COUPLING DYNAMICS MODEL TO EXPLORE THE IMPACTS OF THE WATER-ENERGY-FOOD NEXUS IN CHINA

by

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Original scientific paper
https://doi.org/10.2298/TSCI2502243H

As no systematic frameworks on the overall relationships in the water-energy-food nexus have yet been developed, in this paper we sought to quantify and capture the final key demand categories that impact China's water-energy-food use. A co-operative and competitive coupling model was developed for the quantitative analysis of the water-energy-food system focused on sustainable water, energy and food production in the industrial, agricultural, and livestock sectors, which share economic activities. The results show that the consumption of energy and water has a certain correlation with grain production, which is negatively correlated and the correlation will be significantly reduced, while the amount of water is positively correlated.

Key words: *water-energy-food nexus, coupling model, conflict, cooperation*

Introduction

While water, energy, and food are known to be the three basic elements for human survival, they have very sensitive, fragile relationships [1]. However, in 2015, about 40% of the current world population suffered from a lack of water shortages, nearly 1.3 billion people has no or little electricity, about 2.7 billion people depended on traditional biomass as fuel [2], and about 800 million people were experiencing hunger, with around 160 million children under the age of five stunted due to undernourishment [3].

The global demand for water, energy, and food is forecast to rise by 40%, 50%, and 35% by 2030, respectively [4, 5]. The 2015 UN Summit on sustainable development officially adopted 17 sustainable development goals (SDG), with the first, sixth, and seventh items being to eliminate hunger, achieve food security, provide clean drinking water for all, and ensure access for all to affordable, reliable, and sustainable modern energy [6].

China is a major global consumer of water, energy, and food resources, with its energy and food being increasingly dependent on international markets [7]. Because of increasing urbanization and population growth as well as the inevitable effects of climate change, the pressure on water, energy, and food supplies is growing, which is challenging the global water, energy and food sectors. Therefore, clarifying China's water, energy, and food relationships through comprehensive studies is needed to guarantee future water resource, energy, and food security.

Most past researches [8-10] have only involved simple connections between the water, energy, and food (WEF) sectors, and no WEF system differential equation models have

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yet been developed to quantitatively analyze the WEF system interactions and influences from competition and cooperation perspectives. This paper uses a dynamic system to establish a simulation model for China's WEF Nexus relationship and analyze the production and consumption of China's water, energy, and food resources from 2009 to 2023, from which four different development plans are proposed to provide a scientific basis for China's WEF resource allocation.

Modelling

As water, energy and food mutually unify and restrict each other in competitive and cooperative relationships, their mutual synergies are the internal factors to ensure sustainable and co-ordinated development. The WEF co-ordinated development can promote social progress as long as the relationships are handled correctly by fully utilizing the mutual promotions and reducing the mutual hindrances.

The co-evolution of the WEF composite system process involves an exchange of the materials, energy and information produced in the environment, with the evolutionary process moving through birth, growth, maturity, decline, and death phases to achieved the development equilibrium. As this evolution conforms to the *S*-shaped curve, a logistic growth model can be used to describe the composite system:

$$\frac{\mathrm{d}X}{\mathrm{d}t} = \alpha X(1-X) \tag{1}$$

where X is the development level of the composite system, α – the growth rate, and $1 - X$ – the deceleration factor. If only the competitive and co-operative system is considered and the external environment impact on the water resources system ignored, the following model can be established:

The WEF integrated management comprises three subsystems; water (supply subsystem), energy (energy subsystem), and food (demand subsystem), which are denoted as three state variables to determine the specific impact factors. Let W, E, and F denote the water, energy and food systems, respectively. The subsystems definition:

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \alpha W(1-W) \tag{2}$$

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \delta E(1-E) \tag{3}$$

$$\frac{\mathrm{dF}}{\mathrm{dt}} = \gamma F(1-F) \tag{4}$$

where α is the water subsystem variation, δ – the tax for the maintenance of the local environment, and γ – the increasing grain output proportion.

Even though external environment impacts on the system are inevitable, this paper is focused on the WEF system relationships; for example, when studying the water resources system, only the energy and food impacts are considered. Therefore, the following model is established.

