

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

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15 **Abstract:** Sustainable management of water-energy-food (WEF) nexus remains an
16 urgent challenge, as interactions between WEF and human sensitivity and reservoir
17 operation in the water system are typically neglected. This study proposes a new
18 approach for modeling WEF nexus by incorporating human sensitivity and reservoir
19 operation into the system. The co-evolution behaviors of the nexus across water,
20 energy, food, and society (WEFS) were simulated using the system dynamic model.
21 Reservoir operation was simulated to determine the water supply for energy and food
22 systems by the Interactive River-Aquifer Simulation water resources allocation model.
23 Shortage rates for water, energy, and food resulting from the simulations were used to
24 qualify their impacts on the WEFS nexus through environmental awareness in society
25 system. Human sensitivity indicated by environmental awareness can then adjust the
26 co-evolution behaviors of the WEFS nexus through feedback loops. The proposed
27 approach was applied to the mid-lower reaches of the Hanjiang river basin in China as
28 a case study. Results indicate environmental awareness shows potential to capture
29 human sensitivity to shortages from water, energy, and food systems. Parameters
30 related to boundary conditions and critical values can dominate environmental
31 awareness feedback to regulate socioeconomic expansion to maintain the integrated
32 system from constant resources shortages. The annual average energy shortage rate
33 thereby decreased from 17.16% to 5.80% by taking environmental awareness
34 feedback, contributing to the sustainability of the WEFS nexus. Rational water
35 resources allocation can ensure water supply through reservoir operation. The annual
36 average water shortage rate decreased from 15.89% to 7.20% as water resources

37 allocation was considered. Threats from water shortage on the concordant
38 development of the WEFS nexus are significantly alleviated, particularly for the area
39 with limited regulating capacity of water project. Therefore, this study contributes to
40 the understanding of interactions across the WEFS systems and helps in improving
41 the efficiency of resources management.

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

44 **1. Introduction**

45 Water, energy, and food are indispensable resources for sustainable development
46 of society. With the growing population, urbanization, globalization, and economic
47 development, the expected global demands for water, food, and energy in 2030 will
48 increase by 40%, 50%, and 50%, respectively, compared to the 2010 levels
49 (Alexandratos and Bruinsma, 2012; Mckinsey & Company, 2009; International
50 Energy Agency, 2012). Resource scarcity will be exacerbated by the single-sector
51 strategy in traditional water, energy, and food management (El Gafy et al., 2017). To
52 increase resource use efficiency and benefits in production and consumption, taking
53 the inextricable interactions among sectors across water, energy, and food into rational
54 resources management has become an important strategy (Hsiao et al., 2007;
55 Vörösmarty et al., 2000). Considering these interactions, the water-energy-food (WEF)
56 nexus concept was first presented at the Bonn Conference in 2011 as an approach to
57 determine synergies and trade-offs between WEF sectors to support sustainable

58 development goals (Hoff, 2011).

59 Various methods have been proposed for integrated systems to quantify the
60 interactions in the WEF nexus. There are three main types of methods: system of
61 systems model (Eusgeld et al., 2011; Housh et al., 2015), agent-based model
62 (Bonabeau, 2002; Dawson et al., 2011), and system dynamic model (El Gafy, 2014;
63 Swanson, 2002). The system of systems model comprises several subsystems as a
64 holistic system to address the nexus by optimizing system behavior. The agent-based
65 model simulates the interactions between agents and environments as well as different
66 agents based on predefined rules obtained from long-term observations. These two
67 methods have been established to be capable of simulating the behaviors of an
68 integrated system. However, neither of them has emphasized feedback within the
69 integrated systems, which is considered an important driving force for nexus system
70 (Chiang et al., 2004; Kleinmuntz, 1993; Makindeodusola and Marino, 1989). The
71 results of these two methods for WEF security remain at risk. The system dynamic
72 model explicitly focuses on feedback connections between key elements in a model to
73 determine the co-evolution process and long-term characteristics of integrated
74 systems (Liu, 2019; Simonovic, 2002). Therefore, system dynamic model was
75 adopted in this study to simulate the co-evolution process of the nexus system.

76 System dynamic model has been widely used to analyze the WEF nexus
77 worldwide at different spatial scales, such as global (Davies and Simonovic, 2010;
78 Susnik, 2018), national (Laspidou et al., 2020; Linderhof et al., 2020), and basin-scale
79 (Purwanto et al., 2021; Ravar et al., 2020). Most of these models perform the

80 accounting and analysis of the WEF nexus, focusing only on the physical process,
81 while rarely highlighting the social process that indicates human responses to the
82 WEF nexus (Elshafei et al., 2014). As the connection between the WEF nexus and
83 society is intensified under rapid socioeconomic development, both physical and
84 social processes should be considered for the sustainability of the integrated system in
85 the future (Di Baldassarre et al., 2015; Di Baldassarre et al., 2019).

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

100 Reservoirs can adjust the uneven temporal and spatial distribution of available
101 water resources and can ensure water supply to reduce water shortage (Khare et al.,

102 2007; Liu et al., 2019; Zeng et al., 2021; He et al., 2022). However, the available
103 water resources are typically adopted under historical natural water flow scenarios,
104 while reservoirs are seldom considered, or their operational rules are significantly
105 simplified in the WEF nexus. The assessment of water supply security based on the
106 WEF nexus should be improved. Thus, additional details regarding the reservoir
107 operation should be incorporated into the simulation of the WEF nexus.

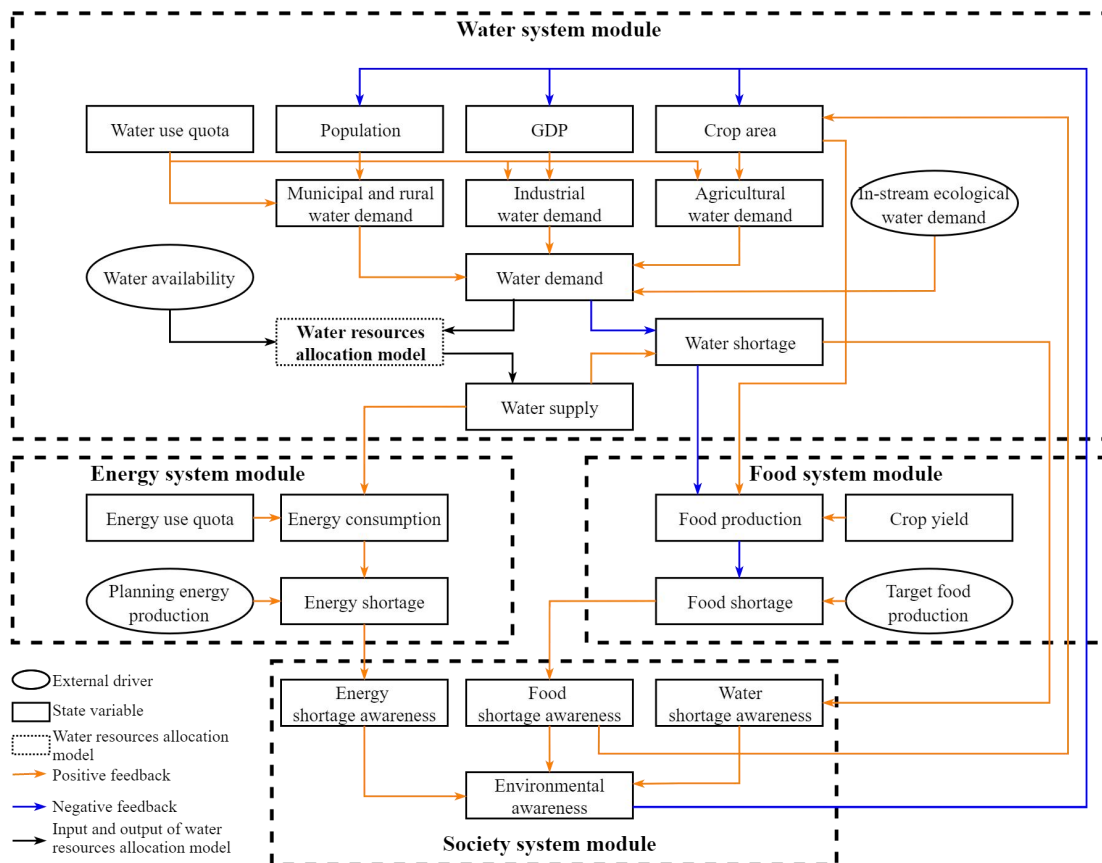
108 The water resources allocation model can simultaneously incorporate reservoir
109 operation and water acquisition, and it has become an effective tool to quantitatively
110 assess the impacts of reservoir operation on water supply security, as well as WEF
111 security (Si et al., 2019; Zhou et al., 2019). Our study aims to establish a system
112 dynamic model for the water-energy-food-society (WEFS) nexus and assess the
113 impacts of reservoir operation on the WEFS nexus by integrating the water resources
114 allocation model into the integrated system. The remainder of this paper is organized as
115 follows: Section 2 introduces the framework for modeling the WEFS nexus and
116 assessing the impacts of water resources allocation on the WEFS nexus. Section 3
117 describes the methodologies applied in the mid-lower reaches of the Hanjiang river
118 basin in China, which is the study area. Section 4 presents the results of the
119 co-evolution process and the sensitivity analysis of the WEFS nexus. The impacts of
120 water resources allocation on the WEFS nexus have also been discussed. The
121 conclusions of this study are presented in Section 5.

122 **2 Methods**

123 System dynamic modeling (SDM) simulates the dynamics among different
124 systems using nonlinear ordinary differential equations and dynamic feedback loops
125 (Wolstenholme and Coyle, 1983; Swanson, 2002). SDM has become an efficient
126 approach to facilitate the integrated analysis of sectors, processes, and interrelations
127 among different system variables (Di Baldassarre et al., 2015; Simonovic, 2002). The
128 SDM for assessing the WEFS nexus comprises four modules (shown in Figure 1):
129 water system module, energy system module, food system module, and society
130 system module.

131 In the water system module, socioeconomic water demand (i.e., municipal, rural,
132 industrial, and agricultural water demand) and in-stream water demand are projected
133 using the quota method and Tennant method (Tennant, 1976), respectively. The water
134 demands and available water resources are further inputted into the water resources
135 allocation model to determine the water supply and water shortage for every water use
136 sector in each operational zone. The water supply for socioeconomic water use sectors
137 and agricultural water shortage rates as outputs from the water system module are
138 taken as the inputs of the energy system module and food system module to determine
139 the energy consumption and food production, respectively. Considering the outputs of
140 the energy and food system modules, the energy and food shortages can be estimated
141 by comparing the planning energy availability and target food production,
142 respectively. The function of the society module is to capture human sensitivity to

143 degradation in the WEF nexus (Elshafei et al., 2014). Environmental awareness is
 144 considered as the conceptual social state variable to indicate human sensitivity (Van
 145 Emmerik et al., 2014). Environmental awareness is composed of water shortage
 146 awareness, energy shortage awareness, and food shortage awareness that are
 147 determined by shortages of water, energy, and food, respectively. As environmental
 148 awareness accumulates over its critical value, negative feedback on socioeconomic
 149 sectors (i.e., population, GDP, and crop area) will be triggered to constrain the
 150 increases in water demand, and further energy consumption, and food production to
 151 sustain the WEFS nexus.



152
 153

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

154 **2.1 Water System Module**

155 **2.1.1 Water Demand Projection**

156 Water user comprises socioeconomic (also called off-stream) user and in-stream
157 user. Socioeconomic water users can be classified into municipal, rural, industrial,
158 and agricultural sectors. The quota method has been considered an efficient approach
159 to project the annual socioeconomic water demand (Brekke et al., 2002). The amount
160 of water demand for the socioeconomic users can be estimated using equation (1).

161
$$WD_{i,j}^t = WQ_{i,j}^t * A_{i,j}^t / U_{i,j}^t \quad (1)$$

162 where $WD_{i,j}^t$ is the amount of water demand for the j -th user in the i -th operational
163 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
164 amount of water units of water user; and $U_{i,j}^t$ represents the utilization rate of water
165 user. The water quota units represent the amount of water consumption per capita in
166 municipal and rural users, the amount of water consumption per ten thousand Yuan in
167 industrial user, and the amount of net irrigation water per unit area in agricultural user,
168 respectively. The amount of water units represents the projected population in
169 municipal and rural users, projected GDP in industrial user, and projected irrigated
170 area in agricultural user.

171 As population, GDP, crop area, and water use quota are prerequisites for water
172 demand projection, the dynamic equations for these socioeconomic variables should
173 be pre-determined. There are two types of methods which are popular in
174 socioeconomic projection, Malthusian model (Bertalanffy, 1976; Malthus, 1798) and

175 Logistic model (Law et al., 2003), which are adopted for the socioeconomic
176 projection. The growth rate in original Malthusian model is constant (Malthus, 1798),
177 which is not consistent with previous studies that the socioeconomic expansion in the
178 future would slow down (He et al., 2017; Lin et al., 2016). Therefore, we used
179 exponential terms to simulate the evolution of socioeconomic variables, which
180 increases with decreasing rate. And feedback functions, as well as environmental
181 carrying capacities (indicating the maximum socioeconomic size that can be carried
182 by the system) of socioeconomic variables are adopted to constrain the evolution of
183 these socioeconomic variables through equations (2)–(4) (Feng et al., 2016;
184 Hritonenko and Yatsenko, 1999). Socioeconomic factors in original Logistic model
185 (Law et al., 2003) are prone to approach to their environmental carrying capacities,
186 while the constrains among subsystems in WEFS nexus are typically neglected, which
187 will lead over-sized socioeconomic projection. Therefore, feedback functions taken as
188 constraints from subsystems are adopted in equation (5)–(7) (Li et al., 2019; Wu et al.,
189 2022).

$$190 \quad \begin{cases} \frac{dN_t}{dt} = r_{P,t} * N_t \\ r_{P,t} = \begin{cases} r_{P,0} * \kappa_P * \exp(-\varphi_P t) + f_1(E) & N_t \leq N_{cap} \\ \text{Min}(0, r_{P,0} * \kappa_P * \exp(-\varphi_P t) + f_1(E)) & N_t > N_{cap} \end{cases} \end{cases} \quad (2)$$

$$191 \quad \begin{cases} \frac{dG_t}{dt} = r_{G,t} * G_t \\ r_{G,t} = \begin{cases} r_{G,0} * \kappa_G * \exp(-\varphi_G t) + f_2(E) & G_t \leq G_{cap} \\ \text{Min}(0, r_{G,0} * \kappa_G * \exp(-\varphi_G t) + f_2(E)) & G_t > G_{cap} \end{cases} \end{cases} \quad (3)$$

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

$$\frac{dN_t}{dt} = N_t * (r_{P,0} * (1 - \frac{N_t}{N_{cap}}) + f_1(E)) \quad (5)$$

$$\frac{dG_t}{dt} = G_t * (r_{G,0} * (1 - \frac{G_t}{G_{cap}}) + f_2(E)) \quad (6)$$

$$\frac{dCA_t}{dt} = CA_t * (r_{CA,0} * (1 - \frac{CA_t}{CA_{cap}}) + f_3(E, FA)) \quad (7)$$

196 where N_t , G_t , and CA_t are the population, GDP, and crop area in the t -th year,
 197 respectively; N_{cap} , G_{cap} , and CA_{cap} denote the environmental carrying capacities of
 198 population, GDP, and crop area, respectively; $r_{P,0}$, $r_{G,0}$, and $r_{CA,0}$ represent the growth
 199 rates of population, GDP, and crop area from historical observed data, respectively; $r_{P,t}$,
 200 $r_{G,t}$, and $r_{CA,t}$ are the growth rates of population, GDP, and crop area in the t -th year,
 201 respectively; $\kappa_P * \exp(-\varphi_P t)$, $\kappa_G * \exp(-\varphi_G t)$, and $\kappa_{CA} * \exp(-\varphi_{CA} t)$ are used to depict the
 202 impacts of social development on the evolution of population, GDP, and crop area,
 203 respectively; E is environmental awareness; FA is food shortage awareness; and f_1 , f_2 ,
 204 and f_3 represent the feedback functions. The equations for E , FA , and feedback
 205 functions are described in detail in Sections 2.4 and 2.5.

