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 human sensitivity and reservoir operation in the water system are typically neglected. This study proposes a new approach for modeling WEF nexus by incorporating human sensitivity and reservoir operation into the system. The co-evolution behaviors of the nexus across water, energy, food, and society (WEFS) were simulated using the system dynamic model. 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 society system. The human sensitivity indicated by environmental awareness can then 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. Results indicate environmental awareness shows potential to capture human sensitivity to shortages from water, energy, and food systems. Parameters related to boundary conditions and critical values can dominate environmental awareness feedback to regulate socioeconomic expansion to maintain the integrated system from constant resources shortages. The energy shortage rate thereby decreased from 17.16% under scenario II to 5.80% under scenario I, contributing to the sustainability of the WEFS nexus. Rational water resources allocation can ensure water supply through reservoir operation, decreasing the water shortage rate from 15.89% under scenario IV to 7.20% under scenario III. Threats from water shortage on the concordant development of the WEFS nexus are significantly alleviated, particularly for the area with limited regulating capacity of water project. 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 target 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.

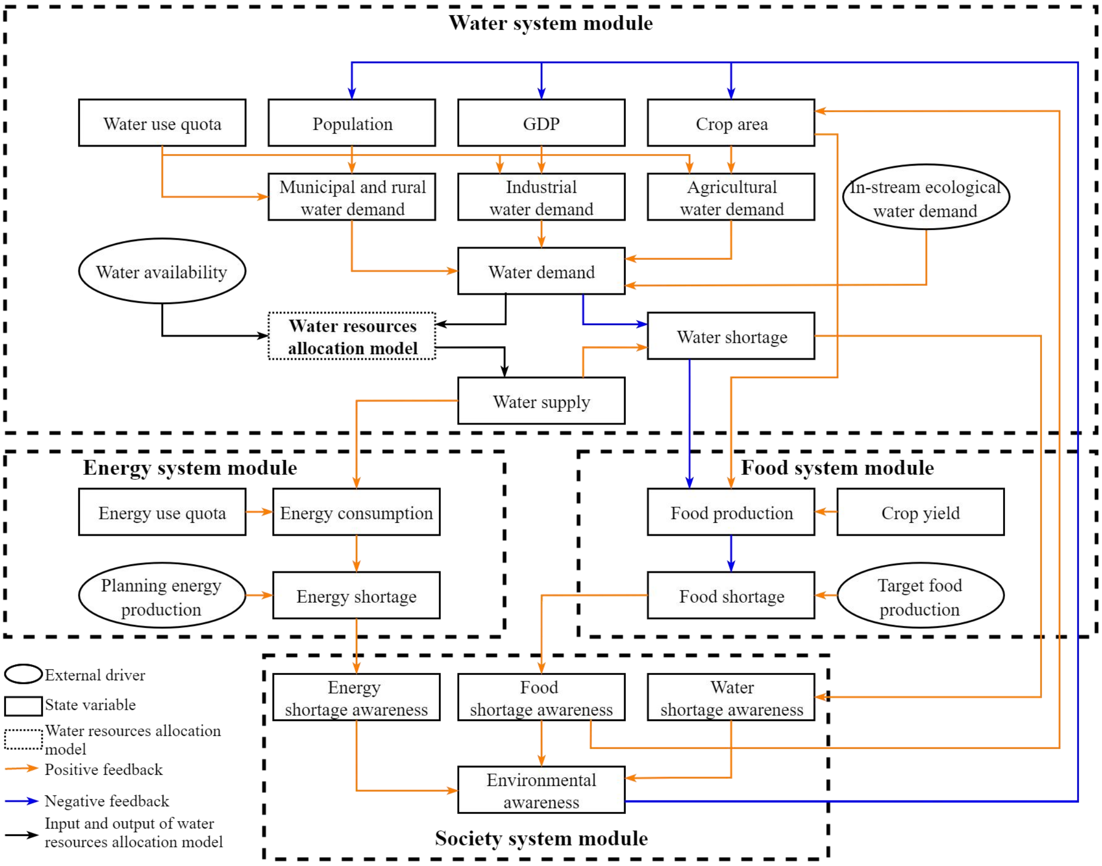


Figure 1. Structure of WEFS nexus model and its feedbacks.

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).

According to previous studies, the socioeconomic expansion in the future will slow down (He et al., 2017; Lin et al., 2016), the growth rate of which will decrease. The constant growth rate in the original Malthusian growth model is thereby not applicable for socioeconomic simulation. Therefore, we used exponential terms to simulate the evolution of socioeconomic variables, which increases with decreasing rate. And feedback functions, as well as environmental carrying capacities of socioeconomic variables, are adopted to constrain the evolution of these socioeconomic variables through equations (2)–(4) (Feng et al., 2016; Hritonenko and Yatsenko, 1999).

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

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

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

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 carrying 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 from historical observed data, respectively; $r_{P,\,t}$, $r_{G,\,t}$, 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 social 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 social 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).

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

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 from historical observed data and *t*-th year, respectively; $WQ_{i,j}^{min}$ is the minimum value of water use quotas; and κ_{qwu}*exp(-$\varphi_{qwu} t$) is used to depict the water-saving effect of social 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 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).

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

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

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

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; $WSR_{i,j}^{t}$ is the water shortage rate in the *t*-th year; and WSR_t is the total water shortage rate.

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).

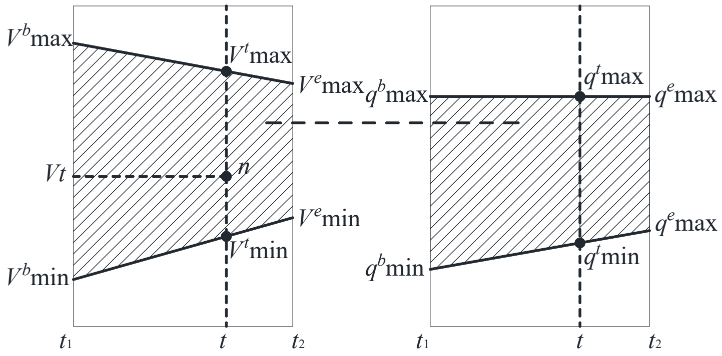


Figure 2. Water release rule for supply-driven reservoir.

$$P_t = (t - t_1)/(t_2 - t_1) \tag{9}$$

$$V_{\max}^{t} = V_{\max}^{b} * (1 - P_t) + V_{\max}^{e} * P_t \tag{10}$$

$$V_{\min}^{t} = V_{\min}^{b} * (1 - P_t) + V_{\min}^{e} * P_t \quad (11)$$

$$q_{\max}^{\mathrm{t}} = q_{\max}^{b} * (1 - P_{\mathrm{t}}) + q_{\max}^{e} * P_t \quad (12)$$

$$q_{\min}^{t} = q_{\min}^{b} * (1 - P_t) + q_{\min}^{e} * P_t \quad (13)$$

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

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

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; $V_{\max}^{t}$, $V_{\min}^{t}$, $V_{\max}^{b}$, $V_{\min}^{b}$, $V_{\max}^{e}$, and $V_{\min}^{e}$ represent the maximum and minimum storages at the current time, beginning, and ending of the period, respectively; $q_{\max}^{t}$, $q_{\min}^{t}$, $q_{\max}^{b}$, $q_{\min}^{b}$, $q_{\max}^{e}$, and $q_{\min}^{e}$ 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 social 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).

$$\begin{cases} \dfrac{dEQ_{i,j}^{t}}{dt} = EQ_{i,j}^{t} * r_{e,t} \\ r_{e,t} = \begin{cases} r_{e,0} * \kappa_e * \exp(-\varphi_e t) & EQ_{i,j}^{t} > EQ_{i,j}^{min} \\ 0 & \text{else} \end{cases} \end{cases} \tag{16}$$

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

$$ESR_t = \frac{ES_t}{EC_t} = \frac{EC_t - PEA_t}{EC_t} \tag{18}$$

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 from historical observed data and the *t*-th year, respectively; $EQ_{i,j}^{min}$ is the minimum value of energy use quotas; $\kappa_e * \exp(-\varphi_e t)$ depicts the energy-saving effect of social 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 target food production which has considered the local and exported food demands of basin, the food shortage rate can then be estimated using equations (20) and (21).

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

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

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

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 from historical observed data and the *t*-th year, respectively; $\kappa_{pro}*\exp(-\varphi_{pro}t)$ depicts the impacts of social 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 TFP_t is the target 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).

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

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

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

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

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).