Let $\beta_{ij}(i, j = 1, 2, 3)$ denote the competitive influence parameters of system i on system j. Also the WEF systems are influenced by the social investments in fixed assets, the per capital resident disposable income, the carbon emissions, and the government subsidies. Therefore, it is assumed that they satisfy the following linear structure:

$$\begin{gathered}\frac{\mathrm{d}W}{\mathrm{d}t}=\left(\alpha_0+\alpha_1E+\alpha_2F+\alpha_3t_z+\alpha_4s_r\right)W(1-W-\beta_{12}E-\beta_{13}F)\\ \frac{\mathrm{d}E}{\mathrm{d}t}=\left(\delta_0+\delta_1E+\delta_2F+\delta_3t_z+\delta_4s_r\right)E(1-E-\beta_{21}W-\beta_{23}F)\\ \frac{\mathrm{d}F}{\mathrm{d}t}=\left(\gamma_0+\gamma_1E+\gamma_2F+\gamma_3t_z+\gamma_4s_r\right)F(1-F-\beta_{31}W-\beta_{32}E)\\ W(0)=W_0, E(0)=E_0,\ F(0)=F_0\end{gathered}\tag{5}$$

where t_z is the fixed assets investment in the energy industry and s_r – the annual per capital resident disposable income.

Model analysis

Coupling model parameter analysis

The primary data were extracted from the 2009 to 2019 National Economic and Social Development Statistical Bulletin of the People's Republic of China and the Statistical Yearbooks issued by the National Bureau of Statistics, tab. 1.

As there are 21 unknowns in eq. (5), the least squares method was employed to determine the values, with the loss function definition being:

$$\min\delta_1=\left\|\frac{\mathrm{d}W}{\mathrm{d}t}-\left(\alpha_0+\alpha_1E+\alpha_2F+\alpha_3t_z+\alpha_4s_r\right)W\left(1-W-\beta_{12}E-\beta_{13}F\right)\right\|_2$$

$$\min\delta_2=\left\|\frac{\mathrm{d}E}{\mathrm{d}t}-\left(\delta_0+\delta_1W+\delta_2F+\delta_3t_z+\delta_4s_r\right)E\left(1-E-\beta_{21}W-\beta_{23}F\right)\right\|_2$$

$$\min\delta_3=\left\|\frac{\mathrm{d}F}{\mathrm{d}t}-\left(\gamma_0+\gamma_1W+\gamma_2E+\gamma_3t_z+\gamma_4s_r\right)F\left(1-F-\beta_{31}W-\beta_{32}E\right)\right\|_2$$

For dW/dt the finite difference method is used to discretize it to dE/dt, and dF/dt. Let dW/dt ≈ $(W_{i+1} - W_i)/h$, where h is the time step.

Table 1. The original database

Years	W (10^9 m^3)	E (10^9 tonne)	F (10^9 ¥)	t_z (10^9 ¥)	s_r (10^9 ¥)
2009	5965.2	33.6	59311.3	181760	10977.5
2010	6022.0	36.1	67763.1	218834	12519.5
2011	6107.2	38.7	78837.0	205036	14550.7
2012	6131.2	40.2	86342.2	241746	16509.5
2013	6183.4	41.7	93173.7	282496	18310.8
2014	6094.9	42.8	97822.5	320331	20167.1
2015	6103.2	43.4	101893.5	347827	21966.2
2016	6040.2	45.6	106478.7	372021	23821.0
2017	6043.4	46.4	109331.7	394926	25973.8
2018	6015.5	47.2	113579.5	418215	28228.0
2019	6021.2	48.7	123967.9	439541	30732.8
2020	5812.9	49.8	137782.2	451155	32189.0
2021	5920.2	52.6	147013.4	473003	35128.0
2022	5998.2	54.1	156065.9	495966	36883.0
2023	5906.5	57.2	158507.2	509708	39218.0

First, the data are standardized, after which MATLAB fitting is employed, with the results shown in tab. 2.

Table 2. Parameter estimation result

Water system	α_0	α_1	α_2	α_3	α_4	β_{12}	β_{13}
	–4.9	6.9	18.3	5.7	–14.4	5.5	–3.3
Energy system	δ_0	δ_1	δ2	δ3	δ_4	β_{21}	β_{23}
	1.9	–1.1	–0.8	–1.2	0.4	–0.1	1.2
Food system	γ_0	γ_1	γ_2	γ_3	γ_4	β_{31}	β_{32}
	6.2	–20.7	37.1	–14.3	–9.9	0.6	–0.2

Stability analysis

As the WEF coupling system becomes stable over time, this section gives the discriminant formula for judging the stable point, for which [11] formula for discriminating the equilibrium point of autonomous differential equations was used, with the rate parameter α considered to be a constant. The formula for discriminating the equilibrium point is as explained in the following subsection.

