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Coupling Efficiency Assessment of Food–Energy–Water (FEW) Nexus Based on Urban Resource Consumption towards Economic Development: The Case of Shenzhen Megacity, China

Chaofan Xian [1,*], Shuo Yang [2], Yupeng Fan [3], Haotong Wu [4] and Cheng Gong [1]

[1] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[2] Hengshui Ruifeng Composite Materials Corporation, Hengshui 053100, China
[3] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[4] China Qiyuan Engineering Corporation, Xi'an 710018, China
* Correspondence: cfxian@rcees.ac.cn; Tel.: +86-010-6284-9815

Abstract: The population aggregation and economic development caused by urbanization significantly influence the efficiency of urban resource consumption. However, the coupling interactions between crucial resource consumptions such as food, energy and water (FEW) and urbanization processes within highly urbanized areas has not been well-studied. In this study, we constructed an assessment framework for the coupling efficiency measurement of FEW resource consumptions in 10 administrative districts across Shenzhen megacity during 2012–2020, based on the data envelopment analysis (DEA). This study demonstrated that, from the perspective of the FEW nexus, increasing efficiencies in the energy consumption of most districts improved the municipal FEW efficiency, while more than half of the districts did not achieve water resource efficiencies throughout the period. Concerning regional economic development, 80% of the districts improved coupling FEW efficiencies by 2020, the average values of which were higher for Yantian, Nanshan, Luohu and Dapeng, and lower for Baoan, Longgang and Guangming, with a downtrend only being observed in Guangming. Overall, the value of the coupling FEW efficiency of Shenzhen megacity rose by 35% from 2012 to 2020. Correlation analysis showed that synergistic effects of efficient resource consumption occurred in most districts, and economic urbanization was the main driving factor of regional FEW efficiencies within Shenzhen megacity. This study provides instructive insights into the status of urban resource consumption and suggests that the coordination of FEW management should be further improved by fiscal intervention to maintain economic development with the limited resources available, which would have valuable implications for synergistic FEW governance in megacities in China and elsewhere.

Keywords: resource consumption; food–energy–water nexus; coupling efficiency; economic development; Shenzhen

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1. Introduction

It is acknowledged that urbanization is prevalent worldwide, accompanied by population growth and economic transitions, which are major drivers of socioeconomic development. However, urbanization also puts increasing pressure on the resource provision of food, energy and water, which are the essential elements for human wellbeing and sustainable development [1]. The food, energy and water (FEW) nexus is regarded as the interactions between FEW resources and economic activities when investigating food, energy and water provisions to meet internal demand at multiple scales, especially for rapidly developing economies, and it promotes sustainable economic growth without shortages of one or more of the sectors constituting this nexus [2–4].

China, as the largest developing country in the world, is experiencing unprecedented urbanization since the reform and opening in the late 1970s [5], and FEW resources are indispensable to regional social and economic development [6]. Recently, the sustainability of China was challenged by the uneven regional distribution and low utilization efficiency of FEW resources [7,8]. Previous nexus-related research mainly concerned the FEW nexus at a national scale [9–11], but more research concerning the impacts of increased economic activity on regional FEW resources is emerging [12]. Most FEW studies concerning provincial resource utilization outlined that the impacts of regional FEW consumption on environment protection and economic development are significant [8,13,14]. Notably, Zhang et al. [6] addressed the fact that the urbanized megacity generally outsourced the negative impacts of FEW by importing freshwater, electricity and food from adjacent regions to satisfy local demand. In addition, Yuan et al. [15] revealed that regional domestic production and regions' FEW were related. These studies demonstrated the essential role of FEW resources in regional economic and resource security in China. However, at the local scale, there are limited studies concerning the input–output efficiency of the FEW nexus in terms of urban resource consumption, which is crucial to guide sustainable urban development since the pressure and utilization status of FEW vary significantly from city to city in specific regions. Previous research focused on the impact of energy on FEW governance in Beijing city and the FEW resource dynamic in Daqing and Shizuishan cities [16–18], while some quantified the impact of urbanization on the food–water–land–ecosystem nexus, thereby enriching the research topic on the resource nexus within a city [19]. These literatures have definitely improved our understanding of the FEW nexus and the relevant issues at an urban scale, but the FEW bond systems within a city and their interlinked sub-city regions with regards to the efficiency of resource consumption have still attracted less attention, which has failed to help urban decision makers to provide their populations with adequate FEW resources to match the Sustainable Development Goals [16,20]. Thus, the results from these studies are inadequate for assessing the urban FEW situations and relevant studies concerning regional FEW efficiencies within a city are warranted.