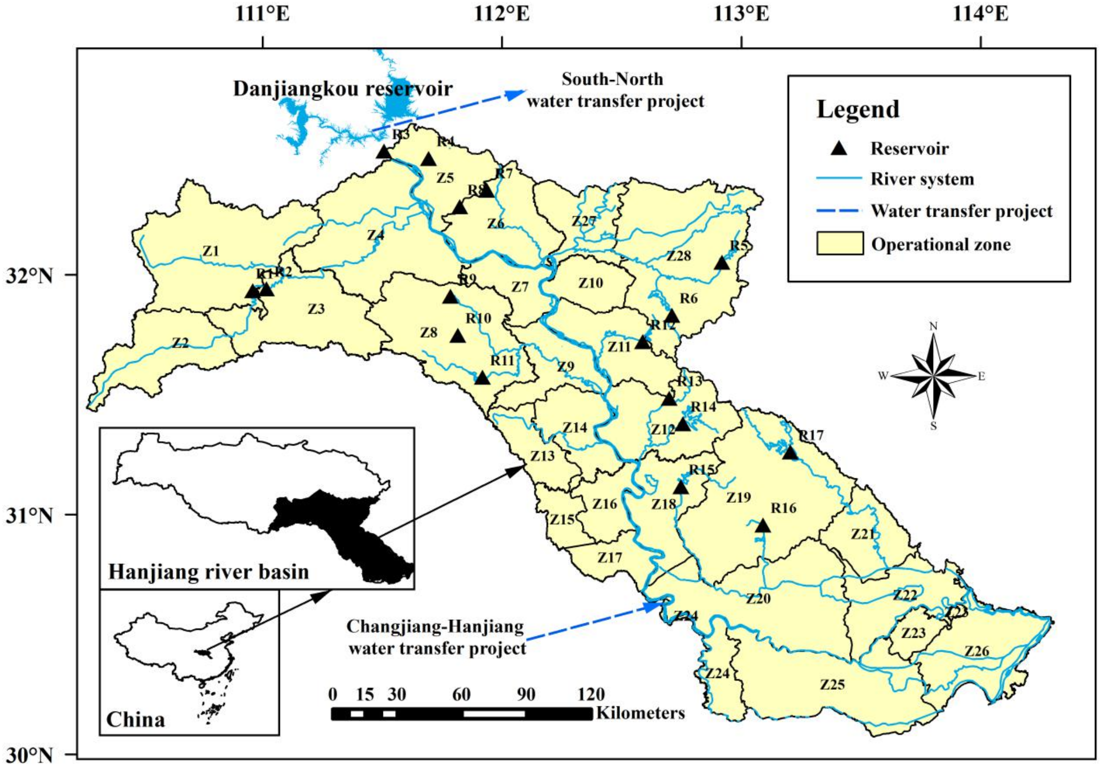


Figure 3. Location of mid-lower reaches of Hanjiang river basin.

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.

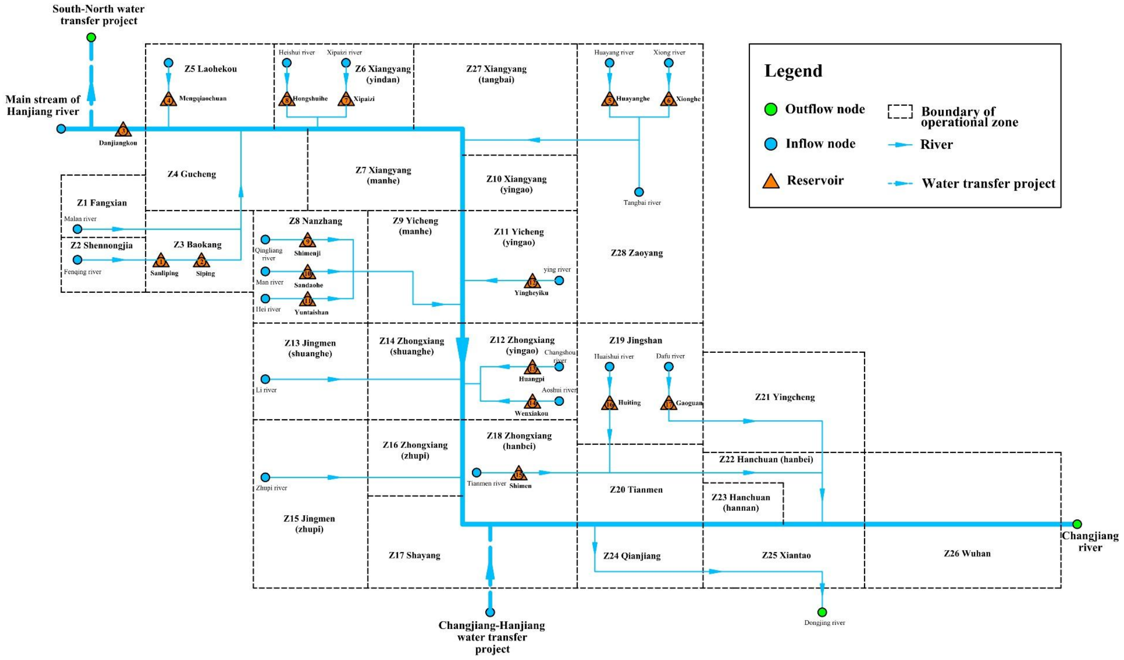


Figure 4. Sketch of the water system for the mid-lower reaches of Hanjiang river basin.

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. Based on the precipitation frequency series during 1956–2016, four typical exceedance frequencies (i.e., P = 50%, 75%, 90%, and 95% are related to the wet, normal, dry, extreme dry years), were adopted to simplify agricultural water demand series. 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	29,050.0	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. Specifically, water availability from 1956 to 2016 was adopted as the future water availability, while dynamic water demand was projected in water system module, both of which were inputted into water resources allocation model. 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 outputted 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) the impacts of environmental awareness feedback and water resources allocation on the WEFS nexus were discussed, and (4) sensitivity analysis for WEFS nexus was tested.

Table 2 Model initial condition setup.

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}	ECC[a] of population	million capita	20.00
G_{cap}	ECC of GDP	billion Yuan	3,000
CA_{cap}	ECC of crop area	km^2	10,000
$WQ_{\bullet,1}^{0}$, $WQ_{\bullet,1}^{min}$	Initial and minimum municipal water use quota	m^3/(year*capita)	56, 28
$WQ_{\bullet,2}^{0}$, $WQ_{\bullet,2}^{min}$	Initial and minimum rural water use quota	m^3/(year*capita)	25, 12.5
$WQ_{\bullet,3}^{0}$, $WQ_{\bullet,3}^{min}$	Initial and minimum industrial water use quota	m^3/(10^4 Yuan)	109, 54.5
$WQ_{\bullet,4}^{0}$, $WQ_{\bullet,4}^{min}$ (P = 50%, 70%, 90%, and 95%)	Initial and minimum agricultural water use quota	million m^3/km^2	0.77, 0.80, 0.90, 0.97 and 0.38, 0.40, 0.45, 0.49
$EQ_{\bullet,j}^{0}$, $EQ_{\bullet,j}^{min}$ (j = 1, 2, 3, and 4)	Energy use quotas for municipal, rural, industry and agriculture sectors	kw*h/m^3	0.29, 0.29, 0.29, 0[b] and 0.15, 0.15, 0.15 0
$\sum_{j} CY_{\bullet,j}^{0} \quad (j = 1, 2)$	Crop yield	t/km^2	654
$r_{P,0}$	Growth rate of population	[-]	0.003
$r_{G,0}$	Growth rate of GDP	[-]	0.040
$r_{CA,0}$	Growth rate of crop area	[-]	0.003
$r_{qwu,0}$	Growth rate of water use quota	[-]	-0.020

$r_{e,0}$	Growth rate of energy use quota	[-]	-0.004
$r_{pro,0}$	Growth rate of crop yield	[-]	0.018
PEA	Planning energy availability	[million kw*h]	1,620
TFP	Target food production	[million t]	6,000

[a] ECC indicates the environmental carrying capacity. [b] 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

As some parameters are adopted as auxiliary parameters, which are not equipped with exactly physical definitions, there is no independent empirical data to calibrate them. Therefore, by reviewing previous studies (Feng et al., 2019; Feng et al., 2016; Van Emmerik et al., 2014) and expert knowledge, we evaluated the order of magnitudes and rational boundaries for these parameters. An initial parameter sensitivity analysis was then adopted to screen out the insensitive parameter, which provided distinguishing 13 insensitive and 21 sensitive parameters. As the insensitive parameters are not able to remarkably alter the system, the empirical values in previous studies (Feng et al., 2019; Feng et al., 2016) were adopted. The sensitive parameters in the model were then calibrated based on the observed data, and the calibrated values are presented in Table 3. 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%, indicating that the established model can effectively fit the observed data of WEFS nexus.

It's worth noting that the observed data can only cover the initial phase of WEFS nexus co-evolution. The environmental awareness stays at a low level and the feedback is not triggered, which indicates that feedback driven by high-level environmental awareness hasn't been calibrated yet. However, as environmental awareness is a subjective variable, there are no empirical data to calibrate it, which requires more evidences to show adaptive human response to environmental awareness. Hepburn et al. (2010) have reviewed studies on environmentally related human behavioral economics. Substantial studies indicate that environmental awareness is considered as an important factor in modelling socioeconomic decisions and policies for water, energy and food systems (Li et al., 2019; Li et al., 2021; Lian et al., 2018; Rockson et al., 2013; Xiong et al., 2016). For instance, Xiong et al. (2016) investigated the evolution newspaper coverage of water issues in China based on water-related articles in a major national newspaper, *People's Daily*. They found that economic development was the primary target of China before 2000. With the conflict between water demand and supply being intensified, concerns about water security arisen in the newspaper since 2000, which indicated that environmental awareness towards water shortage emerged. Related policies (e.g., the strictest water resources control system for water resources management policy in China) were thereby implemented to constrain the over-speed socioeconomic expansion and further ensure water security. Therefore, the established model still has potential to simulate the co-evolution of 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

