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Research Article

Ecological Network Analysis of the Water-Energy-Food Metabolic System Based on the MRIO Model: A Case Study for China's Yangtze River Delta Region

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Water, energy, and food are essential resources for social and economic development, which are highly interwoven in the urban metabolic processes. The 2011 Bonn conference first introduced the concept of water-energy-food (WEF) nexus to describe the interconnection of three resources. In this study, taking the Yangtze River Delta region as a case study, we proposed a hybrid framework to quantify WEF consumption based on an environmentally extended multiregional input-output model. Then, various ecological network analyses were adopted to explore system properties and sectoral interaction. The results indicate that embodied WEF consumption in interregional trade is highly interconnected, in which Jiangsu accounts for the largest proportion of hybrid energy network, while Anhui dominates the hybrid water network and the food network. The recycling rate in the water network (14.5%–20.8%) is lower than that in the energy network (16.7%–23.5%) and the food network (17.2%–23.9%). Predation and exploitation relationships are dominated between sectors, and the whole trade network stays in a low positive environment. The nexus impact on water networks is smaller than that on the energy networks. This analysis may help identify leverage points and feasible pathways of crossregional resources' trade and provide insights for integrated resources management of the Yangtze River Delta region.

1. Introduction

Water, energy, and food are intricately intertwined. Water is used for energy extraction, processing, and conversion, with 90% of energy production being water intensive [1]. Energy is needed for water provision, water use, and water treatment [2, 3]. Food irrigation and processing also require large amounts of water and energy [4]. With rapid economic growth and urban expansion, increasing demand for water, energy, and food is posing significant challenges for urban WEF systems [5, 6]. Worldwide demands for water, energy, and food are projected to increase by 55%, 80%, and 60% by 2050, in which food and energy account for more than 80% of total water consumption [7]. To meet this challenge, the Bonn conference introduced the WEF nexus concept to describe complex interactions and trade-offs between three resources [8]. Thereafter, the United Nations proposed the framework of sustainable development goals (SDGs) [9], in which SDG2 (zero hunger), 6 (clean water and sanitation), and 7 (affordable and clean energy) are strongly related to the WEF system. Coordinated management of WEF resources becomes crucial to achieve sustainable development goals.

So far, there have been increasing studies quantifying WEF resources by integrating the nexus fluxes into urban metabolism systems. In these studies, an input-output analysis (IOA) [10] is adopted to explore resource fluxes through the system. To further study regional disparities, a multiregional input-output (MRIO) analysis has been applied to calculate cross-sectoral and crossregional resource flows and trace environmental impacts along the supply chain [11]. While many studies focus on single elements such as energy [12], virtual water [13], carbon footprint [14, 15], and ecological footprint [16], some studies have attempted to incorporate two or more elements to analyze resource flows. At the global level, Owen et al. [17] calculated UK's water, energy, and food consumption based on the UKMRIO model and identified the WEF-intensive final products. They suggested that final products with high environmental impact and low socioeconomic value should be preferentially reduced. White et al. [5] used a similar approach to examine WEF resources in East Asia, revealing a mismatch between resource availability in different regions and the corresponding final consumption. At the regional level, Zhang et al. [6] inventoried WEF resources in the Greater Bay Area for coordinated resource management based on an environmentally extended multiregional input-output model. Chen et al. [1] proposed an interactive framework for water-energy-carbon nexus consumption between Guangdong and Hongkong. At the urban level, Liu et al. [18] explored the energy-water nexus in Pearl River Delta urban agglomeration. They suggested improving vehicle fuel efficiencies and reducing water consumption for agriculture and energy production. The abovementioned studies are mainly in quantifying embodied resource flows from the consumption-based perspective and underscore the importance of coordinated resources management. However, this process cannot analyze implied ecological elements in the production and exchange of intermediate products.

To solve this problem, a system-oriented technique known as ecological network analysis (ENA) has been applied to model the distribution of implied ecological elements in any product flows, which was first proposed by Patten [19]. By analyzing the indirect paths implied in the direct flows between sectors, ENA is capable of determining built-in relationships and revealing system properties of the metabolic processes [20]. A few attempts have been made to combine the IOA/MRIO and ENA in tracking the metabolic processes of various resources. For example, Chen and Chen [21] proposed an assessment framework for Beijing's energy-water metabolism system for better planning of energy and water consumption based on IOA and ENA. Zhang et al. [22] integrated MRIO with ENA to inventory direct and indirect energy consumption in China and identified how regional policies affect energy flows. The results indicated unbalanced energy consumption among different regions and an urgent need for improving clean energy use and national energy policies. Wang and Chen [2] evaluated the intensities and structure of energy-water nexus networks in the Jing-Jin-Ji region for a more balanced and sustainable system. Zhang et al. [3] applied ENA to appraise the WEF system of the Greater Bay Area. The results indicated that Hongkong and Macao's WEF systems were highly vulnerable, and Guangdong was the key to improving the WEF network structure. By using the metabolism-framed methodology, great efforts have been made in urban resources management. However, most of the previous studies are mainly focused on one or two kinds of resources in the WEF system, while fewer cases consider all three subsystems, which cannot provide sufficient references for local decision-makers. Besides, there is still a lack of WEF nexus studies relating to the Yangtze River Delta region, which is one of the largest coastal megacities clusters in China. With increasing WEF resources consumption and frequent trade between regions, a holistic methodology framework for assessing interregional WEF systems is required, which is conducive to integrated resources management and sustainable development of urban agglomeration.

In this study, we proposed a system-based framework for assessing the water-energy-food system. Taking the Yangtze River Delta region as a case study, we proposed a nexus accounting framework for calculating direct WEF consumption and nexus-oriented footprints. Then, the ecological network model was constructed by combining the MRIO model and ENA. A set of network-related indicators were adopted to assess system properties and sectoral dynamics. We aim to construct a comprehensive assessment framework of the WEF nexus system and identify key factors of crossregional resource trade for helping sustainable resource planning and management.

2. Materials and Methods

2.1. Study Area. The Yangtze River Delta region, located at the intersection of the two national strategies of the "Yangtze River Economic Belt" and the "Belt and Road," is one of the world-class urban clusters in China [23]. As shown in Figure 1, it is a region with dense urban agglomeration, high urbanization, and a relatively complete industrial chain, including three provinces and one municipality, namely, Jiangsu, Zhejiang, Anhui, and Shanghai [24]. In 2019, the Chinese government officially released "the Outline of the Regional Integrated Development Plan of the Yangtze River Delta," making the Yangtze River Delta region a community with shared interests and a shared future. In 2020, this region covered around 3.74% of the land area with 14.91% of the total population and contributed 24.09% to China's annual GDP, which plays a pivotal role in the country's modernization [25].

Urbanization and industrialization have raised a big challenge of sustainable WEF supply for the Yangtze River Delta region. The urbanization rate has increased from 21.4% to 66.8% in the past three decades, while the average annual growth area of construction land exceeded 700 km^2 [26]. The per capita water resources in the four regions are 853.5 m^3, which is much lower than the national level (2,100 m^3) and world level (7500 m^3). As an important manufacturing center in China, there is increasing energy demand. However, the indigenous production of energy in this area only accounts for 21% of the total primary energy supply, most of which is moved from other regions. The energy consumption is mainly coal, resulting in massive carbon emissions and damaging the environment. Besides, the decreasing per capita arable land and the continued food demand would cause great pressure on urban food system. For example, in 2017, Shanghai consumed 2.37×10^6 tons of grain but produced 0.99×10^6 tons, with a self-efficiency of only 41%. There is an urgent need to optimize the configuration of the WEF system in the Yangtze River Delta region.

FIGURE 1: Location and regions of the Yangtze River Delta. *Note.* From “decoupling economic growth from embodied water-energy-food consumption based on a modified MRIO model: a case study of the Yangtze River Delta region in China,” by Y. Huang and D. Huang, 2023, pp. 1–21. (https://www.mdpi.com/2071-1050/15/14/10779).