206 Water use quotas are also assumed to decrease with the social development
 207 owing to the expansion economy (Blanke et al., 2007; Hsiao et al., 2007). As the
 208 difficulties in saving water by technological advancement are increasing, the changing
 209 rate of water use quota is decreasing in equation (8) (Feng et al., 2019).

210

$$\begin{cases} \frac{dWQ_{i,j}^t}{dt} = WQ_{i,j}^t * r_{qwu,t} \\ r_{qwu,t} = \begin{cases} r_{qwu,0} * \kappa_{qwu} * \exp(-\varphi_{qwu} t) & WQ_{i,j}^t > WQ_{i,j}^{min} \\ 0 & \text{else} \end{cases} \end{cases} \quad (8)$$

211 where $WQ_{i,j}^t$ denotes the water use quota of the j -th water user in the i -th operational
 212 zone in the t -th year; $r_{qwu,0}$ and $r_{qwu,t}$ are the growth rates of water use quotas from
 213 historical observed data and t -th year, respectively; $WQ_{i,j}^{min}$ is the minimum value of
 214 water use quotas; and $\kappa_{qwu} * \exp(-\varphi_{qwu} t)$ is used to depict the water-saving effect of
 215 social development on the evolution of water use quota.

216 2.1.2 Water Resources Allocation

217 Based on water availability and projected water demand, available water
 218 resources can be deployed to every water use sector and in-stream water flows using a
 219 water resources allocation model. The Interactive River-Aquifer Simulation (IRAS)
 220 model is a rule-based water system simulation model developed by Cornell University
 221 (Loucks, 2002; Zeng et al., 2021; Matrosov et al., 2011). The year is divided into
 222 user-defined time step, and each time step is broken into user-defined sub-time step,
 223 based on which water resources allocation conducts. The IRAS model was adopted
 224 for water resources allocation owing to its flexibility and accuracy in water system
 225 simulations.

226 As water system comprises water transfer, consumption, and loss components, it
 227 is typically delineated by node network topology for the application of the water
 228 resources allocation model. Reservoir nodes and demand nodes are the most
 229 important elements in the node network topology, as they directly correspond to the

230 processes of water supply, acquisition, and consumption. The water shortage at the
 231 demand node should first be determined based on its water demand and total water
 232 supply. The total water supply comprises natural water inflow (i.e., local water
 233 availability) and water supply from reservoir. In each sub-time step (except the first),
 234 the average natural water inflow in the previous $sts-1$ sub-time steps is estimated as
 235 the projected natural water inflow in the remaining sub-time steps using equation (9).
 236 The water shortage can then be determined by deducting the demand reduction, total
 237 real-time water inflow, and projected natural water inflow from water demand using
 238 equation (10). The total water shortage rate can then be determined using equation
 239 (11).

$$240 \quad WE_{i,j}^{sts} = \left(\sum_1^{sts-1} WTSup_{i,j}^{sts} - \sum_1^{sts-1} WRSup_{i,j}^{sts} \right) * \frac{(Tsts - sts + 1)}{(sts - 1)} \quad (9)$$

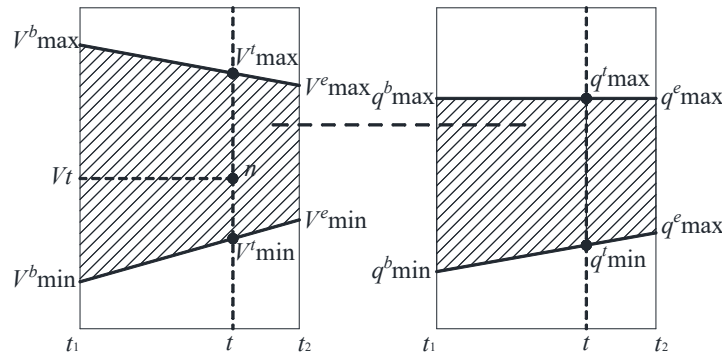
$$241 \quad WS_{i,j}^{sts} = \frac{WD_{i,j}^{ts} (1 - f_{red}) - \sum_1^{sts} WTSup_{i,j}^{sts} - WE_{i,j}^{sts}}{Tsts - sts + 1} \quad (10)$$

$$242 \quad WSR_t = \frac{\sum_{i,j} WSR_{i,j}^t}{f_{red} * \sum_{i,j} WD_{i,j}^t} = \frac{\sum_{i,j} \sum_{ts} \sum_{sts} WS_{i,j}^{sts}}{f_{red} * \sum_{i,j} \sum_{ts} WD_{i,j}^{ts}} \quad (11)$$

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

249 The water shortage at the demand node requires water release from the

250 corresponding reservoir nodes according to their hydrological connections. The
 251 amount of water released from the reservoir depends on the water availability for
 252 demand-driven reservoirs and operational rules for supply-driven reservoirs,
 253 respectively. The water release for the supply-driven reservoir is linearly interpolated
 254 based on Figure 2 and equations (12)–(18). Additional details on the IRAS model can
 255 be found in Matrosov et al. (2011).



256
 257 **Figure 2. Water release rule for supply-driven reservoir.**

258
$$P_t = (t - t_1) / (t_2 - t_1) \quad (12)$$

259
$$V_{\max}^t = V_{\max}^b * (1 - P_t) + V_{\max}^e * P_t \quad (13)$$

260
$$V_{\min}^t = V_{\min}^b * (1 - P_t) + V_{\min}^e * P_t \quad (14)$$

261
$$q_{\max}^t = q_{\max}^b * (1 - P_t) + q_{\max}^e * P_t \quad (15)$$

262
$$q_{\min}^t = q_{\min}^b * (1 - P_t) + q_{\min}^e * P_t \quad (16)$$

263
$$P_v = (V^t - V_{\min}^t) / (V_{\max}^t - V_{\min}^t) \quad (17)$$

264
$$q^t = q_{\min}^t * (1 - P_v) + q_{\max}^t * P_v \quad (18)$$

265 where t , t_1 , and t_2 are the current time, initial time, and end time in the period,
 266 respectively; P_t denotes the ratio of current time length to period length; V_{\max}^t , V_{\min}^t ,
 267 V_{\max}^b , V_{\min}^b , V_{\max}^e , and V_{\min}^e represent the maximum and minimum storages at the
 268 current time, beginning, and ending of the period, respectively; q_{\max}^t , q_{\min}^t , q_{\max}^b ,

269 q_{\min}^b , q_{\max}^e , and q_{\min}^e denote the maximum and minimum releases, respectively; P_v
 270 is the ratio of current storage; and q_t is the current release.

271 2.2 Energy System Module

272 The energy system module focuses on the energy consumption during the water
 273 supply process for socioeconomic water users to further investigate the energy
 274 co-benefits of water resources allocation schemes (Zhao et al., 2020; Smith et al.,
 275 2016). Energy consumption for water heating and water end-use was not included in
 276 this study. Energy consumption is determined by the energy use quota and amount of
 277 water supply for the water use sectors (Smith et al., 2016). As energy use efficiency
 278 will be gradually improved with social development, the energy use quota is assumed
 279 to decrease with decreasing rate. The trajectory of the energy use is formulated in
 280 equation (19). The water supply for water use sectors derived from the water system
 281 module is used to estimate energy consumption using equation (20). The energy
 282 shortage rate will be further determined with planning energy availability using
 283 equation (21).

$$284 \begin{cases} \frac{dEQ_{i,j}^t}{dt} = EQ_{i,j}^t * r_{e,t} \\ r_{e,t} = \begin{cases} r_{e,0} * \kappa_e * \exp(-\varphi_e t) & EQ_{i,j}^t > EQ_{i,j}^{min} \\ 0 & \text{else} \end{cases} \end{cases} \quad (19)$$

$$285 EC_t = \sum_{i,j} WTSup_{i,j}^t * EQ_{i,j}^t \quad (20)$$

$$286 ESR_t = \frac{ES_t}{EC_t} = \frac{EC_t - PEA_t}{EC_t} \quad (21)$$

287 where $EQ_{i,j}^t$ is the energy use quotas of the j -th water user in the i -th operational zone
 288 in the t -th year; $r_{e,0}$ and $r_{e,t}$ denote the growth rates of energy use quotas from

289 historical observed data and the t -th year, respectively; $EQ_{i,j}^{min}$ is the minimum value
 290 of energy use quotas; $\kappa_e \cdot \exp(-\phi_e t)$ depicts the energy-saving effect of social
 291 development; EC_t is the total energy consumption; $WTSup_{i,j}^t$ is the total water
 292 supply of the j -th water user in the i -th operational zone; ES_t and ESR_t are the
 293 energy shortage and energy shortage rate, respectively; and PEA_t is the planning
 294 energy availability.

295 2.3 Food System Module

296 The food system module focuses on estimating the amount of food production.
 297 As water is a crucial determinant for crop yield, the agricultural water shortage rate
 298 can constrain the potential crop yield (French and Schultz, 1984; Lobell et al., 2009).
 299 Owing to the technological advancements in irrigation, the amount of potential crop
 300 yield is assumed to increase with decreasing rate, as indicated by equation (22). With
 301 the target food production which has considered the local and exported food demands
 302 of basin, the food shortage rate can then be estimated using equations (23) and (24).

$$303 \quad \begin{cases} \frac{dCY_{i,j}^t}{dt} = CY_{i,j}^t * r_{pro,t} \\ r_{pro,t} = r_{pro,0} * \kappa_{pro} \exp(-\phi_{pro} t) \end{cases} \quad (22)$$

$$304 \quad FP_t = \sum_{i,j} CY_{i,j}^t * CA_{i,j}^t * (1 - WSR_{i,A}^t) \quad (23)$$

$$305 \quad FSR_t = \frac{FS_t}{TFP_t} = \frac{TFP_t - FP_t}{TFP_t} \quad (24)$$

306 where $CY_{i,j}^t$ is the potential crop yields of the j -th crop in the i -th operational zone in
 307 the t -th year; $r_{pro,0}$ and $r_{pro,t}$ are the growth rates of crop yields from historical
 308 observed data and the t -th year, respectively; $\kappa_{pro} \cdot \exp(-\phi_{pro} t)$ depicts the impacts of

309 social development on the evolution of crop yield; FP_t denotes the total food
310 production; $CA_{i,j}^t$ is the crop area; $WSR_{i,4}^t$ represents the water shortage rate of
311 agriculture sector; FS_t and FSR_t are the food shortage and food shortage rate,
312 respectively; and TFP_t is the target food production.

313 **2.4 Society System Module**

314 The society system module is deployed to simulate the social process of the
315 integrated system. Environmental awareness and community sensitivity are two
316 primary terms of social state variables in socio-hydrologic modeling that indicate the
317 perceived level of threat to a community's quality of life (Roobavannan et al., 2018).
318 Environmental awareness describes societal perceptions of environmental degradation
319 within the prevailing value systems (Feng et al., 2019; Feng et al., 2016;
320 Roobavannan et al., 2018; Van Emmerik et al., 2014). Community sensitivity
321 indicates people's attitudes towards not only the environmental control, but also the
322 environmental restoration (Chen et al., 2016; Elshafei et al., 2014; Roobavannan et al.,
323 2018). As this study focuses on societal perceptions on environmental degradation,
324 environmental awareness based on the concept described in Van Emmerik et al. (2014)
325 was adopted as the social state variable. As water, energy, and food systems are
326 considered part of the environment in this study, environmental awareness is assumed
327 to be determined by the shortage rates of water, energy, and food. Environmental
328 awareness accumulates when the shortage rates of water, energy, and food exceed the
329 given critical values, but decreases otherwise. The dynamics of environmental

330 awareness can be described by equations (25)–(28).

$$331 \quad \frac{dE}{dt} = \frac{dWA}{dt} + \frac{dEA}{dt} + \frac{dFA}{dt} \quad (25)$$

$$332 \quad \frac{dWA}{dt} = \begin{cases} \eta_W * (\exp(\theta_W * (WSR - WSR_{crit})) - 1) & WSR > WSR_{crit} \\ -\omega_W * WA & WSR \leq WSR_{crit} \end{cases} \quad (26)$$

$$333 \quad \frac{dEA}{dt} = \begin{cases} \eta_E * (\exp(\theta_E * (ESR - ESR_{crit})) - 1) & ESR \geq ESR_{crit} \\ -\omega_E * EA & ESR < ESR_{crit} \end{cases} \quad (27)$$

$$334 \quad \frac{dFA}{dt} = \begin{cases} \eta_F * (\exp(\theta_F * (FSR - FSR_{crit})) - 1) & FDR \geq FDR_{crit} \\ -\omega_F * FA & FDR < FDR_{crit} \end{cases} \quad (28)$$

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

344 2.5 Respond Links

345 Respond links are used to link society and water system modules through
 346 feedback. Respond links are driven by environmental awareness and food shortage
 347 awareness. The terms of feedback functions are based on the studies of Feng et al.
 348 (2019) and Van Emmerik et al. (2014), which have been established to have good
 349 performance and suitability, as they have been successfully applied to simulate the

350 human response to environmental degradation in the Murrumbidgee river basin
 351 (Australia) and Hehuang region (China).

