, and further energy consumption, and food production to sustain the WEFS nexus.

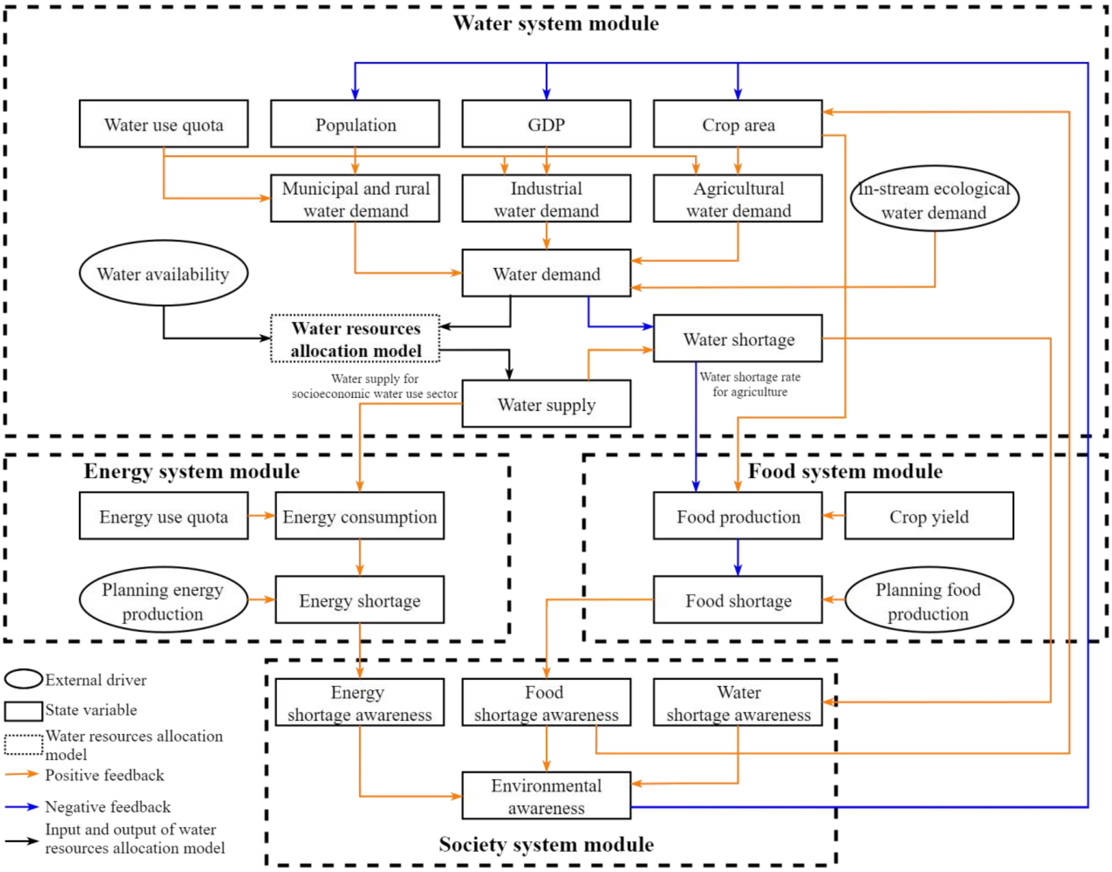


Figure 1. Structure of WEFS nexus model and its feedbacks.

2.1 Water System Module

2.1.1 Water Demand Projection

Water user comprises socioeconomic (also called off-stream) user and in-stream user. Socioeconomic water users can be classified into municipal, rural, industrial, and agricultural sectors. The quota method has been considered an efficient approach to project the annual socioeconomic water demand (Brekke et al., 2002). The amount of water demand for the socioeconomic users can be estimated using 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 zone in the *t*-th year; $WQ_{i,j}^{t}$ denotes the water use quota unit of water user; $A_{i,j}^{t}$ is the amount of water units of water user; and $U_{i,j}^{t}$ represents the utilization rate of water user. The water quota units represent 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 represents the projected population in municipal and rural users, projected GDP in industrial user, and projected irrigated area in agricultural user.

As population, GDP, crop area, and water use quota are prerequisites for water demand projection, the dynamic equations for these socioeconomic variables should be pre-determined. The Malthusian growth model is a succinct approach that has been widely applied to socioeconomic projections (Bertalanffy, 1976; Malthus, 1798). As the growth rate in the original Malthusian growth model is adopted as a constant, socioeconomic factors will reach infinity in a long-time evolution. Therefore, we assume that population, GDP, and crop area increase with decreasing rates over time, based on previous studies (He et al., 2017; Lin et al., 2016). And feedback functions, as well as environmental capacities of socioeconomic variables, are adopted to constrain the infinite evolution of these socioeconomic variables through equations

(2)–(4) (Feng et al., 2016; Hritonenko and Yatsenko, 1999).

$$\begin{cases} \dfrac{dN_t}{dt} = r_{P,t} * N_t \\ r_{P,t} = \begin{cases} r_{P,0} * (1+\kappa_P * \exp(-\varphi_P t)) + f_1(E) & N_t \le N_{cap} \\ \mathrm{Min}(0, r_{P,0} * (1+\kappa_P * \exp(-\varphi_P t)) + f_1(E)) & N_t > N_{cap} \end{cases} \end{cases} \tag{2}$$

$$\begin{cases} \dfrac{dG_t}{dt} = r_{G,t} * G_t \\ r_{G,t} = \begin{cases} r_{G,0} * (1+\kappa_G * \exp(-\varphi_G t)) + f_2(E) & G_t \le G_{cap} \\ \mathrm{Min}(0, r_{G,0} * (1+\kappa_G * \exp(-\varphi_G t)) + f_2(E)) & G_t > G_{cap} \end{cases} \end{cases} \tag{3}$$

$$\begin{cases} \dfrac{dCA_t}{dt} = r_{CA,t} * CA_t \\ r_{CA,t} = \begin{cases} r_{CA,0} * (1+\kappa_{CA} * \exp(-\varphi_{CA} t)) + f_3(E, FA) & CA_t \le CA_{cap} \\ \mathrm{Min}(0, r_{CA,0} * (1+\kappa_{CA} * \exp(-\varphi_{CA} t)) + f_3(E, FA)) & CA_t > CA_{cap} \end{cases} \end{cases} \tag{4}$$

where N_t, G_t, and CA_t are the population, GDP, and crop area in the t-th year, respectively; N_{cap}, G_{cap}, and CA_{cap} denote the environmental capacities of population, GDP, and crop area, respectively; $r_{P,0}$, $r_{G,0}$, and $r_{CA,0}$ represent the growth rates of population, GDP, and crop area in the baseline year, respectively, which are observed from historical data; $r_{P,t}$, $r_{G,t}$, and $r_{CA,t}$ are the growth rates of population, GDP, and crop area in the t-th year, respectively; κ_P*exp(-$\varphi_P t$), κ_G*exp(-$\varphi_G t$), and κ_{CA}*exp(-$\varphi_{CA} t$) are used to depict the impacts of technological development on the evolution of population, GDP, and crop area, respectively; E is environmental awareness; FA is food shortage awareness; and f_1, f_2, and f_3 represent the feedback functions. The equations for E, FA, and feedback functions are described in detail in Sections 2.4 and 2.5.

Water use quotas are also assumed to decrease with the technological development owing to the expansion economy (Blanke et al., 2007; Hsiao et al., 2007). As the difficulties in saving water by technological advancement are increasing, the changing rate of water use quota is decreasing in equation (5) (Feng et al., 2019).

$$\begin{cases} \dfrac{dWQ_{i,j}^{t}}{dt} = WQ_{i,j}^{t} * r_{qwu,t} \\ r_{qwu,t} = r_{qwu,0}(1 - \kappa_{qwu} * \exp(-\varphi_{qwu} t)) \end{cases} \tag{5}$$

where $WQ_{i,j}^{t}$ denotes the water use quota of the *j*-th water user in the *i*-th operational zone in the *t*-th year; $r_{qwu,0}$ and $r_{qwu,t}$ are the growth rates of water use quotas in the baseline year and *t*-th year, respectively; and $\kappa_{qwu}*\exp(-\varphi_{qwu}t)$ is used to depict the water-saving effect of technological development on the evolution of water use quota.

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 flows using a water resources allocation model. The Interactive River-Aquifer Simulation (IRAS) model is a rule-based water system simulation model developed by Cornell University (Loucks, 2002; Zeng et al., 2021; Matrosov et al., 2011). The IRAS model runs on a yearly loop. The year is divided into user-defined time step, and each time step is broken into user-defined sub-time step, based on which water resources allocation conducts. The IRAS model was adopted for water resources allocation owing to its flexibility and accuracy in water system simulations.

As water system comprises water transfer, consumption, and loss components, it is typically delineated by node network topology for the application of the water resources allocation model. Reservoir nodes and demand nodes are the most important elements in the node network topology, as they directly correspond to the processes of water supply, acquisition, and consumption. The water shortage at the demand node should first be determined based on its water demand and total water supply. The total water supply comprises natural water inflow (i.e., local water availability) and water supply from reservoir. In each sub-time step (except the first), the average natural water inflow in the previous *sts*-1 sub-time steps is estimated as the extrapolated natural water inflow in the remaining sub-time steps using equation (6). The water shortage can then be determined by deducting the demand reduction, total real-time water inflow, and extrapolated natural water inflow from water demand using equation (7). The total water shortage rate can then be determined using equation (8).

$$WE_{i,j}^{sts} = \left(\sum_{1}^{sts-1} WTSup_{i,j}^{sts} - \sum_{1}^{sts-1} WRSup_{i,j}^{sts}\right) * \frac{(Tsts - sts + 1)}{(sts - 1)} \tag{6}$$

$$WS_{i,j}^{sts} = \frac{WD_{i,j}^{ts}(1 - f_{red}) - \sum_{1}^{sts} WTSup_{in}^{sts} - WE_{i,j}^{sts}}{Tsts - sts + 1} \tag{7}$$

$$WSR_{i,j}^{t} = \frac{\sum_{ts}\sum_{sts} WS_{i,j}^{sts}}{\sum_{ts} WD_{i,j}^{ts}} \tag{8}$$

where *ts* is the current time step; *Tsts* denotes the total number of the sub-time steps; *sts* is the current sub-time step; $WE_{i,j}^{sts}$ represents the extrapolated natural water inflow for the *j*-th water use sector in the *i*-th operational zone; $WTSup_{i,j}^{sts}$ is the total water supply; $WRSup_{i,j}^{sts}$ is the water supply from reservoir; $WD_{i,j}^{ts}$ is the water demand; f_{red} is the demand reduction factor; $WS_{i,j}^{st}$ is the water shortage; and $WSR_{i,j}^{t}$ is the water shortage rate in the *t*-th year.

The water shortage at the demand node requires water release from the corresponding reservoir nodes according to their hydrological connections. The amount of water released from the reservoir depends on the water availability for demand-driven reservoirs and operational rules for supply-driven reservoirs, respectively. The water release for the supply-driven reservoir is linearly interpolated based on Figure 2 and equations (9)–(15). Additional details on the IRAS model can be found in Matrosov et al. (2011).