2.2. WEF Nexus Consumption Accounting. In this study, we first calculated direct and nexus-oriented WEF consumption by economic sectors. Different types of WEF nexus were identified for illustrating interregional resources trade. Direct water was calculated as the sum of all water types (i.e., surface water, groundwater, and desalinated water) [21]. Direct energy was comprised of various types of energy consumption (e.g., coal, gasoline, diesel, natural gas, and electricity) [12]. Direct food mainly referred to the physical consumption of grains, legumes, edible oil, meats, eggs, dairy, and aquatic products [17], as shown in equation (1). To standardize the data, energy and food products were converted into consistent units by using the standard coal-equivalent coefficient and feed conversion ratio, respectively. The accounting of nexus-oriented consumption enables a unified evaluation of the WEF nexus, which then can be calculated by multiplying direct WEF and the corresponding consumption coefficient [27, 28], as shown in equation (2). Water-related energy (W-energy) considers energy consumption for water abstraction, supply, and treatment. Energy-related water (E-water) refers to water requirements for primary energy production, electricity generation, transportation, and consumption. Food-related water (F-water) and food-related energy (F-energy) denote water and energy consumption in irrigation, food processing, and edible process. The water-related food and energy-related food were not considered because they lack the corresponding consumption coefficient [6] and relevant data. Meanwhile, hybrid water was termed as a combination of direct water, energy-related water, and food-related water consumption. Analogously, hybrid energy is calculated by summing direct energy, water-related energy, and food-related energy consumption, as shown in equation (3).

$$f_{r,i}^{a} = \sum_{1}^{n} a_{r,i}^{n}, \tag{1}$$

$$f_{r,i}^{b} = \sum_{1}^{n} b_{r,i}^{n} \times \beta, \tag{2}$$

$$f_{r,i}^{h} = f_{r,i}^{a} + f_{r,i}^{b}, \tag{3}$$

where $f_{r,i}^{a}$, $f_{r,i}^{b}$, and $f_{r,i}^{h}$ are direct, nexus-oriented, and hybrid WEF flows from sector i in region r, respectively. n represents the resource or material type (i.e., water, energy, food, and nexus-oriented flows). $a_{r,i}^{n}$ and $b_{r,i}^{n}$ represent the direct and nexus-oriented consumption for the n^{th} type. β represents the consumption coefficient of the corresponding nexus-oriented flows. r and i represent the region and the sector, respectively.

2.3. Environmentally Extended Multiregional Input-Output Model. Multiregional input-output analysis (MRIO) has been widely used for quantifying the relationships between pairs of industrial components and tracking the resource and material flows across nations [5, 29], regions [2, 3], and cities [1, 30]. By adding extra satellite accounts and complementary physical matrix to the monetary MRIO model [31], environmentally extended MRIO (EE-MRIO) can then be constructed, and the WEF consumption triggered by the final demand categories were inventoried to analyze the direct and indirect nexus pathways. In our study, the original 42 economic sectors were grouped into 7 larger components (agriculture, mining, manufacture, electricity and gas supply, water supply, construction, and transport and services) based on the common activities in the industry, as shown in Table 1. Next, embodied WEF

Table 1: Compilation of sectors in the urban system.

Aggregated 7 sectors	Original 42 sectors	Code
Agriculture (Ag)	Agriculture, forestry, animal husbandry, and fishery	1
Mining (Mi)	Mining and washing of coal	2
	Extraction of petroleum and natural gas	3
	Mining and processing of metal ores	4
	Mining and processing of nonmetal and other ores	5
Manufacture (Ma)	Food and tobacco processing	6
	Textile industry	7
	Manufacture of leather, fur, feather, and related products	8
	Processing of timber and furniture	9
	Manufacture of paper, printing, and articles for culture, education and sport activity	10
	Processing of petroleum, coking, processing of nuclear fuel	11
	Chemical industry	12
	Nonmetallic mineral products	13
	Smelting and processing of metals	14
	Metal products	15
	General purpose machinery	16
	Special purpose machinery	17
	Transport equipment	18
	Electrical machinery and equipment	19
	Communication equipment, computers, and other electronic equipment	20
	Manufacture of measuring instruments	21
	Other manufacturing and waste resources	22
	Repair of metal products, machinery and equipment	23
Electricity and gas supply (El)	Production and distribution of electric power and heat power	24
	Production and distribution of gas	25
Water supply (Wa)	Production and distribution of tap water	26
Construction (Co)	Construction	27
Transport and services (St)	Wholesale and retail trades	28
	Transport, storage, and postal services	29
	Accommodation and catering	30
	Information transfer, software and information technology services	31
	Finance	32
	Real estate	33
	Leasing and commercial services	34
	Scientific research	35
	Polytechnic services	36
	Administration of water, environment, and public facilities	37
	Resident, repair, and other services	38
	Education	39
	Health care and social work	40
	Culture, sports, and entertainment	41
	Public administration, social insurance, and social organizations	42

nexus flows of urban sectors triggered by final consumption can be calculated by the Leontief inverse matrix, as shown in equations (4)–(6).

$$\delta_{r,i}^{n} = \frac{f_{r,i}^{n}}{X_i^r}, \tag{4}$$

$$A = \left[\frac{t_{i,j}^{r,s}}{X_j^s}\right]_{n\times n}, \tag{5}$$

$$P = \delta_{n\times n}^{diag} (I - A)^{-1} F, \tag{6}$$

where n is the resource type, $\delta_{r,i}^{n}$ is the intensity of the resource flow of n^{th} type of sector i in region r, and X_i^r is the total economic output flow of sector i in region r. A is the coefficient matrix calculated by interregional and intersectoral monetary flows ($t_{i,j}^{r,s}$) divided by the corresponding economic output (X_j^s) in the MRIO table. $\delta_{n\times n}^{\text{diag}}$ is a diagonal matrix. $(I-A)^{-1}$ is the Leontief inverse matrix in which I is an $n\times n$ identity matrix; F represents the vector of embodied resource and material consumption triggered by final consumption.

In this study, economic data were available, whereas physical flow data were not; thus, an embodied ecological element intensity factor representing the quantity of the resource or material element per unit of monetary value was used to transform the monetary input-output tables into physical input-output tables [32]. The embodied ecological element coefficient matrix (ε) can be formulated as equations (7)–(8).

$$S + \varepsilon P = \varepsilon T, \tag{7}$$

$$\varepsilon = S(T - P)^{-1}, \tag{8}$$

where $S = [p_{sj}]_{s\times n}, P = [p_{ij}]_{n\times n}, \varepsilon = [\varepsilon_{sj}]_{s\times n}, T = diag\ [t_i]_{n\times 1}$. S is the resource and material input matrix, P is the intermediate flow matrix, and T is the total economic output.

2.4. Ecological Network Analysis. Based on the physical input-output table, the WEF nexus network models were developed. Figure 2 illustrated the crossboundary mutual relationships across different regions. In this model, R_n represents the region and f_{ij} represents the resources and materials fluxes from region j to region i. z_i represents the flow from the external environment into sector i and y_i represents the resources flowing from sector i to the external environment. Since the network model has been assumed at equilibrium, the inputs should be equal to the outputs in a system. Thus, the total input flows were used to replace the output flows, which can be calculated by intermediate flows and $T_{i,\text{in}}$. The R package is capable of encoding the ecological network algorithms, and more details can be obtained by Borrett and Lau et al. [33, 34].

Ecological network analysis (ENA) is a system-oriented method used to assess the cycling and resilience of the resources and materials in the ecosystem [2, 35]. In this study, Finn's cycling index (FCI), the control allocation coefficient (CA), the dependence allocation coefficient (DA), system robustness (SR), the driving and pulling index, and the utility index were used to assess the relationships between sectors and regions. Network flow analysis is the foundation for the network model and can provide basic data for the following functional analyses. According to the direct flow f_{ij} between pairs of nodes, T_i is defined as the sum of into and out of each node (equation (9)), and then the direct output-oriented (G) and input-oriented (G') efficiencies matrix can be computed (equations (10) and (11)). Next, the dimensionless integral flow intensity matrix can be used to explain the influence that one sector exerts on another within the overall system configuration, defined as N or N' (equations (12) and (13)). The cycling index is used to simulate the cycle rate of resources and material flow throughout the system and indicates the efficiency of WEF consumption. FCI [20] is calculated based on the increment of diagonal elements in the integral flow matrix, as shown in equation (14). Total system throughflow (TST) is the sum of total input (equation (15)).

$$T_i = T_{i,\text{in}} = z_i + \sum_{j=1}^{n} f_{\text{ij}} = T_{i,\text{out}} = y_i + \sum_{j=1}^{n} f_{\text{ji}}, \tag{9}$$

$$G = \left(g_{\text{ij}}\right) = \left(\frac{f_{\text{ij}}}{T_j}\right), \tag{10}$$

$$G' = \left({g_{ij}}'\right) = \left(\frac{f_{ij}}{T_i}\right), \tag{11}$$

$$N = \left(n_{\text{ij}}\right) = G^0 + G^1 + G^2 + G^3 + \cdots + G^n = (I - G)^{-1}, \tag{12}$$

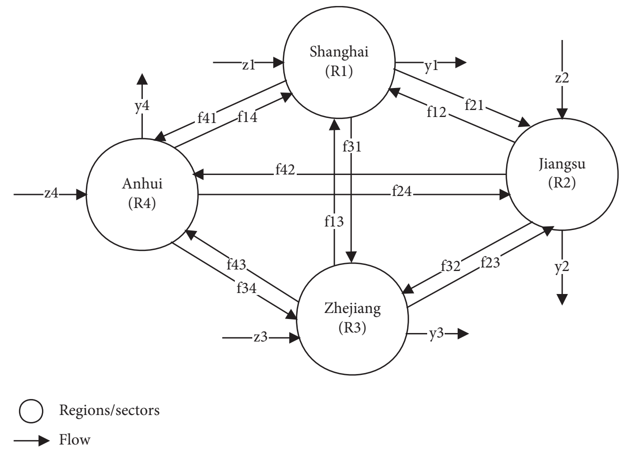

Figure 2: The ecological network for the Yangtze River Delta.