Data envelopment analysis (DEA) is a nonparametric statistical approach in the field of econometrics, mathematics and management, which provides the assessment of relative efficiency performance on multiple inputs and outputs and has been applied to select the best alternatives for improving efficiency [21–28]. Recently, DEA was widely adopted to assess the eco-efficiency of resource consumption and circular economy development across different scales in China, including provinces [29,30], city agglomerations [31–33] and industrial parks [34]. However, less relevant studies concerned regional FEW efficiencies within a city. To conduct a typical case study based on DEA, we attempt to assess the regional FEW efficiencies within Shenzhen City, which is a pilot city for sustainable development in China. The motivation of this study is to fill the research gap in the nexus field within a city and thus to contribute to the limited current research in terms of FEW efficiency assessment since the FEW nexus framework has not previously been addressed comprehensively within a city. The objectives are listed as follows:

(1) Assess temporally and spatially characteristics of the regional FEW efficiencies for economic development during 2012–2020.
(2) Explore the interactions among coupling FEW efficiencies with economic development.
(3) Explore the impacts of urbanization on the coupling FEW efficiencies of the city.

2. Materials and Methods

2.1. Study Area

Shenzhen City is situated in Guangdong Province, South China (Figure 1). The administrative area of the city encompasses around 2000 km^2 (not including those in the enclaved territory of the Shenzhen–Shantou Special Cooperation Zone), and comprises 10 administrative districts (Futian, Luohu, Nanshan, Yantian, Baoan, Longgang, Longhua, Guangming, Pingshan and Dapeng) (Table 1). As China's first Special Economic Zone [35], Shenzhen had a large population of 17.63 million at the end of 2020 with highest population density in China, about 52 times that of 1980, and the Gross Domestic Product (GDP) increased by more than 10,000 times [36]. The unprecedented urbanization has caused the demand for urban FEW resources to far exceed its own resource supply capacity [28,37,38], posing challenges to importing numerous resources from outside. In 2017, the Chinese central government approved Shenzhen to build the National Sustainable Development Agenda Innovation Demonstration Zone to pilot the implementation of Sustainable Development Goals (SDGs) issued by the United Nations, which required the improvement in resource use efficiency with less environmental pollution [39,40]. This indicates that the solutions for sustainable resource consumption by such heterotrophic city as Shenzhen are valuable references for other cities at the national level. Therefore, exploring the efficiencies of inner FEW resource consumption within Shenzhen will provide useful policy implications for megacities to seek FEW resources' governance towards sustainable development.