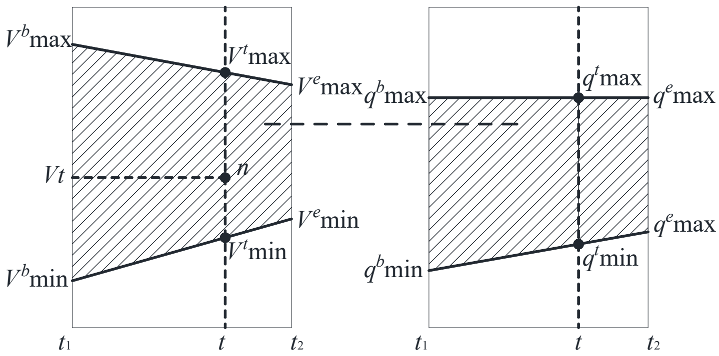


Figure 2. Water release rule for supply-driven reservoir.

$$P_t = (t - t_1)/(t_2 - t_1) \quad (9)$$

$$V^t_{\max} = V^b_{\max} * (1 - P_t) + V^e_{\max} * P_t \quad (10)$$

$$V^t_{\min} = V^b_{\min} * (1 - P_t) + V^e_{\min} * P_t \quad (11)$$

$$q^{\mathrm{t}}_{\max} = q^b_{\max} * (1 - P_{\mathrm{t}}) + q^e_{\max} * P_t \quad (12)$$

$$q^t_{\min} = q^b_{\min} * (1 - P_t) + q^e_{\min} * P_t \quad (13)$$

$$P_v = (V^t - V^t_{\min})/(V^t_{\max} - V^t_{\min}) \quad (14)$$

$$q^t = q^t_{\min} * (1 - P_v) + q^t_{\max} * P_v \quad (15)$$

where t, t_1, and t_2 are the current time, initial time, and end time in the period, respectively; P_t denotes the ratio of current time length to period length; $V^t_{\max}$, $V^t_{\min}$, $V^b_{\max}$, $V^b_{\min}$, $V^e_{\max}$, and $V^e_{\min}$ represent the maximum and minimum storages at the current time, beginning, and ending of the period, respectively; $q^t_{\max}$, $q^t_{\min}$, $q^b_{\max}$, $q^b_{\min}$, $q^e_{\max}$, and $q^e_{\min}$ denote the maximum and minimum releases, respectively; P_v is the ratio of current storage; and q_t is the current release.

2.2 Energy System Module

The energy system module focuses on the energy consumption during the water supply process for socioeconomic water users to further investigate the energy co-benefits of water resources allocation schemes (Zhao et al., 2020; Smith et al., 2016). Energy consumption for water heating and water end-use was not included in this study. Energy consumption is determined by the energy use quota and amount of water supply for the water use sectors (Smith et al., 2016). As energy use efficiency will be gradually improved with technological development, the energy use quota is assumed to decrease with decreasing rate. The trajectory of the energy use is formulated in equation (16). The water supply for water use sectors derived from the water system module is used to estimate energy consumption using equation (17). The energy shortage rate will be further determined with planning energy availability using equation (18).

$$\begin{cases} \frac{dEQ_{i,j}^{t}}{dt} = EQ_{i,j}^{t} * r_{e,t} \\ r_{e,t} = r_{e,0} * (1 - \kappa_e \exp(-\varphi_e t)) \end{cases} \quad (16)$$

$$EC_t = \sum_{i,j} WTSup_{i,j}^{t} * EQ_{i,j}^{t} \quad (17)$$

$$ESR_t = \frac{ES_t}{EC_t} = \frac{EC_t - PEA_t}{EC_t} \quad (18)$$

where $EQ_{i,j}^{t}$ is the energy use quotas of the j-th water user in the i-th operational zone in the t-th year; $r_{e,0}$ and $r_{e,t}$ denote the growth rates of energy use quotas in baseline year and the t-th year, respectively; κ_e*exp($-\varphi_e t$) depicts the energy-saving effect of technological development; EC_t is the total energy consumption; $WTSup_{i,j}^{t}$ is the total water supply of the j-th water user in the i-th operational zone; ES_t and ESR_t

are the energy shortage and energy shortage rate, respectively; and PEA_t is the planning energy availability.

2.3 Food System Module

The food system module focuses on estimating the amount of food production. As water is a crucial determinant for crop yield, the agricultural water shortage rate can constrain the potential crop yield (French and Schultz, 1984; Lobell et al., 2009). Owing to the technological advancements in irrigation, the amount of potential crop yield is assumed to increase with decreasing rate, as indicated by equation (19). With the planning food production, the food shortage rate can then be estimated using equations (20) and (21).

$$\begin{cases} \dfrac{dCY_{i,j}^{t}}{dt} = CY_{i,j}^{t} * r_{pro,t} \\ r_{pro,t} = r_{pro,0} * (1 + \kappa_{pro} \exp(-\varphi_{pro} t)) \end{cases} \tag{19}$$

$$FP_t = \sum_{i,j} CY_{i,j}^{t} * CA_{i,j}^{t} * (1 - WSR_{i,4}^{t}) \tag{20}$$

$$FSR_t = \frac{FS_t}{PFP_t} = \frac{PFP_t - FP_t}{PFP_t} \tag{21}$$

where $CY_{i,j}^{t}$ is the potential crop yields of the j-th crop in the i-th operational zone in the t-th year; $r_{pro,0}$ and $r_{pro,t}$ are the growth rates of crop yields in baseline year and the t-th year, respectively; $\kappa_{pro}*\exp(-\varphi_{pro}t)$ depicts the impacts of technological development on the evolution of crop yield; FP_t denotes the total food production; $CA_{i,j}^{t}$ is the crop area; $WSR_{i,4}^{t}$ represents the water shortage rate of agriculture sector; FS_t and FSR_t are the food shortage and food shortage rate, respectively; and PFP_t is the planning food production.

2.4 Society System Module

The 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 variables in socio-hydrologic modeling that indicate the perceived level of threat to a community's quality of life (Roobavannan et al., 2018). Environmental awareness describes societal perceptions of 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 not only the environmental control, but also the environmental restoration (Chen et al., 2016; Elshafei et al., 2014; Roobavannan et al., 2018). As this study focuses on societal perceptions on environmental degradation, environmental awareness based on the concept described in Van Emmerik et al. (2014) was adopted as the social state variable. As water, energy, and food systems are considered part of the environment in this study, environmental awareness is assumed to be determined by the shortage rates of water, energy, and food. Environmental awareness accumulates when the shortage rates of water, energy, and food exceed the given critical values, but decreases otherwise. The dynamics of environmental awareness can be described by equations (22)–(25).

$$\frac{dE}{dt} = \frac{dWA}{dt} + \frac{dEA}{dt} + \frac{dFA}{dt} \tag{22}$$

$$\frac{dWA}{dt} = \begin{cases} \eta_W * (\exp(\theta_W * (WSR - WSR_{crit})) - 1) & WSR > WSR_{crit} \\ -\omega_W * WA & WSR \le WSR_{crit} \end{cases} \tag{23}$$

$$\frac{dEA}{dt} = \begin{cases} \eta_E * (\exp(\theta_E * (ESR - ESR_{crit})) - 1) & ESR \ge ESR_{crit} \\ -\omega_E * EA & ESR < ESR_{crit} \end{cases} \tag{24}$$

$$\frac{dFA}{dt} = \begin{cases} \eta_F * (\exp(\theta_F * (FSR - FSR_{crit})) - 1) & FDR \geq FDR_{crit} \\ - \omega_F * FA & FDR < FDR_{crit} \end{cases} \tag{25}$$

where E, WA, EA, and FA are environmental awareness, water shortage awareness, energy shortage awareness, and food shortage awareness, respectively; WSR, ESR, and FSR denote the shortage rates of water, energy, and food, respectively; WSR_{crit}, ESR_{crit}, and FSR_{crit} represent 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, and θ_F are the auxiliary factors for environmental awareness accumulation; and ω_W, ω_E, and ω_F denote the lapse factors that represent the decreasing rate of the shortage awareness of water, energy, and food, respectively.

2.5 Respond Links

Respond links are used to link society and water system modules through feedback. Respond links are driven by environmental awareness and food shortage awareness. The terms of feedback functions are based on the studies of Feng et al. (2019) and Van Emmerik et al. (2014), which have been established to have good performance and suitability, as they have been successfully applied to simulate the human response to environmental degradation in the Murrumbidgee river basin (Australia) and Hehuang region (China).

Environmental awareness increases with constant shortages in water, energy, and food. As environmental awareness accumulates above its critical value, negative feedback on socioeconomic factors is triggered (Figure 1). The growth of population, GDP, and crop area will be constrained to alleviate the stress on the integrated system. Notably, positive feedback on the expansion of crop area will be triggered to fill food shortage as food shortage awareness exceeds its critical value (Figure 1). Although food shortage awareness is part of environmental awareness, the negative feedback driven by environmental awareness on crop area can only be triggered with the prerequisite that food shortage awareness is below its threshold value, as food production should first be assured. The respond links deployed by assuming feedback functions are expressed in equations (26)–(28).

$$f_1(E) = \begin{cases} \delta_{rp}^{E} * (1 - \exp(\zeta_1 * (E - E_{crit})) & E > E_{crit} \\ 0 & else \end{cases} \tag{26}$$

$$f_2(E) = \begin{cases} \delta_{rg}^{E} * (1 - \exp(\zeta_2 * (E - E_{crit})) & E > E_{crit} \\ 0 & else \end{cases} \tag{27}$$

$$f_3(E, FA) = \begin{cases} \delta_{ra}^{F} * (\exp(\zeta_3^{F} * (FA - FA_{crit}) - 1) & FA > FA_{crit} \\ \delta_{ra}^{E} * (1 - \exp(\zeta_3^{E} * (E - E_{crit})) & FA < FA_{crit} \ \& \ E > E_{crit} \\ 0 & else \end{cases} \tag{28}$$

where E_{crit} and FA_{crit} are the critical values for environmental awareness and food shortage awareness, respectively; δ_{rp}^{E} , δ_{rg}^{E} , and δ_{ra}^{E} denote the factors describing feedback capability from environmental awareness; δ_{ra}^{F} is the factor describing feedback capability from food shortage awareness; ζ_1 , ζ_2 , and ζ_3^{E} represent the auxiliary factors for feedback functions driven by environmental awareness; and ζ_3^{F} is the auxiliary factor for feedback functions driven by food shortage awareness.

3 Case Study

3.1 Study Area

The Hanjiang river is the longest tributary of the Yangtze river. The total area of the Hanjiang river basin is 159,000 km^2, divided into upper and mid-lower reaches covering 95,200 and 63,800 km^2, respectively (shown in Figure 3). The Danjiangkou reservoir is located at the upper boundary of the mid-lower reaches of the Hanjiang river basin (MLHRB) and serves as the water source for the middle route of the South–North water transfer project in China. Thus, the water availability in the MLHRB is remarkably affected by the reservoir operation. In terms of energy, as the population is large and the industry is developed in the MLHRB, the energy consumption for urban water supply is high. For agriculture, as the land is flat and fertile, MLHRB is considered an important grain-producing area, occupying one of the nine major commodity grain bases in China (i.e., Jianghan plain) (Xu et al., 2019).

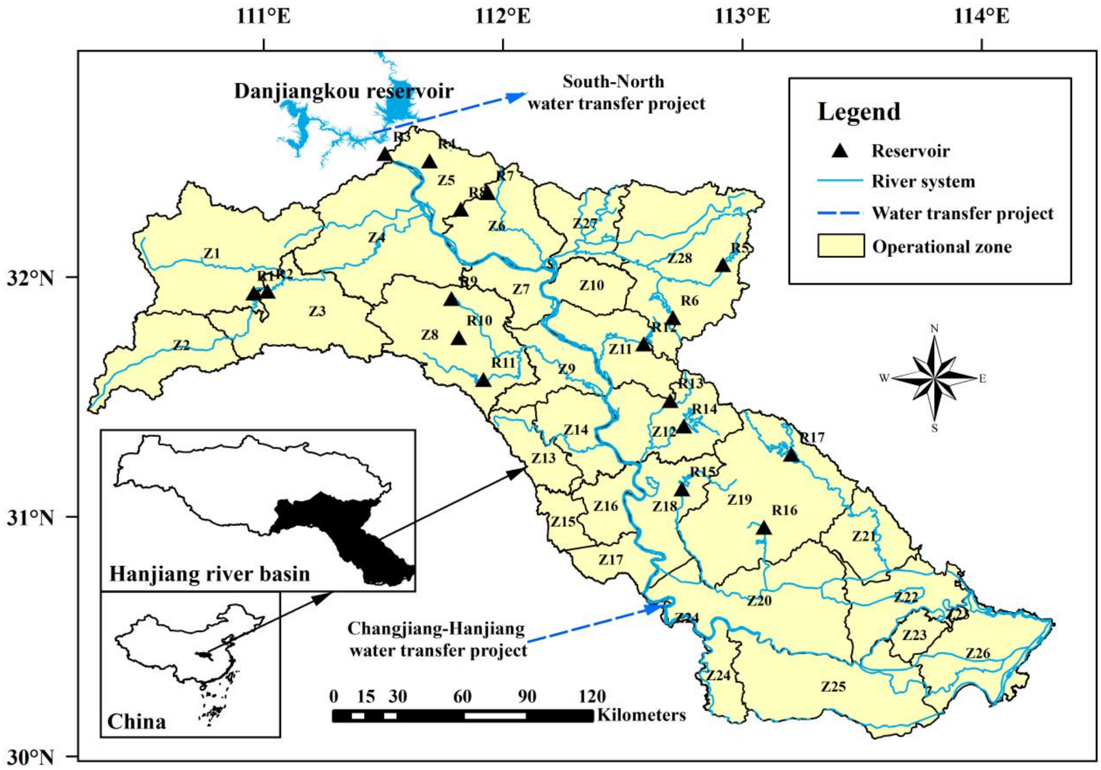


Figure 3. Location of mid-lower reaches of Hanjiang river basin.