$$N' = \left(n'_{\text{ij}}\right) = \left(G'\right)^0 + \left(G'\right)^1 + \left(G'\right)^2 + \left(G'\right)^3 + \cdots + \left(G'\right)^n = \left(I - G'\right)^{-1}, \tag{13}$$

$$\text{FCI} = \sum_{i=1}^{n} \frac{\left(\left(n_{\text{ii}} - 1/n_{\text{ii}}\right)T_i\right)}{\text{TST}}, \tag{14}$$

$$\text{TST} = \sum_{i=1} T_i, \tag{15}$$

where $T_{i,\text{in}}$ and $T_{i,\text{out}}$ are the sum of into and out of each node. f_{ij} is the intermediate flow between node i and node j. z_i and y_i are input and output flow for node i. G (G') is a matrix of flows of a given path length, where G^0 and $(G')^0$ are initial input flows. G^1 and $(G')^1$ reflect flows with a path length of 1 between a pair of nodes, G^2 and $(G')^2$ reflect flows of length 2, and so on. I is an identity matrix. N and N' are dimensionless integral flow intensity matrices. TST is the total input/output of the entire system.

According to the abovementioned flow analysis, the network driving/pulling force and robustness indicators can be calculated to evaluate the whole system's sustainability. The contribution weight of each sector (V) can be obtained by multiplying the diagonal of the flow matrix by the integral flow intensity matrix [36]. The driving force (DW_i) and pulling force (PW_j) illustrate the downstream sector's ability to drive the upstream sector through supply and demand linkages, respectively (equations (16)–(18)).

$$\text{V} = \left(v_{\text{ij}}\right) = \text{diag}(T)N', \tag{16}$$

$$\text{DW}_i = \frac{\sum_{\text{i}=1}^{n} v_{\text{ij}}}{\sum_{\text{i}=1}^{n}\sum_{\text{j}=1}^{n} v_{\text{ij}}}, \tag{17}$$

$$\text{PW}_j = \frac{\sum_{\text{j}=1}^{n} v_{\text{ij}}}{\sum_{\text{i}=1}^{n}\sum_{\text{j}=1}^{n} v_{\text{ij}}}. \tag{18}$$

The process of system evolution consists of both ascendency and redundancy. Ascendency (A) represents the orderly and efficient part of the system, while redundancy indicates the disordered and ineffective part of the system [37]. The combination of ascendency and redundancy constitutes the development capacity (C) of a system, which reflects how efficiently the network circulates resources while staying flexible enough to adapt and develop [38]. Here, the system robustness (SR) indicator can be used to signify a balance between flow efficiency and resilience, as formulated in equations (19) and (20). The ratio of ascendency and capacity reflects a synergistic state of the system and is an important indicator to evaluate system sustainability. A detailed description of the formulae can be found in Chen et al. and Fath's work [39, 40].

$$\mathrm{C} = -\mathrm{TST}^2 \sum_{i,j}^{n} \frac{f_{\mathrm{ij}}}{\mathrm{TST}} \ln \frac{f_{\mathrm{ij}}}{\mathrm{TST}}, \tag{19}$$

$$\mathrm{A} = \mathrm{TST}^2 \sum_{i,j}^{n} \frac{f_{\mathrm{ij}}}{\mathrm{TST}} \ln \frac{f_{\mathrm{ij}}\mathrm{TST}}{T_i T_j}, \tag{20}$$

$$\beta = \frac{\mathrm{A}}{\mathrm{C}}, \tag{21}$$

$$\mathrm{SR} = -\beta \ln \beta, \tag{22}$$

where A is ascendency; C is capacity, β is a robust coefficient, and SR is system robustness.

Apart from system properties, the sectors' intrinsic connections can be quantified by the utility analysis and sectoral dynamics evaluation. The utility analysis is used to describe the mutual relationships between pairs of components of the urban metabolic system, which was first conducted by pattern [41]. A dimensionless direct utility intensity matrix can be computed, within which matrix element d_{ij} represents the intercompartmental flow utilities. With further consideration of indirect influence caused by extended flow pathways, a dimensionless integral utility intensity matrix (U) can be computed based on power series [22] (equations (23) and (24)). Using the positive and negative signs of the elements in the integral utility matrix, the nature of the interrelationships between two components can be determined (equation (25)). For instance, (+, +) stands for mutualism, (+, −) for predation, (−, +) for exploitation, (−, −) for competition, and (0,0) for neutralism [42]. Besides, a network mutualism index (NM) is introduced to illustrate the fitness of the whole system (equation (26)). When NM > 1, the trade network is dominated by a positive effect; otherwise, the negative is the dominant effect [43].

$$D = \left[d_{\mathrm{ij}}\right] = \frac{f_{\mathrm{ij}} - f_{\mathrm{ji}}}{T_i}, \tag{23}$$

$$\begin{aligned} U = \left[u_{\mathrm{ij}}\right] &= D^0 + D^1 + D^2 +, \ldots, + D^n \\ &= (I - D)^{-1}, \end{aligned} \tag{24}$$

$$\operatorname{Sign} U \equiv \left[\operatorname{sign}\left(u_{\mathrm{ij}}\right)\right], \tag{25}$$

$$\mathrm{NM} = \frac{\operatorname{Sign} U\,(+)}{\operatorname{Sign} U\,(-)}, \tag{26}$$

where D represents the direct utility intensity matrix; U is the integral utility matrix; NM is network mutualism.

The changes in sectoral dynamics in the multiregional network due to the WEF nexus are measured by network control analysis, which is utilized to assess the control or dominance of one sector over another [44, 45]. Based on the integral flow matrices (N and N') through the network flow analysis mentioned above, we calculated the control allocation coefficient (CA) and the dependence allocation coefficient (DA) to quantify the control and dependence relationships between one sector and the other using equations (27)–(29). To further investigate the nexus impacts on the control relationship between sectors in the network, we defined ca_{ij}^{c} based on the CA of direct water/energy and nexus-related water/energy, and da_{ij}^{c} based on DA of direct water/energy and nexus-related water/energy, as shown in equations (30) and (31)) [46, 47].

$$\mathrm{CN} = \left(\mathrm{cn}_{\mathrm{ij}}\right) = \begin{cases} n_{\mathrm{ij}} - n'_{\mathrm{ji}}, & \left(n_{\mathrm{ij}} - n'_{\mathrm{ji}} > 0\right), \\ 0, & \left(n_{\mathrm{ij}} - n'_{\mathrm{ji}} \leqslant 0\right), \end{cases} \tag{27}$$

$$\mathrm{CA} = \left(\mathrm{ca}_{\mathrm{ij}}\right) = \frac{\mathrm{cn}_{\mathrm{ij}}}{\sum_{\mathrm{j}=1}^{m} \mathrm{cn}_{\mathrm{ij}}}, \tag{28}$$

$$\mathrm{DA} = \left(\mathrm{da}_{\mathrm{ij}}\right) = \frac{\mathrm{cn}_{\mathrm{ij}}}{\sum_{\mathrm{i}=1}^{m} \mathrm{cn}_{\mathrm{ij}}}, \tag{29}$$

$$\mathrm{ca}_{\mathrm{ij}}^{c} = \frac{\mathrm{ca}_{\mathrm{ij}}^{\mathrm{related}} \times f_{\mathrm{ij}}^{\mathrm{related}} + \mathrm{ca}_{\mathrm{ij}} \times f_{\mathrm{ij}}}{f_{\mathrm{ij}}^{\mathrm{related}} + f_{\mathrm{ij}}}, \tag{30}$$

$$\mathrm{da}_{\mathrm{ij}}^{c} = \frac{\mathrm{da}_{\mathrm{ij}}^{\mathrm{related}} \times f_{\mathrm{ij}}^{\mathrm{related}} + \mathrm{da}_{\mathrm{ij}} \times f_{\mathrm{ij}}}{f_{\mathrm{ij}}^{\mathrm{related}} + f_{\mathrm{ij}}}, \tag{31}$$

where CN is the control index; CA and DA are the control allocation coefficient and dependence allocation coefficient; $\mathrm{ca}_{\mathrm{ij}}^{\mathrm{related}}$ represents the CA of energy-related water and food-related water (or the CA of water-related energy and food-related energy); ca_{ij} is the CA of direct water/energy; $da_{ij}^{related}$ is the DA of energy-related water and food-related water (or the DA of water-related energy and food-related energy); and da_{ij} is the DA of direct water/energy.