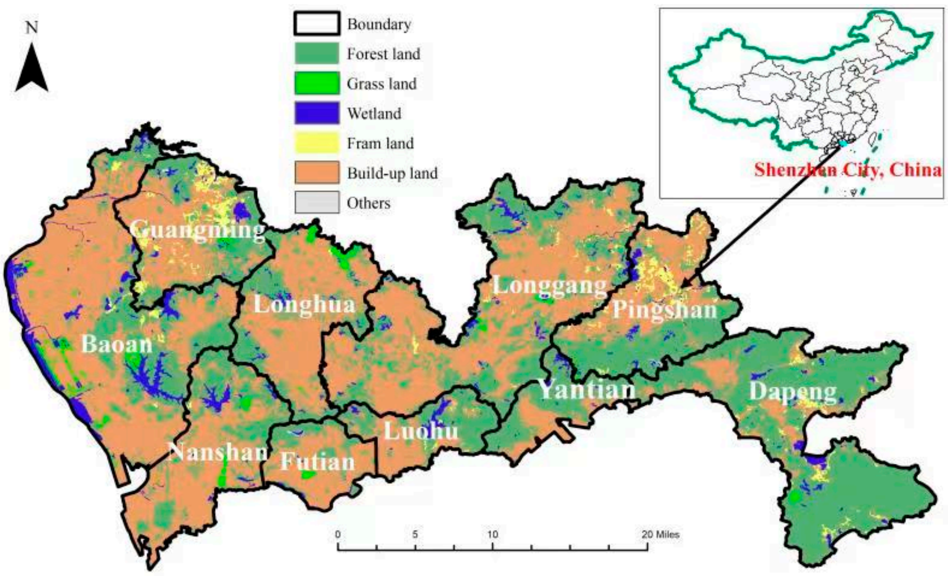

Figure 1. The location of Shenzhen City and its constituent administrative districts with the land use pattern by 2020.

Table 1. The socioeconomic and geomorphic characteristics of the administrative districts within Shenzhen City during 2012–2020.

Regions	Average Annual Population Density (Thousand/km^2)	Average Annual GDP (Billion RMB)	Average Annual Percentage of Municipal Investment in Fixed Assets (%)	Average Annual Percentage of Build-Up Land (%)	Average Annual Percentage of Forest Land(%)
Futian	18.48	370.55	7.20	64.88	19.21
Luohu	13.12	200.05	4.17	39.35	43.38
Nanshan	7.88	457.80	18.47	53.81	13.43
Yantian	2.89	55.01	3.01	23.22	60.25
Baoan	9.40	311.14	16.92	51.28	15.32
Longgang	7.66	352.13	19.74	52.49	26.52
Longhua	12.73	198.44	12.49	61.42	19.42
Pingshan	2.65	58.39	7.00	36.39	37.99
Guangming	4.38	81.54	8.33	41.74	14.89
Dapeng	0.48	30.70	2.01	10.20	67.00

2.2. The Conceptual Framework for Coupling FEW Efficiency Assessment

It is acknowledged that FEW nexus has been widely promoted in policies and development circles with potential strengths since 2011, but it also faces challenges if it is to be widely adopted to assess resource efficiency [3]. In this study, we determine the DEA efficiency to assess the input–output efficiency of FEW resource consumption, which focuses on the human factor through resource governance to enhance efficiency [13]. The constructed network articulating various decision units for DEA proposed by Sun et al. [8] can provide an approach to turn the "black box" into a "gray box" during DEA process, based on the efficiency of the decision unit embodied in each subprocess. However, to further improve the understanding of FEW coupling efficiency for municipal economic development, the proposed network for large-scale provinces was modified for smaller city scale (Figure 2), which is essential to indicate the impacts of economic system on urban FEW nexus [2]. Based on regional decomposition, the measurement of FEW efficiency for single administrate district within the city can be divided further into the efficiency measurement of the three subsystems of FEW, including food subsystem, energy subsystem and water subsystem. Normally, for urban economic development, GDP has been regarded as a relevant signpost of progress in economic development [41]. During the process of pursuing GDP, the material resources are inputs, and products (or values) are produced with unavoidable waste production. More GDP and less waste production based on substantive inputs of FEW resources demonstrate higher efficiencies of FEW subsystems towards increasing coupling FEW efficiency for the administrative district. As Figure 2 shows, the three subsystems have their own external resource inputs indicated for the FEW nexus (food, energy and water), as well as those for capital input (government investments) for maintaining and promoting resource consumption towards municipal economic development, which are regarded as the optimized indicators for the quantitative measurement of governmental intervention in the economy [11,33]. Meanwhile, each subsystem has its own financial outputs, including the GDP for water system, added value of secondary industry for energy system, total net resident income for food system [8]. Notably, the food system considered in this framework only concerns the food resource consumption, based on the characteristics of consumption-type cities such as Shenzhen [37]. Different from the water resource related to the production in energy subsystem and the energy resource related to production in water subsystem, no direct food resources for production link to other two subsystems. The intersystem supportive resource flows from water system to food system are neglected in Shenzhen because of limited water being used for shrinking agricultural production. Similarly, those from food system to energy system are excluded from the assessment since there is no bioenergy production in Shenzhen and therefore no bioenergy raw materials such as crop straws and sugarcane are needed to be produced for energy system. The overall food consumption by whole population was accounted for in the food system, and those consumed by the labors engaged in water and energy systems were not considered in case of double accounting.