However, owing to population expansion, rapid urbanization, and economic development, the local demand for water, energy, and food is increasing enormously (Zeng et al., 2021; Zhang et al., 2018). The contradictions between increasing demand and limited resources will be intensified. Therefore, improving use efficiencies for water, energy and food in MLHRB is urgent (Zhang et al., 2018; Liu et al., 2019). The strictest water resources control system for water resources management policy, the total quantity control of water consumed policy, and the energy-saving and emission-reduction policy in China are implemented in the MLHRB to promote the expansion of resource-saving technology and further improve the resource use efficiencies in water, energy, and food systems. Therefore, the impacts of human activities on the WEF nexus should be assessed to sustain the collaborative development of the integrated system.

The socioeconomic data (i.e., population, GDP, and crop area) for water demand projection were collected based on administrative units, whereas the hydrological data were typically collected based on river basins. To ensure that the socioeconomic and hydrological data are consistent in operational zones, the study area was divided into 28 operational zones based on the superimposition of administrative units and sub-basins. Seventeen existing medium or large size reservoirs (the total storage volume is 37.3 billion m^3) were considered to regulate water flows. Based on the water connections between operational zones and river systems, the study area is shown in Figure 4, including 2 water transfer projects (the South–North and Changjiang–Hanjiang water transfer projects), 17 reservoirs, and 28 operational zones.

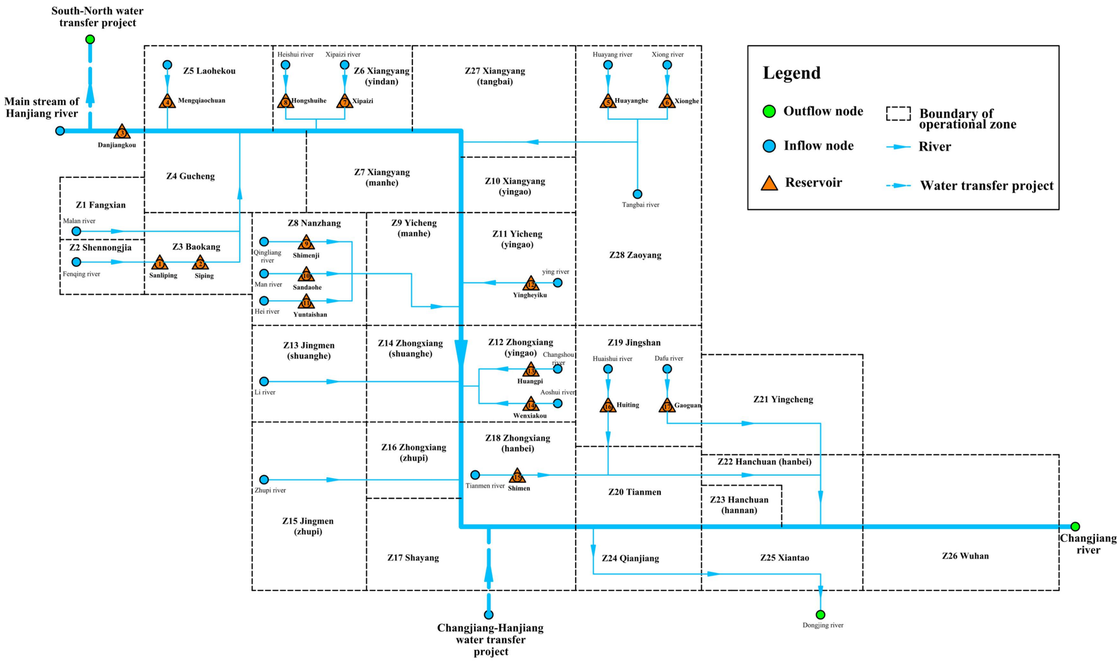


Figure 4. Sketch of the water system for the mid-lower reaches of Hanjiang river basin.

3.2 Data Sources

There are two main types of data: hydrological and socioeconomic data. The monthly historical discharge series of each operational zone and inflow of reservoirs from 1956 to 2016 were provided by the Changjiang Water Resources Commission (CWRC, 2016). The characteristics and operational rules of the 17 reservoirs listed in Table 1 were retrieved from the Hubei Provincial Department of Water Resources (HPDWR, 2014). 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 from the Statistical Database of China's Economic and Social Development (http://data. cnki.net/). Notably, the agricultural water use quota was related to the annual effective precipitation frequency. Four typical exceedance frequencies, defined as P = 50%, 75%, 90%, and 95%, were adopted to determine agricultural water demand. These historical data were further used to predict the 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 was applied to the MLHRB. The established WEFS nexus ran on a yearly loop. Specifically, as the water resources allocation model in the water system module took a monthly time step in the study (and the sub-time step was the default value: 1 day), the annual water supply and water shortage were first determined before being output to the energy system and food system modules, respectively. The annual shortage rates of water, energy, and food were then used to determine environmental awareness and further the feedback. Table 2 lists the initial settings of the external variables for the integrated system. The co-evolutionary behaviors of the WEFS nexus were analyzed as follows: (1) the system dynamic model was calibrated using observed data, (2) co-evolution of the WEFS nexus was then interpreted and analyzed, (3) parameter sensitivity was tested to identify the most important parameters for the model, and (4) the impacts of environmental awareness feedback and water resources allocation on the WEFS nexus were discussed.

Table 2 Model initial condition setup.[a]

Notation	Description	Unit	Value
N_0	Population	million capita	14.92
G_0	GDP	billion Yuan	419
CA_0	Crop area	km^2	7,733
N_{cap}	Environmental capacity of population	million capita	20.00
G_{cap}	Environmental capacity of GDP	billion Yuan	3,000
CA_{cap}	Environmental capacity of crop area	km^2	10,000
$WQ^0_{\bullet,1}$	Municipal water use quota	m^3/(year*capita)	56
$WQ^0_{\bullet,2}$	Rural water use quota	m^3/(year*capita)	25
$WQ^0_{\bullet,3}$	Industrial water use quota	m^3/(10^4 Yuan)	109
$WQ^0_{\bullet,4}$ (P = 50%, 70%, 90%, and 95%)	Agricultural water use quota	million m^3/km^2	0.77, 0.80, 0.90, 0.97
$EQ^0_{\bullet,j}$ (j = 1, 2, 3, and 4)	Energy use quotas for municipal, rural, industry and agriculture water uses	kw*h/m^3	0.29, 0.29, 0.29, 0
$\sum_j CY^0_{\bullet,j}$ $(j = 1, 2)$	Crop yield	t/km^2	654

$r_{P,0}$	Initial growth rate of population	[-]	0.003
$r_{G,0}$	Initial growth rate of GDP	[-]	0.040
$r_{CA,0}$	Initial growth rate of crop area	[-]	0.003
$r_{qwu,0}$	Initial growth rate of water use quota	[-]	-0.020
$r_{e,0}$	Initial growth rate of energy use quota	[-]	-0.004
$r_{pro,0}$	Initial growth rate of crop yield	[-]	0.018
PEA	Planning energy availability	[million kw*h]	1,620
PFP	Planning food production	[million t]	6,000

[a] As the primary source of water supply for agricultural use in the study area is surface water, rather than groundwater, the energy consumption in the water supply process for agricultural water use is negligible, and the energy use quota for agricultural water use is set as 0.

4.1 Model Calibration

An initial parameter sensitivity analysis was adopted to screen out the insensitive parameter, which provided distinguishing 13 insensitive and 21 sensitive parameters. The setting of the insensitive parameter was based on expert knowledge and the study of Feng et al. (2019), which has been established to have good performance and suitability. The sensitive parameters in the model were then calibrated based on expert knowledge and the observed data, and the calibrated values are presented in Table 3 (insensitive parameters are set to 0.0856). The Nash–Sutcliffe Efficiency (NSE) coefficient and percentage bias (PBIAS) (Krause et al., 2005; Nash and Sutcliffe, 1970) were used to calibrate the model. When the NSE was >0.7 and absolute value of PBIAS was <15%, the modeling performance was considered reliable. The simulated state variables, including annual water demand, energy consumption, food production, population, GDP, and crop area, were compared with their observed values during 2010–2019. As shown in Table 4, the NSEs (i.e., 0.91, 0.74, 0.79, 0.97, 0.86, and 0.94, respectively) range from 0.74 to 0.97, and the corresponding PBIASs (i.e., -0.7%, 1.9%, -0.6%, -4.2%, -0.2%, and -0.8%, respectively) are within -15% to 15%, suggesting that the established model is reliable for simulating the co-evolution of the WEFS nexus.

Table 3 Calibrated parameters for the WEFS model.

Notation	Description	Unit	Value
κ_P, φ_P	Auxiliary parameters for population evolution	[-]	1.0, 0.0856
κ_G, φ_G	Auxiliary parameters for GDP evolution	[-]	3.3, 0.0856
κ_{CA}, φ_{CA}	Auxiliary parameters for crop area evolution	[-]	6.0, 0.0856
κ_{qwu}, φ_{qwu}	Auxiliary parameters for water use quota simulation	[-]	3.8, 0.0856
κ_e, φ_e	Auxiliary parameters for energy use quota evolution	[-]	15.0, 0.0856
κ_{pro}, φ_{pro}	Auxiliary parameters for crop yield evolution	[-]	24.5, 0.0856
η_W	Perception factors describing the community's ability to identify the threats of degradation in water system	[-]	450
η_E	Perception factors describing the community's ability to identify the threats of degradation in energy system	[-]	50
η_F	Perception factors describing the community's ability to identify the threats of degradation in food system	[-]	120

θ_W	Accumulation factor for water shortage awareness	[-]	0.0856
θ_E	Accumulation factor for energy shortage awareness	[-]	0.0856
θ_F	Accumulation factor for food shortage awareness	[-]	0.0856
ω_W	Lapse factor for water shortage awareness	[-]	0.1
ω_E	Lapse factor for energy shortage awareness	[-]	0.1
ω_F	Lapse factor for food shortage awareness	[-]	0.1
$WSRcrit$	Critical water shortage rate	[-]	0.07
$ESRcrit$	Critical energy shortage rate	[-]	0.05
$FSRcrit$	Critical food shortage rate	[-]	0.05
FA_{crit}	Critical food shortage awareness	[-]	1.5
E_{crit}	Critical environmental awareness	[-]	8
ζ_1	Auxiliary factors for feedback on population	[-]	0.0856
ζ_2	Auxiliary factors for feedback on GDP	[-]	0.0856
ζ_3^E	Auxiliary factors for feedback on crop area by E	[-]	0.0856
ζ_3^F	Auxiliary factors for feedback on crop area by FA	[-]	0.0856
δ_{rp}^E	Factor describing feedback capability of environmental awareness to population	[-]	0.005
δ_{rg}^E	Factor describing feedback capability of environmental awareness to GDP	[-]	0.05
δ_{ra}^E	Factors describing feedback capability of environmental awareness to crop area	[-]	0.03
δ_{ra}^F	Factors describing feedback capability of food	[-]	0.1

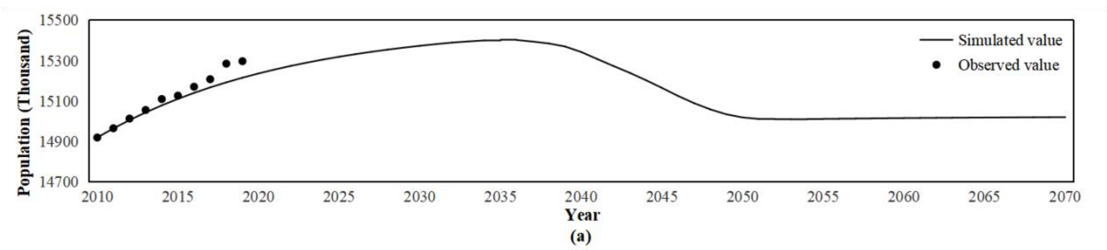
shortage awareness to crop area

Table 4 NSE and PBIAS of state variables.