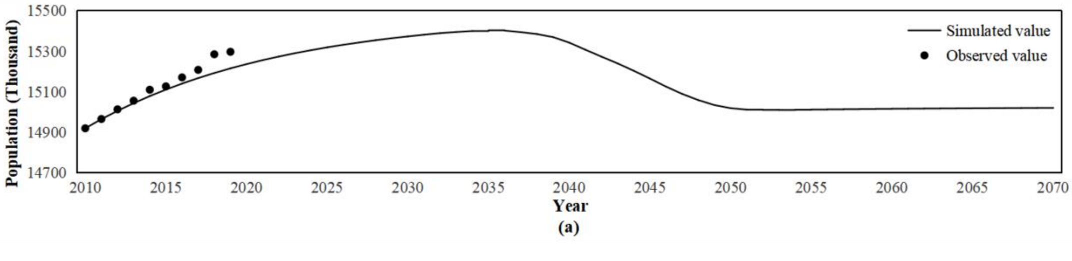
θ_E	Accumulation factor for energy shortage awareness	[-]	0.0856
θ_F	Accumulation factor for food shortage awareness	[-]	0.0856
ω_W	Lapse factor for water shortage awareness	[-]	0.1
ω_E	Lapse factor for energy shortage awareness	[-]	0.1
ω_F	Lapse factor for food shortage awareness	[-]	0.1
$WSRcrit$	Critical 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 shortage awareness to crop area	[-]	0.1

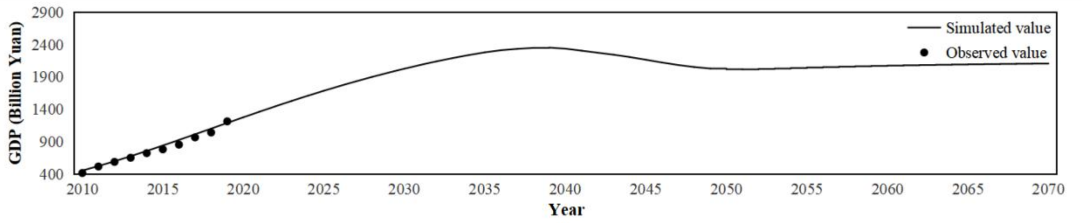
Table 4 NSE and PBIAS of state variables.

	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

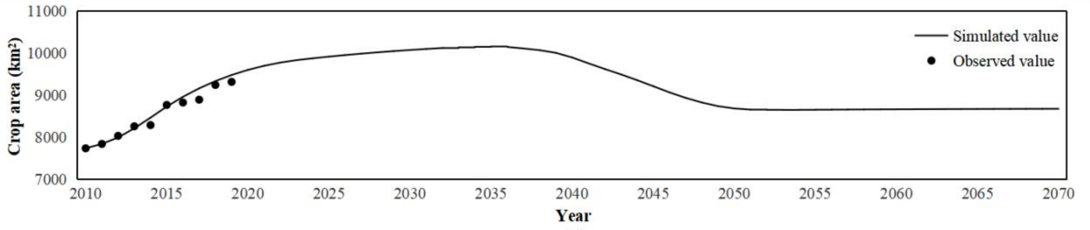
4.2 Co-evolution of WEFS Nexus

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. According to the phase dividing rules in Feng et al. (2016) and Elshafei et al. (2014), the co-evolution processes of water demand and energy consumption were divided into four phases: expansion, contraction, recession, and recovery, based on the trajectory of environmental awareness. Food production was divided into five phases based on the trajectory of food shortage awareness: accelerating expansion, natural expansion, contraction, recession, and recovery.

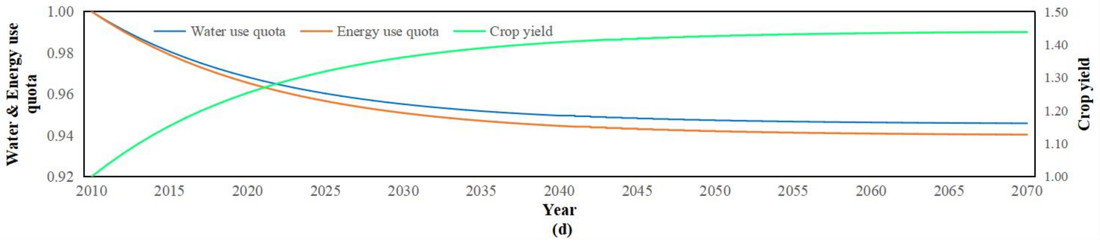



GDP (Billion Yuan)
2900
2400
1900
1400
900
400
Simulated value
Observed value
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Year

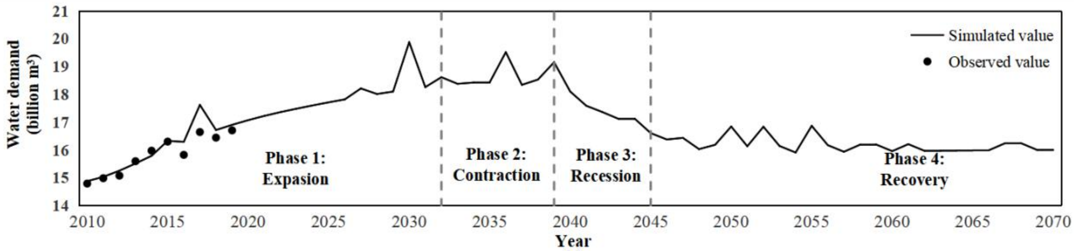
(b)


Crop area (km²)
11000
10000
9000
8000
7000
Simulated value
Observed value
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Year

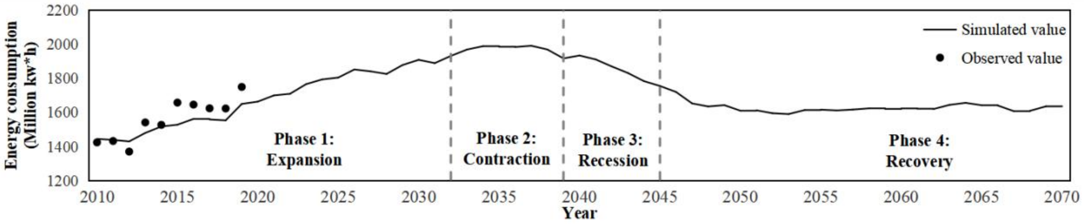
(c)


Water & Energy use quota
1.00
0.98
0.96
0.94
0.92
Water use quota
Energy use quota
Crop yield
Crop yield
1.50
1.40
1.30
1.20
1.10
1.00
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Year

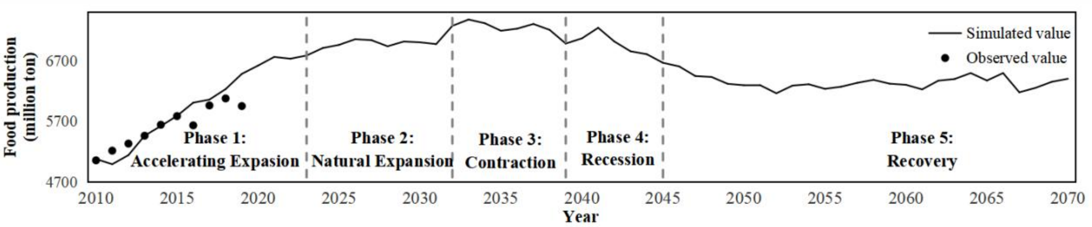
(d)


Water demand (billion m³)
21
20
19
18
17
16
15
14
Simulated value
Observed value
Phase 1: Expasion
Phase 2: Contraction
Phase 3: Recession
Phase 4: Recovery
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Year

(e)


Energy consumption (Million kw*h)
2200
2000
1800
1600
1400
1200
Simulated value
Observed value
Phase 1: Expansion
Phase 2: Contraction
Phase 3: Recession
Phase 4: Recovery
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Year

(f)


Food production (million ton)
6700
5700
4700
Simulated value
Observed value
Phase 1: Accelerating Expasion
Phase 2: Natural Expansion
Phase 3: Contraction
Phase 4: Recession
Phase 5: Recovery
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Year

(g)