2.5. Data Sources. The data on direct consumption of WEF were mainly collected from the 2017 Water Resources Bulletin, China Environmental Statistics Yearbook, China's Energy Statistical Yearbook, China Agriculture Yearbook, and some other references [48–55]. The input-output data used in this calculation were derived from the China Statistical Bureau and China Accounts and Datasets (CEADs) and were aggregated into seven sectors according to National Economic Industry Classification for modeling urban WEF nexus networks. Nexus-oriented consumption is calculated based on direct WEF consumption and the corresponding consumption coefficient which was derived from Liu, Xiang, and Jia [27, 28].

3. Results and Discussions

3.1. Water-Energy-Food Nexus Flows among Sectors and Regions. Figure 3 summarizes the interregional WEF interaction between Shanghai, Jiangsu, Zhejiang, and Anhui. Judging from the width of flows, we can discern the amount of embodied WEF consumption and identify the dominant sectors. Directions of flows represent the role of sectors or regions in the resources network. Clearly, resource trade between Jiangsu and Zhejiang dominates most types of WEF networks, with Jiangsu being the greatest exporter and Zhejiang being the leading importer. Dominant sectors vary in different types of resource networks. For example, Jiangsu transfers a substantial amount of flow in the water network, whereas Anhui dominates the food-related water network and hybrid water network. Shanghai and Zhejiang are more dependent on Jiangsu's WEF resources supply while Anhui is more self-sufficient. The major export-import pairs of hybrid water are AH-Ma to ZJ-Ma, AH-Ma to JS-St, and JS-Ma to ZJ-Ma. Anhui, followed by Jiangsu, exports huge amounts of water footprint to fulfill final demand in the other three regions. Although such transfers are beneficial to regional economic development, they may exacerbate local water resource tensions. Previous research has indicated that Anhui and Jiangsu suffered from water resource stress, and the net virtual water output in the two regions is not coordinated with the carrying capacity of local water resources [56], signaling an urgent need for integrated water management.

For the energy-related networks, Shanghai and Zhejiang are also more reliant on Jiangsu. Ma is the major exporting sector while St is the most active importing sector. The main export-import pairs of hybrid energy are JS-Ma to ZJ-Ma, JS-Ei to ZJ-Ma, JS-Ei to ZJ-St, and ZJ-Ei to SH-St. Jiangsu plays an important role in providing energy for the other regions, which is consistent with the results of Guo et al. [57]. In their research, Jiangsu's direct energy consumption significantly outweighs its embodied energy consumption, but Shanghai and Zhejiang had higher embodied energy consumption. As the principal provider of energy-intensive products, Jiangsu is under great pressure from a tight energy supply and rising energy demand, which may have an impact on the cross-regional supply-demand system of WEF resources. For the food network, Anhui's agriculture sector was the largest provider, while Shanghai and Zhejiang were the main receivers.

The reasons for these results are as follows: first, the natural resources endowment differs by region. Jiangsu and Anhui have plentiful freshwater supplies and cultivated land, and therefore, they have an edge in producing goods with high WEF footprints. In 2017, total water resources in Jiangsu and Anhui were roughly 11 and 23 times more than in Shanghai. Jiangsu and Anhui had five times the arable land area of Shanghai and Zhejiang [51]. Second, industrial structure has a great impact on the WEF network. For example, Shanghai is a consumption-type region with a fast developing service industry, which contributes to a high demand for embodied WEF products. Jiangsu and Zhejiang are dominated by the manufacturing industry, which demands a substantial amount of WEF resources in the industrial process of raw material processing, product treatment, equipment cooling, etc. Anhui's agriculture is still in its early stages, it enjoys the advantage of exporting water-intensive food products to neighboring regions. This is consistent with the findings of Zhuang et al.'s research regarding resource utilization in various parts of China, which found that manufacturing industries and the service sector in Jiangsu and Zhejiang consumed the most fossil energy and biomass [58]. From the nexus perspective, energy-related water and food-related energy consumption contributed a minor percentage of hybrid energy network, whereas food-related water accounted for the majority of hybrid water network, which is consistent with the composition in the Greater Bay Area [8]. To maximize resource use, differentiated nexus management strategies should be developed. Also, while crossregional trade mitigated resource scarcity in consumption-type regions, it transferred resources and environmental pressure to those production-type areas [59]. Enhancing interregional cooperation and the coordinated management of WEF resources would be a good way to balance benefits and support the realization of sustainable cities and communities.

3.2. System Properties for WEF Systems. FCI is used to characterize the proportion of resource fluxes that are caused by cycling. To investigate the impact of the WEF system, three single-element networks (i.e., the water network, the energy network, and the food network), hybrid water network, and hybrid energy network are modeled to estimate the magnitude of cycling flows in the nexus system, as shown in Figure 4. Overall, the recycling rates in water networks range from 14.5% to 20.8%, which is lower than energy networks (16.7%–23.5%) and the food network (17.2%–23.9%). Furthermore, the WEF nexus impact has been identified by variations in water and hybrid water use, as well as energy and hybrid energy consumption. For

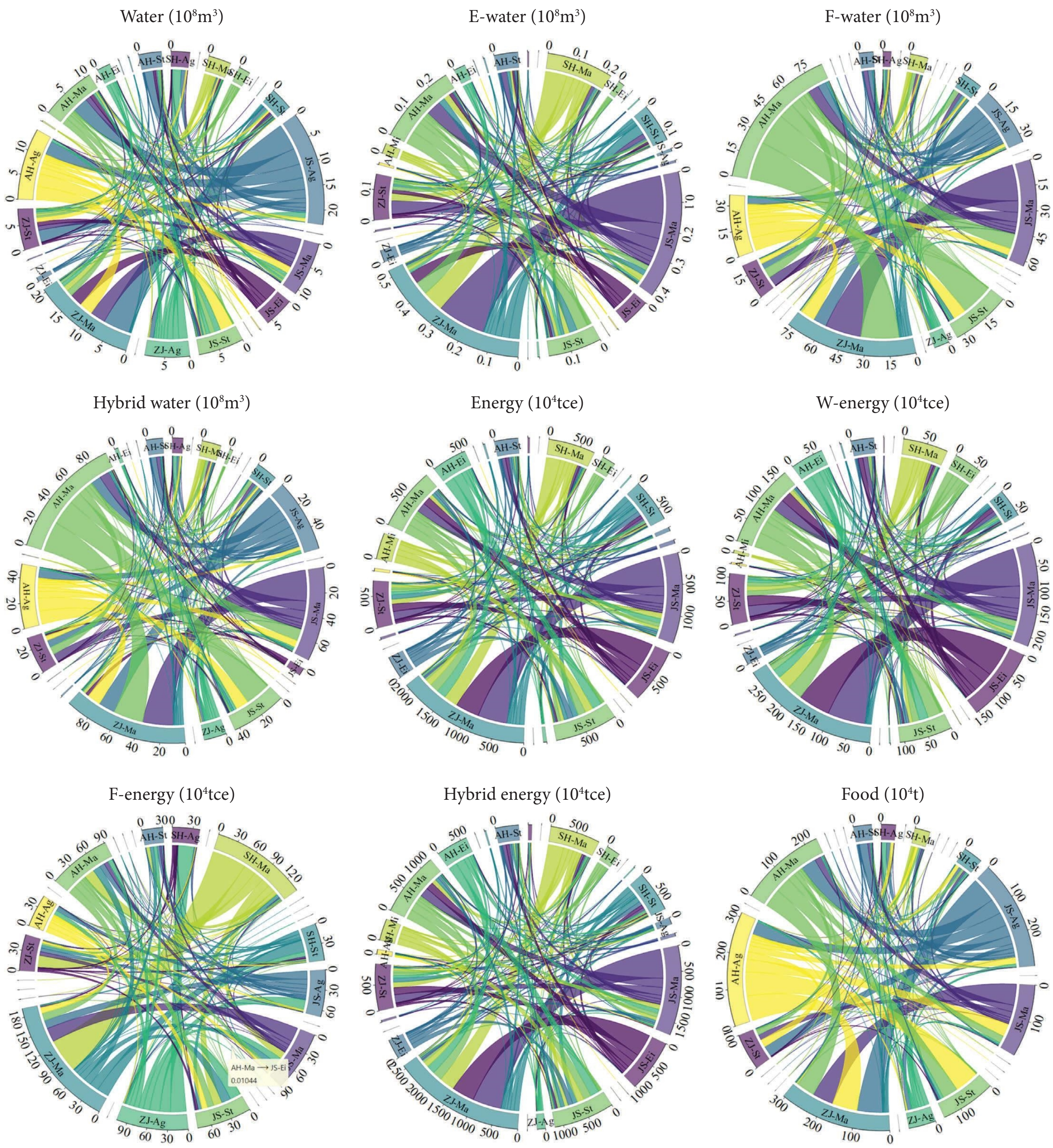

Figure 3: Interregional sectoral water, energy, and food flows.

example, the FCI of flows recycled back to sectors in the water network is 19.6% in Jiangsu, which is lower than the hybrid water network (20.8%), implying that the impact of the WEF nexus has been recognized, albeit the effect is small. Similarly, the recycling rate of the energy network in Jiangsu is 23.4%, which is slightly lower than the hybrid energy network (23.6%). It can be concluded that Jiangsu province has the highest recycling rates in the WEF networks.