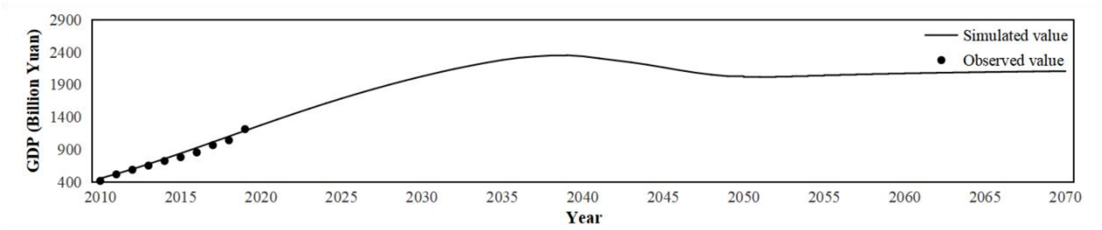
	Water demand	Energy consumption	Food production	Population	GDP	Crop area
NSE	0.91	0.74	0.79	0.97	0.86	0.94
PBIAS (%)	-0.7	1.9	-0.6	-4.2	0.2	-0.8

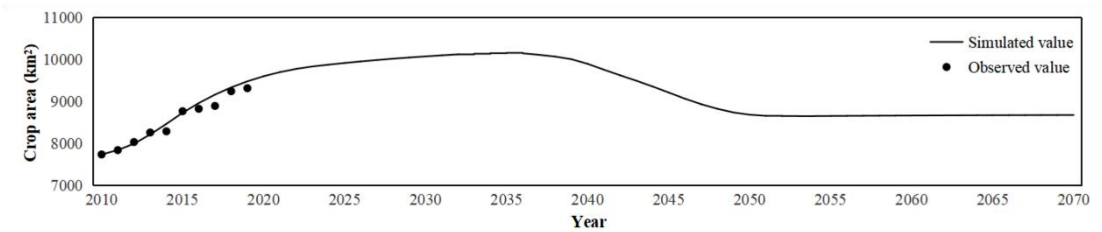
4.2 Co-evolution of WEFS Nexus

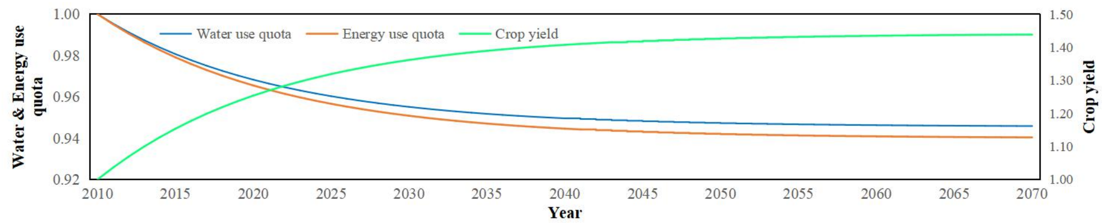
The calibrated system dynamic model was used to examine the properties of the integrated system by simulating the co-evolution of state variables in the WEFS nexus. Figure 5 shows the trajectories of population; GDP; crop area; water demand; energy consumption; food production; shortage rates for water, energy, and food; awareness for water shortage, energy shortage, and food shortage; and environmental awareness during 2010–2070. Based on 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 five phases based on the trajectory of food shortage awareness: accelerating expansion, natural expansion, contraction, recession, and recovery.

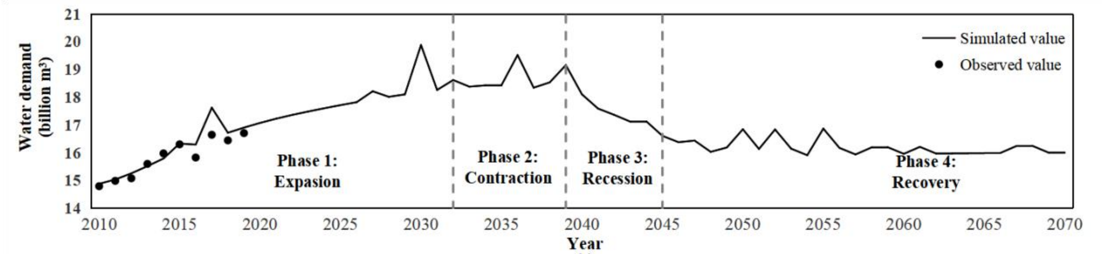


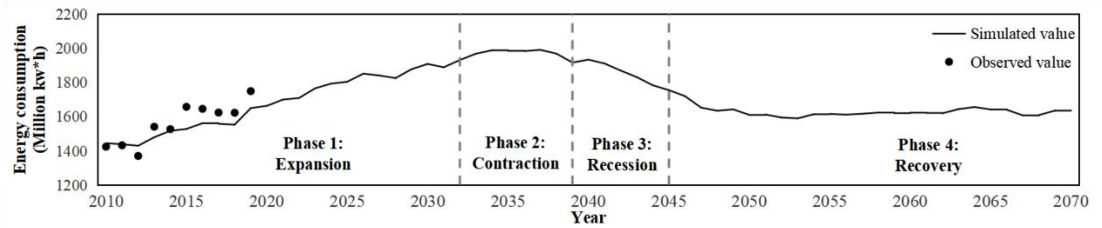
(a)

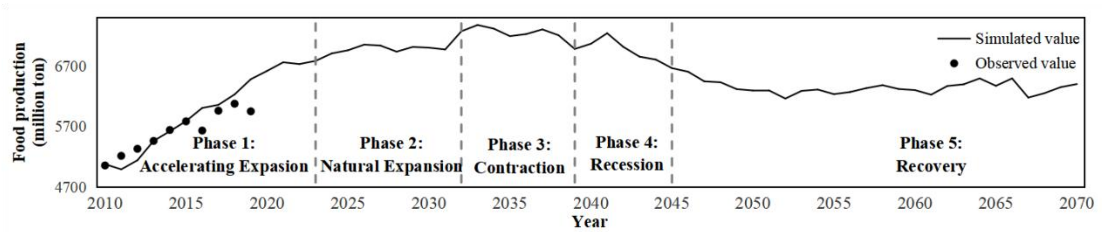

GDP (Billion Yuan)
Simulated value
Observed value
Year
(b)

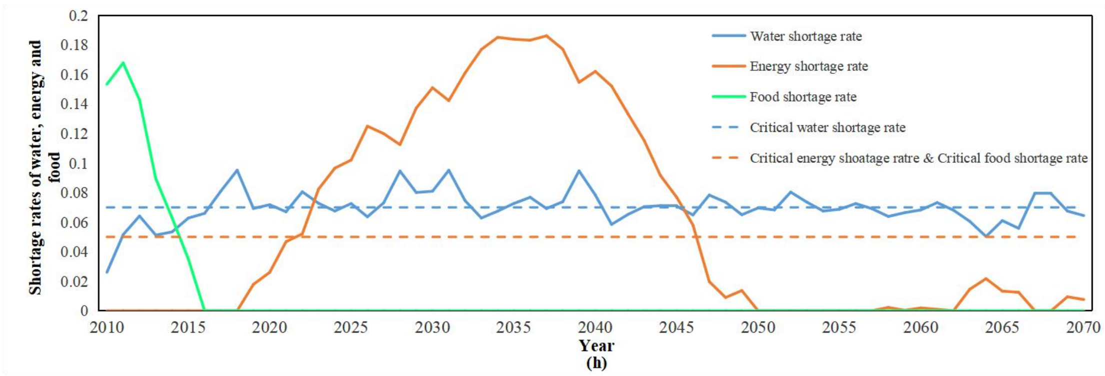

Crop area (km²)
Simulated value
Observed value
Year
(c)


Water & Energy use quota
Crop yield
Water use quota
Energy use quota
Crop yield
Year
(d)


Water demand (billion m³)
Simulated value
Observed value
Phase 1: Expasion
Phase 2: Contraction
Phase 3: Recession
Phase 4: Recovery
Year
(e)


Energy consumption (Million kw*h)
Simulated value
Observed value
Phase 1: Expansion
Phase 2: Contraction
Phase 3: Recession
Phase 4: Recovery
Year
(f)


Food production (million ton)
Simulated value
Observed value
Phase 1: Accelerating Expasion
Phase 2: Natural Expansion
Phase 3: Contraction
Phase 4: Recession
Phase 5: Recovery
Year
(g)



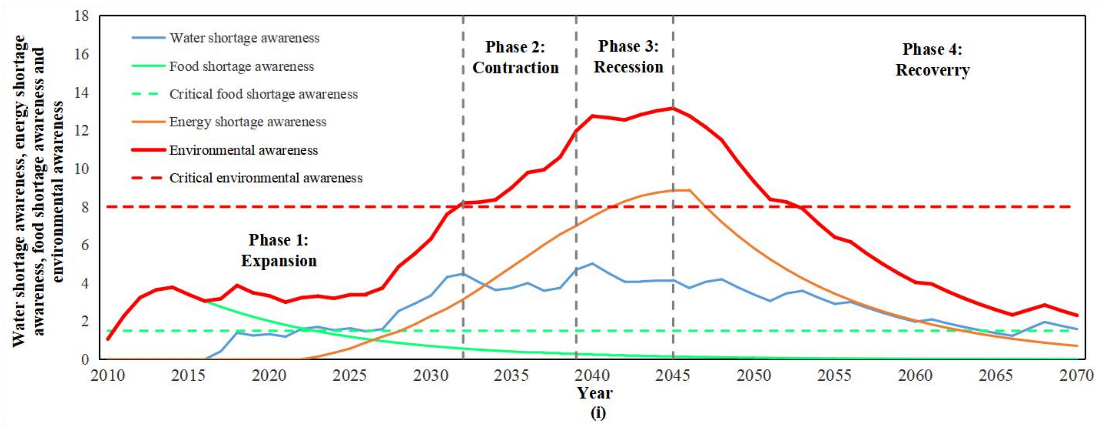


Figure 5. Trajectories of state variables in WEFS nexus: (a) population; (b) GDP; (c) crop area; (d) percentage variations (compared with initial values) of water use quota, energy use quota, and crop yield; (e) water demand; (f) energy consumption; (g) food production; (h) shortage rates of water, energy, and food; (i) water shortage awareness, energy shortage awareness, food shortage awareness, and environmental awareness.

The four phases in the co-evolution process for water demand and energy consumption can be interpreted as follows.