352 Environmental awareness increases with constant shortages in water, energy, and
 353 food. As environmental awareness accumulates above its critical value, negative
 354 feedback on socioeconomic factors is triggered (Figure 1). The growth of population,
 355 GDP, and crop area will be constrained to alleviate the stress on the integrated system.
 356 Notably, positive feedback on the expansion of crop area will be triggered to fill food
 357 shortage as food shortage awareness exceeds its critical value (Figure 1). Although
 358 food shortage awareness is part of environmental awareness, the negative feedback
 359 driven by environmental awareness on crop area can only be triggered with the
 360 prerequisite that food shortage awareness is below its threshold value, as food
 361 production should first be assured. The respond links deployed by assuming feedback
 362 functions are expressed in equations (29)–(31).

$$363 \quad f_1(E) = \begin{cases} \delta_{rp}^E * (1 - \exp(\zeta_1 * (E - E_{crit}))) & E > E_{crit} \\ 0 & \text{else} \end{cases} \quad (29)$$

$$364 \quad f_2(E) = \begin{cases} \delta_{rg}^E * (1 - \exp(\zeta_2 * (E - E_{crit}))) & E > E_{crit} \\ 0 & \text{else} \end{cases} \quad (30)$$

$$365 \quad f_3(E, FA) = \begin{cases} \delta_{ra}^F * (\exp(\zeta_3^F * (FA - FA_{crit})) - 1) & FA > FA_{crit} \\ \delta_{ra}^E * (1 - \exp(\zeta_3^E * (E - E_{crit}))) & FA < FA_{crit} \ \& \ E > E_{crit} \\ 0 & \text{else} \end{cases} \quad (31)$$

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

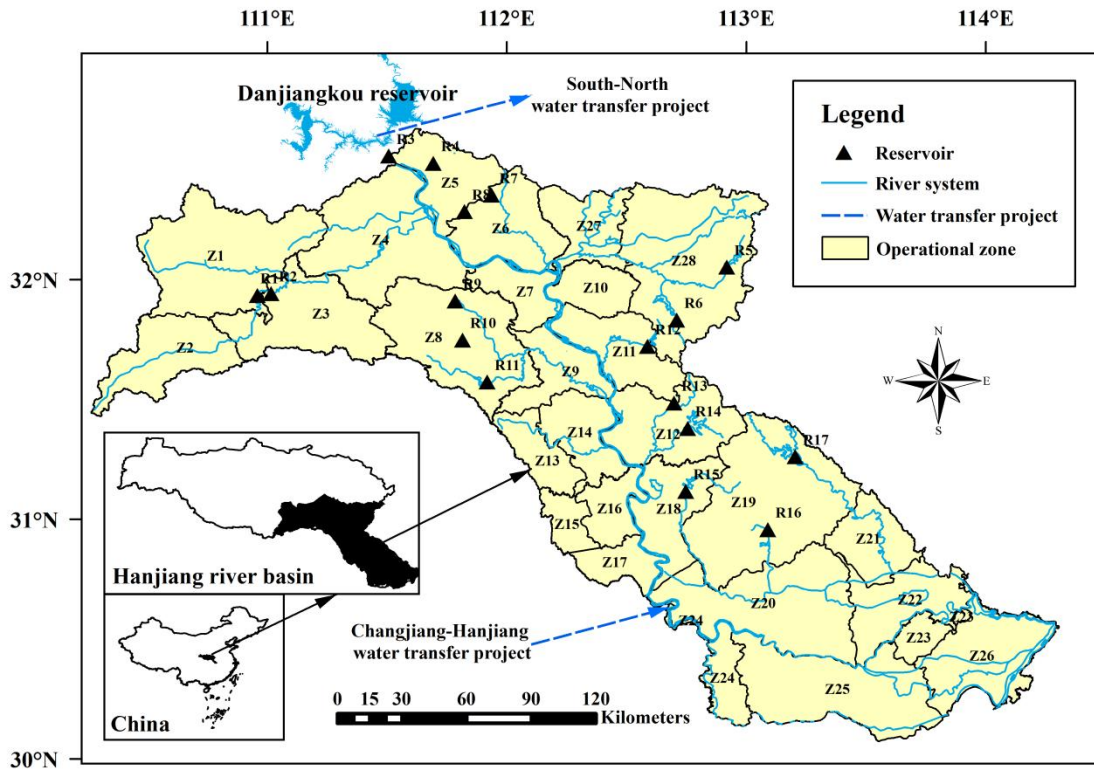
370 auxiliary factors for feedback functions driven by environmental awareness; and ζ_3^F

371 is the auxiliary factor for feedback functions driven by food shortage awareness.

372 **3 Case Study**

373 **3.1 Study Area**

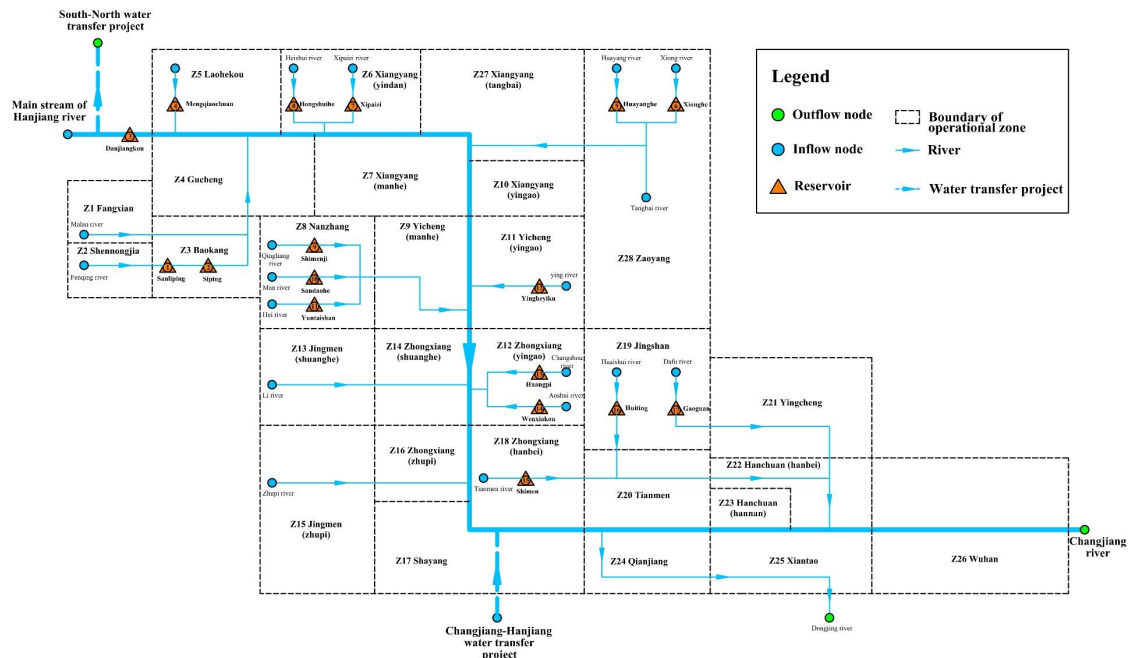
374 The Hanjiang river is the longest tributary of the Yangtze river. The total area of
375 the Hanjiang river basin is 159,000 km², divided into upper and mid-lower reaches
376 covering 95,200 and 63,800 km², respectively (shown in Figure 3). The Danjiangkou
377 reservoir is located at the upper boundary of the mid-lower reaches of the Hanjiang
378 river basin (MLHRB) and serves as the water source for the middle route of the
379 South–North water transfer project in China. Thus, the water availability in the
380 MLHRB is remarkably affected by the reservoir operation. In terms of energy, as the
381 population is large and the industry is developed in the MLHRB, the energy
382 consumption for urban water supply is high. For agriculture, as the land is flat and
383 fertile, MLHRB is considered an important grain-producing area, occupying one of
384 the nine major commodity grain bases in China (i.e., Jiangnan plain) (Xu et al., 2019).



385
386 **Figure 3. Location of mid-lower reaches of Hanjiang river basin.**

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

399 The socioeconomic data (i.e., population, GDP, and crop area) for water demand
 400 projection were collected based on administrative units, whereas the hydrological data
 401 were typically collected based on river basins. To ensure that the socioeconomic and
 402 hydrological data are consistent in operational zones, the study area was divided into
 403 28 operational zones based on the superimposition of administrative units and
 404 sub-basins. Seventeen existing medium or large size reservoirs (the total storage
 405 volume is 37.3 billion m³) were considered to regulate water flows. Based on the
 406 water connections between operational zones and river systems, the study area is
 407 shown in Figure 4, including 2 water transfer projects (the South–North and
 408 Changjiang–Hanjiang water transfer projects), 17 reservoirs, and 28 operational
 409 zones.



410
 411 **Figure 4. Sketch of the water system for the mid-lower reaches of Hanjiang river basin.**

412 **3.2 Data Sources**

413 There are two main types of data: hydrological and socioeconomic data. The
414 monthly historical discharge series of each operational zone and inflow of reservoirs
415 from 1956 to 2016 were provided by the Changjiang Water Resources Commission
416 (CWRC, 2016). The characteristics and operational rules of the 17 reservoirs listed in
417 Table S1 in supplementary file were retrieved from the Hubei Provincial Department
418 of Water Resources (HPDWR 2014). Socioeconomic data, including population, GDP,
419 crop area, water use quota, energy use quota, and crop yield, during 2010–2019 were
420 collected from the yearbooks of Hubei Province, which can be obtained from the
421 Statistical Database of China’s Economic and Social Development ([http://data.
422 cnki.net/](http://data.cnki.net/)). Notably, the agricultural water use quota was related to the annual effective
423 precipitation frequency. Based on the precipitation frequency series during 1956–2016,
424 four typical exceedance frequencies (i.e., $P = 50\%$, 75% , 90% , and 95% are related to
425 the wet, normal, dry, extreme dry years), were adopted to simplify agricultural water
426 demand series. These historical data were further used to predict the future trajectories
427 of the WEFS nexus.

428 **4 Results and Discussion**

429 The SDM was applied to the MLHRB. Specifically, water availability from 1956
430 to 2016 was adopted as the future water availability, while dynamic water demand
431 was projected in water system module, both of which were inputted into water

432 resources allocation model. As the water resources allocation model in the water
 433 system module took a monthly time step in the study (and the sub-time step was the
 434 default value: 1 day), the annual water supply and water shortage were first
 435 determined before being outputted to the energy system and food system modules,
 436 respectively. The annual shortage rates of water, energy, and food were then used to
 437 determine environmental awareness and further the feedback. Table 1 lists the initial
 438 settings of the external variables for the integrated system. The co-evolutionary
 439 behaviors of the WEFS nexus were analyzed as follows: (1) the system dynamic
 440 model was calibrated using observed data, (2) co-evolution of the WEFS nexus was
 441 then interpreted and analyzed, (3) the impacts of environmental awareness feedback
 442 and water resources allocation on the WEFS nexus were discussed, and (4) sensitivity
 443 analysis for WEFS nexus was tested.

444 **Table 1 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	$m^3/(10^4 \text{ Yuan})$	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
$\sum_j CY_{\bullet,j}^0$ (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
$r_{qu,0}$	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

445 ^a ECC indicates the environmental carrying capacity. ^b As the primary source of water supply for agricultural use in
446 the study area is surface water, rather than groundwater, the energy consumption in the water supply process for
447 agricultural water use is negligible, and the energy use quota for agricultural water use is set as 0.

448 **4.1 Model Calibration**

449 As some parameters are adopted as auxiliary parameters, which are not equipped
450 with exactly physical definitions, there is no independent empirical data to calibrate
451 them. Therefore, by reviewing previous studies (Feng et al., 2019; Feng et al., 2016;
452 Van Emmerik et al., 2014) and expert knowledge, we evaluated the order of
453 magnitudes and rational boundaries for these parameters. An initial parameter
454 sensitivity analysis was then adopted to screen out the insensitive parameter, which
455 provided distinguishing 13 insensitive and 21 sensitive parameters. As the insensitive
456 parameters are not able to remarkably alter the system, the empirical values in
457 previous studies (Feng et al., 2019; Feng et al., 2016) were adopted. The sensitive
458 parameters in the model were then calibrated based on the observed data, and the
459 calibrated values are presented in Table S2 in supplementary file. The Nash–Sutcliffe
460 Efficiency (NSE) coefficient and percentage bias (PBIAS) (Krause et al., 2005; Nash
461 and Sutcliffe, 1970) were used to calibrate the model. When the NSE was >0.7 and
462 absolute value of PBIAS was $<15\%$, the modeling performance was considered
463 reliable. The simulated state variables, including annual water demand, energy
464 consumption, food production, population, GDP, and crop area, were compared with
465 their observed values during 2010–2019. As shown in Table 2, the NSEs range from
466 0.74 to 0.97, and the corresponding PBIASs are from -4.2% to 5.2% , indicating that
467 both Malthusian model and Logistic model can effectively fit the observed data of
468 WEFS nexus.