Equilibrium criterion

Let:

$$f_1(W,E,F) = \left(\alpha_0 + \alpha_1 E + \alpha_2 F + \alpha_3 t_z + \alpha_4 s_r\right) W \left(1 - W - \beta_{12} E - \beta_{12} F\right) = 0 \tag{6}$$

$$f_2(W,E,F) = \left(\delta_0 + \delta_1 W + \delta_2 F + \delta_3 t_z + \delta_4 s_r\right) E \left(1 - E - \beta_{21} W - \beta_{23} F\right) = 0 \tag{7}$$

$$f_3(W,E,F) = \left(\gamma_0 + \gamma_1 W + \gamma_2 E + \gamma_3 t_z + \gamma_4 s_r\right) F \left(1 - F - \beta_{31} W - \beta_{32} E\right) = 0 \tag{8}$$

As China's economy is still rapidly developing, its water, energy, and food consumption is in an evolutionary stage; therefore, it can be assumed that $a_0 + a_1E + a_2F + a_3t_z + a_4s_r$ is non-zero as in eqs. (7) and (8). The equation system therefore, has five equilibrium points:

$$Q_1 = (0,0,0), Q_2 = (0,0,1), Q_3 = (0,1,0), Q_4 = (1,0,0), Q_5 = \left(\frac{A_1}{A}, \frac{A_2}{A}, \frac{A_3}{A}\right)$$

where

$$A = \begin{vmatrix} 1 & \beta_{12} & \beta_{12} \\ \beta_{21} & 1 & \beta_{23} \\ \beta_{31} & \beta_{32} & 1 \end{vmatrix}, \quad A_1 = \begin{vmatrix} 1 & \beta_{12} & \beta_{12} \\ 1 & 1 & \beta_{23} \\ 1 & \beta_{32} & 1 \end{vmatrix}, \quad A_2 = \begin{vmatrix} 1 & 1 & \beta_{12} \\ \beta_{21} & 1 & \beta_{23} \\ \beta_{31} & 1 & 1 \end{vmatrix}, A_3 = \begin{vmatrix} 1 & \beta_{12} & 1 \\ \beta_{21} & 1 & 1 \\ \beta_{31} & \beta_{32} & 1 \end{vmatrix}$$

If $p < 0$, $q < 0$, $r < 0$, the equilibrium point $A(x_0, x_1, x_2)$ is stable. However, if $p \geq 0$, the equilibrium point A is unstable, where:

$$p = \frac{\partial f_1}{\partial W} + \frac{\partial f_2}{\partial E} + \frac{\partial f_1}{\partial F} \tag{9}$$

$$q=\begin{vmatrix}\dfrac{\partial f_1}{\partial W} & \dfrac{\partial f_1}{\partial E} & \dfrac{\partial f_1}{\partial F}\\ \dfrac{\partial f_2}{\partial W} & \dfrac{\partial f_2}{\partial E} & \dfrac{\partial f_2}{\partial F}\\ \dfrac{\partial f_3}{\partial W} & \dfrac{\partial f_3}{\partial E} & \dfrac{\partial f_3}{\partial F}\end{vmatrix} \tag{10}$$

$$r=\frac{\partial f_2}{\partial F}\frac{\partial f_3}{\partial W}+\frac{\partial f_1}{\partial E}\frac{\partial f_2}{\partial W}+\frac{\partial f_1}{\partial F}\frac{\partial f_3}{\partial W}-\frac{\partial f_1}{\partial W}\frac{\partial f_2}{\partial E}-\frac{\partial f_1}{\partial W}\frac{\partial f_3}{\partial F}-\frac{\partial f_2}{\partial F}\frac{\partial f_3}{\partial W} \tag{11}$$

When the coupled system is finally stable, China's WEF consumption tends toward a certain fixed value, after which the system does not change and the final competition and cooperation form between the WEF systems is found, that is, from this point, the WEF systems co-evolve towards a stable structural state. At this time, the relationships between the three are no longer fragile, and there will no longer be any drastic changes due to the changes in one system.