We selected all the administrative districts within Shenzhen City as decision units for DEA analysis and the relevant time span was from 2012 to 2020. Nitrogen pollution was the main environmental problem in Shenzhen City, mainly resulting from food, energy and water resource consumption [42–44]; thereby, the gaseous and aquatic nitrogen pollutants were selected as the detailed undesired outputs, which indicate the waste gas and water considered in previous studies concerning provincial FEW efficiencies [11]. The introduction and calculation of relevant input and output indicators for urban FEW efficiency assessments are outlined in Table 2.

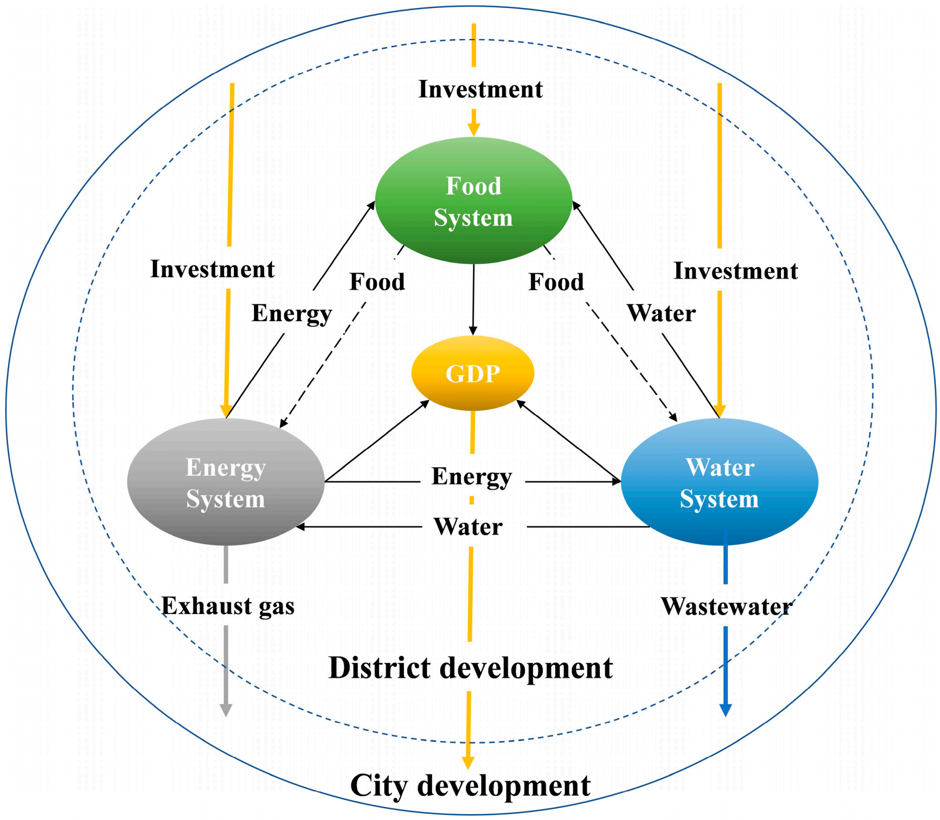

Figure 2. Conceptual framework of an urban FEW system towards economic development. (Dash line meaning that no actual food production link to energy and water systems, and the relationships among them indicate that food consumption accounting in food system include those in energy and water systems).

Table 2. The outline of the input and output indicators for urban FEW efficiency assessments.

FEW Systems	Items	Units	Calculation	Parameter Definition	References
Energy system	Energy input	Ton of SCE * (Standard Coal Equivalent)	EC × GDP	GDP: Gross domestic production EC: Energy consumption per unit GDP	[36]
	Water input	m^3	IWC	IWC: Industrial water consumption	[45]
	Investment input	Yuan	IEG	IEG: Investment in fixed assets for production and supply of electricity	[8,31,36]
	Desired output	Yuan	IGDP	IGDP: Value added of secondary industry	[8,31,36]
	Undesired output	Ton	NO_x	NO_x: Industrial nitrogen oxide emission	[36]