With environmental awareness below its critical value, the negative feedback on socioeconomic sectors is not triggered, and water demand, as well as energy consumption, increases rapidly, which is defined as the expansion phase (2010–2032). At the beginning of co-evolution, the water demand from the socioeconomic sectors can be satisfied owing to abundant water availability. The water shortage rate was typically <0.07 and below its critical value (Figure 5 (h)), and thus, water shortage awareness remained at a low level, which was less than 5.0, as shown in Figure 5 (i). As water use increased with increasing water demand (Figure 5 (e)), energy consumption increased but within its planning value. A small energy shortage was observed, and thus, no energy shortage awareness was accumulated, as shown in Figure 5 (h) and (i). Energy shortage awareness has accumulated gradually as the energy shortage rate slightly exceeded its critical value since 2022. Food production was less than its planning value at the beginning of co-evolution. The initial food shortage rate was 0.153 and more than its critical value of 0.05, accounting for the rapid increase in food shortage awareness in Figure 5 (i). With food shortage awareness increasing over its critical value of 1.5 (but less than critical environmental awareness 8.0), positive feedback was triggered to increase crop area, as observed in Figure 5 (c). Meanwhile, crop yield increased with the technological advancement under rapid economic expansion (Figure 4 (d)). Food production was thus increased, and planning food production can be ensured further. Food shortage awareness decreased below its critical value in 2023 and remained at a low level in Figure 5 (i). Therefore, as environmental awareness remained below its critical value, negative feedback to constrain the expansion of socioeconomic sectors was not triggered, and water demand, as well as energy consumption, increased remarkably in the expansion phase.

As environmental awareness exceeds its critical value, negative feedback on socioeconomic sectors is triggered, and the increase in water demand and energy consumption is constrained, which is defined as the contraction phase (2033–2039). With technological advancement, the quotas for water use and energy use have been decreasing, as shown in Figure 5 (d). However, there were minor increases in water demand and energy consumption owing to the continuous expansion of population, GDP, and crop area (Figure 5 (a), (b), and (c)), which can exceed the local water and energy carrying capacities. Thus, water shortage awareness and energy shortage awareness continued to increase, as their shortage rates remained over the corresponding critical values, as shown in Figure 5 (h) and (i). The environmental awareness thereby exceeded its critical value in 2033 and continued to increase. Negative feedback on socioeconomic sectors was triggered and strengthened. The water demand and energy consumption gradually increased with decreasing rate and reached their maximum values of 19.2 billion m^3 and 1,916 million kw*h, respectively, at the end of the contraction phase.

Environmental awareness accumulates to the maximum value and water demand, and energy consumption decrease significantly, which can be defined as the recession phase (2040–2045). With the negative feedback due to environmental awareness, the population, GDP, and crop area were constrained to decrease in Figure 5 (a), (b), and (c). The water demand and energy consumption thereby decreased, but still exceeded the local water and energy carrying capacities. Therefore, as the shortage rates of water and energy decreased but remained exceeding the corresponding critical values (Figure 5 (h)), environmental awareness continued accumulating at a decreasing rate and reached the maximum value of 13.2 at the end of the recession phase, thereby decreasing water demand and energy consumption.

As environmental awareness gradually decreases below its critical value, water demand and energy consumption decrease slightly and then tend to stabilize, which is defined as the recovery phase (2046–2070). With the continuous decline of socioeconomic sectors, water demand and energy consumption rapidly decreased within their carrying capacities. The shortage rates of water and energy have then decreased to below the corresponding critical values since 2047, resulting in the decreases in water shortage awareness and energy shortage awareness, as shown in Figure 5 (h) and (i). As the environmental awareness decreased below its critical value, negative feedback was removed, and the integrated system tended to stabilize.

For food production, the co-evolution process comprises accelerating expansion, natural expansion, contraction, recession, and recovery phases. With food shortage awareness exceeding its critical value, positive feedback on crop area is triggered to accelerate the increase in food production, which is defined as the accelerating expansion phase (2010–2022). A comprehensive analysis was demonstrated in the expansion phase during the co-evolution of the water demand and energy consumption. After the increase in food production in the accelerating expansion phase, both food shortage awareness and environmental awareness were lower than their critical values. Food production can cover its planning value and thereby increased slightly without any feedback during 2023–2032, which is defined as the natural expansion phase. As environmental awareness increased over its critical value owing to the rapid expansion of water demand and energy consumption, negative feedback to constrain the increase in crop area was triggered, which is defined as the contraction phase (2033–2039). Food production reached the maximum value of 7,052 million t in the contraction phase. Under the impacts of environmental awareness, food production then began decreasing in the recession phase (2040–2045) and stabilized in the recovery phase (2046–2070) as discussed in the co-evolution of water demand and energy consumption. Although the decreasing crop area to alleviate stress on water supply decreased food production, food production can still ensure its planning value sustaining the integrated system.

According to the analysis on the co-evolution process of the 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. This means that severe socioeconomic degeneration likely occurs after the rapid development of the expansion phase, which will hinder the sustainable development of the integrated system. Moreover, a time lag exists in the contraction phase when the community responds to the deterioration of the WEFS nexus system. As the water demand and energy consumption cannot immediately decrease within the local water and energy carrying capacities, environmental awareness will continue increasing in a short time. Negative feedback will keep on socioeconomic sectors with a durative time lag, which may lead to the violent degradation of the WEFS nexus. Therefore, more attention should be paid to the time lag of the community's response to the deterioration WEFS nexus to prevent the integrated system from collapsing, particularly after the rapid expansion of water demand and energy consumption.

4.3 Sensitivity Analysis for WEFS Nexus

Sensitivity analysis was conducted to assess the impacts of the parameters on the WEFS nexus co-evolution process. As the critical values and boundary conditions of the WEFS nexus are considered vital factors for policymakers and managers to control the integrated system to achieve the concordant development goals, seven parameters were selected for sensitivity analysis (Table 5). Each parameter was varied by the given increment, with the 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 analysis was then conducted by analyzing the trajectories of water demand, energy consumption, food production, and environmental awareness, as shown in Figures 6, 7, 8, and 9.

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	*PEA*	Planning energy availability	1,550	1,750	20
5	*PFP*	Planning food production	5,200	6,200	100
6	*FAcrit*	Critical food shortage awareness	1	3	0.2
7	*Ecrit*	Critical environmental awareness	5	10	0.5

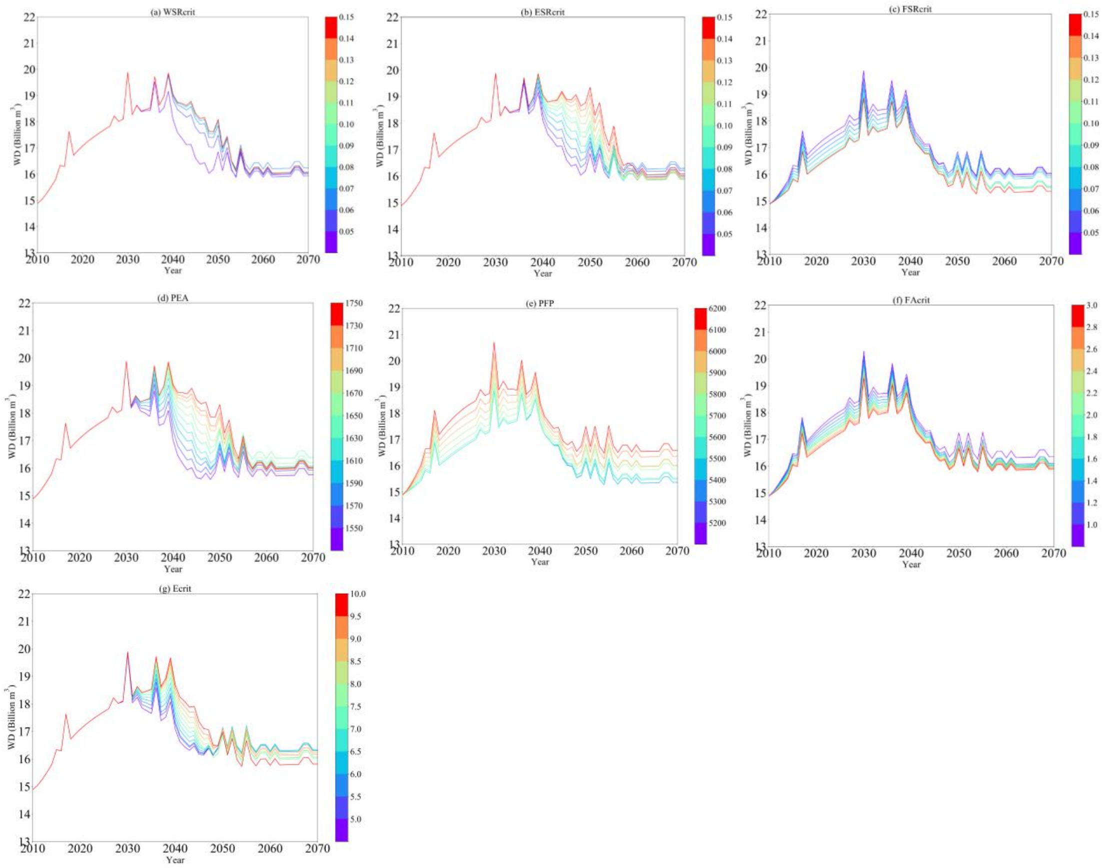


Figure 6. Trajectories of water demand with varied parameters.

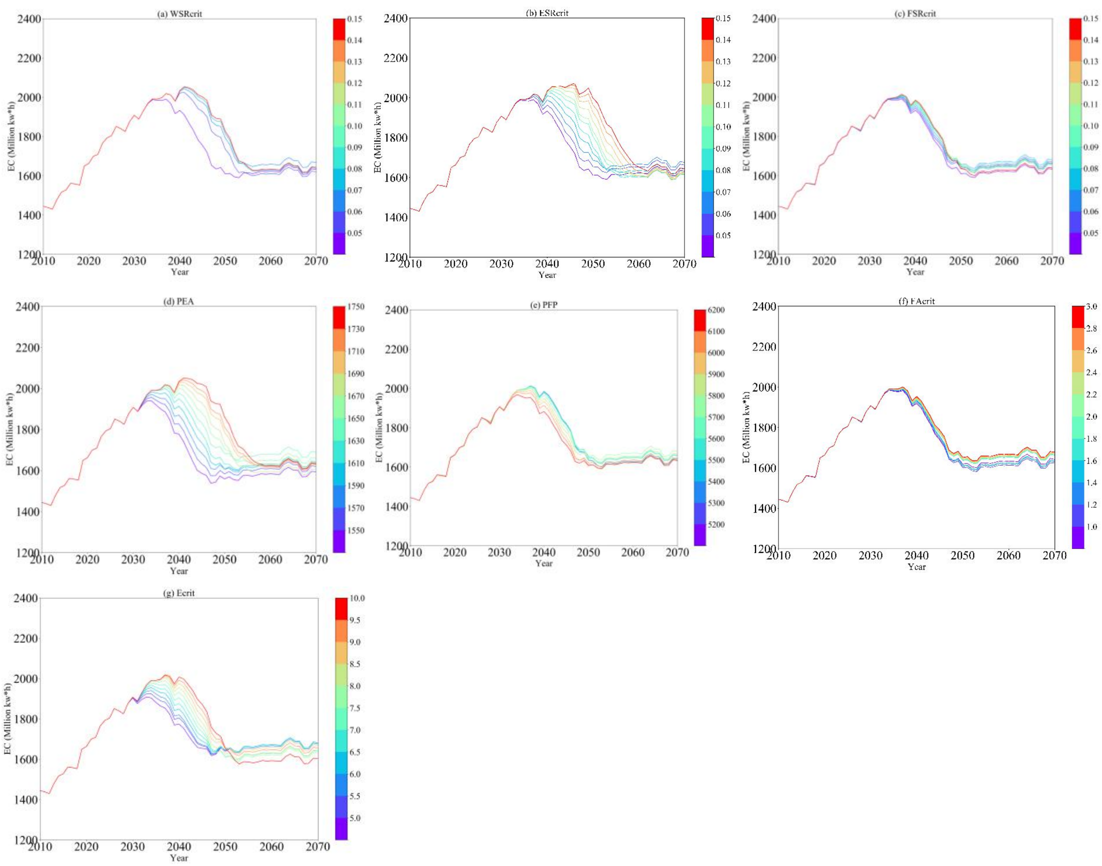


Figure 7. Trajectories of energy consumption with varied parameters.