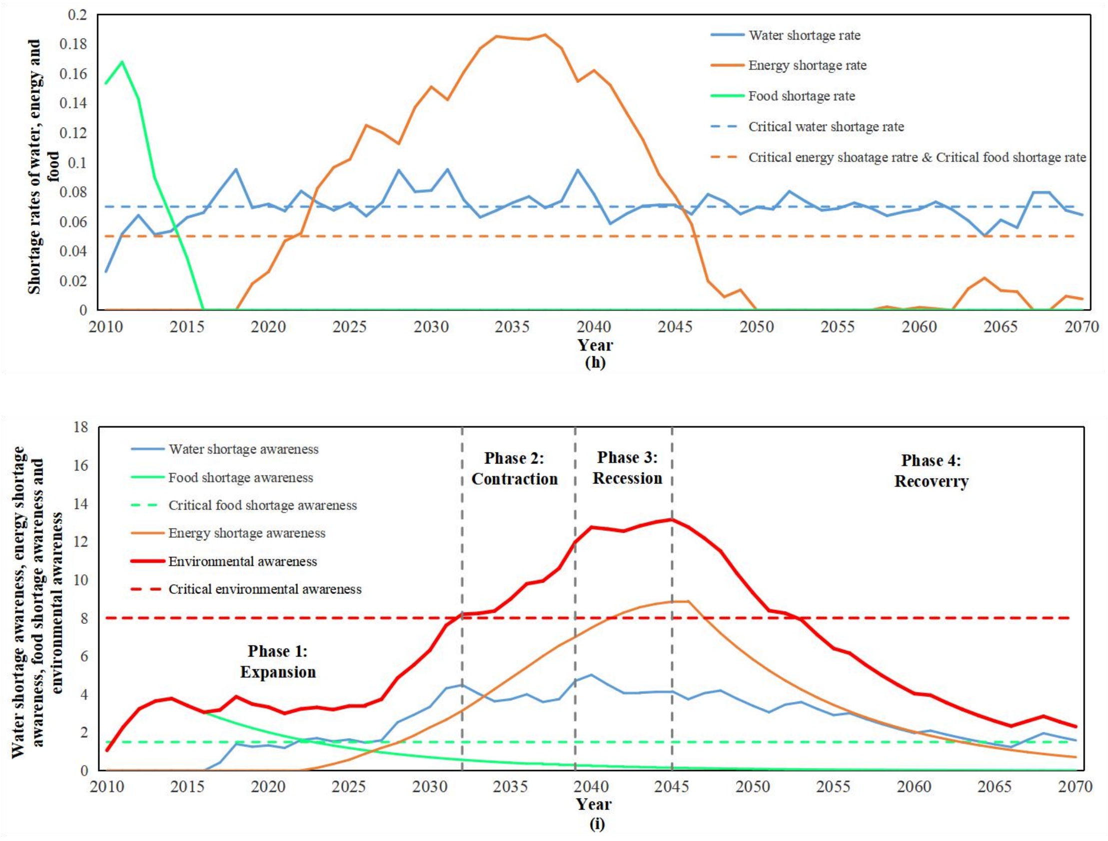


Figure 5. Trajectories of state variables in WEFS nexus: (a) population; (b) GDP; (c) crop area; (d) percentage variations (compared with initial values) of water use quota, energy use quota, and crop yield; (e) water demand; (f) energy consumption; (g) food production; (h) shortage rates of water, energy, 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 expansion phase (2010–2032). In the beginning of co-evolution, the water and energy demands can be satisfied by water and energy availability. The shortage rates of water and energy were typically below their critical values (Figure 5 (h)), and thus, shortage awareness of water and energy remained at a low level as shown in Figure 5 (i). Despite food shortage struck the system in the beginning, the shortage rate of which was 0.153 and more than its critical value 0.05, the environmental awareness led by food shortage awareness was still within its critical value 8.0. Therefore, environmental awareness feedback wasn't triggered to constrain socioeconomic sectors, and water demand, as well as energy consumption, thereby keeps increasing.

As environmental awareness exceeds its critical value, negative feedback on socioeconomic sectors is triggered, and water demand and energy consumption is constrained, which is defined as contraction phase (2033–2039). Although quotas for water use and energy use decreased (Figure 5 (d)) with technological advancement, water demand and energy consumption kept lowly increasing owing to the continuous socioeconomic expansion (Figure 5 (a), (b), and (c)). Shortage rates of water and energy remained over their critical values (Figure 5 (h), and (i)), leading the increases of water shortage awareness and energy shortage awareness, and further environmental awareness. Consequently, environmental awareness exceeded its critical value in 2033 and continued to increase. Negative feedback on socioeconomic sectors was triggered and strengthened. 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.

As environmental awareness accumulates to the maximum value, water demand,

and energy consumption decrease significantly, which is defined as recession phase (2040–2045). Environmental awareness feedback indeed constrained water demand and energy consumption, which decreased but still exceeded local water and energy carrying capacities. Therefore, as the shortage rates of water and energy remained exceeding their critical values (Figure 5 (h)), environmental awareness continued accumulating 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 recovery phase (2046–2070). With continuous decline of socioeconomic sectors, water demand and energy consumption gradually decreased within their carrying capacities. The shortage rates of water and energy have then decreased to below their critical values since 2047, resulting in the decreases in water shortage awareness and energy shortage awareness (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.

The co-evolution process of food production can be interpreted in the similar way. It’s worth noting that the accelerating expansion phase (2010–2022) is unique for food production. As the food production cannot satisfy the target value in the beginning of co-evolution, food shortage emerged and led the increase of food shortage awareness (Figure 5 (h), and (i)). With food shortage awareness increasing over its critical value, positive feedback on crop area was triggered, and further accelerated the increase of food production.

4.3 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 5. 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 6. Figure 6 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.

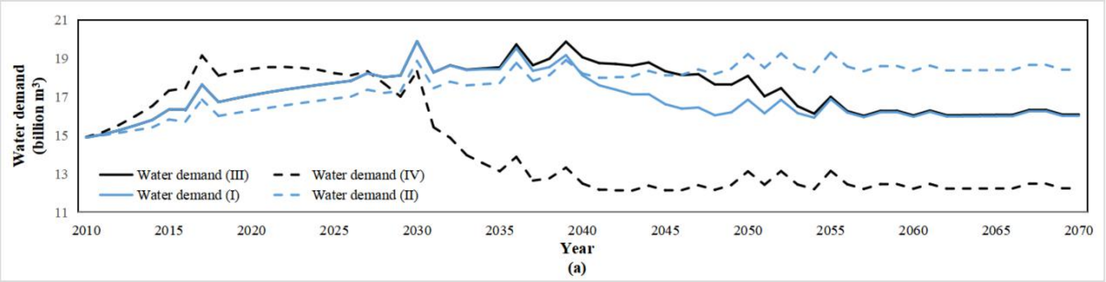
Table 5 Scenario description for assessing the impacts of environmental awareness feedback and water resources allocation on WEFS nexus.

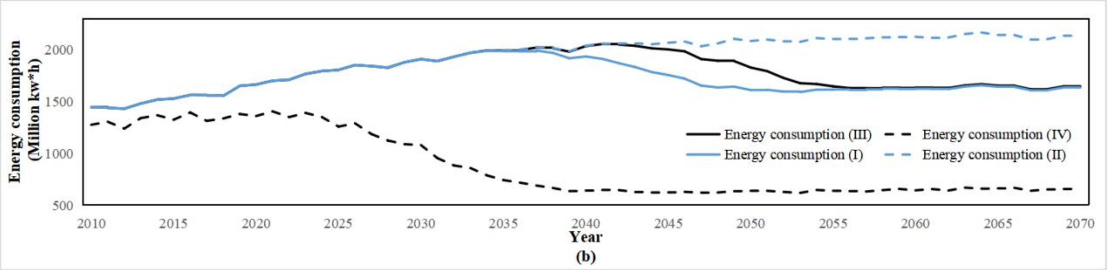
Scenario	Environmental	Water resources	Parameter setting

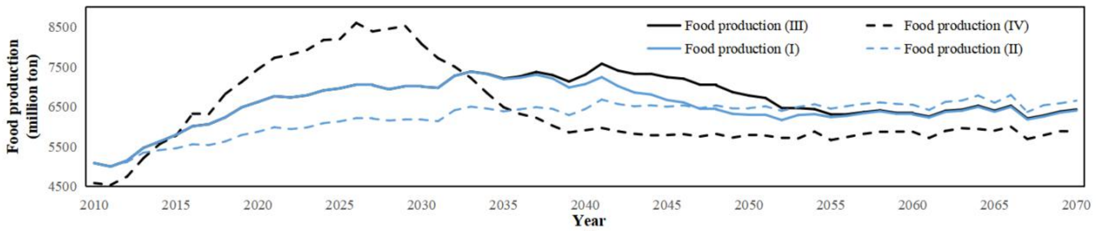
	awareness feedback	allocation	
I	Yes	Yes	Calibrated values
II	No	Yes	*Ecrit*, *FAcrit*: 10,000; others: calibrated values
III	Yes	Yes	*WSRcrit*: 0.15; others: calibrated values
IV	Yes	No	*WSRcrit*: 0.15; others: calibrated values

Table 6 Average annual values for the state variables in WEFS nexus.

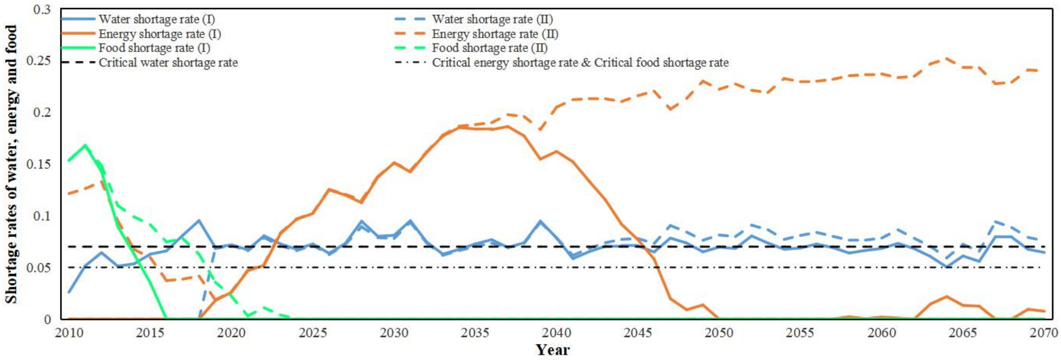
Scenario	Water demand (billion m^3)	Energy consumption (million kw*h)	Food production (million t)	Water shortage rate	Energy shortage rate	Food shortage rate
I	16.94	1,710	6,519	7.03%	5.80%	1.07%
II	17.66	1,930	6,248	7.44%	17.16%	1.74%
III	17.29	1,761	6,638	7.20%	8.25%	1.08%
IV	14.36	884	6,344	15.89%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