Table 2. *Cont.*

FEW Systems	Items	Units	Calculation	Parameter Definition	References
Water system	Energy input	Ton of SCE (Standard Coal Equivalent)	GAS × EG + DIS × ED	GAS: Gasoline for production and supply of water DIS: Diesel for production and supply of water EG: Conversion coefficients for gasoline to SCE ED: Conversion coefficients for diesel to SCE	[36,46]
	Water input	m^3	AWC + IWC + RWC	AWC: Industrial water consumption RWC: Residential water consumption	[45]
	Investment input	Yuan	IWM	IWM: Completed investment in water resource management	[8,31,36]
	Desired output	Yuan	GDP	GDP: Gross domestic production	[8,31,36]
	Undesired output	m^3	(AWC + IWC + RWC) × PT-RWW + (AWC + IWC + RWC) × (1 − PT)	PT: Wastewater treatment rate RWW: Reuse of wastewater	[42,45]
Food system	Energy input	Ton of SCE	EC × GDP × (ER/EU)	ER: Energy consumption for whole city EU: Energy for residential consumption	[36]
	Water input	m^3	RWC	RWC: Residential water consumption	[45]
	Investment input	Yuan	IHC	IHC: Investment in fixed assets for hotels and catering services	[8,31,36]
	Food input	Ton of protein	$\sum_{i=1}^{9} FC_i \times PRO_i \times RPOP$	FC_i: Daily food *i* consumption PRO: Protein content of food *i* RPOP: Regional population by the end of year	[47,48]
	Desired output	Yuan	PWA × RPOP × (TPEP/TPOP)	PWA: Average wage for fully employed staff and workers TPEP: Total number of employed persons TPOP: Total population by the end of year	[8,36]
	Undesired output	Ton	NH_3	NH_3: Ammonia nitrogen discharge	[36,42,47]

* SCE: Standard Coal Equivalent.

2.3. DEA Analysis

The data envelopment analysis (DEA) model was first proposed to evaluate the relation of decision making units (DMUs) with multiple inputs and outputs [49]. Normally, two conceptual means of DEA modeling production process have been developed by researchers including the multiplier and envelopment forms of DEA. For a standard production process (e.g., urban resource consumption for product output), which only considers the overall transformation from main inputs into the main outputs, these two forms of DEA are equivalent [50]. Significantly, the application of an envelopment DEA would provide targets for efficiency improvement, which is important to provide useful information for resource governance to improve resource efficiency. Consistent with previous studies concerning economic–ecological efficiency [31,33], we therefore selected the envelopment

DEA to measure the 9-year FEW efficiencies in 10 administrative districts of Shenzhen City, which provides an approach to estimate the efficiencies of resource consumption by administrative districts (indicated by DMUs), based on the multiple input and output indictors for FEW efficiency assessments (Table 2).

Considering the pollutants released by resource consumption, the undesired outputs are added to the DEA assessment after reciprocal proceeding [31,51]. Moreover, this model does not need the specific forms of production function and unified dimension to demonstrate the noneffective units with parallel comparison of DMUs, which simplifies the complex production process for cities to provide conducive information about correct resource allocations [33]. Thus, a Charnes–Cooper–Rhodes (CCR) model for DEA, which was widely applied to identify whether "scale effective" and "technical efficiency" occur simultaneously in constant returns to scale [33], is adopted to evaluate the efficiencies of food, energy and water subsystems as DMUs in the specific administrative district, which can be expressed as:

$$\min\theta_c$$

Subject to

$$\theta_C x_0 - X\lambda - s^- = 0 \quad (1)$$

$$Y\lambda - s^+ = y_0 \quad (2)$$

$$\lambda \geq 0,\ s^- \geq 0,\ s^+ \geq 0. \quad (3)$$

where θ_c presents the input–output efficiency of DMU_0 in CCR model, indicating overall efficiency of resource efficiency in current and future scale. X and Y denote the input and output matrixes; λ presents 10-dimensional weight vector; x_0 and y_0 present input and output vectors, respectively. Accordingly, s^- and s^+ denote the vectors of input and output slack variables. When both slack vectors are zero and none of the input variables of DMU_0 are larger than any linear combination of other assessed DMUs, the $\theta_c = 1$ occurs or otherwise $\theta_c < 1$ [52].