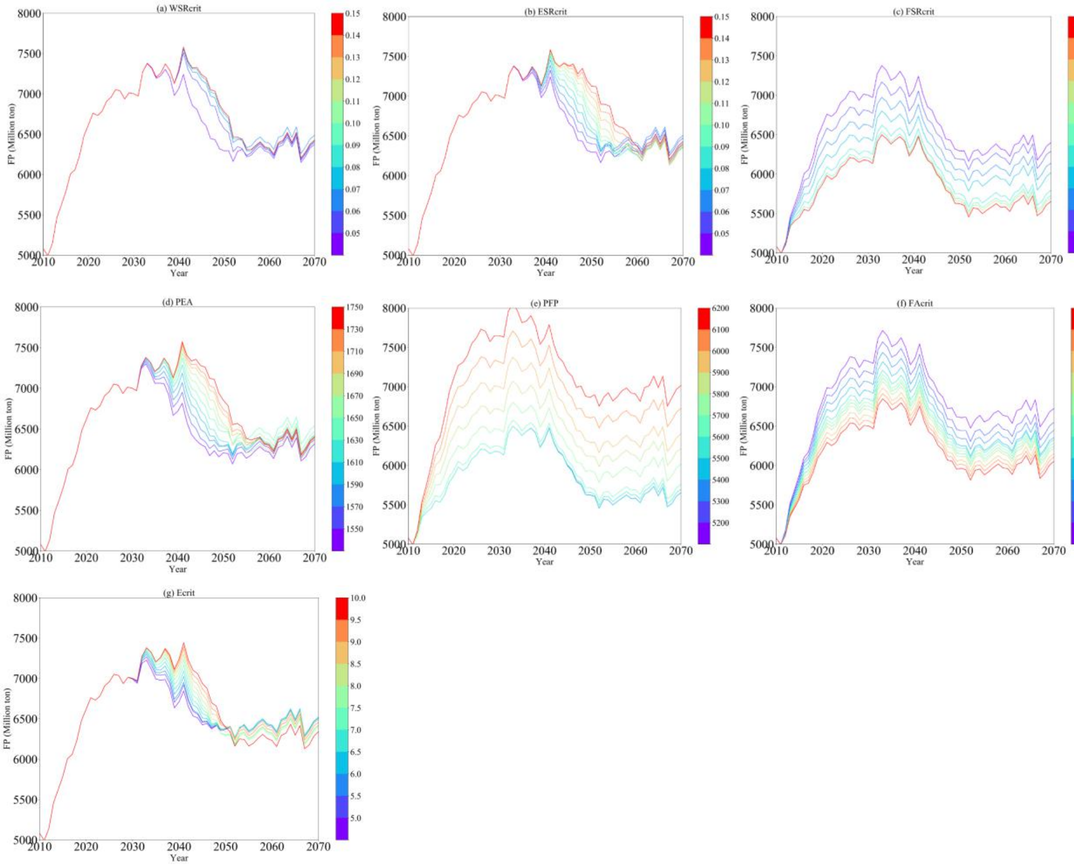
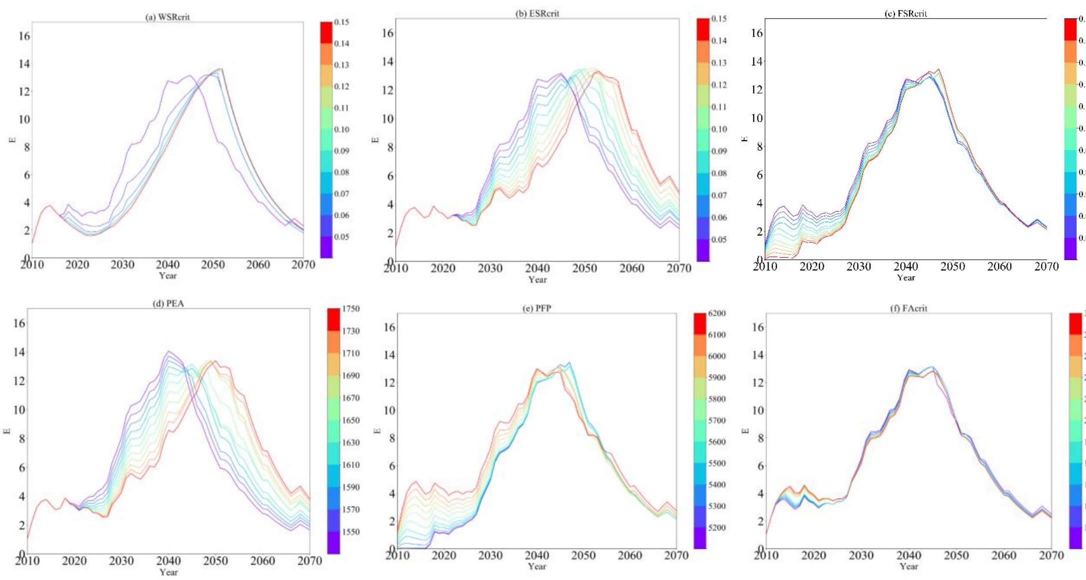


Figure 8. Trajectories of food production with varied parameters.



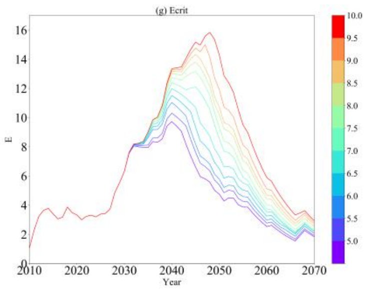


Figure 9. Trajectories of environmental awareness with varied parameters.

The variations in the seven parameters can remarkably change the trajectory of water demand, as shown in Figure 6, indicating that water demand is sensitive to the seven parameters. Specifically, the sensitive responses to parameters *WSRcrit*, *ESRcrit*, *PEA*, and *Ecrit* primarily occur in the contraction and recession phases of the co-evolution process for water demand. Limited water and energy shortages were observed in the expansion phase, as the demand can always be ensured by abundant resources availability. Environmental awareness was accumulated primarily from food shortage awareness but remained below its critical value (Figure 5 (i)). As the feedback due to environmental awareness was not sufficiently strong, the impacts on the co-evolution were negligible and were considered as the insensitivity of water demand in the expansion phase. However, with social development, water demand and energy consumption continued to grow and increase over the local carrying capability, leading to an increase in environmental awareness and negative feedback on socioeconomic expansion. *WSRcrit* and *ESRcrit* are the critical values that determine the awareness of water and energy shortages to accumulate, and *PEA* indicates the amount of planning energy availability, which directly determines the energy shortage. The environmental awareness accumulation can be advanced and strengthened by constraining *WSRcrit*, *ESRcrit*, and *PEA*, as shown in Figure 9 (a), (b), and (d). *Ecrit* is the threshold for the negative feedback triggering driven by environmental awareness. A lower *Ecrit* indicates that feedback is triggered more easily. Therefore, water demand exhibits sensitivity and decreases more remarkably with lower *WSRcrit*, *ESRcrit*, *PEA*, and *Ecrit* in the contraction and recession phases, as shown in Figure 6 (a), (b), (d), and (g). Parameters like *FSRcrit*, *PFP,* and *FAcrit* are always sensitive during the entire co-evolution process. As food shortages were remarkable in the accelerating expansion phase of food production, food shortage awareness increased rapidly, and feedback to increase crop area was triggered. *PFP* can directly determine food shortages, and *FSRcrit* and *FAcrit* determine thresholds for food shortage awareness accumulation and feedback triggering by food shortage awareness, respectively. Positive feedback on crop area to increase food production can thus be advanced and strengthened by constraining *FSRcrit*, *PFP*, and *FAcrit*. The crop area then continued increasing until negative feedback driven by environmental awareness was triggered, resulting in an increase in food production and agricultural water demand. Therefore, water demand exhibits sensitivity and increases more remarkably with lower *FSRcrit*, *FAcrit*, or higher *PFP* during the entire co-evolution process, as shown in Figure 6 (c), (e), and (f).

Similarly, sensitivity analysis for energy consumption, food production, and environmental awareness (Figures 7, 8, and 9) can be interpreted. Notably, energy consumption is not sensitive to parameters *FSRcrit*, *FAcrit*, and *PFP*, despite the increase in agricultural water demand by constraining *FSRcrit*, *FAcrit*, and *PFP*. As the primary source of water supply for agricultural use in the study area is surface water, rather than groundwater, the energy consumption in the water supply process for agricultural water use is negligible.

Therefore, parameters like *WSRcrit*, *ESRcrit*, *PEA*, and *Ecrit* can regulate the negative feedback on socioeconomic sectors driven by environmental awareness, impacting the contraction and recession phases in the co-evolution of water demand and energy consumption. Parameters such as *FSRcrit*, *FAcrit*, and *PFP* can regulate the positive feedback on crop area driven by food shortage awareness, which impacts the entire co-evolution of water demand and food production. Notably, although constraining *WSRcrit*, *ESRcrit*, *PEA*, and *Ecrit* can maintain the integrated system from constant water shortage and energy shortage, the over-constrained condition can also lead to violent degradation of socioeconomic sectors (indicated by a drastic decrease in water demand in Figure 6 (a), (b), (d), and (g)), which will challenge the stability of society. Similarly, despite food production can be effectively increased by constraining *FSRcrit*, *FAcrit*, and *PFP*, the over-constrained condition will cause a remarkable increase in water demand, as shown in Figure 6 (c), (e), and (f), which will further put stress on the water supply. Moreover, the regulating capacity of the local system should be simultaneously considered during parameter selection. For example, there was an abrupt decrease when *WSRcrit* was set to 0.05, as shown in Figure 6 (a), Figure 7 (a), and Figure 8 (a). Violent socioeconomic degradation is triggered to decrease environmental awareness, indicating that the *WSRcrit* is over-constrained and has exceeded the regulating capacity of the local water system. Therefore, a rational parameter setting should be based on the sustainability of long-term co-evolution for socioeconomic sectors and the regulating capacity of the local system, which is of great significance for sustaining the stability of the WEFS nexus.

4.4 Impacts of Environmental Awareness Feedback and Water Resources Allocation on WEFS Nexus

To determine the potential impacts of environmental awareness feedback and water resources allocation on the WEFS nexus, four scenarios were set, the description of which is provided in Table 6. The *Ecrit* and *FAcrit* under scenario II were set as 10,000 to ensure that the feedback cannot be triggered in the study, and the *WSRcrit* in scenarios III and IV were set as 0.15 to avoid the explosion of water shortage awareness. The other parameters in scenarios II, III, and IV were consistent with the calibrated values of scenario I, as listed in Table 3. Scenarios I and II and scenarios III and IV were used to investigate the impacts of environmental awareness feedback and water resources allocation on the WEFS nexus, respectively. The average annual values of water demand, energy consumption, food production, and shortage rates for water, energy, and food are listed in Table 7. 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 of water shortage, energy shortage, and food shortage; and environmental awareness.