469 **Table 2 NSE and PBIAS of state variables.**

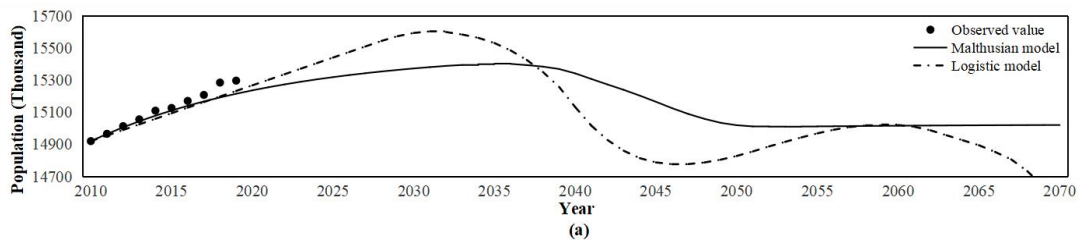
Model	Indicator	Water demand	Energy consumption	Food production	Population	GDP	Crop area
Malthusian model	NSE	0.91	0.74	0.79	0.97	0.86	0.94
	PBIAS (%)	-0.7	1.9	-0.6	-4.2	0.2	-0.8
Logistic model	NSE	0.79	0.74	0.82	0.94	0.85	0.96
	PBIAS (%)	-1.0	2.0	-0.2	5.2	0.3	-0.1

470 It's worth noting that the observed data can only cover the initial phase of WEFS
471 nexus co-evolution. The environmental awareness stays at a low level and the
472 feedback is not triggered, which indicates that feedback driven by high-level
473 environmental awareness hasn't been calibrated yet. However, as environmental
474 awareness is a subjective variable, there are no empirical data to calibrate it, which
475 requires more evidences to show adaptive human response to environmental
476 awareness. Hepburn et al. (2010) have reviewed studies on environmentally related
477 human behavioral economics. Substantial studies indicate that environmental
478 awareness is considered as an important factor in modelling socioeconomic decisions
479 and policies for water, energy and food systems (Li et al., 2019; Li et al., 2021; Lian
480 et al., 2018; Rockson et al., 2013; Xiong et al., 2016). For instance, Xiong et al. (2016)
481 investigated the evolution newspaper coverage of water issues in China based on
482 water-related articles in a major national newspaper, *People's Daily*. They found that
483 economic development was the primary target of China before 2000. With the conflict
484 between water demand and supply being intensified, concerns about water security
485 arisen in the newspaper since 2000, which indicated that environmental awareness

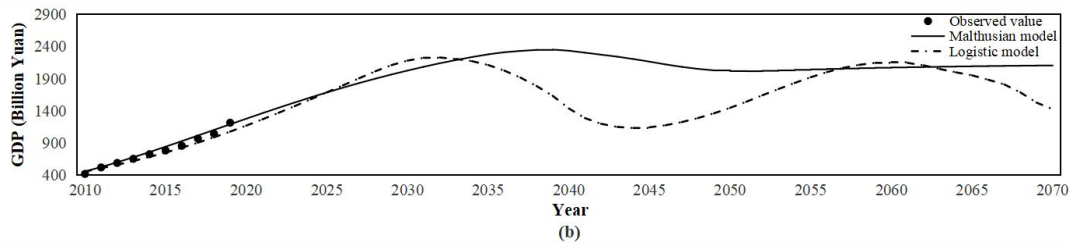
486 towards water shortage emerged. Related policies (e.g., the strictest water resources
 487 control system for water resources management policy in China) were thereby
 488 implemented to constrain the over-speed socioeconomic expansion and further ensure
 489 water security. Therefore, the established model still has potential to simulate the
 490 co-evolution of WEFS nexus.

491 **4.2 Co-evolution of WEFS Nexus**

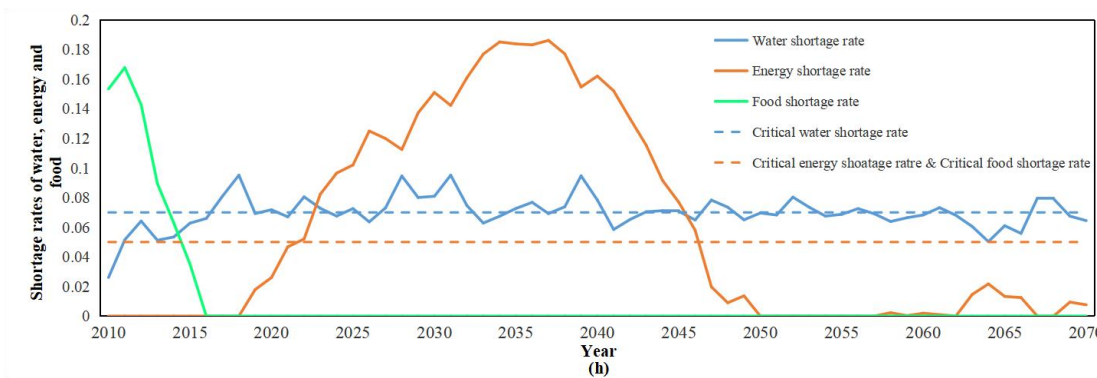
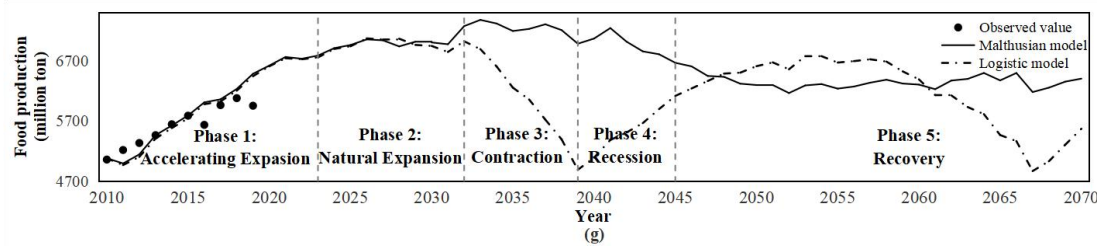
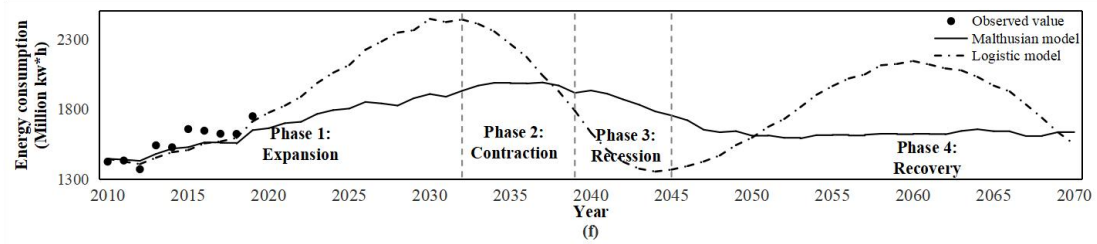
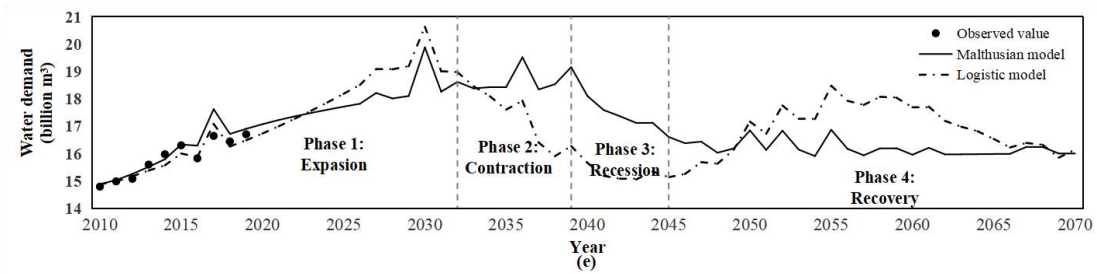
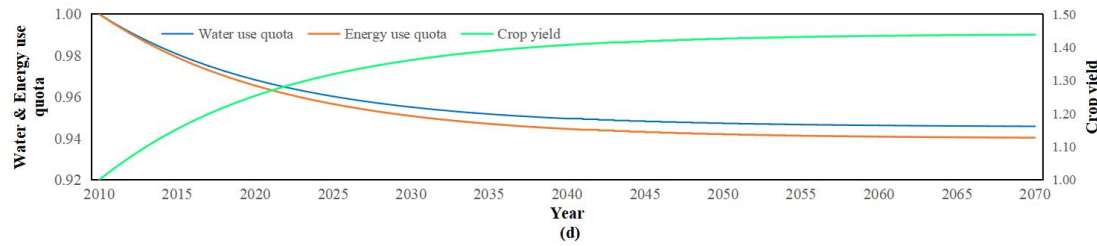
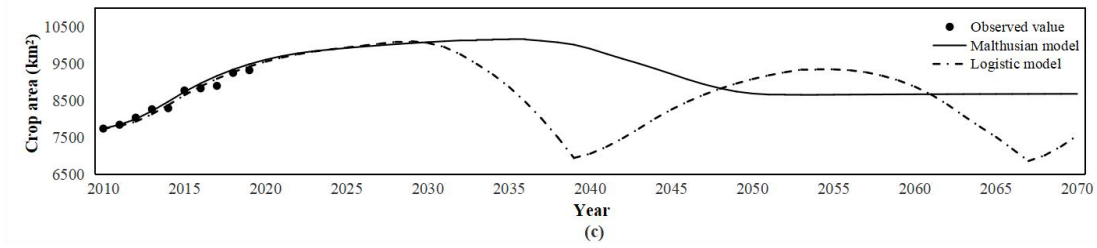
492 The calibrated system dynamic model was used to examine the properties of the
 493 integrated system by simulating the co-evolution of state variables in the WEFS nexus.
 494 Figure 5 shows the trajectories of population; GDP; crop area; water demand; energy
 495 consumption; food production; shortage rates for water, energy, and food; awareness
 496 for water shortage, energy shortage, and food shortage; and environmental awareness
 497 during 2010–2070.

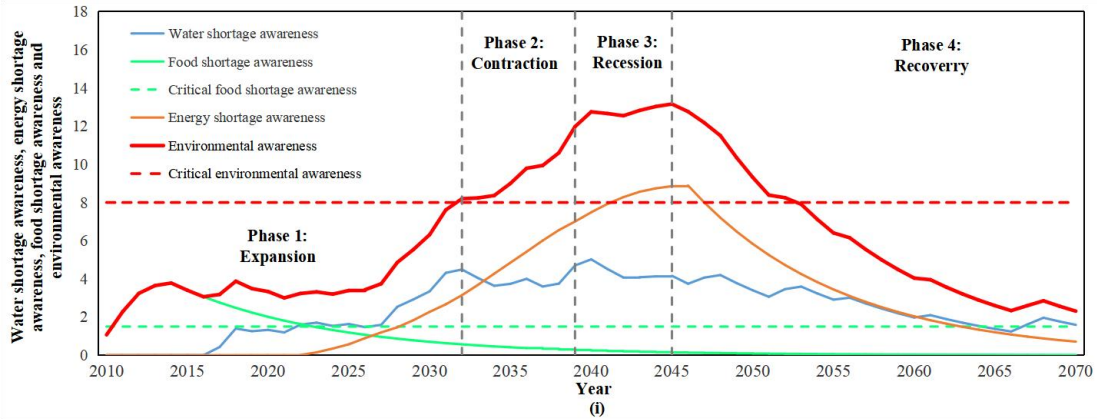


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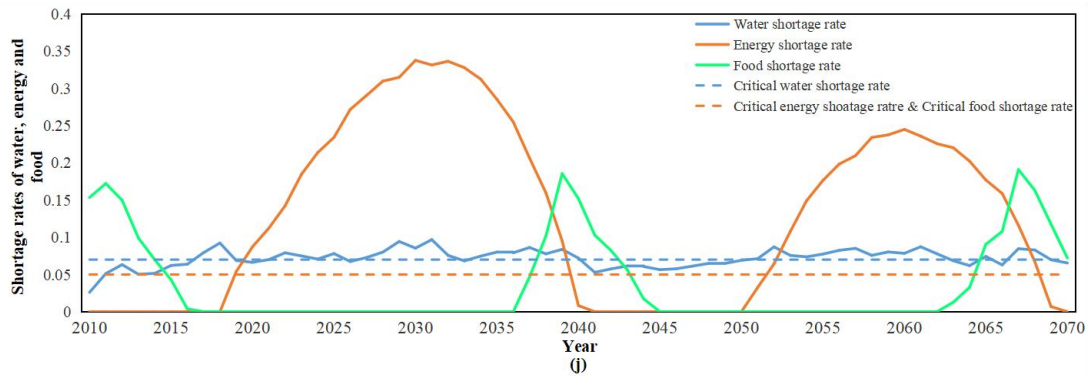


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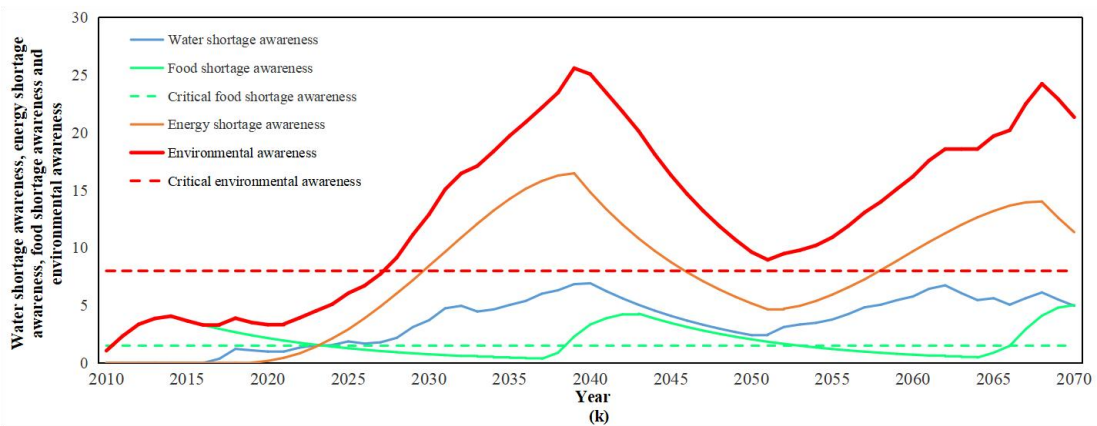




506



507



508

509 **Figure 5. Trajectories of state variables in WEFS nexus: (a) population; (b) GDP; (c) crop**
 510 **area; (d) percentage variations (compared with initial values) of water use quota, energy use**
 511 **quota, and crop yield; (e) water demand; (f) energy consumption; (g) food production; (h)**
 512 **shortage rates of water, energy, and food in Malthusian model; (i) water shortage awareness,**
 513 **energy shortage awareness, food shortage awareness, and environmental awareness in**
 514 **Malthusian model; (j) shortage rates of water, energy, and food in Logistic model; (k) water**
 515 **shortage awareness, energy shortage awareness, food shortage awareness, and**
 516 **environmental awareness in Logistic model.**

517 Based on the trajectory of environmental awareness, the co-evolution processes

518 of water demand and energy consumption in Malthusian model were divided into four

519 phases: expansion, contraction, recession, and recovery, which was consistent with the
520 results in Feng et al. (2016) and Elshafei et al. (2014).. Food production was divided
521 into five phases based on the trajectory of food shortage awareness: accelerating
522 expansion, natural expansion, contraction, recession, and recovery. The four phases in
523 the co-evolution process for water demand and energy consumption can be interpreted
524 as follows.