2.4. Coupling Efficiency of Regional and Municipal FEW

The three subsystems of food–energy–water (FEW) within an administrative district are interrelated and strongly dependent on each other, and they may be influenced by those of other districts. Accordingly, the efficiency value of each subsystem can be obtained by the DEA model [13], then the overall composite efficiency for an administrative district can be obtained by weighting the efficiencies of above three subsystems. Different from the previous provincial case study where the weights of three subsystems are equal for integrated efficiency score calculation [11], the determination of weight coefficient is processed using the ratio of the common external input (investment) of each subsystem to the total investment for FEW system as its weight [8], the equations are shown as follows

$$E_i = F\theta_C^i \times WF_i + E\theta_C^i \times WE_i + W\theta_C^i \times WW_i \quad (4)$$

$$WF_i = \frac{IF_i}{IF_i + IE_i + IW_i} \quad (5)$$

$$WE_i = \frac{IE_i}{IF_i + IE_i + IW_i} \quad (6)$$

$$WW_i = \frac{IW_i}{IF_i + IE_i + IW_i} \quad (7)$$

where E_i presents the composite efficiency value of the administrate district i in the specific year during 2012–2020. $F\theta_C^i$, $E\theta_C^i$ and $W\theta_C^i$ denote the efficiency values of food, energy and water subsystems in the specific district i, respectively, and WF_i, WE_i and WW_i, accordingly, demonstrate the weight coefficients of food, energy and water subsystems. Considering regional investments for the development of district i, IF_i, IE_i and IW_i present the corresponding investment inputs for food, energy and water subsystems, respectively.

Furthermore, the overall efficiency of resource consumption by Shenzhen City can be similarly obtained by weighting FEW efficiencies of subordinate districts, based on their contributions to the total GDP of city. The relevant equations are shown as follows

$$E_{SZ} = \sum_{i}^{10} E_i \times W_i \tag{8}$$

$$W_i = \frac{GDP_i}{GDP_{SZ}} \tag{9}$$

where E_{SZ} presents the overall efficiency value of Shenzhen city in the specific year during 2012–2020. Higher value demonstrates better level of regional FEW efficiency. W_i denotes the weight coefficient of each district i, which is the ratio of district GDP to Shenzhen GDP.

2.5. Correlation and Driving Force Analysis

For Shenzhen city, the economic and social development levels, as well as environmental endowment, between administrative districts are large, leading to the development of urban regions with different levels of understanding. Considering above reasons, three quantitative factors indicating three aspects of urbanization (e.g., population urbanization, economic urbanization and land urbanization) were selected to explore the influencing mechanisms in this paper [9]. For population urbanization (PU), we use population density (the concentration of urban population in urban regions) rather than urbanization rate, because the percentage of urbanized population in Shenzhen has reached 100% since 2012 [43,47]. Moreover, per capita GDP was selected to demonstrate the progress in economic urbanization (EU) [31,36], and the percentage of build-up land was proposed to be optimized index for indicating land urbanization (LU), which can be retrieved from the official statistics of Shenzhen land survey [53].

The Pearson correlation analysis was first applied to explore the relationships among coupling FEW efficiencies of districts, aiming at exploring the regional synergies of sustainable resource consumptions. Then the multiple linear regression was adopted to explore the influences of above three factors (independent variables) on the coupling FEW efficiencies (dependent variables), aiming to reveal the main driving force on the sustainable resource consumption across regions in Shenzhen City.

2.6. Data Source

The statistical data applied in this study, covering socioeconomic and environmental data, were derived from the Guangdong Statistical Yearbook [54], Shenzhen Statistical Yearbook [36], and Shenzhen Water Resource Bulletin [45] with the database supplements focusing on pollution monitoring and land utilization provided by the local department of environmental protection and land-use planning. The corresponding coefficients for food-source protein estimations were retrieved from local case studies in Shenzhen City [47,48].