FCI differences at the sectoral level indicate various recycling performances for economic activities in the four areas. For Shanghai, most of the total throughflow in the WEF networks is contributed by St (6%–12%). The main reason for this is that the services sector connects a diverse variety of economic activity across numerous industries, making it simpler to reuse resources through the embodiment of goods and services [21]. Ma accounts for the largest proportion of throughflow in WEF networks in Jiangsu, Zhejiang, and Anhui. Recycling rates in Mi, Co, and Wa, on the other hand, are negligible. While Ag is a large water-consuming sector, it contributes only a small percentage of total throughflow, indicating a significant possibility to enhance water use efficiency. As an analogy of the natural ecosystem, FCI could identify the possibility of reusing resources by incorporating direct and indirect effects among

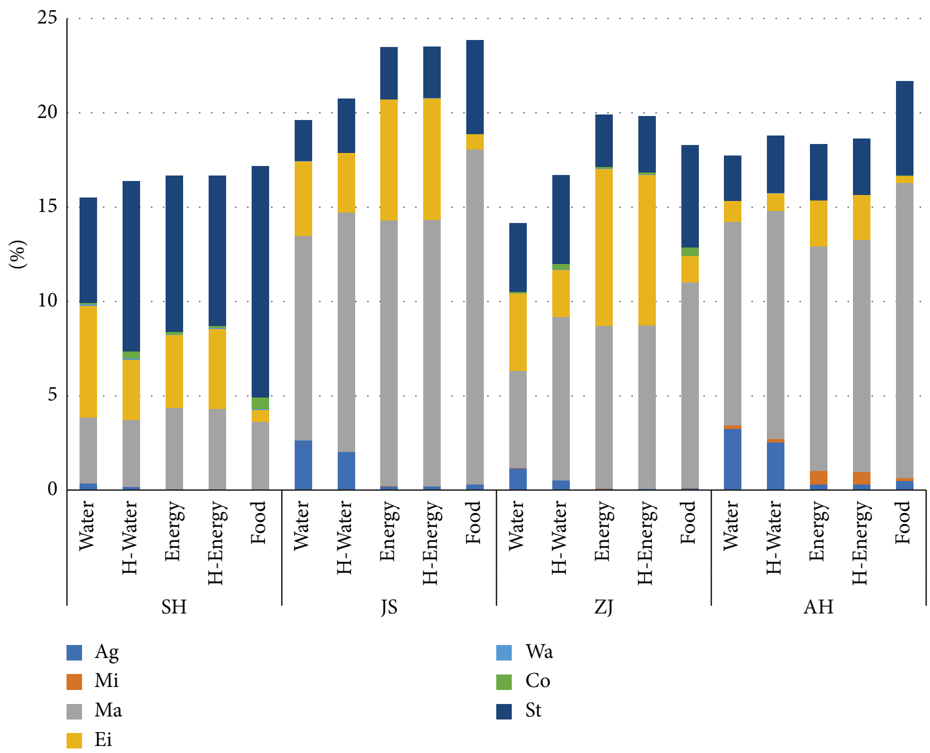

Figure 4: FCI of WEF nexus network for the Yangtze River Delta.

economic sectors connected by WEF flows. The above-mentioned results approximate the recycling rate in the water-energy metabolism of the Beijing-Tianjin-Hebei region (20%–27%) [2] but are lower than some natural ecosystems, such as nitrogen or phosphorus flows in lake ecosystems (30%–75%) [60, 61], implying the potential to strengthen collaboration between sectors and regions.

The system robustness indicates the overall performance of the system regarding a push-pull tradeoff between efficiency and resilience. If SR is located on the right side of the function curve, the system performs with high efficiency at the expense of built-in redundancy. In this case, the system could be vulnerable to collapse in the face of internal or external shocks. If SR is located on the left side of the curve, the system is low in efficiency but high in resilience. Only with the value close to the optimal value ($\beta = 0.3679$) could maintain the system moderately elastic and relatively efficient [62], which is regarded as "the Window of Vitality" [38].

Figure 5 shows the system robustness (SR) of WEF nexus systems of different regions. The average SR of water-related systems is 0.28, with the robustness of the water network in Shanghai being the highest (0.32) and the robustness of hybrid water network in Anhui being the lowest (0.27). The hybrid water network has a lower average SR (0.28) than the water network (0.30). The reason could be ascribed to redundant pathways created by the WEF nexus, which could erode vitality by dissipating weak system throughflow via inefficient sectors.

In terms of energy, the hybrid energy network has a higher SR (0.30) than the energy network (0.29), owing to the integration of more connections formed by the nexus impact. The average SR of the food network is 0.29, with Shanghai still being the highest, followed by Zhejiang. Compared to natural networks (0.4–0.5) [37], the robustness of the WEF networks is substantially lower, and it approximates the SR of the oil network (0.32) and the iron network (0.26) [21, 63]. Overall, the SR of the energy network is higher than that of the water and food networks. The value of SR in Shanghai is higher than in the other regions, indicating that Shanghai has less redundancy and more efficiency. The main reason for this could be attributed to the high input-output efficiency caused by pure technical efficiency in Shanghai [64]. In addition, the implementation of WEF-related policies may improve resource utilization. Shanghai is one of the first areas to adopt the most stringent water resources management and energy conservation regulations, which may raise public awareness of resource conservation and thus indirectly affect industrial technology innovation.

The ecological hierarchy analysis indicates pulling and driving functions between different regions and sectors. The pulling function reflects the capacity to receive products from other sectors while the driving function shows the ability to exert influence on other sectors. As an analogy of the natural ecosystem, the WEF metabolism can be regarded as a combination of producers and consumers. Producers represent sectors that could utilize resources to produce primary products (i.e., agriculture and mining sectors); consumers are sectors that can utilize primary products to produce advanced products (e.g., manufacturing and transformation sectors) or directly consume terminal products (e.g., services industries) [31]. Here, we combine

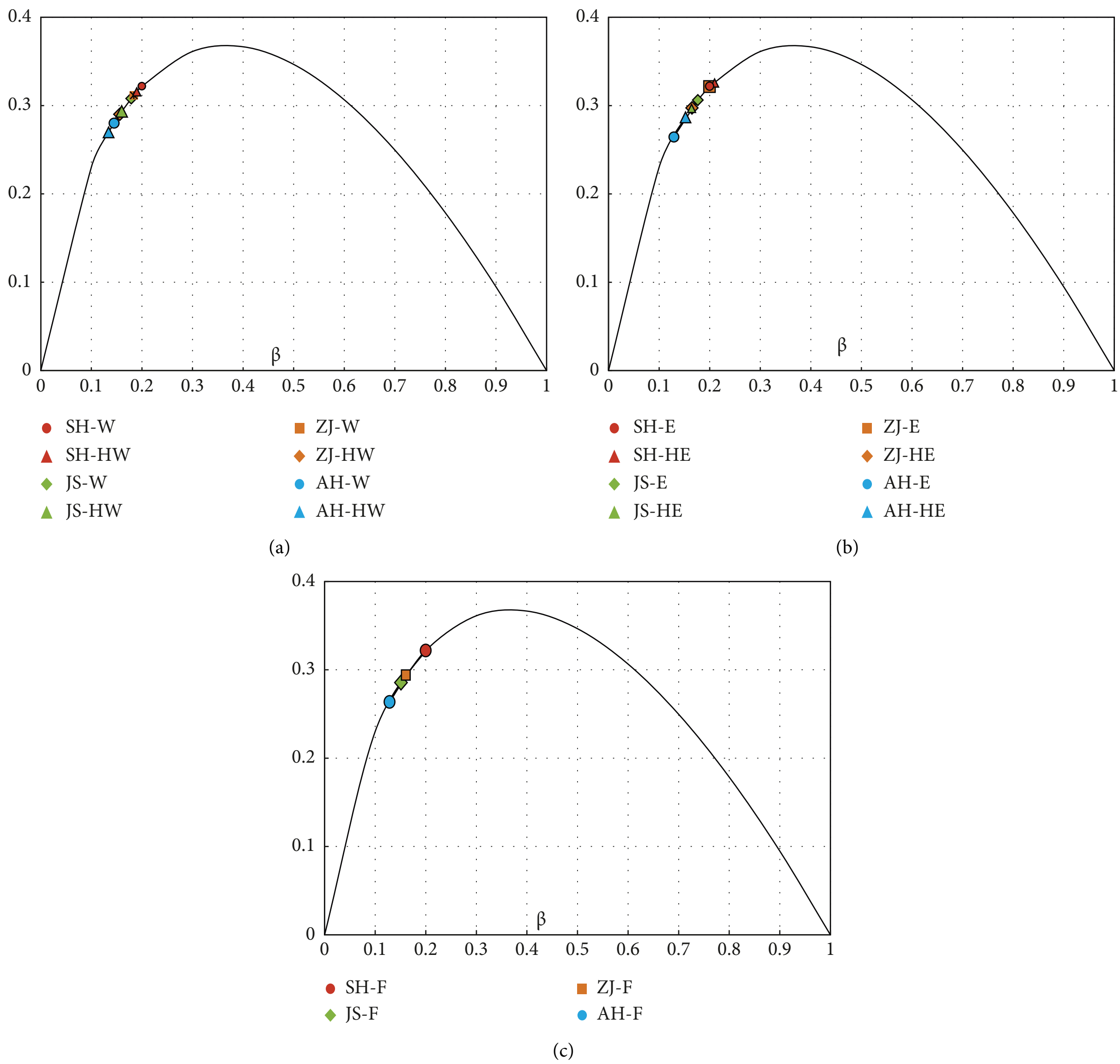

Figure 5: System robustness of WEF nexus systems in the Yangtze River Delta. (a) Hybrid water network. (b) Hybrid energy network. (c) Hybrid food.