Table 6 Scenario description for assessing the impacts of environmental awareness feedback

682 **and water resources allocation on WEFS nexus.**

Scenario	Environmental awareness feedback	Water resources allocation	Parameter setting
I	Yes	Yes	Calibrated values
II	No	Yes	*Ecrit*, *FAcrit*: 10,000; others: calibrated values
III	Yes	Yes	*WSRcrit*: 0.15; others: calibrated values
IV	Yes	No	*WSRcrit*: 0.15; others: calibrated values

683 **Table 7 Average annual values for the state variables in WEFS nexus.**

Scenario	Water demand (billion m^3)	Energy consumption (million kw*h)	Food production (million t)	Water shortage rate	Energy shortage rate	Food shortage rate
I	16.94	1,710	6,519	7.03%	5.80%	1.07%
II	17.66	1,930	6,248	7.44%	17.16%	1.74%
III	17.29	1,761	6,638	7.20%	8.25%	1.08%
IV	14.36	884	6,344	15.89%	0.00%	3.08%

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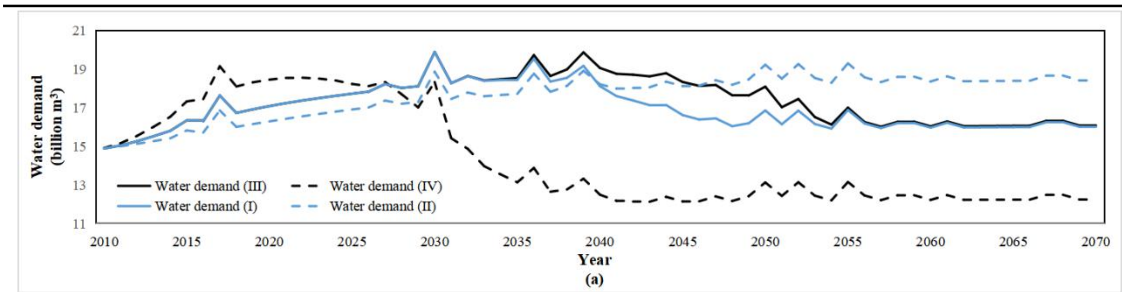
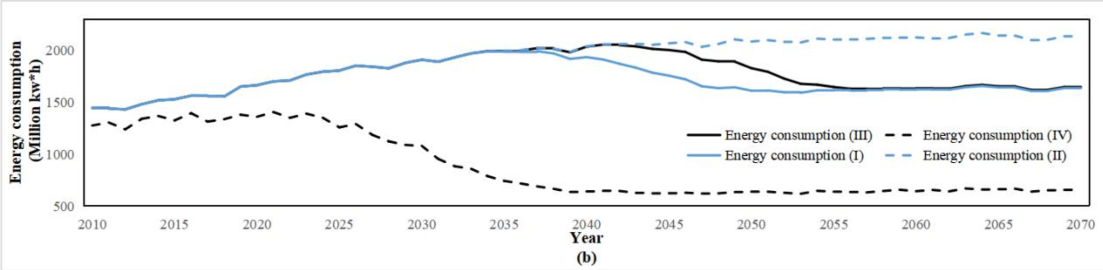
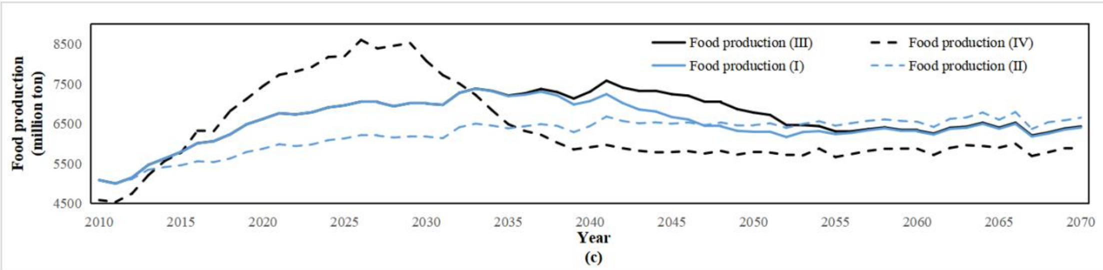
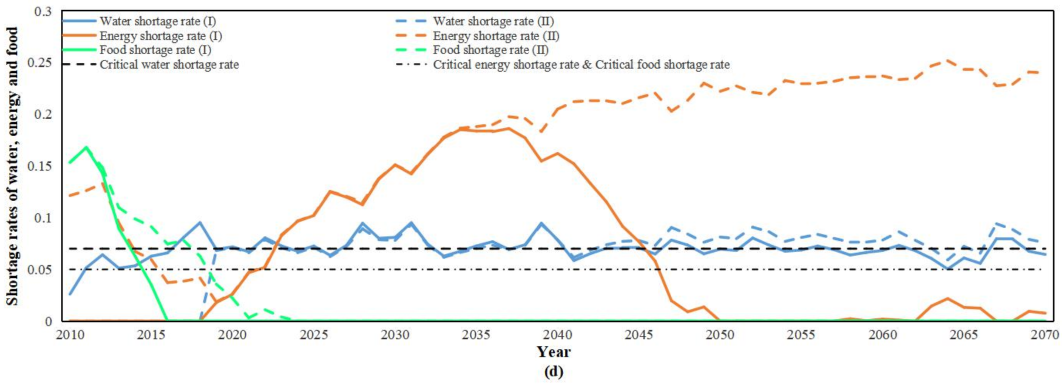
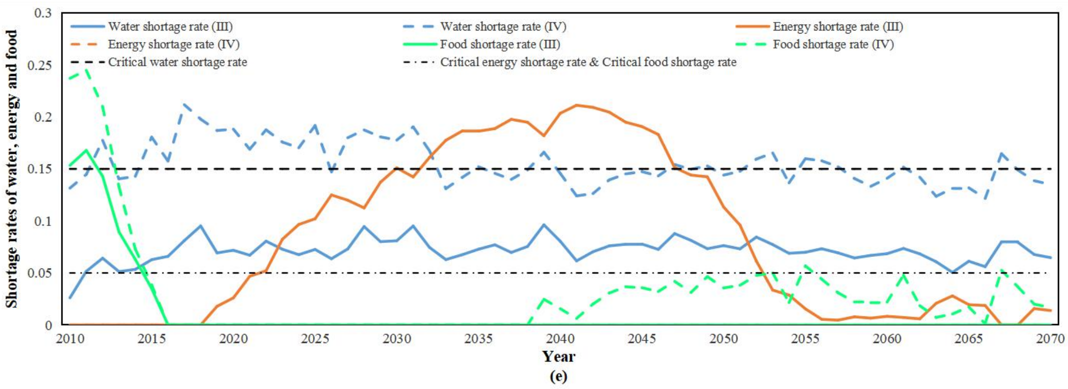
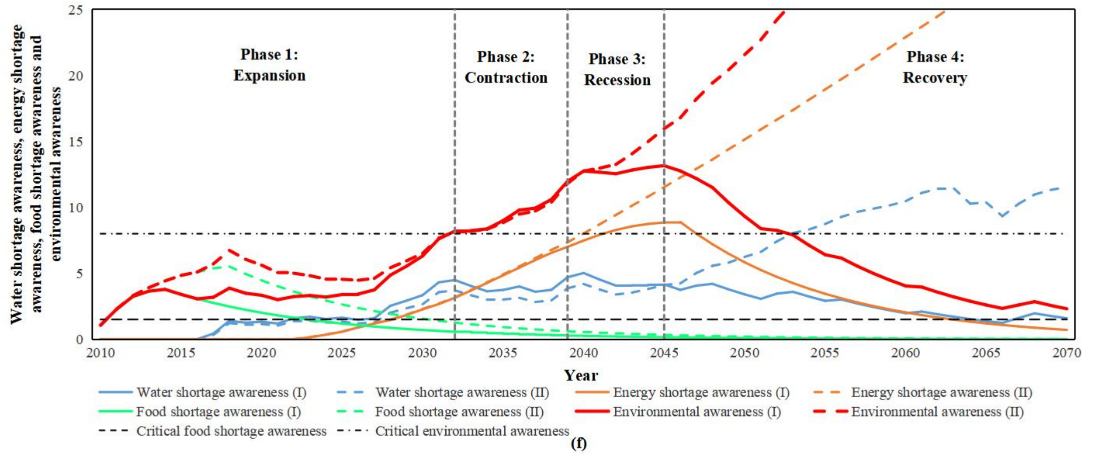



Energy consumption (Million kw*h)
500
1000
1500
2000
2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070
Energy consumption (III)
Energy consumption (IV)
Energy consumption (I)
Energy consumption (II)
Year
(b)


Food production (million ton)
4500
5500
6500
7500
8500
2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070
Food production (III)
Food production (IV)
Food production (I)
Food production (II)
Year
(c)


Shortage rates of water, energy and food
0
0.05
0.1
0.15
0.2
0.25
0.3
Water shortage rate (I)
Water shortage rate (II)
Energy shortage rate (I)
Energy shortage rate (II)
Food shortage rate (I)
Food shortage rate (II)
Critical water shortage rate
Critical energy shortage rate & Critical food shortage rate
2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070
Year
(d)


Shortage rates of water, energy and food
0
0.05
0.1
0.15
0.2
0.25
0.3
Water shortage rate (III)
Water shortage rate (IV)
Energy shortage rate (III)
Energy shortage rate (IV)
Food shortage rate (III)
Food shortage rate (IV)
Critical water shortage rate
Critical energy shortage rate & Critical food shortage rate
2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070
Year
(e)



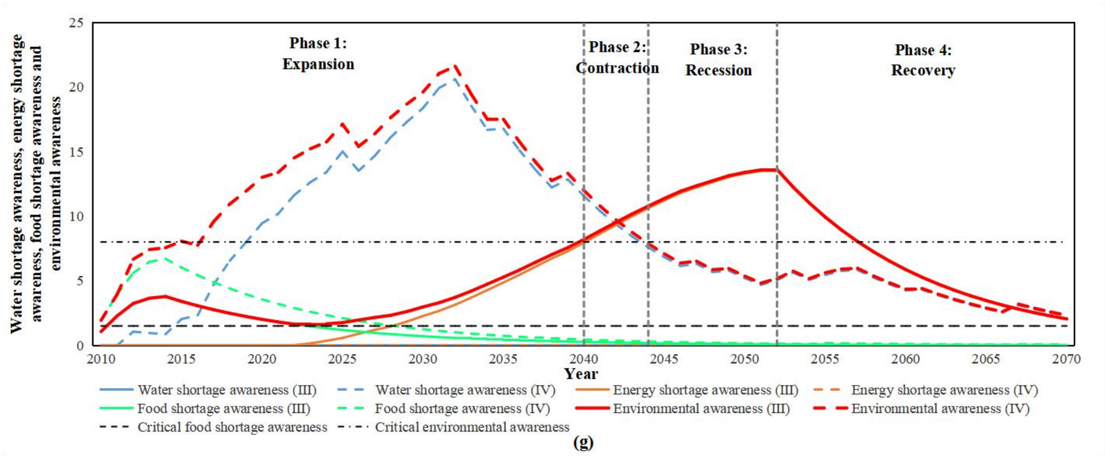


Figure 10. Trajectories of state variables in WEFS nexus under scenario I, II, III, and IV: (a) water demand; (b) energy consumption; (c) food production; (d) and (e) shortage rates of water, energy, and food; (f) and (g) water shortage awareness, energy shortage awareness, food shortage awareness, and environmental awareness.

4.4.1 WEFS Nexus Response to Environmental Awareness Feedback

Environmental awareness indicates societal perceptions of resources shortages and is the driving factor of feedback on socioeconomic sectors. Both the average annual water demand and energy consumption increased from 16.94 billion m^3 and 1,710 million t under scenario I to 17.66 billion m^3 and 1,930 million t under scenario II, respectively, as environmental awareness feedback was removed, whereas the food production decreased slightly, from 6,519 million t to 6,248 million t. Specifically, owing to high food shortage in the accelerating expansion phase of food production, the positive feedback on crop area was triggered by food shortage awareness to accelerate the increase in crop area. Food production was thus evidently larger when feedback was considered in Figure 10 (c). Food shortage was then alleviated, and the average shortage rate decreased from 1.74% to 1.07%. The increasing crop area meanwhile led to an increase in agricultural water demand, as shown in Figure 10 (a). However, as the increasing water demand remained within the carrying capacity, little difference in the water shortage rate existed between scenarios I and II (i.e., 7.03% and 7.44%, respectively). As the water supply was efficiently ensured, the impacts on urban water supply and the corresponding energy consumption were negligible. As water demand and energy consumption increased rapidly in the expansion phase, environmental awareness increased remarkably owing to the constant water and energy shortages, as shown in Figure 10 (d) and (f). Negative feedback was triggered to constrain the socioeconomic expansion. Compared with scenario II, water demand and energy consumption decreased remarkably under scenario I. The stress on water and energy supplies was thus relieved, particularly for the energy system, the shortage rate of which decreased from 17.16% to 5.80%. Therefore, environmental awareness can efficiently capture resources shortages and regulate the pace of socioeconomic expansion through feedback, which can maintain the integrated system from constant resources shortages to sustain the concordant development of the WEFS nexus.