525 With environmental awareness below its critical value, the negative feedback on
526 socioeconomic sectors is not triggered, and water demand, as well as energy
527 consumption, increases rapidly, which is defined as expansion phase (2010–2032). In
528 the beginning of co-evolution, the water and energy demands can be satisfied by
529 water and energy availability. The shortage rates of water and energy were typically
530 below their critical values (Figure 5 (h)), and thus, shortage awareness of water and
531 energy remained at a low level as shown in Figure 5 (i). Despite food shortage struck
532 the system in the beginning, the shortage rate of which was 0.153 and more than its
533 critical value 0.05, the environmental awareness led by food shortage awareness was
534 still within its critical value 8.0. Therefore, environmental awareness feedback wasn't
535 triggered to constrain socioeconomic sectors, and water demand, as well as energy
536 consumption, thereby keeps increasing.

537 As environmental awareness exceeds its critical value, negative feedback on
538 socioeconomic sectors is triggered, and water demand and energy consumption is
539 constrained, which is defined as contraction phase (2033–2039). Although quotas for
540 water use and energy use decreased (Figure 5 (d)) with technological advancement,

541 water demand and energy consumption kept lowly increasing owing to the continuous
542 socioeconomic expansion (Figure 5 (a), (b), and (c)). Shortage rates of water and
543 energy remained over their critical values (Figure 5 (h), and (i)), leading the increases
544 of water shortage awareness and energy shortage awareness, and further
545 environmental awareness. Consequently, environmental awareness exceeded its
546 critical value in 2033 and continued to increase. Negative feedback on socioeconomic
547 sectors was triggered and strengthened. Water demand and energy consumption
548 gradually increased with decreasing rate and reached their maximum values of 19.2
549 billion m³ and 1,916 million kw*h, respectively, at the end of the contraction phase.

550 As environmental awareness accumulates to the maximum value, water demand,
551 and energy consumption decrease significantly, which is defined as recession phase
552 (2040–2045). Environmental awareness feedback indeed constrained water demand
553 and energy consumption, which decreased but still exceeded local water and energy
554 carrying capacities. Therefore, as the shortage rates of water and energy remained
555 exceeding their critical values (Figure 5 (h)), environmental awareness continued
556 accumulating and reached the maximum value of 13.2 at the end of the recession
557 phase, thereby decreasing water demand and energy consumption.

558 As environmental awareness gradually decreases below its critical value, water
559 demand and energy consumption decrease slightly and then tend to stabilize, which is
560 defined as recovery phase (2046–2070). With continuous decline of socioeconomic
561 sectors, water demand and energy consumption gradually decreased within their
562 carrying capacities. The shortage rates of water and energy have then decreased to

563 below their critical values since 2047, resulting in the decreases in water shortage
564 awareness and energy shortage awareness (Figure 5 (h) and (i)). As the environmental
565 awareness decreased below its critical value, negative feedback was removed, and the
566 integrated system tended to stabilize.

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

574 For Logistic model, socioeconomic sectors kept increasing in the initial phase.
575 The rapid socioeconomic expansion was slowed down until the negative feedback
576 driven by environmental awareness was triggered. With the increasing environmental
577 awareness, socioeconomic recession was followed. Since the decreasing
578 socioeconomic sectors were much lower than their environmental capacities and
579 feedback driven by environmental awareness was weakening, the variables turned to
580 increase again to approach to their environmental capacities, and rolled in cycles.

581 One of the major differences between results of Malthusian model and Logistic
582 model is that state variable evolution in logistic model fluctuates remarkably and
583 performs periodicity. However, it's worth noting that the socioeconomic expansion in
584 the future will slow down and tend to stabilization (He et al., 2017; Lin et al., 2016),

585 the growth rate of which will thereby decrease as time goes. Moreover, the economic
586 development in the study area is also expected to gradually grow and then remains
587 stable according to the Integrated Water Resources Planning of Hanjiang River Basin
588 (CWRC, 2016). As the periodic fluctuation for WEFS nexus evolution through
589 Logistic model is not consistent with the slowed socioeconomic expansion in
590 foreseeable future and cannot fitly satisfy the planning in the study area, Logistic
591 model is not adopted. Malthusian model can fitly meet the demand mentioned above,
592 which is thereby applied for further analysis on WEFS nexus in our study.

593 **4.3 Impacts of Environmental Awareness Feedback and Water Resources** 594 **Allocation on WEFS Nexus**

595 To determine the potential impacts of environmental awareness feedback and
596 water resources allocation on the WEFS nexus, four scenarios were set, the
597 description of which is provided in Table 3. The *Ecrit* and *FAcrit* under scenario II
598 were set as 10,000 to ensure that the feedback cannot be triggered in the study, and the
599 *WSRcrit* in scenarios III and IV were set as 0.15 to avoid the explosion of water
600 shortage awareness. The other parameters in scenarios II, III, and IV were consistent
601 with the calibrated values of scenario I, as listed in Table S2. Scenarios I and II and
602 scenarios III and IV were used to investigate the impacts of environmental awareness
603 feedback and water resources allocation on the WEFS nexus, respectively. The
604 average annual values of water demand, energy consumption, food production, and
605 shortage rates for water, energy, and food are listed in Table 4. Figure 6 shows the

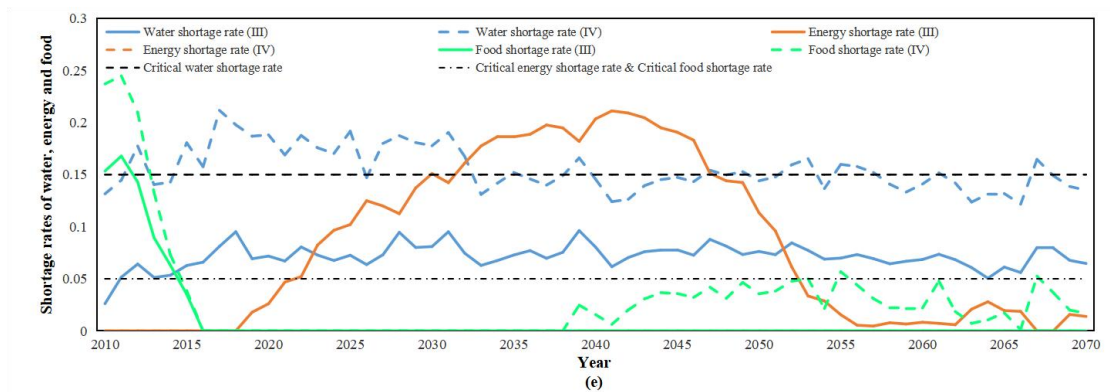
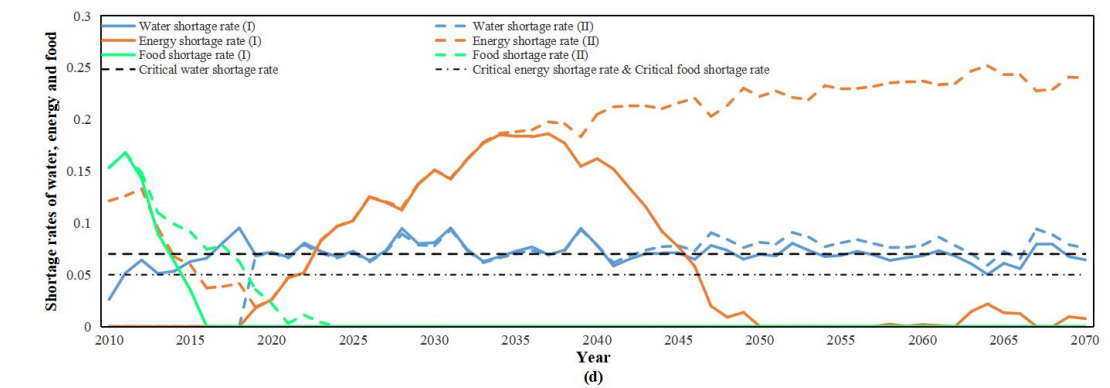
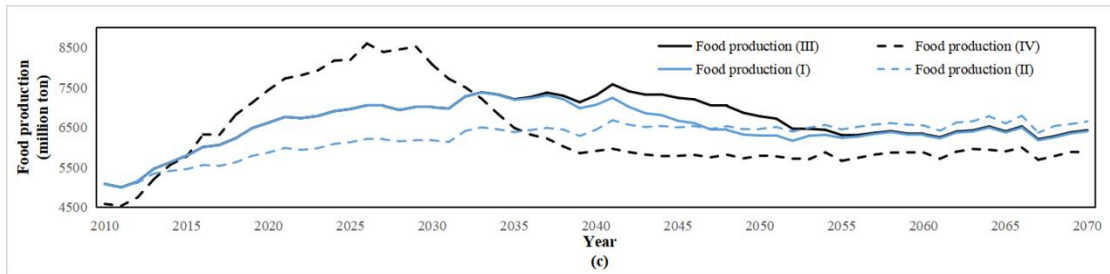
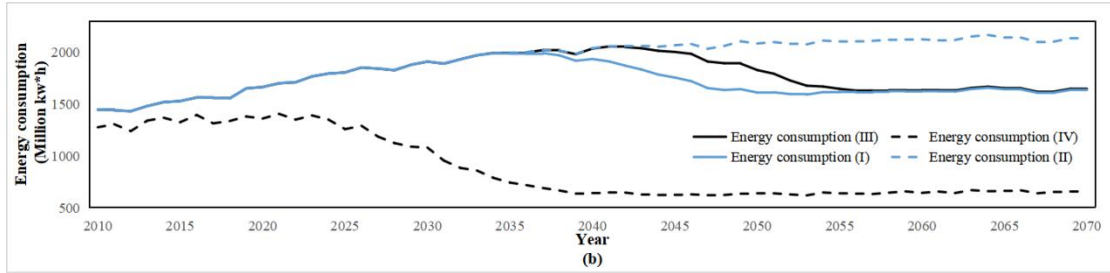
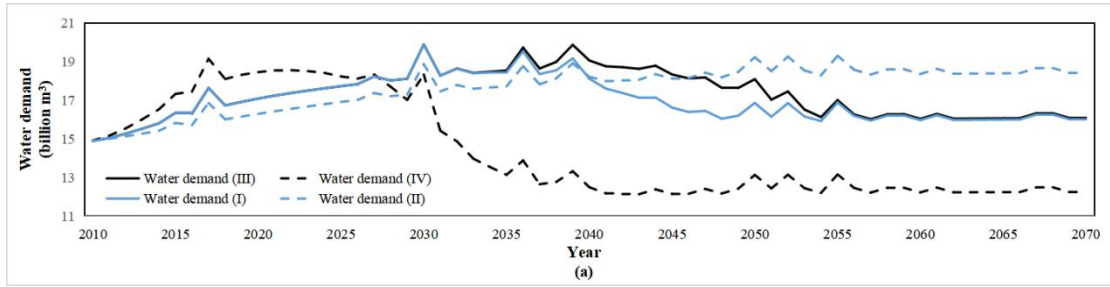
606 trajectories of key state variables of the integrated system, including water demand;
 607 energy consumption; food production; shortage rates for water, energy, and food;
 608 awareness of water shortage, energy shortage, and food shortage; and environmental
 609 awareness.

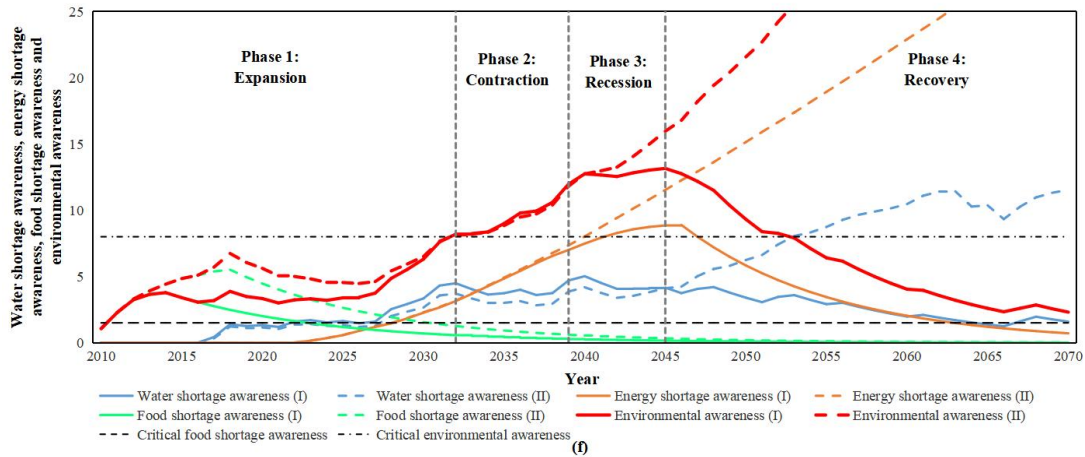
610 **Table 3 Scenario description for assessing the impacts of environmental awareness feedback**
 611 **and water resources allocation on WEFS nexus.**

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

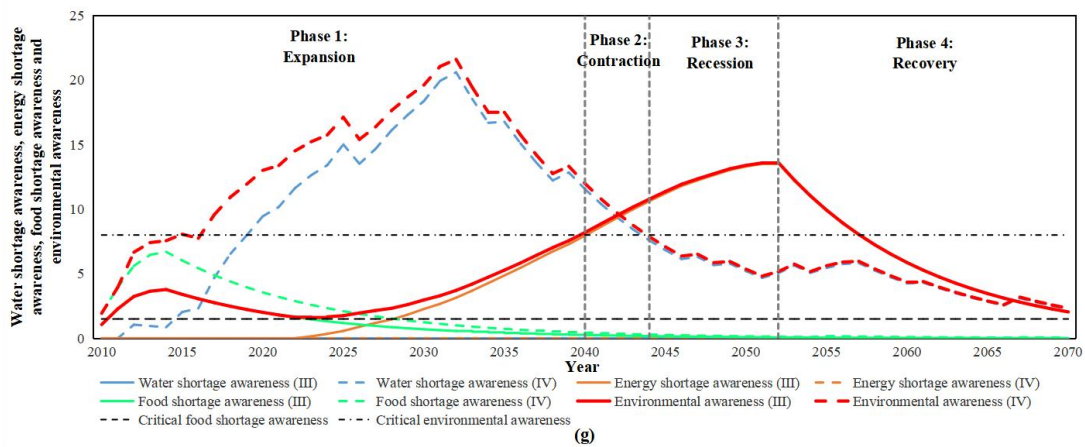
612 **Table 4 Average annual values for the state variables in WEFS nexus.**