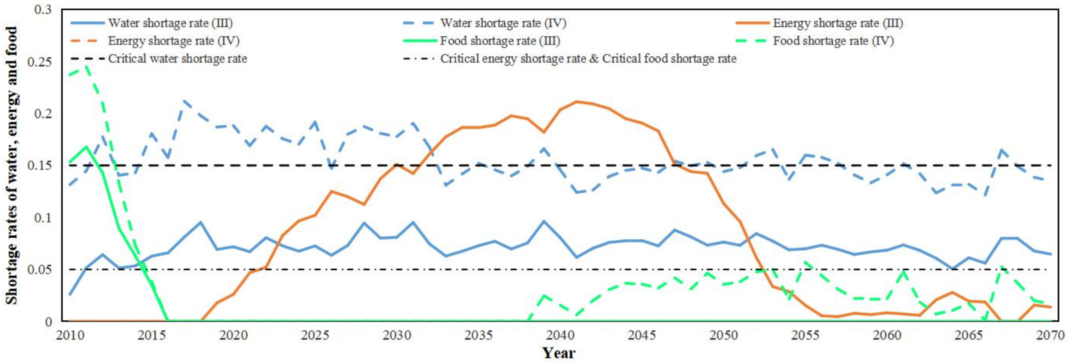



Food production (million ton)
8500
7500
6500
5500
4500
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Year
Food production (III)
Food production (IV)
Food production (I)
Food production (II)

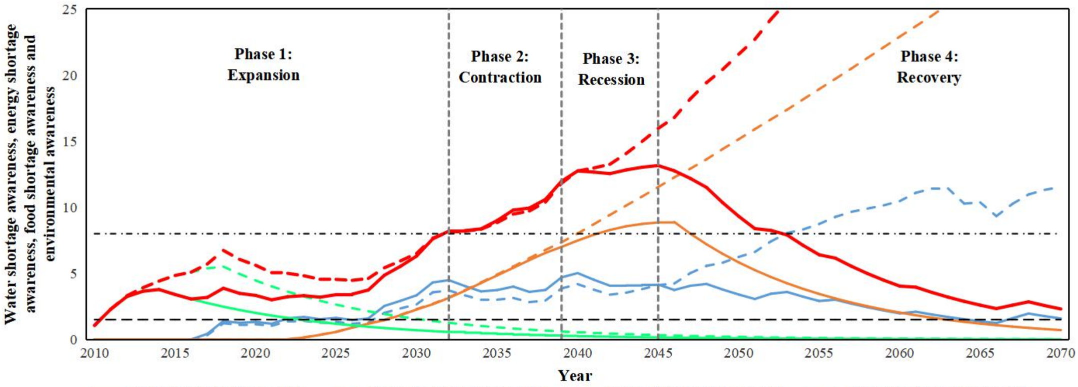
(c)


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

(d)


Shortage rates of water, energy and food
0.3
0.25
0.2
0.15
0.1
0.05
0
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Year
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

(e)


Water shortage awareness, energy shortage awareness, food shortage awareness and environmental awareness
25
20
15
10
5
0
Phase 1:
Expansion
Phase 2:
Contraction
Phase 3:
Recession
Phase 4:
Recovery
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
2065
2070
Year
Water shortage awareness (I)
Water shortage awareness (II)
Energy shortage awareness (I)
Energy shortage awareness (II)
Food shortage awareness (I)
Food shortage awareness (II)
Environmental awareness (I)
Environmental awareness (II)
Critical food shortage awareness
Critical environmental awareness

(f)

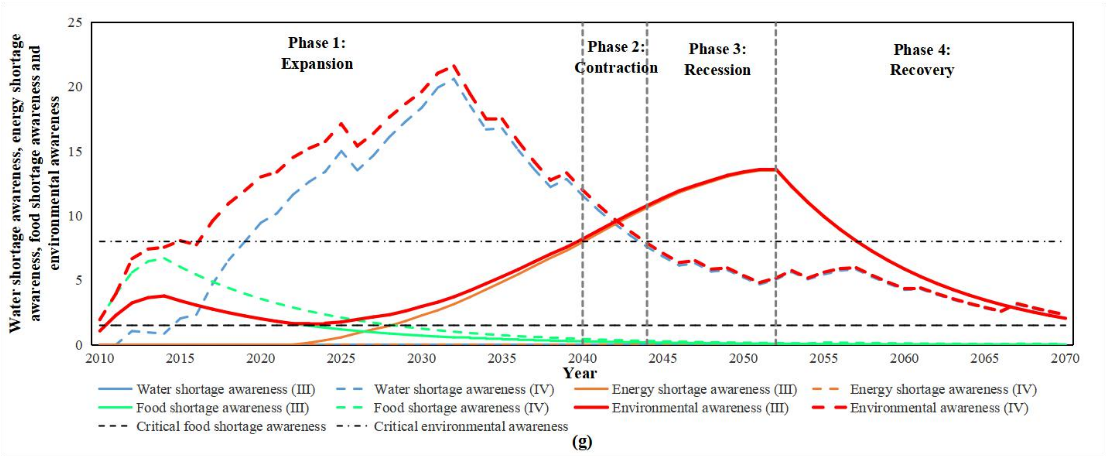


Figure 6. Trajectories of state variables in WEFS nexus under scenario I, II, III, and IV: (a) water demand; (b) energy consumption; (c) food production; (d) and (e) shortage rates of water, energy, and food; (f) and (g) water shortage awareness, energy shortage awareness, food shortage awareness, and environmental awareness.

4.3.1 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 6 (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 (Figure 6 (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 6 (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.

4.3.2 WEFS Nexus Response to Water Resources Allocation

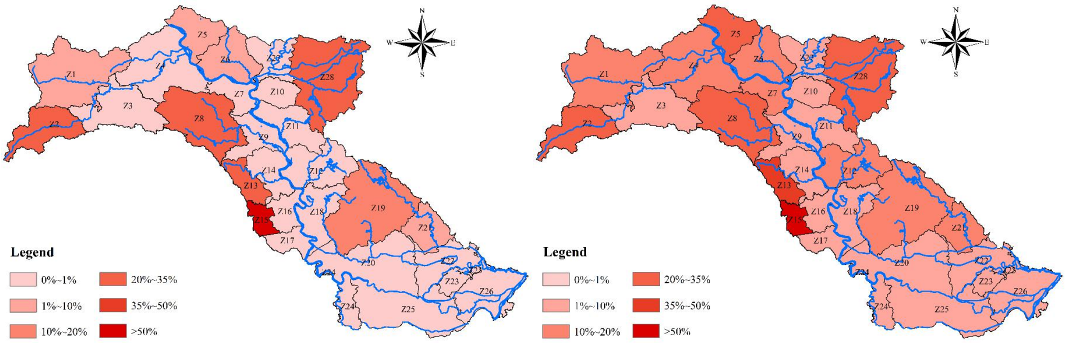
Water is considered the major driving factor for the WEFS nexus. Rational water resources management plays an important role in the sustainable development of the WEFS nexus. Water resources allocation can regulate the water flow by reservoir operation, which is considered one of the most effective tools 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 7.

Table 7 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 rational 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 7, 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 7 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.



(a) Scenario III

(b) Scenario IV

Figure 7. 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 (Figure 6 (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 shown in Figure 6 (g). Meanwhile, as agricultural water demand cannot be ensured, food production was also lowered (Figure 6 (c)). Higher food shortages then led to higher food shortage awareness (Figure 6 (e), and (g)). Thus, positive feedback to increase crop area was strengthened. As observed in Figure 6 (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 6 (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 6 (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 6 (e)). Thus, there was no accumulation of water shortage awareness shown in Figure 6 (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.

4.4 Sensitivity Analysis for WEFS Nexus

As is discussed above, both environmental awareness feedback and water resources allocation are of great significance to WEFS nexus, the sensitivity analysis of which is conducted to help managers to identify the important parameters and rational water resources allocation schemes for the integrated system.

As environmental awareness feedback is dominated by the critical values and boundary conditions of the WEFS nexus, seven parameters were selected for sensitivity analysis (i.e., parameter 1~7 in Table 8). For water resources allocation, different reservoir operation schemes were adopted by adjusting water release from reservoir. Specifically, a multiplier for water release was added as a parameter to demonstrate the ratio to water release in scenario I (i.e., parameter 8 in Table 8). 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 8. Parameter sensitivity analysis was then conducted by analyzing the trajectories of environmental awareness, water demand, energy consumption, and food production, as shown in Figures 8, 9, 10, and 11.