As seen in tab. 3, $Q_1(0, 0, 0)$ is not a stable point as the coupling systems are in an initial development stage and non-e can attain a stable state. The $Q_2(0, 0, 1)$, $Q_3(0, 1, 0)$, and $Q_4(1, 0, 0)$ are the respective extreme WEF system points, that is, each system can only reach its maximum by crowding out the other systems; if one system reaches the limit state of 1, the other two systems die out, which reflects the complete independence of the system.

Table 3. Judgment of equilibrium point

Equilibrium point	p	q	r
$Q_1(0, 0, 0)$	0.5660	0.0061	–0.0818
$Q_2(0, 0, 1)$	0.2885	0.0045	0.1754
$Q_3(0, 1, 0)$	–0.4917	0.0318	–0.0555
$Q_4(1, 0, 0)$	0.1750	–0.0026	0.0678
$Q_1(0.7670, 0.4004, 0.5905)$	–0.3212	–0.0004	–0.0190

Meanwhile, from tab. 3, it shows that China's domestic WEF systems are developing together towards a stable point $Q_1(0.7670, 0.4004, 0.5905)$, and with the development of the composite system, they will be in a co-evolutionary state, that is, while the water, energy and food systems competitively evolve, the collaborative development is the internal driving force for the entire complex system. The competition stimulates the development of the water, energy, and food systems and the cooperation expands the WEF system development space to allow for the final emergence of a stable point. However, the impact of external environmental changes and policies must also be considered. Through the systems' innovation, new development vitality and power are formed to achieve co-ordinated development and a higher stable point.

Conflict and co-operation analysis

As the system development must be stable in the end, the equilibrium point represents the development direction of the system, which can be determined through calculation.

As shown in tab. 3, if $\beta_{12} > 0$ and $\beta_{21} < 0$, the conclusion can be drawn that the water resource system and the energy system are in a win-win complementary relationship. Water resource development needs energy, which promotes energy industry development, therefore, the water resource and energy systems have a cooperative relationship. However, as China has recently introduced stringent energy and carbon emissions policies, China does not take energy system growth as its sole administrative goal as its water resource development is also important. Therefore, to a certain extent, the energy system plays a competitive role in the water resources system.

For the case $\beta_{13} < 0$ and $\beta_{31} > 0$, the results indicate that the energy and food systems are in a complementary win-win relationship. However, as energy industry and food resource development are inseparable from water resources, the use and distribution of production factors may lead to a competitive relationship. As certain water resources are put into the energy industry, inevitably leading to a reduction in the water resources available to the food system. Conversely, any increase in crop sowing, irrigation, or animal husbandry increases the use of water resources, which means that the water available to the energy industry decreases. That is, there is a competitive relationship between the food system and the energy system. As agricultural mechanization requires both energy and water, the grain industry and the energy industry have a cooperative relationship. However, grain industry development promotes social stability, which then affects the stability of the energy industry.

Finally, when $\beta_{23} > 0$ and $\beta_{32} > 0$, we can see that the energy system and the food system have a complementary relationship, which is primarily because China has strict energy conservation and emissions reduction policies that have encouraged the energy industry to develop energy-saving and emission-reduction systems in recent years. By protecting the resources and the environment, the investment environment has improved and the low carbon development of agriculture, forestry, animal husbandry, and fishery industries has been promoted. Thus, the energy system has a cooperative relationship with the food system. However, as a large agricultural country, China has vigorously developed agricultural mechanization, provided support to agriculture, rural areas, and farmers, and, through theoretical and system innovations, has established a set of effective guarantee mechanisms. Therefore, there is also a competitive relationship between the energy system and the food system.

Conclusion

This research contributes to addressing China's water-energy-food nexus by providing comprehensive solutions for resource governance across different economic sectors. By simultaneously considering the water, energy, and food footprints and determining the location of these specific resources within the economic sector, this method can maximize synergies between the WEF resource systems.

Acknowledgment

The work is supported by Talent Program of Chengdu Technological University (No. 2024RC021), Funding of Chengdu Technological University (No. 2021ZR018) and Quality Program of Talent Cultivation and Teaching Reform in Higher Education (No. 20241226Y).

Nomenclature

E – energy consumption, [standard coal]
F – food consumption, [s]
s_r – annual per capital resident disposable income, [¥]
t_z – fixed assets investment, [¥]
W – water consumption, [¥]

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Paper submitted: October 3, 2024
Paper revised: November 25, 2024
Paper accepted: November 28, 2024