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%





618



619

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

624 **4.3.1 WEFS Nexus Response to Environmental Awareness Feedback**

625 Environmental awareness indicates societal perceptions of resources shortages
 626 and is the driving factor of feedback on socioeconomic sectors. Both the average
 627 annual water demand and energy consumption increased from 16.94 billion m³ and
 628 1,710 million t under scenario I to 17.66 billion m³ and 1,930 million t under scenario
 629 II, respectively, as environmental awareness feedback was removed, whereas the food
 630 production decreased slightly, from 6,519 million t to 6,248 million t. Specifically,
 631 owing to high food shortage in the accelerating expansion phase of food production,

632 the positive feedback on crop area was triggered by food shortage awareness to
633 accelerate the increase in crop area. Food production was thus evidently larger when
634 feedback was considered in Figure 6 (c). Food shortage was then alleviated, and the
635 average shortage rate decreased from 1.74% to 1.07%. The increasing crop area
636 meanwhile led to an increase in agricultural water demand (Figure 6 (a)). However, as
637 the increasing water demand remained within the carrying capacity, little difference in
638 the water shortage rate existed between scenarios I and II (i.e., 7.03% and 7.44%,
639 respectively). As the water supply was efficiently ensured, the impacts on urban water
640 supply and the corresponding energy consumption were negligible. As water demand
641 and energy consumption increased rapidly in the expansion phase, environmental
642 awareness increased remarkably owing to the constant water and energy shortages, as
643 shown in Figure 6 (d) and (f). Negative feedback was triggered to constrain the
644 socioeconomic expansion. Compared with scenario II, water demand and energy
645 consumption decreased remarkably under scenario I. The stress on water and energy
646 supplies was thus relieved, particularly for the energy system, the shortage rate of
647 which decreased from 17.16% to 5.80%. Therefore, environmental awareness can
648 efficiently capture resources shortages and regulate the pace of socioeconomic
649 expansion through feedback, which can maintain the integrated system from constant
650 resources shortages to sustain the concordant development of the WEFS nexus.

651 **4.3.2 WEFS Nexus Response to Water Resources Allocation**

652 Water is considered the major driving factor for the WEFS nexus. Rational water
653 resources management plays an important role in the sustainable development of the

654 WEFS nexus. Water resources allocation can regulate the water flow by reservoir
655 operation, which is considered one of the most effective tools for water resources
656 management. Based on the Integrated Water Resources Planning of Hanjiang River
657 Basin (CWRC, 2016), domesticity and ecology water uses should be ensured first.
658 The priorities for water use from high to low are municipal and rural domesticity,
659 in-stream ecology, and industrial and agricultural sectors, respectively. The average
660 annual water demand, supply, and shortage under scenarios III and IV are listed in
661 Table 5.

662 **Table 5 Water resources allocation results under scenarios III and IV (million m³).**

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%

663 Despite the increase in water demand from 14,359 to 17,286 million m³ under
664 scenario III, the water supply also increased from 12,077 to 16,042 million m³. The
665 total water shortage rate decreased from 15.89% to 7.20% owing to rational water

666 resources allocation. As more available water resources can be stored in the flood
667 season and then released in the dry season through reservoir operation, the uneven
668 temporal and spatial distributions of available water resources were remarkably
669 relieved, thereby increasing the water supply insurance. For water use sectors, water
670 shortages were primarily found in industrial and agricultural sectors (719 and 399
671 million m³, respectively), and other sectors can be satisfied under scenario III. Water
672 shortage became more serious under scenario IV, as the water shortage rates of these
673 five sectors increased significantly in Table 5, from 0.24%, 0.23%, 11.05%, 6.21%,
674 and 3.29% to 8.67%, 8.69%, 21.26%, 15.80%, and 12.34%, respectively. To analyze
675 the spatial distribution of water shortage rates, Figure 7 shows the water shortage rate
676 in each operational zone under scenarios III and IV. The water shortage rates of the
677 study area under scenario IV were evidently higher than those under scenario III,
678 particularly for the operational zones located at the basin boundaries (e.g., operational
679 zones Z1, Z2, Z8, Z12, Z13, Z21 and so on). As the boundary zones are far away from
680 the mainstream of the Hanjiang river and their local water availability is unevenly
681 distributed, the regulating capacity of the water system is limited and is not
682 sufficiently strong to ensure the water supply.

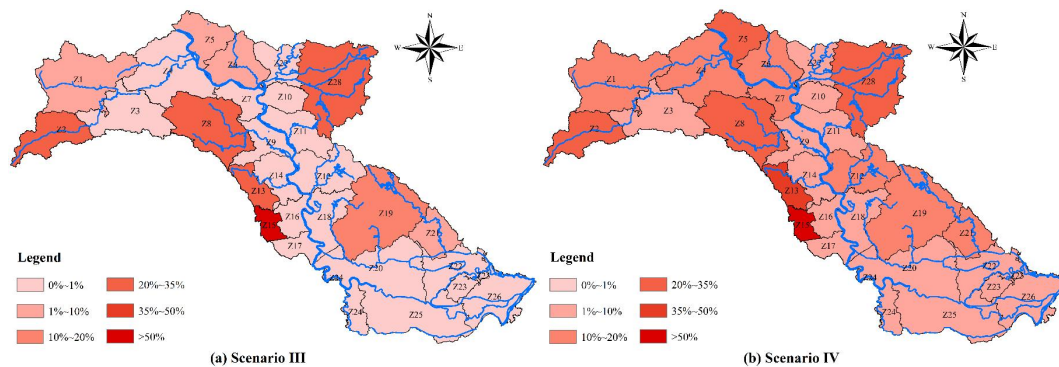


Figure 7. Distribution of water shortage rates.

685 For the co-evolution of WEFS nexus, a remarkable decrease in the average
686 annual water demand and energy consumption was observed as water resources
687 allocation was removed from 17.29 billion m³ and 1,761 million t under scenario III
688 to 14.36 billion m³ and 884 million t under scenario IV, while the food production
689 also decreased slightly from 6,638 million t to 6,344 million t. Under scenario IV
690 without considering water resources allocation, the average water shortage rate was
691 15.89%, exceeding the critical value. Water shortage awareness continued to
692 accumulate (Figure 6 (g)). As the water supply could not be effectively ensured and
693 remained at a low level, the energy consumption for urban water supply was small
694 and always within its planning value. No energy shortage awareness was accumulated
695 at the beginning of the co-evolution shown in Figure 6 (g). Meanwhile, as agricultural
696 water demand cannot be ensured, food production was also lowered (Figure 6 (c)).
697 Higher food shortages then led to higher food shortage awareness (Figure 6 (e), and
698 (g)). Thus, positive feedback to increase crop area was strengthened. As observed in
699 Figure 6 (a) and (c), the water demand increased slightly and food production
700 increased rapidly. As environmental awareness accumulated over its critical value in
701 2015 and continued to increase, negative feedback to constrain the socioeconomic
702 expansion was triggered and continued to strengthen. The energy consumption
703 thereby continued to decrease in Figure 6 (b), accounting for the significant decrease
704 in the energy shortage rate (i.e., from 8.25% to 0). Environmental awareness increased
705 and reached the maximum value of 21.6 in 2032 owing to the constant water shortage.
706 With the strong negative feedback, the water demand and food production decreased

707 remarkably and remained at a low level, as shown in Figure 6 (a) and (c), which
708 accounts for the increasing food shortage rate (i.e., from 1.08% to 3.08%).

709 With water resources allocation taken into account, water shortage was
710 significantly alleviated under scenario IV, as discussed in the water resources
711 allocation results (from 15.89% scenario IV to 7.20% under scenario III). The water
712 shortage rate remained below its critical value in the entire co-evolution process
713 (Figure 6 (e)). Thus, there was no accumulation of water shortage awareness shown in
714 Figure 6 (g). Energy consumption continued to increase as the water supply was
715 ensured. Environmental awareness accumulation was primarily due to energy
716 shortage.

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

728 **4.4 Sensitivity Analysis for WEFS Nexus**

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

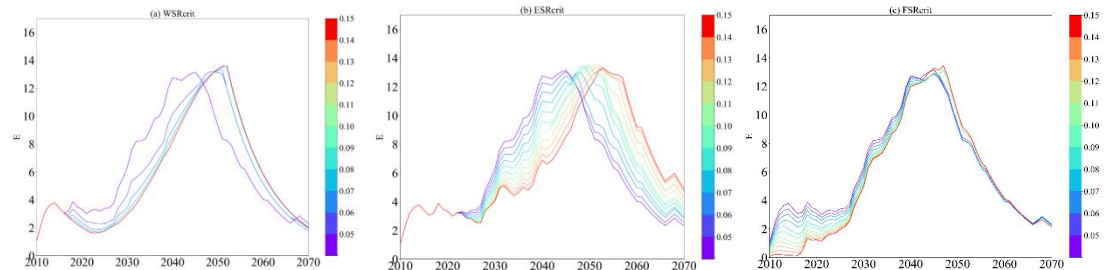
733 As environmental awareness feedback is dominated by the critical values and
 734 boundary conditions of the WEFS nexus, seven parameters were selected for
 735 sensitivity analysis (i.e., parameter 1~7 in Table 6). For water resources allocation,
 736 different reservoir operation schemes were adopted by adjusting water release from
 737 reservoir. Specifically, a multiplier for water release was added as a parameter to
 738 demonstrate the ratio to water release in scenario I (i.e., parameter 8 in Table 6). Each
 739 parameter was varied by the given increment, with the other parameters remaining
 740 unchanged. The maximum and minimum values, as well as the increments for the
 741 seven parameters, are listed in Table 6. Parameter sensitivity analysis was then
 742 conducted by analyzing the trajectories of environmental awareness, water demand,
 743 energy consumption, and food production, as shown in Figures 8, 9, 10, and 11.

744 **Table 6 Parameter set for sensitivity analysis.**

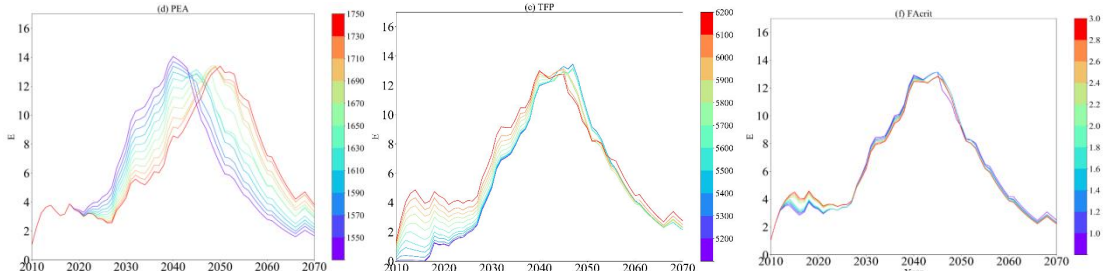
No.	Parameter	Description	Min.	Max.	Increment
1	<i>WSRcrit</i>	Critical water shortage rate	0.05	0.15	0.01
2	<i>ESRcrit</i>	Critical energy shortage rate	0.05	0.15	0.01
3	<i>FSRcrit</i>	Critical food shortage rate	0.05	0.15	0.01
4	<i>PEA</i>	Planning energy availability	1,550	1,750	20

5	<i>TFP</i>	Target food production	5,200	6,200	100
6	<i>FAcrit</i>	Critical food shortage awareness	1	3	0.2
7	<i>Ecrit</i>	Critical environmental awareness	5	10	0.5
8	<i>Qmultiplier</i>	Multiplier of water release from reservoir	0.5	1.5	0.1

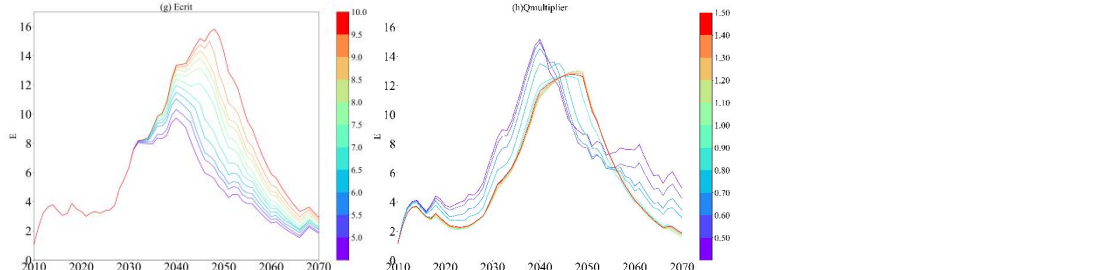
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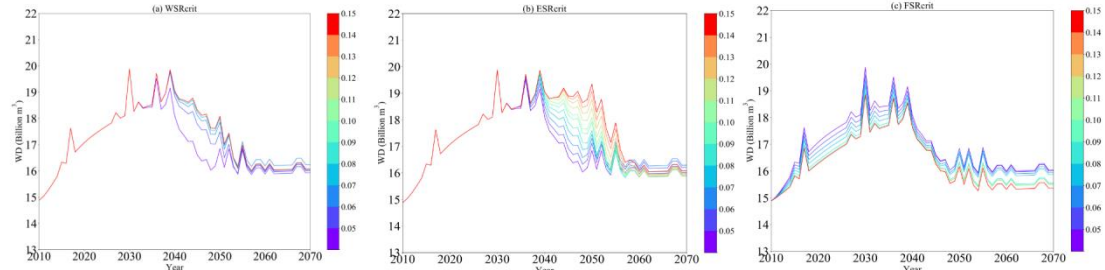
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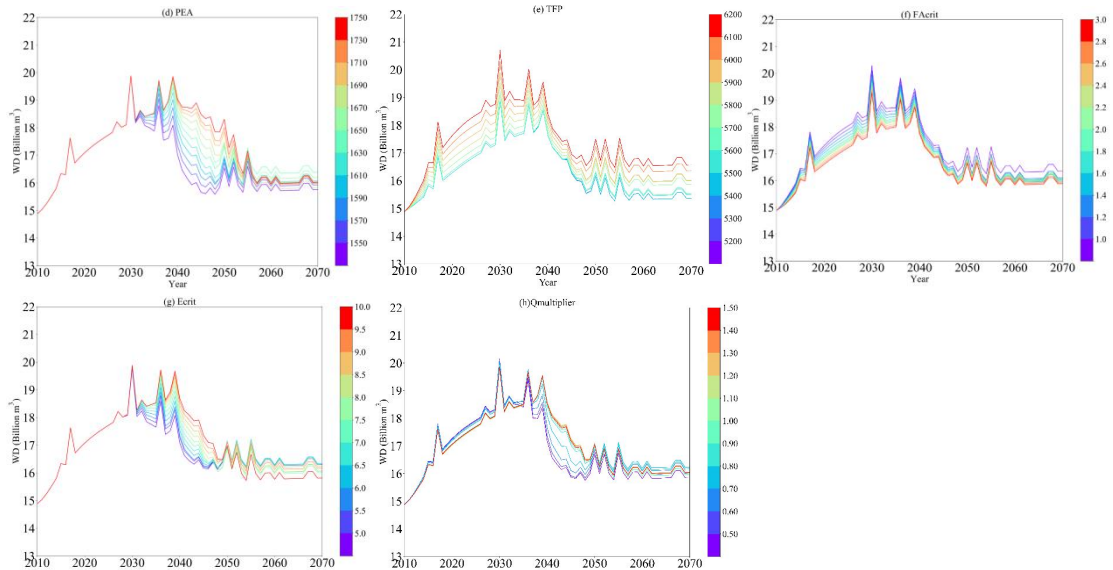


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Figure 8. Trajectories of environmental awareness with varied parameters.