Table 8 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	*TFP*	Target 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

8	*Qmultiplier*	Multiplier of water release from reservoir	0.5	1.5	0.1

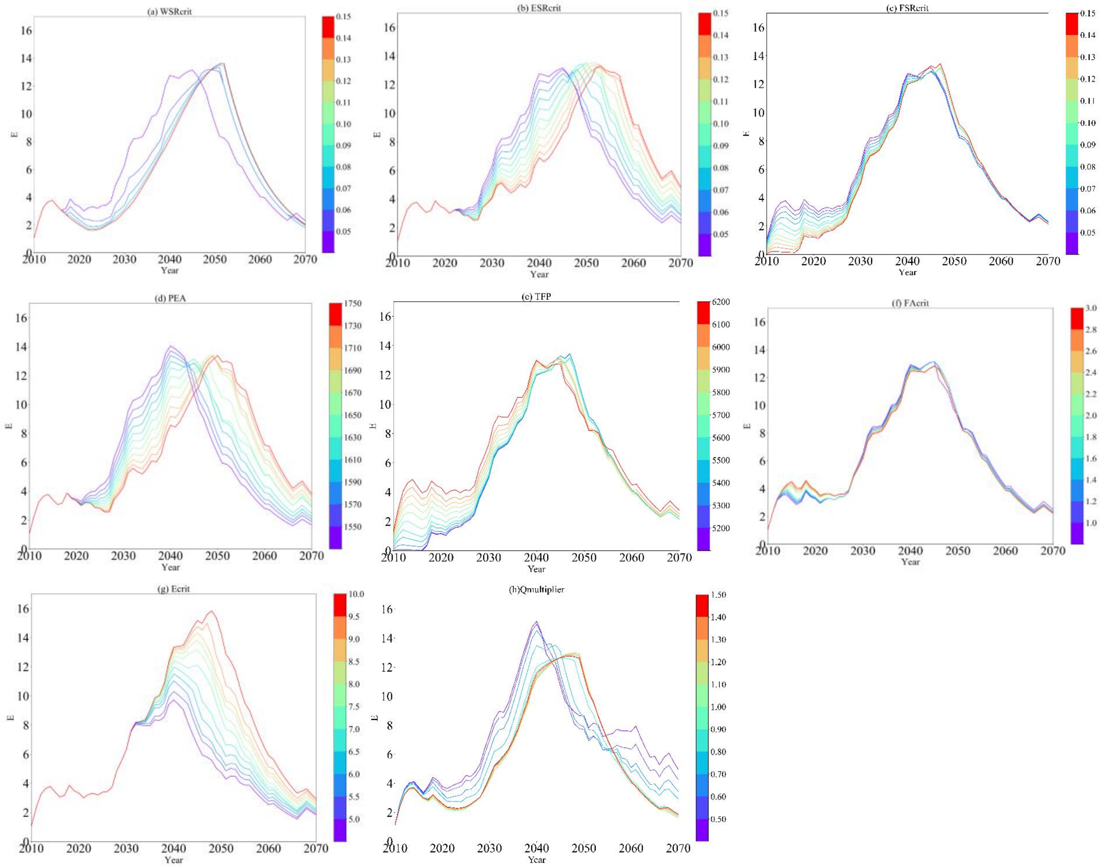
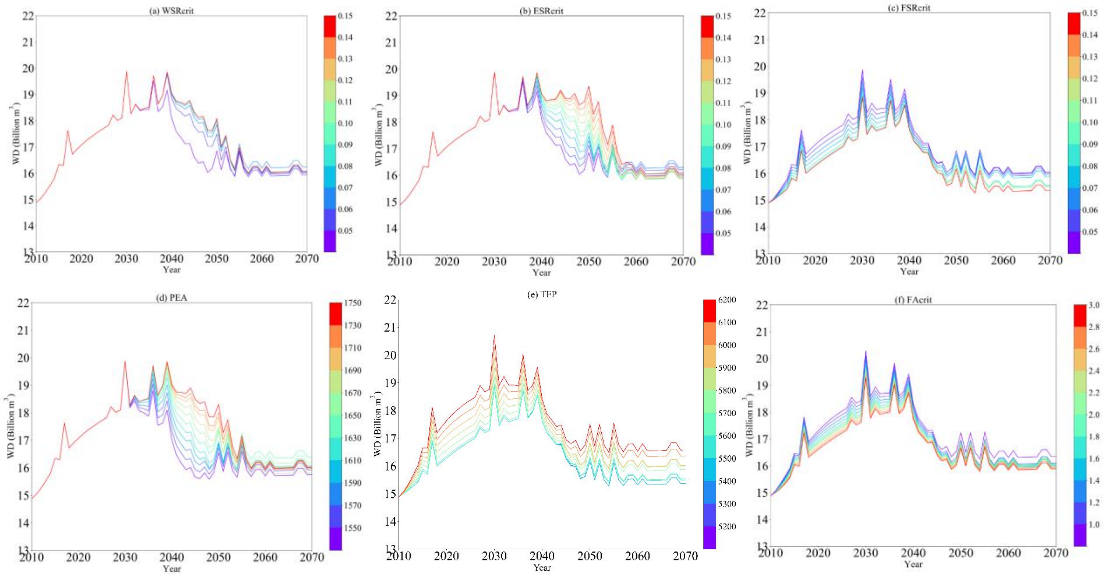


Figure 8. Trajectories of environmental awareness with varied parameters.



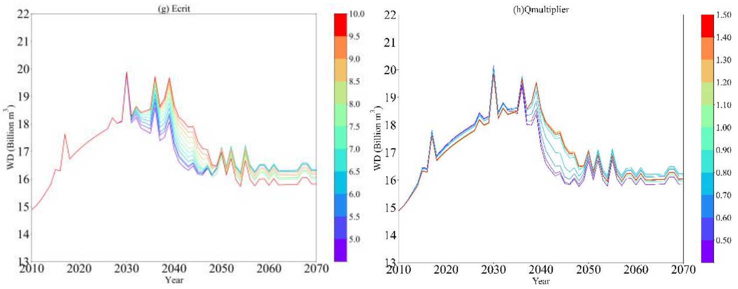


Figure 9. Trajectories of water demand with varied parameters.

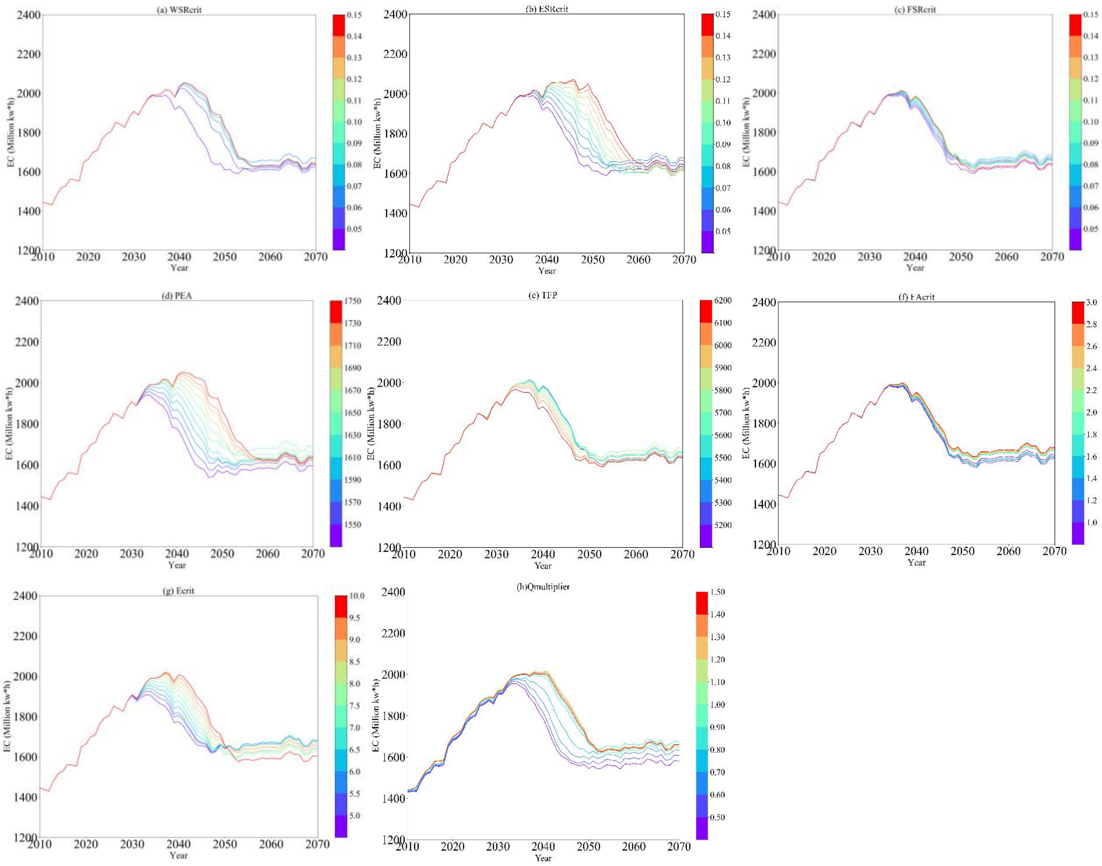
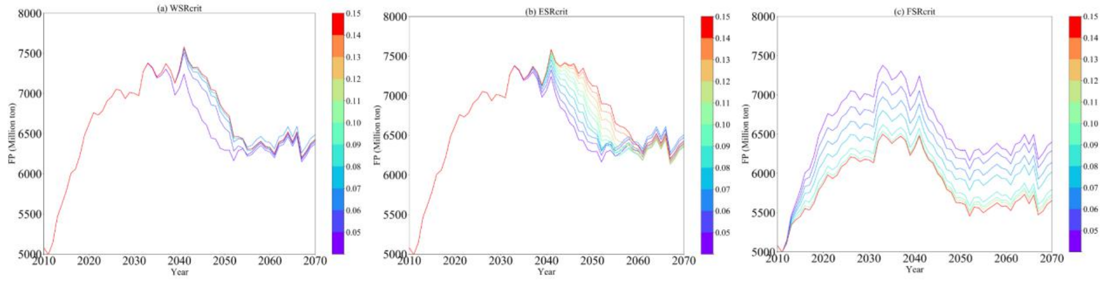


Figure 10. Trajectories of energy consumption with varied parameters.