4.4.2 WEFS Nexus Response to Water Resources Allocation

Water is considered the major driving factor for the WEFS nexus. Rational water resources management plays an important role in the sustainable development of the WEFS nexus. Water resources allocation can regulate the water flow by reservoir operation, which is considered one of the most effective tools for water resources management. Based on the Integrated Water Resources Planning of Hanjiang River Basin (CWRC, 2016), domesticity and ecology water uses should be ensured first. The priorities for water use from high to low are municipal and rural domesticity, in-stream ecology, and industrial and agricultural sectors, respectively. The average annual water demand, supply, and shortage under scenarios III and IV are listed in Table 8.

Table 8 Water resources allocation results under scenarios III and IV (million m^3).

Scenario	Variables	Municipal	Rural	Industry	Agriculture	In-stream ecology	Total
III	Demand	388	181	6,504	6,433	3,779	17,286
	Supply	387	181	5,785	6,034	3,654	16,042
	Shortage	1	0	719	399	124	1,244
	Shortage rate	0.24%	0.23%	11.05%	6.21%	3.29%	7.20%
IV	Demand	361	170	3,330	6,720	3,779	14,359
	Supply	330	155	2,622	5,658	3,312	12,077
	Shortage	31	15	708	1,062	466	2,282
	Shortage rate	8.67%	8.69%	21.26%	15.80%	12.34%	15.89%

Despite the increase in water demand from 14,359 to 17,286 million m^3 under scenario III, the water supply also increased from 12,077 to 16,042 million m^3. The total water shortage rate decreased from 15.89% to 7.20% owing to the proper water resources allocation. As more available water resources can be stored in the flood season and then released in the dry season through reservoir operation, the uneven temporal and spatial distributions of available water resources were remarkably relieved, thereby increasing the water supply insurance. For water use sectors, water shortages were primarily found in industrial and agricultural sectors (719 and 399 million m^3, respectively), and other sectors can be satisfied under scenario III. Water shortage became more serious under scenario IV, as the water shortage rates of these five sectors increased significantly in Table 8, from 0.24%, 0.23%, 11.05%, 6.21%, and 3.29% to 8.67%, 8.69%, 21.26%, 15.80%, and 12.34%, respectively. To analyze the spatial distribution of water shortage rates, Figure 11 shows the water shortage rate in each operational zone under scenarios III and IV. The water shortage rates of the study area under scenario IV were evidently higher than those under scenario III, particularly for the operational zones located at the basin boundaries (e.g., operational zones Z1, Z2, Z8, Z12, Z13, Z21 and so on). As the boundary zones are far away from the mainstream of the Hanjiang river and their local water availability is unevenly distributed, the regulating capacity of the water system is limited and is not sufficiently strong to ensure the water supply.

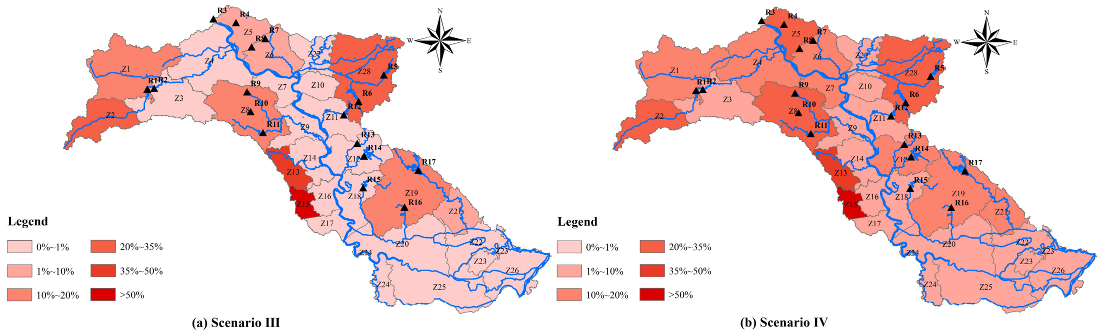


Figure 11. Distribution of water shortage rates.

For the co-evolution of WEFS nexus, a remarkable decrease in the average annual water demand and energy consumption was observed as water resources allocation was removed from 17.29 billion m^3 and 1,761 million t under scenario III to 14.36 billion m^3 and 884 million t under scenario IV, while the food production also decreased slightly from 6,638 million t to 6,344 million t. Under scenario IV without considering water resources allocation, the average water shortage rate was 15.89%, exceeding the critical value. Water shortage awareness continued to accumulate, as shown in Figure 10 (g). As the water supply could not be effectively ensured and remained at a low level, the energy consumption for urban water supply was small and always within its planning value. No energy shortage awareness was accumulated at the beginning of the co-evolution, as shown in Figure 10 (g). Meanwhile, as agricultural water demand cannot be ensured, food production was also lowered, as shown in Figure 10 (c). Higher food shortages then led to higher food shortage awareness, as shown in Figure 10 (e) and (g). Thus, positive feedback to increase crop area was strengthened. As observed in Figure 10 (a) and (c), the water demand increased slightly and food production increased rapidly. As environmental awareness accumulated over its critical value in 2015 and continued to increase, negative feedback to constrain the socioeconomic expansion was triggered and continued to strengthen. The energy consumption thereby continued to decrease in Figure 10 (b), accounting for the significant decrease in the energy shortage rate (i.e., from 8.25% to 0). Environmental awareness increased and reached the maximum value of 21.6 in 2032 owing to the constant water shortage. With the strong negative feedback, the water demand and food production decreased remarkably and remained at a low level, as shown in Figure 10 (a) and (c), which accounts for the increasing food shortage rate (i.e., from 1.08% to 3.08%).

With water resources allocation taken into account, water shortage was significantly alleviated under scenario IV, as discussed in the water resources allocation results (from 15.89% scenario IV to 7.20% under scenario III). The water shortage rate remained below its critical value in the entire co-evolution process (Figure 10 (e)). Thus, there was no accumulation of water shortage awareness (Figure 10 (g)). Energy consumption continued to increase as the water supply was ensured. Environmental awareness accumulation was primarily due to energy shortage.

Overall, water resources allocation can effectively alleviate water shortage to decrease water shortage awareness by increasing the water supply. The increase in environmental awareness is primarily due to the constant high-level energy shortage rate. Therefore, planning energy availability is the primary boundary condition for sustainable development of the WEFS nexus when water resources allocation is considered. Under the scenario without considering water resources allocation, the risk of water shortage is high. Water shortage awareness continues to accumulate and remains at a high level under scenario IV, which further contributes to high-level environmental awareness. The energy consumption and food production will be decreased by negative feedback. Water availability becomes the vital resource constraining the concordant development of the WEFS nexus.

5. Conclusions

The sustainable management of the WEF nexus remains an urgent challenge, as human sensitivity and reservoir operation are seldom considered in recent studies. This study used environmental awareness to capture human sensitivity and simultaneously incorporated reservoir operation in the form of water resources allocation model (i.e., IRAS model) into water system to develop a system dynamic model for the WEFS nexus. The proposed approach was applied to the MLHRB in China. The conclusions drawn from the study are as follows.

The proposed approach provides a valid analytical tool for exploring the long-term co-evolution of the nexus across the water, energy, food, and society systems. Environmental awareness in the society system can effectively capture human sensitivity to shortages from water, energy, and food systems. The feedback caused by environmental awareness can regulate the pace of socioeconomic expansion to maintain the integrated system from constant resources shortages, which contributes to the sustainability of the WEFS nexus co-evolution. The co-evolution of water demand, energy consumption, and food production can be divided into expansion (accelerating and natural expansion for food production), contraction, recession, and recovery phases based on environmental awareness. The co-evolution mode of the WEFS nexus functioning strongly depends on the selection of certain parameter values. The rational parameter setting of boundary conditions and critical values is important for managers to keep the socioeconomic sectors from violent expansion and deterioration, particularly in contraction and recession phases. Water shortage can be effectively relieved by the increased water supply through reservoir operation. Thus, the high-level environmental awareness caused by water shortage is remarkably alleviated. As negative feedback due to environmental awareness is weakened, the socioeconomic sectors develop rapidly. Water is no longer the vital factor constraining the concordant development of the WEFS nexus in the expansion phase. Therefore, water resources allocation is of great significance for the sustainable development of the WEFS nexus.

We acknowledge that the model calibration is challenging, as the data series is not sufficiently long and the forms and parameters of the feedback function are not prescribed. We consider that sufficient case studies will gradually emerge over time, which could gradually cover a range of scenarios and slowly provide reliability in the WEFS nexus modeling. Moreover, as the primary input of the proposed WEFS nexus model, water availability was adopted based on the historical scenario in this study. Future climate change has not been considered for the sake of simplicity. The considerable uncertainties in water availability can be brought into the water system in the WEFS nexus due to climate change (Chen et al., 2011). The propagation of the uncertainties can also be complicated, with interactions among water, energy, food, and society systems during the co-evolution process. Therefore, more attention should be paid to the uncertainty analysis on the WEFS nexus under climate change. However, the proposed framework and our research results not only provide 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.

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

Blanke, A., Rozelle, S., Lohmar, B., Wang, J., and Huang, J.: Water saving technology and saving water in China, Agric. Water Manag., 87, 139-150, 10.1016/j.agwat.2006.06.025, 2007.

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.

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.

Di Baldassarre, G., 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.

Di Baldassarre, G., Sivapalan, M., Rusca, M., Cudennec, C., Garcia, M., Kreibich, H., Konar, M., Mondino, E., Mard, J., Pande, S., Sanderson, M. R., Tian, F., Viglione, A., Wei, J., Wei, Y., Yu, D. J., Srinivasan, V., and Bloeschl, G.: Sociohydrology: Scientific Challenges in Addressing the Sustainable Development Goals, Water Resour. Res., 55, 6327-6355, 10.1029/2018wr023901, 2019.

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.

He, S. Y., Lee, J., Zhou, T., and Wu, D.: Shrinking cities and resource-based economy: The economic restructuring in China's mining cities, Cities, 60, 75-83, 10.1016/j.cities.2016.07.009, 2017.

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)

Hritonenko, N. and Yatsenko, Y.: Mathematical Modeling in Economics, Ecology and the Environment, Kluwer Academic Publishers, Dordrecht/Boston/London1999.

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.

Lin, J. Y., Wan, G., and Morgan, P. J.: Prospects for a re-acceleration of economic growth in the PRC, J. Comp. Econ., 44, 842-853, 10.1016/j.jce.2016.08.006, 2016.

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.

Matrosov, E. S., Harou, J. J., and Loucks, D. P.: A computationally efficient open-source water resource system simulator - Application to London and the Thames Basin, Environmental Modelling & Software, 26, 1599-1610, 10.1016/j.envsoft.2011.07.013, 2011.

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.

Smith, K., Liu, S., Liu, Y., Savic, D., Olsson, G., Chang, T., and Wu, X.: Impact of urban water supply on energy use in China: a provincial and national comparison, Mitigation and Adaptation Strategies for Global Change, 21, 1213-1233, 10.1007/s11027-015-9648-x, 2016.

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.

Zhang, P., Zhang, Y. Y., Ren, S. C., Chen, B., Luo, D., Shao, J. A., Zhang, S. H., and Li, J. S.: Trade reshapes the regional energy related mercury emissions: A case study on Hubei Province based on a multi-scale input-output analysis, Journal of Cleaner Production, 185, 75-85, 10.1016/j.jclepro.2018.03.013, 2018.

Zhao, S., Liu, Y., Liang, S., Wang, C., Smith, K., Jia, N., and Arora, M.: Effects of urban forms on energy consumption of water supply in China, Journal of Cleaner Production, 253, 10.1016/j.jclepro.2020.119960, 2020.

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.