the 7 sectors into 4 large groups based on a bottom-up method: agriculture and mining (Ag + Mi), electrical and water supply (Ei + Wa), manufacturing sector (Ma), and the tertiary industry (Co + St). Generally, an inverted pyramidal configuration of the metabolic system reflects the significant pulling/driving force of upstream sectors on the downstream sector [65], which can be used to identify irregular layers and sectors.

Figure 6 illustrates different degrees of pulling/driving force between regions and sectors in all types of WEF networks. In hybrid water and hybrid energy networks, the ecological hierarchy of Shanghai shows an inverted pyramid shape, suggesting that consumption at the upper levels of the hierarchy occupies a large amount of the resource flows and could promote the development of downstream industries. Yet, Shanghai's primary industry was less than 1%, indicating a low self-sufficiency ability for agricultural products and a strong reliance on external supply. In contrast, Jiangsu and Anhui show an irregular pyramid structure in the WEF network, indicating that the WEF metabolism system is in a subhealth state. Jiangsu's manufacturing sector accounts for the largest proportion of the pulling and driving force in hybrid energy network, which is a critical part of the industrial supply chain. The main reasons for the irregular inverted pyramid structure of pulling and driving force are unbalanced industrial development. In particular, the tertiary industry pulled the downstream sectors insufficiently, whereas the manufacturing sector pulled other sectors too fast. Therefore, Jiangsu and Anhui should adjust their industrial structure and gradually shift from the secondary industry to the primary and tertiary industries.

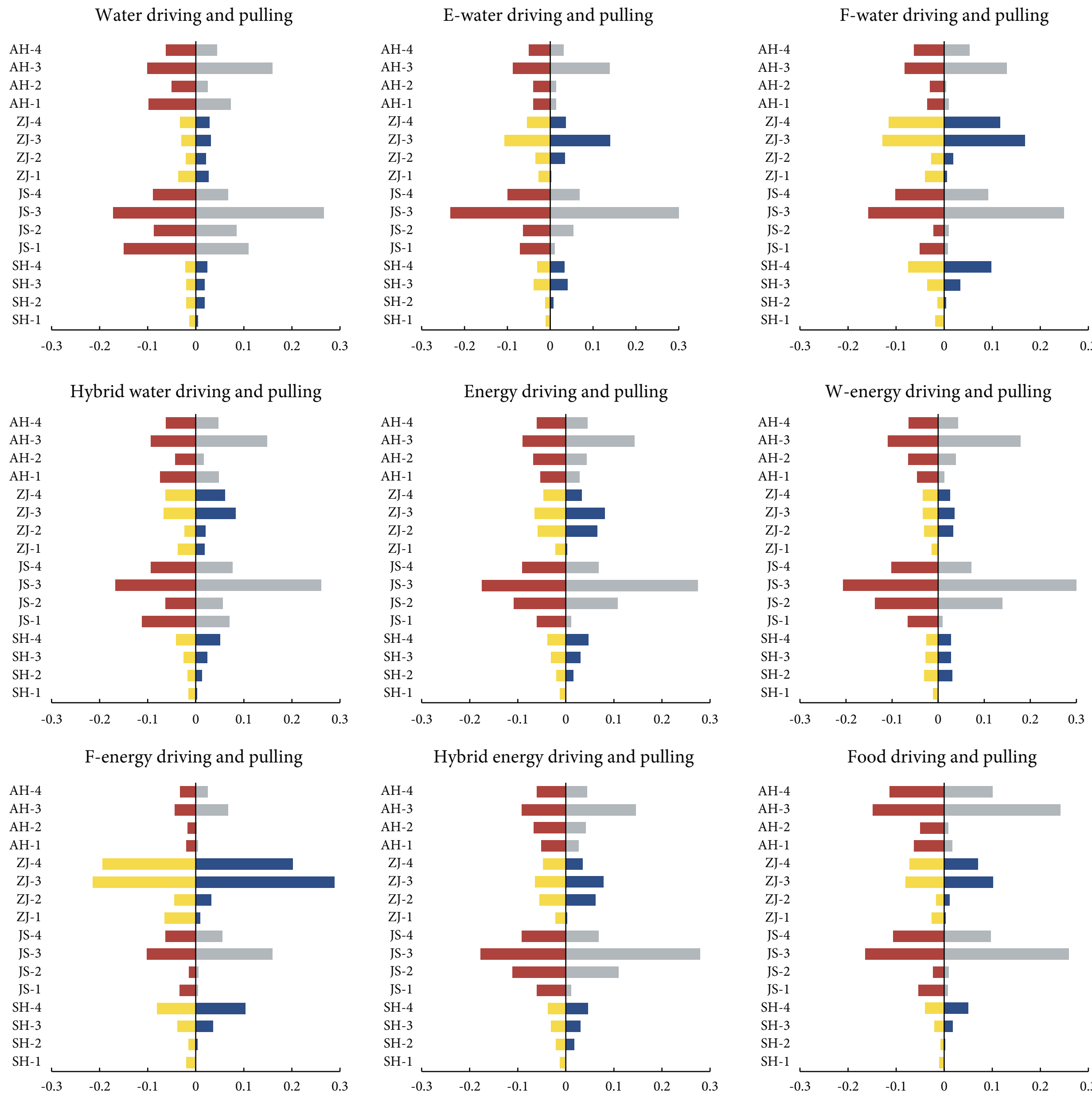

Figure 6: The ecological hierarchy of the pulling and driving weight. *Note*. SH: Shanghai; JS: Jiangsu; ZJ: Zhejiang; AH: Anhui; 1: Ag + Mi; 2: Ei + Wa; 3: Ma; 4: Co + St. The left side of the axis represents the driving force, and the right side of the axis shows the pulling force.

The FCI of water and energy networks are comparatively lower than in the Jing-Jin-Ji region, primarily due to higher recycling efficiency in the service sectors of Beijing and Tianjin [2]. In comparison with the Greater Bay Area [3], the SR of water and food networks in the Yangtze River Delta is relatively high, while the energy network in the Greater Bay Area is more efficient. Therefore, it is necessary to reduce circular paths in the energy network. Regarding pulling and driving force, both Shanghai and Guangzhou exhibit inverted pyramid shapes, which is a sign of a healthy system. Because China's economic development goal is to reduce investment in manufacturing sectors and increase final consumption [31]. In addition, the ecological hierarchy atlas in the Yangtze River Delta shows a relatively homogeneous industrial structure, in which Ma accounts for the largest proportion in most provinces, leading to industrial overcapacity and waste of resources [66]. Therefore, these regions should optimize the industrial structure for efficient use of regional resources.