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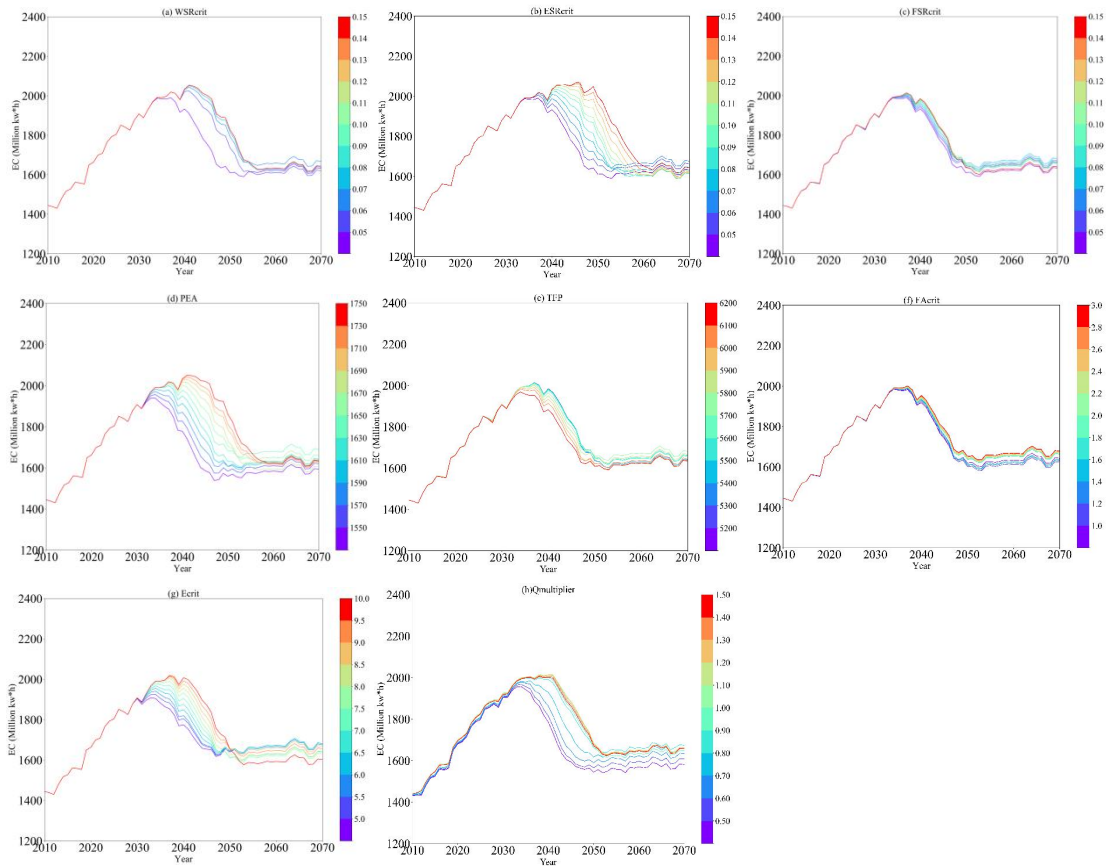


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Figure 9. Trajectories of water demand with varied parameters.



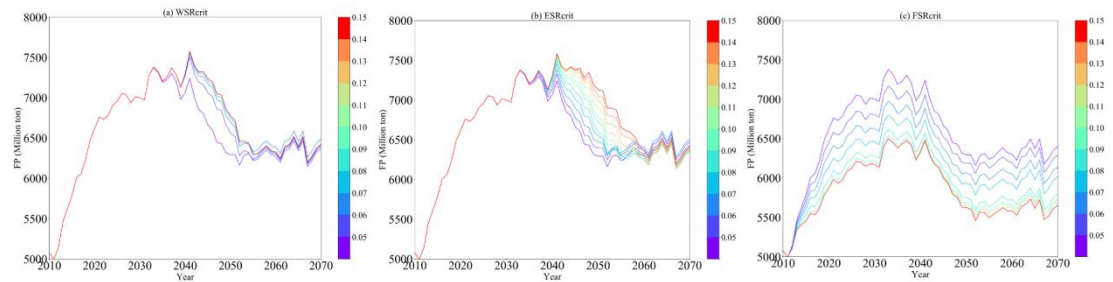
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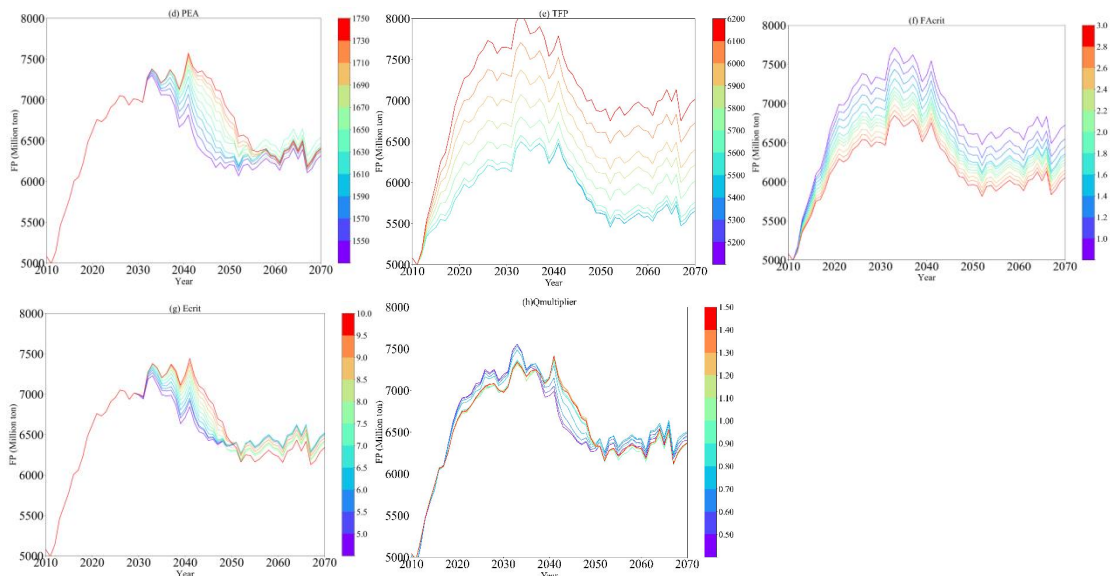
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Figure 10. Trajectories of energy consumption with varied parameters.



757



758
759
760 **Figure 11. Trajectories of food production with varied parameters.**

761 **4.4.1 Sensitivity Analysis of Environmental Awareness Feedback on WEFS Nexus**

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

767 Specifically, the sensitive responses to parameters *WSRcrit*, *ESRcrit*, *PEA*, and
 768 *ECrit* primarily occurred in the contraction and recession phases of the co-evolution
 769 process for WEFS nexus. As demands from water and energy systems can always be
 770 ensured by abundant resources availability in the expansion phase, limited water and
 771 energy shortages were observed. Environmental awareness accumulated primarily
 772 from food shortage awareness but remained below its critical value (Figure 5 (i)). As
 773 the feedback due to environmental awareness was not sufficiently strong, the impacts
 774 on the co-evolution of WEFS nexus were negligible and were considered as the

775 insensitivity. However, with social development, water demand and energy
776 consumption continued to grow and increase over the local carrying capability,
777 leading an increase in environmental awareness. Negative feedback on socioeconomic
778 sectors was then triggered. WSR_{crit} and ESR_{crit} are the critical values that determine
779 the awareness of water and energy shortages to accumulate, and PEA indicates the
780 amount of planning energy availability, which directly determines the energy shortage.
781 The environmental awareness accumulation can be thereby accelerated by
782 constraining WSR_{crit} , ESR_{crit} , and PEA (Figure 8 (a), (b), and (d)). E_{crit} is the
783 threshold for the negative feedback triggering driven by environmental awareness. A
784 lower E_{crit} means community is more sensitive to resources shortage and feedback is
785 easier to trigger (Figure 8 (g)). Therefore, environmental awareness feedback to
786 constrain socioeconomic expansion can be advanced and strengthened by lowering
787 WSR_{crit} , ESR_{crit} , PEA , and E_{crit} , accounting for the sensitive response of WEFS
788 nexus in contraction and recession phases.

789 FSR_{crit} , TFP , and FA_{crit} performed sensitivity during the entire co-evolution
790 process for WEFS nexus. As food shortages were considerable in the accelerating
791 expansion phase, food shortage awareness increased rapidly, driving the feedback to
792 increase crop area. TFP can directly determine food shortage, and FSR_{crit} and FA_{crit}
793 determine thresholds for food shortage awareness accumulation and feedback
794 triggering by food shortage awareness, respectively. Positive feedback on crop area to
795 increase food production can thus be advanced and strengthened by constraining
796 FSR_{crit} , TFP , and FA_{crit} (Figure 8 (c), (e), and (f)). The crop area then continued

797 increasing until environmental awareness feedback was triggered, resulting in the
798 increases in food production (Figure 11 (c), (e), and (f)) and water demand from
799 agricultural sector (Figure 9 (c), (e), and (f)). As the agricultural water use was
800 directly drawn from river system, the energy use quota during water supply was small
801 and negligible. Energy consumption was thus not sensitive to *FSRcrit*, *FAcrit*, and
802 *TFP* as shown in Figure 10. Therefore, constraining *FSRcrit*, *FAcrit*, and *TFP* is an
803 effective way to increase food production by advancing and strengthening the
804 feedback driven by food shortage awareness, which accounts for the sensitive
805 responses of environmental awareness, water demand, and food production in
806 expansion phase.

807 Simultaneously, it's worth noting that although constraining *WSRcrit*, *ESRcrit*,
808 *PEA*, and *Ecrit* can maintain the integrated system from constant water shortage and
809 energy shortage, the over-constrained condition can also sharply increase
810 environmental awareness (Figure 8 (a), (b), (d), and (e)). Environmental awareness
811 feedback was remarkably advanced, which shortened the expansion phase and led to
812 violent degradation of socioeconomic sectors (indicated by drastic decreases of water
813 demand, energy consumption and food production in Figure 9, 10, and 11,
814 respectively). The sustainability of WEFS nexus was seriously challenged. Similarly,
815 despite food production can be effectively increased by constraining *FSRcrit*, *FAcrit*,
816 and *TFP*, the over-constrained condition will cause a considerable increase in water
817 demand, as shown in Figure 9 (c), (e), and (f), which will further put stress on the
818 water supply. Moreover, the regulating capacity of the local system should also be

819 considered during parameter selection. For example, there was an abrupt decrease
820 when WSR_{crit} was set to 0.05, as shown in Figure 9 (a), Figure 10 (a), and Figure 11
821 (a). Violent socioeconomic degradation dominated by environmental awareness
822 feedback was triggered to decrease environmental awareness, indicating that the
823 WSR_{crit} was over-constrained and exceeded the regulating capacity of the local water
824 system. Therefore, a rational parameter setting should be based on the sustainability
825 of long-term co-evolution for socioeconomic sectors and the regulating capacity of
826 the local system, which is of great significance for sustaining the stability of the
827 WEFS nexus.

828 As each shortage is experienced by different users with different connections to
829 basin development dynamics (e.g., shortages from water, energy, and food are
830 aggregated into environmental awareness, despite the food which is planned to be
831 exported is considered in target food production), it's necessary to discuss the
832 contributions to environmental awareness from water, energy, and food systems.
833 Therefore, three weight factors were assigned to shortage awareness of water, energy,
834 and food in equation (32) to adjust the over-estimated or under-estimated
835 environmental awareness due to discordant scales. For instance, considering the target
836 food production comprises inner food demand and exported food, the environmental
837 awareness within the basin is over-estimated, and the weight factor for food shortage
838 awareness can be set lower than 1.0 as a reduction factor to decrease current food
839 shortage awareness. Sensitivity analysis was then conducted. Each weight factor was
840 varied by given increment, while the other two weight factors were set to 1.0 as

841 reference. The results are presented in Figure S1, S2, S3, and S4 in supplementary
842 file.

$$843 \quad \frac{dE}{dt} = wf_1 * \frac{dWA}{dt} + wf_2 * \frac{dEA}{dt} + wf_3 * \frac{dFA}{dt} \quad (32)$$

844 where wf_1 , wf_2 , and wf_3 are the weight factors for water, energy, and food shortage
845 awareness, respectively.