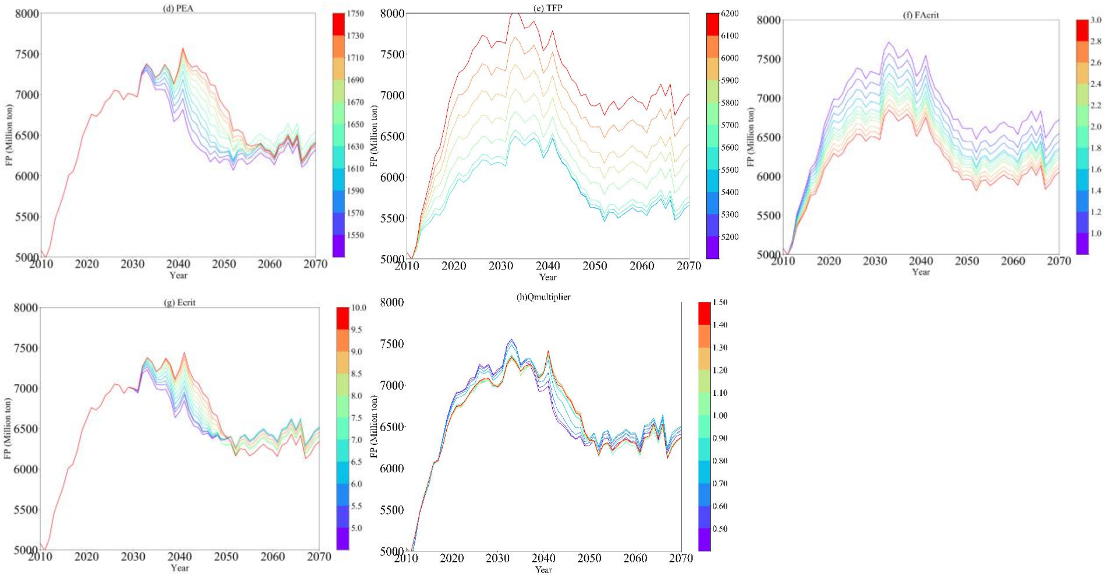


Figure 11. Trajectories of food production with varied parameters.

4.4.1 Sensitivity Analysis of Environmental Awareness Feedback on WEFS Nexus

The variations in the parameters 1~7 can evidently change the trajectory of environmental awareness shown in Figure 8. The socioeconomic sectors including water demand, energy consumption, and food production were then changed by feedback driven by environmental awareness (Figure 9, 10, and 11), indicating that WEFS nexus is sensitive to the seven parameters.

Specifically, the sensitive responses to parameters *WSRcrit*, *ESRcrit*, *PEA*, and *Ecrit* primarily occurred in the contraction and recession phases of the co-evolution process for WEFS nexus. As demands from water and energy systems can always be ensured by abundant resources availability in the expansion phase, limited water and energy shortages were observed. Environmental awareness 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 of WEFS nexus were negligible and were considered as the insensitivity. However, with social development, water demand and energy consumption continued to grow and increase over the local carrying capability, leading an increase in environmental awareness. Negative feedback on socioeconomic sectors was then triggered. *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 thereby accelerated by constraining *WSRcrit*, *ESRcrit*, and *PEA* (Figure 8 (a), (b), and (d)). *Ecrit* is the threshold for the negative feedback triggering driven by environmental awareness. A lower *Ecrit* means community is more sensitive to resources shortage and feedback is easier to trigger (Figure 8 (g)). Therefore, environmental awareness feedback to constrain socioeconomic expansion can be advanced and strengthened by lowering *WSRcrit*, *ESRcrit*, *PEA*, and *Ecrit*, accounting for the sensitive response of WEFS nexus in contraction and recession phases.

FSRcrit, *TFP,* and *FAcrit* performed sensitivity during the entire co-evolution process for WEFS nexus. As food shortages were considerable in the accelerating expansion phase, food shortage awareness increased rapidly, driving the feedback to increase crop area. *TFP* can directly determine food shortage, 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*, *TFP*, and *FAcrit* (Figure 8 (c), (e), and (f)). The crop area then continued increasing until environmental awareness feedback was triggered, resulting in the increases in food production (Figure 11 (c), (e), and (f)) and water demand from agricultural sector (Figure 9 (c), (e), and (f)). As the agricultural water use was directly drawn from river system, the energy use quota during water supply was small and negligible. Energy consumption was thus not sensitive to *FSRcrit*, *FAcrit*, and *TFP* as shown in Figure 10. Therefore, constraining *FSRcrit*, *FAcrit*, and *TFP* is an effective way to increase food production by advancing and strengthening the feedback driven by food shortage awareness, which accounts for the sensitive responses of environmental awareness, water demand, and food production in expansion phase.

Simultaneously, it’s worth noting that 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 sharply increase environmental awareness (Figure 8 (a), (b), (d), and (e)). Environmental awareness feedback was remarkably advanced, which shortened the expansion phase and led to violent degradation of socioeconomic sectors (indicated by drastic decreases of water demand, energy consumption and food production in Figure 9, 10, and 11, respectively). The sustainability of WEFS nexus was seriously challenged. Similarly, despite food production can be effectively increased by constraining *FSRcrit*, *FAcrit*, and *TFP*, the over-constrained condition will cause a considerable increase in water demand, as shown in Figure 9 (c), (e), and (f), which will further put stress on the water supply. Moreover, the regulating capacity of the local system should also be considered during parameter selection. For example, there was an abrupt decrease when *WSRcrit* was set to 0.05, as shown in Figure 9 (a), Figure 10 (a), and Figure 11 (a). Violent socioeconomic degradation dominated by environmental awareness feedback was triggered to decrease environmental awareness, indicating that the *WSRcrit* was over-constrained and 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.

4.4.2 Sensitivity Analysis of Water Resources Allocation Schemes on WEFS Nexus

The WEFS nexus in the study area was evidently constrained under water resources allocation schemes with smaller water release from reservoir. The decreasing water supply directly increased water shortage, the average annual shortage rate of which increased from 6.41% to 8.01%. The rapid increase of water shortage awareness then accelerated environmental awareness accumulation and further the feedback shown in Figure 8 (h). As the negative feedback on socioeconomic sectors was strengthened, water demand decreased rapidly in recession phase (Figure 9 (h)). Water supply was thereby decreased with decreasing water demand, which accounts for the decreasing energy consumption during water supply process shown in Figure 10 (h). For food system, decreasing water release notably altered the stability of food production evolution (Figure 11 (h)). Higher water shortage rate led smaller food production and further larger food shortage awareness. Feedback driven by food shortage awareness was strengthened to increase crop area. Food production thereby increased in expansion phase. However, increasing crop area was accompanied by increasing agricultural water demand, which brought increases of water shortage and environmental awareness. With stronger environmental awareness feedback, food production in recession phase thereby decreased rapidly.

To assess the impacts of water resources allocation schemes in different operational zones, the spatial distributions of water shortage and socioeconomic variables including water demand, energy consumption, and food production were considered. Operational zones were classified into four types as shown in Figure 12. The zone with small water shortage, and the water shortage rate, and socioeconomic variables of which perform insensitivity, is defined as type A. If water shortage can be almost removed and socioeconomic variables are sensitive, the zone is defined as type B. If water shortage can be partly alleviated and socioeconomic variables are sensitive, the zone is defined as type C. The zone with considerable water shortage, and the water shortage rate, and socioeconomic variables of which perform insensitivity, is defined as type D. Four representative zones including Z9 (Yichengmanhe) in type A, Z1 (Fangxian) in type B, Z8 (Nanzhang) in type C, and Z13 (Jingmenzhupi) in type D were selected to study the responses to different water resources allocation schemes. The water shortages and socioeconomic variables are presented in Figure 13.