In summary, FCI, SR, and pulling and driving weight are conducted to assess the performance of the WEF system. FCI is used to estimate the cycling flows of the WEF network, which also measures how well resources are utilized. Meanwhile, a system also requires proper resilience to respond to external distractions [37]. SR can be used to gauge system sustainability by considering the balance between efficiency and resilience. Based on pulling and driving weight indicators, the WEF metabolism hierarchy of

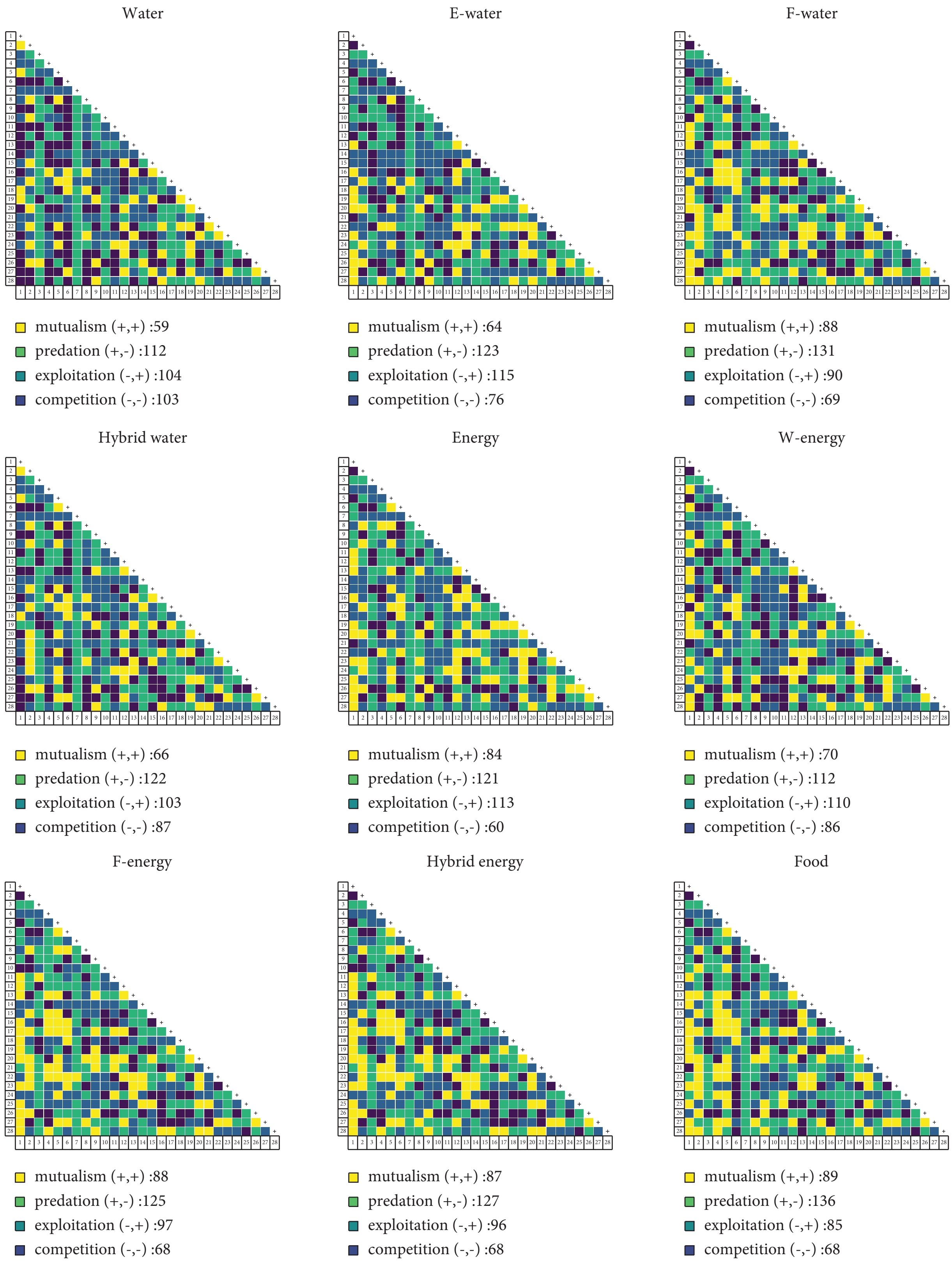

FIGURE 7: The integral utility intensity matrix mutual relationship. *Notes*. 1: agriculture of Shanghai; 2: mining of Shanghai; 3: manufacturing of Shanghai; 4: electricity supply of Shanghai; 5: water supply of Shanghai; 6: construction of Shanghai; 7: transport and services of Shanghai; 8: agriculture of Jiangsu; 9: mining of Jiangsu; 10: manufacturing of Jiangsu; 11: electricity supply of Jiangsu; 12: water supply of Jiangsu; 13: construction of Jiangsu; 14: transport and services of Jiangsu; 15: agriculture of Zhejiang; 16: mining of Zhejiang; 17: manufacturing of Zhejiang; 18: electricity supply of Zhejiang; 19: water supply of Zhejiang; 20: construction of Zhejiang; 21: transport and services of Zhejiang; 22: agriculture of Anhui; 23: mining of Anhui; 24: manufacturing of Anhui; 25: electricity supply of Anhui; 26: water supply of Anhui; 27: construction of Anhui; and 28: transport and services of Anhui.

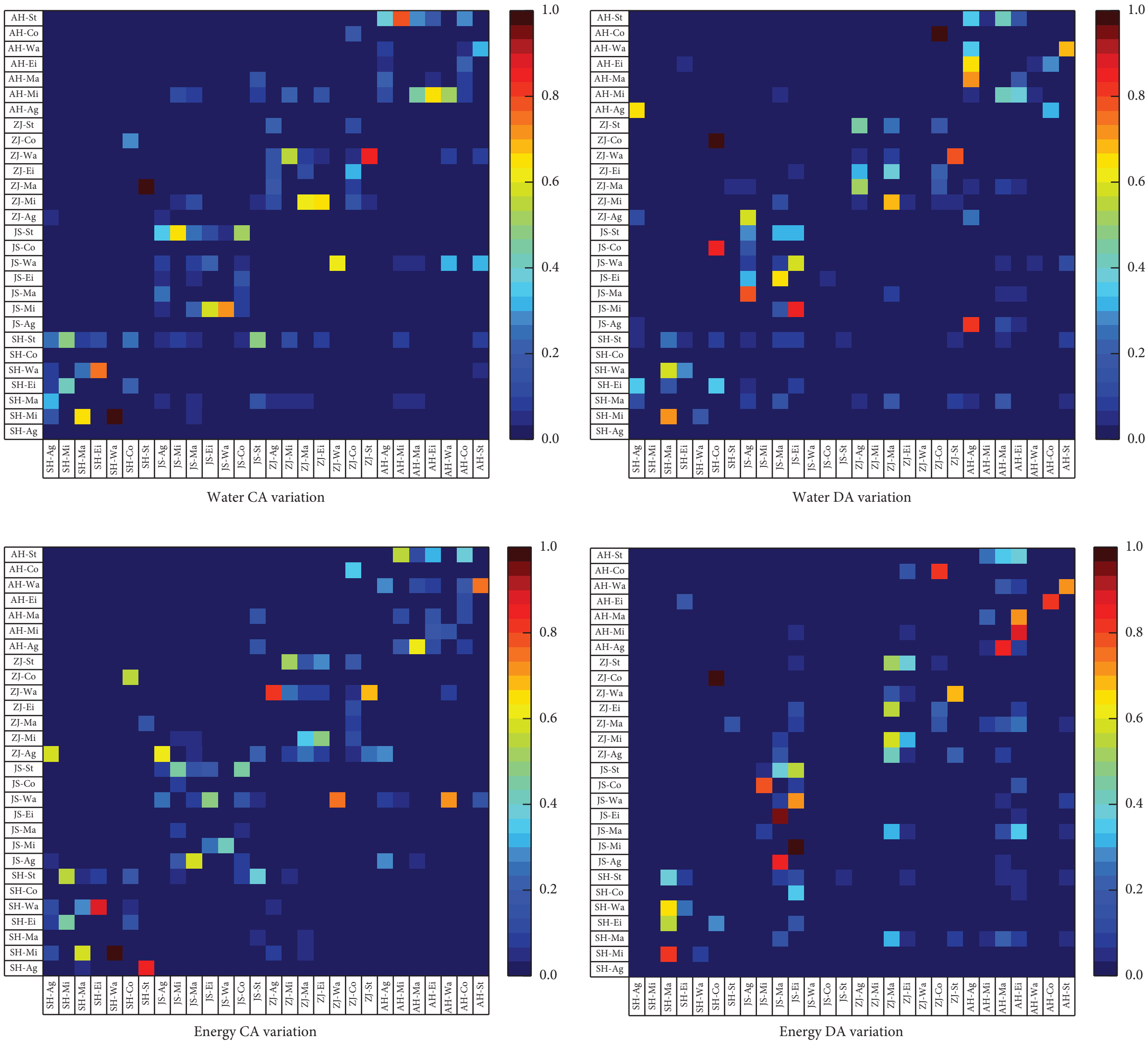

Figure 8: Changes of control and dependence relationships among sectors from a comparison of water/energy networks and hybrid water/energy networks.

different regions can then be constructed to describe the industry chain and investigate problems in the whole system structure.