846 WEFS nexus is sensitive to shortage awareness weight factors. Specifically,
847 weight factors for water and energy shortage awareness can remarkably impact the
848 recession phases of water demand, energy consumption, and food production. Lower
849 weight factor can delay environmental awareness accumulation, and thus extend the
850 contraction phase. However, more violent socioeconomic deterioration was also
851 accompanied in the later recession phase, which consequently led the slightly smaller
852 socioeconomic size in recovery phase. Weight factor for food shortage awareness can
853 effectively dominate the whole evolution of water demand, and energy consumption.
854 Lower weight factor indicated that smaller food shortage awareness can be
855 accumulated. Feedback to increase crop area was thereby weakened. Both agriculture
856 water demand and food production were decreased. As energy use quota for
857 agricultural water supply is negligible, little response of energy consumption can be
858 found.

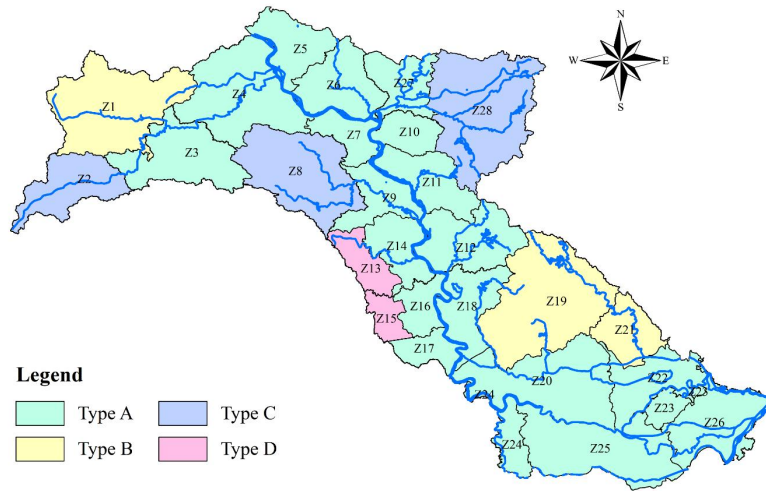
859 **4.4.2 Sensitivity Analysis of Water Resources Allocation Schemes on WEFS** 860 **Nexus**

861 The WEFS nexus in the study area was evidently constrained under water
862 resources allocation schemes with smaller water release from reservoir. The

863 decreasing water supply directly increased water shortage, the average annual
864 shortage rate of which increased from 6.41% to 8.01%. The rapid increase of water
865 shortage awareness then accelerated environmental awareness accumulation and
866 further the feedback shown in Figure 8 (h). As the negative feedback on
867 socioeconomic sectors was strengthened, water demand decreased rapidly in recession
868 phase (Figure 9 (h)). Water supply was thereby decreased with decreasing water
869 demand, which accounts for the decreasing energy consumption during water supply
870 process shown in Figure 10 (h). For food system, decreasing water release notably
871 altered the stability of food production evolution (Figure 11 (h)). Higher water
872 shortage rate led smaller food production and further larger food shortage awareness.
873 Feedback driven by food shortage awareness was strengthened to increase crop area.
874 Food production thereby increased in expansion phase. However, increasing crop area
875 was accompanied by increasing agricultural water demand, which brought increases
876 of water shortage and environmental awareness. With stronger environmental
877 awareness feedback, food production in recession phase thereby decreased rapidly.

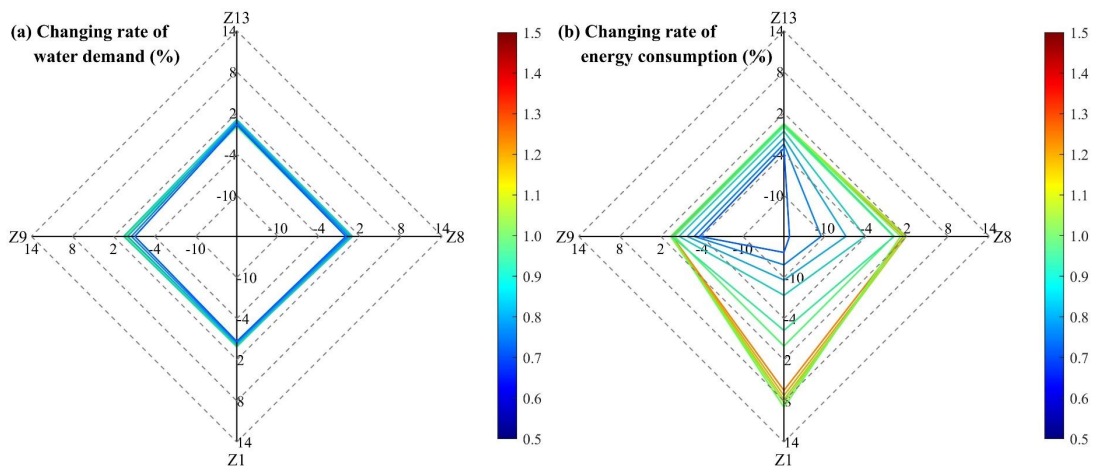
878 To assess the impacts of water resources allocation schemes in different
879 operational zones, the spatial distributions of water shortage and socioeconomic
880 variables including water demand, energy consumption, and food production were
881 considered. Operational zones were classified into four types as shown in Figure 12.
882 The zone with small water shortage, and the water shortage rate, and socioeconomic
883 variables of which perform insensitivity, is defined as type A. If water shortage can be
884 almost removed and socioeconomic variables are sensitive, the zone is defined as type

885 B. If water shortage can be partly alleviated and socioeconomic variables are sensitive,
 886 the zone is defined as type C. The zone with considerable water shortage, and the
 887 water shortage rate, and socioeconomic variables of which perform insensitivity, is
 888 defined as type D. Four representative zones including Z9 (Yichengmanhe) in type A,
 889 Z1 (Fangxian) in type B, Z8 (Nanzhang) in type C, and Z13 (Jingmenzhupi) in type D
 890 were selected to study the responses to different water resources allocation schemes.
 891 The water shortages and socioeconomic variables are presented in Figure 13.

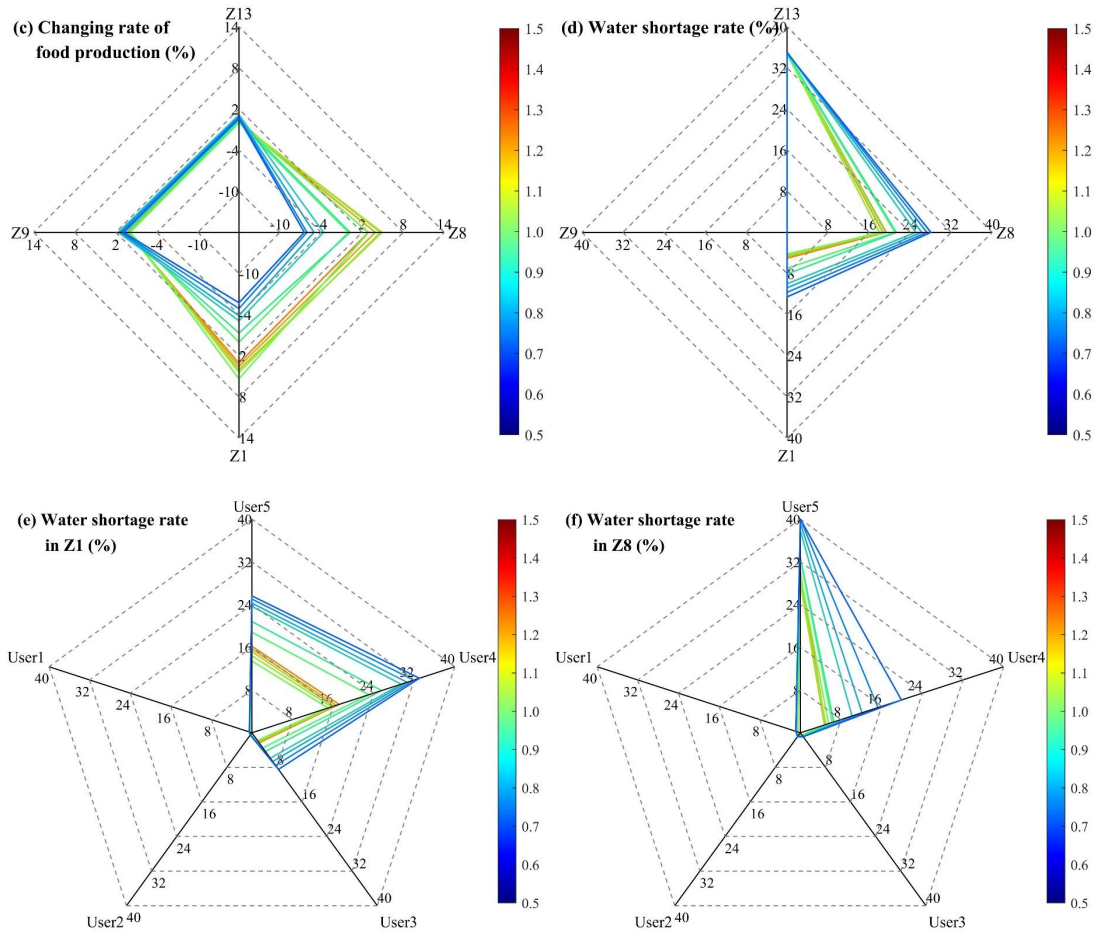


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893 **Figure 12. Spatial distribution of A, B, C, and D types of operational zones.**



894



895

896

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

902

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

906

No water shortage was observed in Z9 under different water resources allocation
 907 schemes (Figure 13 (d)), and the energy consumption, and food production also
 908 exhibited insensitivity shown in Figure 13 (b), and (c). As Z9 located along the main
 909 stream of Hanjiang river, the regulating capacity of water project was strong due to

910 Danjiangkou reservoir (whose total storage is 33,910 million m³). Despite of the
911 reduction of water release, the water demand can always be ensured, and the energy
912 consumption, and food production thereby remained stability. Water shortage rate in
913 Z1 decreased evidently with the increase of water release (Figure 13 (d)), and the
914 energy consumption, and food production further increased remarkably, as shown in
915 Figure 13 (b), and (c). Z1 located at the boundary of study area, the water supply of
916 which mainly depended on Sanliping reservoir (shown in Figure 3). The regulating
917 capacity of water project was strong enough to cover most part of water demand.
918 Therefore, the increasing water release remarkably relived water shortage (water
919 shortage rate decreased from 12.56% to 4.20%), particularly in industrial and
920 agricultural users, as shown in Figure 13 (e). Energy consumption during water
921 supply process thus increased, and food production also increased owing to the
922 decreasing agricultural water shortage rate. Response of Z8 to water resources
923 allocation schemes was similar to Z1. The difference was that local reservoirs in Z8
924 can provide limited regulating capacity, which can only cover part of water demand.
925 Water shortage was effectively alleviated, but still considerable (water shortage rates
926 were always more than 18% shown in Figure 13(d)). Z13 was far away from the
927 mainstream and there was no local reservoir. The regulating capacity of water project
928 was so weak that no response to water resources allocation schemes was observed.
929 Water was always the key resource constraining the development of Z13 (Figure 13
930 (d)).

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

945 **5. Conclusions**

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

952 China. The conclusions drawn from the study are as follows.

953 The proposed approach provides a valid analytical tool for exploring the
954 long-term co-evolution of the nexus across the water, energy, food, and society
955 systems. Environmental awareness in the society system shows potential to capture
956 human sensitivity to shortages from water, energy, and food systems. The feedback
957 driven by environmental awareness can regulate the pace of socioeconomic expansion
958 to maintain the integrated system from constant resources shortages, which
959 contributes to the sustainability of the WEFS nexus. The co-evolution of water
960 demand, energy consumption, and food production can be divided into expansion
961 (accelerating and natural expansion for food production), contraction, recession, and
962 recovery phases based on environmental awareness. Rational parameter setting of
963 boundary conditions and critical values can effectively control environmental
964 awareness feedback to help managers to keep the socioeconomic sectors from violent
965 expansion and deterioration in contraction and recession phases. Water resources
966 allocation can effectively relieve water shortage by increasing water supply. As
967 high-level environmental awareness led by water shortage is remarkably alleviated,
968 environmental awareness feedback is weakened and the socioeconomic sectors
969 develop rapidly. Threats from water shortage on the concordant development of
970 WEFS nexus are significantly alleviated. Regulating capacity of water project is an
971 important factor in water resources allocation to ensure the stability of water system
972 to sustain WEFS nexus. Particularly for the area with certain regulating capacity of
973 water project but cannot totally cover the water demand, regulating the water release

974 from reservoir by rational water resources allocation schemes can further ensure water
975 supply and is of great significance for the sustainable development of the WEFS
976 nexus.

977 We acknowledge that environmental awareness feedback functionality remains
978 to be further improved. Indeed, environmental awareness also has potential to
979 contribute to socioeconomic expansion by promoting resources-saving technology.
980 It's the function of the level and duration of environmental awareness, and the sizes of
981 socioeconomic factors, which will become the focus of our further study. The model
982 calibration is also challenging, as the data series is not sufficiently long and the forms
983 and parameters of the feedback function are not prescribed. We consider that
984 sufficient case studies will gradually emerge over time, which could gradually cover a
985 range of scenarios and slowly provide reliability in the WEFS nexus modeling.
986 Moreover, as the primary input of the proposed WEFS nexus model, water availability
987 was adopted based on the historical scenario in this study. Future climate change has
988 not been considered for the sake of simplicity. The considerable uncertainties in water
989 availability can be brought into the water system in the WEFS nexus due to climate
990 change (Chen et al., 2011). The propagation of the uncertainties can also be
991 complicated, with interactions among water, energy, food, and society systems during
992 the co-evolution process. Therefore, more attention should be paid to the uncertainty
993 analysis on the WEFS nexus under climate change. However, the proposed
994 framework and our research results not only provide useful guidelines for local
995 sustainable development but also demonstrate the potential for effective application in

996 other basins.

997

998 **Data availability:** The socioeconomic data used in producing this paper are
999 available at <http://data.cnki.net/>

1000

1001 **Author contributions:** Conceptualization, DL and YZ; Methodology, YZ;
1002 Software, YZ; Data Curation, YZ, ZW and LD; Formal analysis, YZ and DL;
1003 Writing-Original Draft preparation, YZ and LD; Writing-Review and Editing, SG, LX,
1004 PL, JY and DL; Funding acquisition, DL.

1005

1006 **Competing interests:** The authors declare that they have no conflict of interest.

1007

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