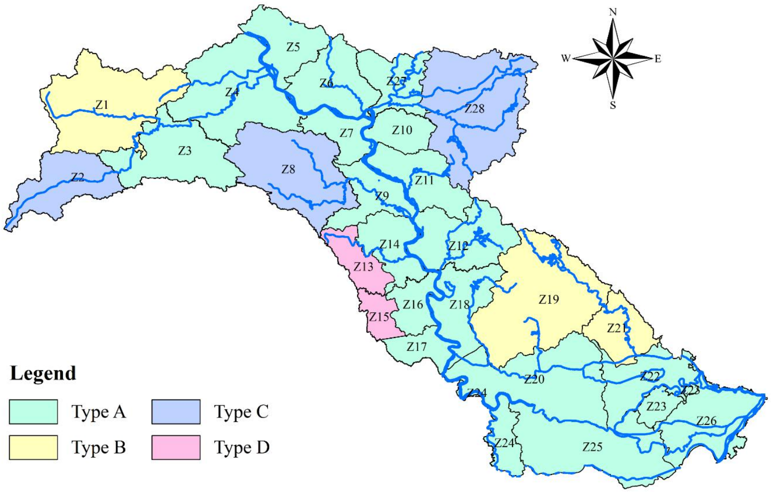
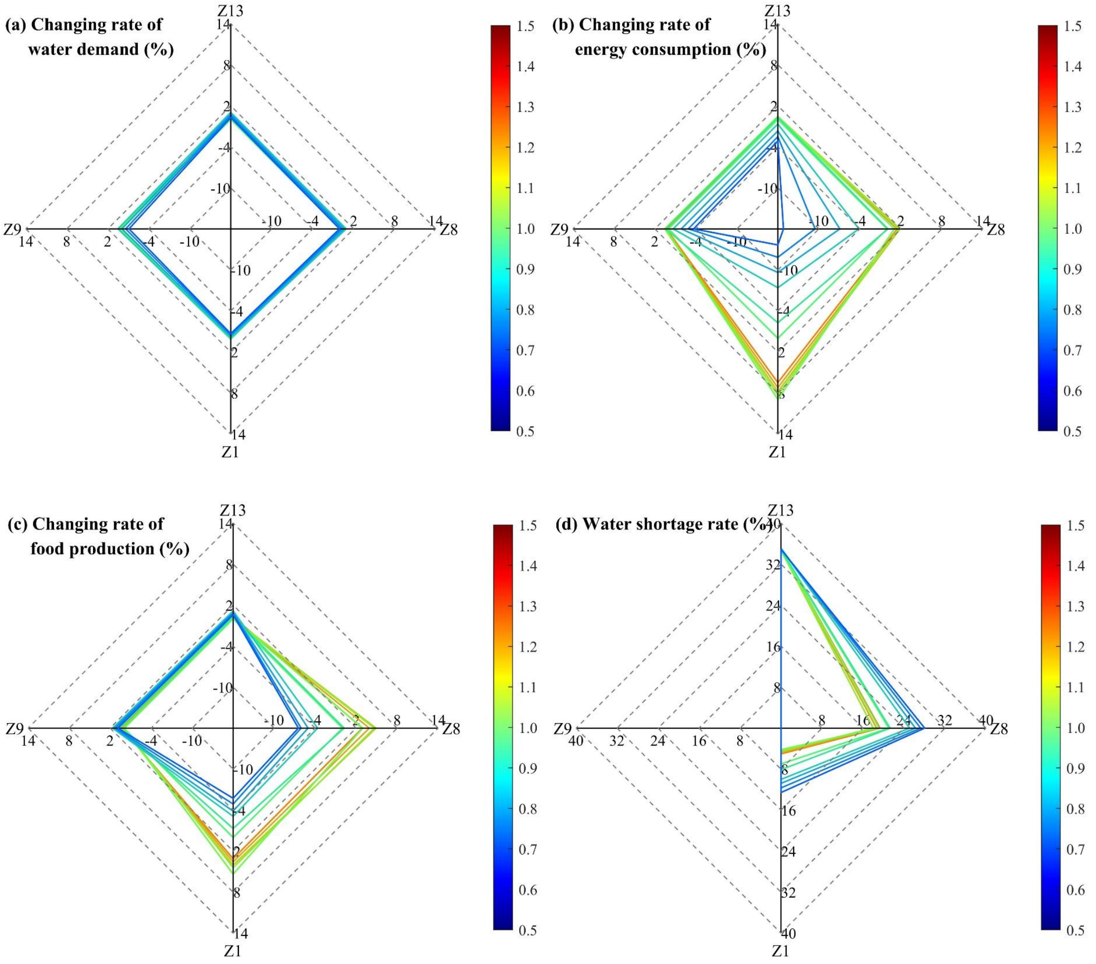


Figure 12. Spatial distribution of A, B, C, and D types of operational zones.


(a) Changing rate of water demand (%)

(b) Changing rate of energy consumption (%)

(c) Changing rate of food production (%)

(d) Water shortage rate (%)

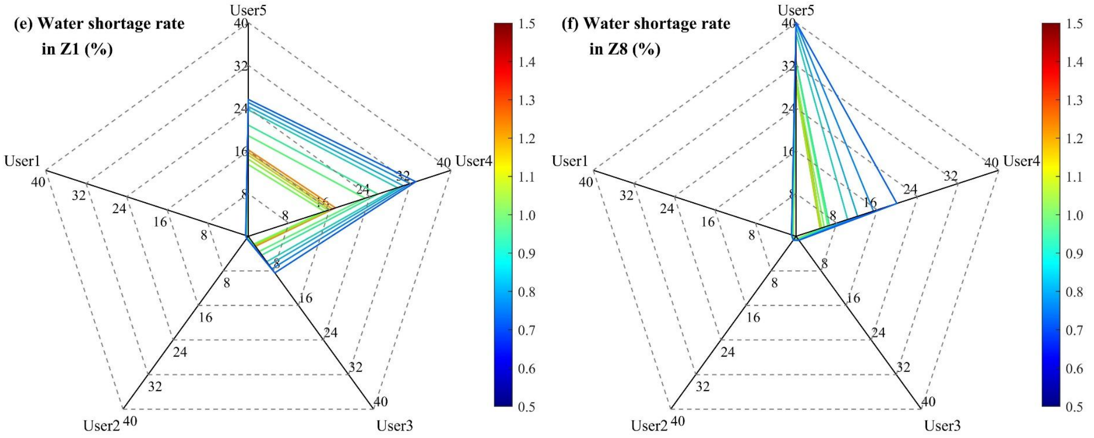


Figure 13. Socioeconomic variables with varied reservoir release multiplier in Z9, Z1, Z8, and Z13: (a) changing rates of water demand; (b) changing rates of energy consumption; (c) changing rate of food production; (d) water shortage rates; (e) water shortage rates of water users in Z1 (user 1, 2, 3, 4, and 5 are related to municipal, rural, in-stream ecology, industrial, and agricultural users); (f) water shortage rates of water users in Z8.

As environmental awareness feedback on population, GDP, and crop area was conducted in the entire study area, the water demand variations in Z1, Z8, Z9, and Z13 were similar, and all of them were small (Figure 13 (a)), which indicated that water supply was the primary factor affecting the integrated system.

No water shortage was observed in Z9 under different water resources allocation schemes (Figure 13 (d)), and the energy consumption, and food production also exhibited insensitivity shown in Figure 13 (b), and (c). As Z9 located along the main stream of Hanjiang river, the regulating capacity of water project was strong due to Danjiangkou reservoir (whose total storage is 33,910 million m^3). Despite of the reduction of water release, the water demand can always be ensured, and the energy consumption, and food production thereby remained stability. Water shortage rate in

Z1 decreased evidently with the increase of water release (Figure 13 (d)), and the energy consumption, and food production further increased remarkably, as shown in Figure 13 (b), and (c). Z1 located at the boundary of study area, the water supply of which mainly depended on Sanliping reservoir (shown in Figure 3). The regulating capacity of water project was strong enough to cover most part of water demand. Therefore, the increasing water release remarkably relived water shortage (water shortage rate decreased from 12.56% to 4.20%), particularly in industrial and agricultural users, as shown in Figure 13 (e). Energy consumption during water supply process thus increased, and food production also increased owing to the decreasing agricultural water shortage rate. Response of Z8 to water resources allocation schemes was similar to Z1. The difference was that local reservoirs in Z8 can provide limited regulating capacity, which can only cover part of water demand. Water shortage was effectively alleviated, but still considerable (water shortage rates were always more than 18% shown in Figure 13(d)). Z13 was far away from the mainstream and there was no local reservoir. The regulating capacity of water project was so weak that no response to water resources allocation schemes was observed. Water was always the key resource constraining the development of Z13 (Figure 13 (d)).

It's worth noting that it doesn't mean more water release from reservoir can always promote the development of the integrated system. As shown in Figure 13 (e), and (f), remarkable decreases of water shortage were no longer observed, since reservoir release multiplier was more than 1.2. As excessive water release may decrease reservoir storage in dry season, even more water shortages were found, as shown in Figure 13 (e), and (f), which further constrained socioeconomic expansion (Figure 13 (b), and (c)). Therefore, regulating capacity of water project is an important factor to ensure the stability of water system to sustain WEFS nexus. In the area equipped with strong regulating capacity of water project, water demand can always be covered and the integrated system is not sensitive to varied water release from reservoir. While in the area with certain regulating capacity of water project but can not totally cover the water demand, regulating the water release from reservoir by rational water resources allocation schemes can effectively ensure water supply and thereby contributes to the sustainable development of the integrated system.

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 shows potential to capture human sensitivity to shortages from water, energy, and food systems. The feedback driven 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. 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. Rational parameter setting of boundary conditions and critical values can effectively control environmental awareness feedback to help managers to keep the socioeconomic sectors from violent expansion and deterioration in contraction and recession phases. Water resources allocation can effectively relieve water shortage by increasing water supply. As high-level environmental awareness led by water shortage is remarkably alleviated, environmental awareness feedback is weakened and the socioeconomic sectors develop rapidly. Threats from water shortage on the concordant development of WEFS nexus are significantly alleviated. Regulating capacity of water project is an important factor in water resources allocation to ensure the stability of water system to sustain WEFS nexus. Particularly for the area with certain regulating capacity of water project but cannot totally cover the water demand, regulating the water release from reservoir by rational water resources allocation schemes can further ensure water supply and is of great significance for the sustainable development of the WEFS nexus.

We acknowledge that environmental awareness feedback functionality remains to be further improved. Indeed, environmental awareness also has potential to contribute to socioeconomic expansion by promoting resources-saving technology. It's the function of the level and duration of environmental awareness, and the sizes of socioeconomic factors, which will become the focus of our further study. The model calibration is also 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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