3.3. Sectoral Dynamics for WEF Systems. Network utility analysis gives a holistic picture of ecological relationships between sectors by using the integral utility intensity matrix. As shown in Figure 7, a total of 378 pairs of ecological relationships are identified in each type of the WEF networks, where the relationship of mutualism, predation, exploitation, and competition account for 20.4%, 32.6%, 26.8%, and 20.1%, respectively. The positive sign on the diagonal of matrix U demonstrates its positive effect on itself. The results show that the WEF metabolic system is dominated by predation and exploitation relationships. The mutualism relationship accounts for a relatively low proportion. For example, the water and E-water networks had a low level of mutualism compared with other types of networks. Besides, Jiangsu and Anhui's secondary and tertiary sectors as well as Shanghai's primary industry had strong competition in the water network. To further illustrate the system's fitness, the network mutualism index (NM) is introduced. If NM > 1, it implies that the positive effect dominates the system. Otherwise, the system has a negative effect. For instance, the NM of direct water and hybrid water are 0.86 and 0.96, respectively, indicating a negative effect dominated. Other types of WEF networks' NM range from 1.02 to 1.26 and showed positive effects. In general, the current water network is more competitive than the energy and food networks. More attention should be paid to water utilization and management, such as adopting stricter water control measures and increasing penalties for water pollution and water waste.

Figure 8 illustrates how control and dependence relationships among sectors of the water and energy systems have changed after considering the WEF nexus impact. By comparing water/energy networks and hybrid water/energy networks, control and dependent relationships between some sectors have been enhanced, and significant changes in sectoral interactions have been detected. In the water networks, the average change of the control relationships between the sectors ranged from 6.44% to 8.69%, with Shanghai seeing the greatest change. For Shanghai, the control of Mi over Wa and Ma, and Wa's control over Ei have been greatly strengthened due to the nexus impact (as shown in the upper left figure). For Jiangsu, the control of Mi over Wa has greatly increased. For Zhejiang, the control of Wa over St becomes stronger as a result of the nexus effect. In Anhui, the control of St over Ag and Mi has been strengthened. There are also changes in the control relationships across regions. For example, the control of Ma in Zhejiang over St in Shanghai has been strengthened significantly owing to the WEF nexus effect. Compared with the control relationship, the dependence relationship has been more influenced by the nexus impact (as shown in the upper right figure). For example, many sectors within regions become more dependent on Ag and Ma because of the nexus influence. Co in Jiangsu and Zhejiang are more dependent on Co in Shanghai. Ag in Jiangsu becomes more reliant on Ag in Anhui.

Similarly, major changes in sectoral control and dependence relationships for the energy networks can be identified (the bottom figures). The average change of the control relationship between the sectors ranges from 8.44% to 11.31%. It can be seen from Figure 8 that the WEF nexus effect on the energy network is larger than that on the water network. Besides, the nexus has a bigger influence on Ma and Ei for the energy network, while Ag and Ma are more influenced by the water network. From the CA perspective, Wa has more control over Ag and Ei within regions. From the DA perspective, many of the sectors become more dependent on Ma and Ei owing to the nexus effect. Besides, the nexus effect on sectors within a region is stronger than that between regions. The abovementioned results reveal that the dynamic changes in sectoral relations affected by the WEF nexus could be the critical pathways for coordinated resources management.

Similar findings from earlier studies in other regions have been observed. For example, the water network exhibits negative competition in the Greater Bay Area, but the energy and food networks operate in a positive environment [3]. Besides, the energy network shows strong competition in the Jing-Jin-Ji region [67] as well as other provinces like Guangdong and Anhui [68, 69]. The similarity between their results and our study indicates that symbiotic levels of the water and energy networks need to be improved. There are too many predation and exploitation relationships in the Yangtze River Delta region, that is, the development of one sector is at the expense of another. Similarly, there are too many competition relationships, which may reduce sectors' efficiency as well. Therefore, competition can be used as a tool to encourage other sectors to increase effective collaboration. Besides, sectoral dynamics analysis could further identify key sectors affected by the nexus effect. Our results show that the manufacturing sector was strongly influenced by the water and energy networks, revealing that WEF resources savings in this sector had greater synergistic benefits. In other words, optimizing resources in the manufacturing sector could indirectly reduce resource consumption of other sectors, thereby improving network stability.

4. Conclusions and Managerial Implications

4.1. Main Conclusions. In this study, we combined MRIO and ENA to examine water-energy-food nexus flows in the Yangtze River Delta region. A system-based framework for the WEF nexus assessment was proposed. Various network analyses weres adopted to identify the key factors of cross-sectoral and interregional resources trade. The results of this research can provide empirical support for coordinated resources management of the WEF resources. Specific conclusions are as follows:

(1) Shanghai, Jiangsu, Zhejiang, and Anhui are highly shared with WEF resources. Shanghai and Zhejiang outsource large amounts of WEF footprints to Jiangsu and Anhui. Ma is the most active sector in all types of resource trade networks except the water network. While interregional trade could mitigate resource scarcity, it also increases the ecological burden for those production-type regions. Therefore, a cooperative framework for managing the WEF resources is required to share the responsibility and facilitate cross-border governance. From the nexus perspective, water-related energy and food-related energy consumption account for a small part of total energy footprints. However, food-related water consumption takes up a large proportion of overall water footprints. Thus, there is an urgent need for strict water management.

(2) The system robustness in the four regions is at the medium level, with relatively low efficiency and high redundancy. The water network has lower cycling rates than the energy and food networks, implying a need to strengthen the interaction between economic sectors in the water network. The irregular pyramid-shaped ecological hierarchy of Jiangsu, Zhejiang, and Anhui demonstrates that the WEF network is in a subhealth state in the three regions. As a result, accelerating industrial structure advancement would help resource allocation in the Yangtze River Delta region.

(3) The WEF network is dominated by predation and exploitation relationships and the level of mutualism is relatively low. The current water network is more competitive than the energy and food networks. Industrial integration could be an effective way to alleviate resource competition among sectors and regions. The WEF nexus effect on the water network is smaller than that on the energy network. Many of the sectors become more dependent on Ma after considering the nexus impact. The nexus has a greater influence on Ag and Ma in the water network, while Ma and Ei are more influenced by the energy network.

Main contributions of our research could be concluded from three aspects. First, a nexus accounting framework is proposed to inventory WEF consumption and embodied nexus flows, which can be generalized to address WEF issues in other regions as well. Second, we construct a comprehensive framework to evaluate the functions and properties of WEF systems by combining nexus accounting, MRIO, and ecological network analysis. A wide range of network-related indicators is adopted to identify the critical factors of crossregional resource trade. Third, our research in the Yangtze River Delta region enriches the research in this area and provides a basis for coordinated resource management in Shanghai, Jiangsu, Zhejiang, and Anhui regions.

Several challenges remain to be solved in future research. First, we merged the 42 economic sectors into seven large components, which may not fully reveal the differences among the industries and their WEF flow processes. A more detailed analysis would be possible to minimize the potential errors associated with sector aggregation. Second, ENA is not suitable for time series analysis, and therefore, it is difficult to follow the metabolic dynamics in time. An improvement in the future would be to expand the study period to include more data for comparison.

4.2. Management Implications. The findings of this paper provide reference and policy implications for improving coordinated resources management in the Yangtze River Delta region.

First, consumption-based accounting assigns WEF footprints to final products and services, providing new scope for policymaking on the demand side rather than depending on supply-side measures. To reduce the impact of nexus footprints, Shanghai and Zhejiang should encourage sustainable consumption, environmentally friendly purchases, and frugal habits. For those production-oriented regions such as Jiangsu and Anhui, industries with high water and energy consumption should be shut down and upgraded. Fossil fuels used for electricity need to be restricted or eliminated, while renewable energy should be developed. Besides, the regions could take advantage of coastal resources to increase the source of water, energy, and food. For instance, sea rice cultivation could expand the food supply while improving soil function and the ecological environment, which has been put into practice in some parts of Jiangsu. Offshore wind power and tidal power would be good options to provide clean electricity, which could help energy structure transformation and sustainable energy supply.

Second, low levels of resource recycling and robustness are not conducive to regional sustainable development. Collaboration between economic sectors should be encouraged. On the one hand, an integrated organization could be set up to help coordinate arrangements for WEF resources and manage nexus trade-offs effectively. On the other hand, the establishment of eco-industrial parks could be a good choice to increase the recycling of energy and water in industrial production. To increase resource use efficiency, the producer sectors must control WEF consumption and develop water-and energy-saving technologies, while the consumer sectors should improve production technology to reduce losses of materials and energy during production activities. Besides, local governments could provide financial support and tax preferences to encourage technology innovation and industrial upgrading.

Third, the low level of mutualism relationships suggests a weak collaboration between upstream and downstream industries. Industrial integration development can effectively alleviate sectors' competition for resources and promote regional sustainable development. According to sectoral dynamics analysis, more attention should be focused on the manufacturing sector. Developing the service-oriented manufacturing industry could enhance collaboration between the manufacturing sector and the service sector. Besides, the government should build an information resource-sharing platform for enterprises to enhance cooperation and communication between different departments and regions.

Data Availability

The dataset is sourced from the statistical yearbooks of China's provinces and cities, China environmental statistics yearbook, China's Energy Statistical Yearbook, China Agriculture Yearbook, and statistical documents of water conservancy departments among provinces and cities in China. The detailed data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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