3. Results

3.1. Characteristics of Municipal and Regional FEW Efficiencies

During 2012–2020, the scores presenting resource efficiency levels in the FEW systems show different degrees across administrative districts within Shenzhen City based on numerous input and output indicators (the details seen in Table A1). Efficiency values of the interregional food, energy and water subsystems of each administrative district are shown in Table 3. In terms of food subsystems, 60% of administrative districts increased the values of efficiency during the study period, while 30% of administrative districts remained stable, mainly achieving annual food resource efficiency (value = 1), especially the Guangming district. In contrast to Guangming, Longgang district never achieved food resource efficiency despite its value rising by 2020. Meanwhile, Longhua district decreased its value after the most efficient year 2015 and failed to achieve an improvement in food resource efficiency by 2020 compared to other districts. Concerning the efficiency of energy subsystems, 70% of the districts of Shenzhen reached energy efficiency levels (value = 1) in 2020, and half of the total districts achieved an improvement in energy resource efficiency. Futian and Baoan showed fluctuating efficiency values and Luohu decreased its efficiency value after 2015, and these districts kept their inefficiency levels (value < 1) up to 2020. Notably, Nanshan district, where the only coal-fired power station of Shenzhen is located, kept its annual energy efficiency (value = 1) in these years, which played a key role in achieving the overall energy efficiency of Shenzhen city. The dynamics and geography patterns of the water efficiency levels differed greatly from those of the food and energy subsystems. Futian, Yantian, Nanshan and Dapeng maintained their water resource efficiency (value = 1) throughout the period, whereas Baoan, Longgang, Pingshan, Longhua and Guangming did not achieve water resource efficiency during the period, and the latter two, as well as Luohu, had decreased water efficiency values by 2020. These three districts did not significantly increase their GDP, especially after 2019, but saw substantial rises in the amounts of consumed water and discharged wastewater during the study period. This suggests that these districts faced on-going challenges of water resource security and should be targeted as hotspots by municipal measures for water utilization improvements. Overall, only 30% of districts had improvements in their water efficiency values by 2020, which demonstrated that the water resource issue is still the main obstacle to overall FEW improvement in Shenzhen city, responding to the finding conducted by previous local studies [55].

Table 3. Values for efficiency levels of interregional food, energy and water subsystems from 2012 to 2020.

Regions	2012			2014			2016			2018			2020		
	F	E	W	F	E	W	F	E	W	F	E	W	F	E	W
Futian	0.395	0.152	1	0.356	0.122	1	1	0.552	1	0.395	0.373	1	0.459	0.926	1
Luohu	0.397	1	1	0.398	1	1	1	0.847	0.941	0.397	1	0.970	1	0.888	0.865
Nanshan	0.351	1	1	0.357	1	1	0.767	1	1	0.351	1	1	0.47	1	1
Yantian	1	1	1	1	0.579	1	1	1	1	1	1	1	1	1	1
Baoan	0.349	0.521	0.376	0.517	0.151	0.401	1	1	0.443	0.349	0.741	0.457	0.526	0.697	0.379
Longgang	0.349	0.255	0.375	0.379	0.074	0.388	0.724	0.571	0.576	0.349	1	0.609	0.434	1	0.537
Longhua	0.261	0.911	0.435	0.152	0.277	0.423	0.468	0.939	0.501	0.261	1	0.538	0.200	1	0.427
Pingshan	0.491	1	0.318	0.422	1	0.365	1	1	0.447	0.491	1	0.503	0.868	1	0.473
Guangming	1	1	0.418	1	0.165	0.385	1	1	0.349	1	0.955	0.399	1	1	0.316
Dapeng	1	0.997	1	1	0.409	1	0.997	0.464	1	1	0.986	1	1	1	1

Note: F is the efficiency value of food system; E is the efficiency value of energy system; W is the efficiency value of water system.

From the perspective of regional differences, the coupling FEW efficiency values were relatively higher among eastern and central districts, with 80% of districts increasing relevant FEW efficiency values by 2020 (Figure 3). The average value of coupling FEW efficiencies was highest for Yantian (1.73) during the study period, followed by Nanshan (1.70), Luohu (1.67) and Dapeng (1.58), while those of Baoan, Longgang and Guangming were lower than 1 (Table 4). Significant fluctuations in coupling FEW efficiency values were observed in all districts. Half of the districts, which includes the key zones for economic development (Futian, Luohu and Nanshan) and ecological conservation (Yantian and Dapeng), showed a gradual upwards trend reaching higher efficiency values, and others, mainly for industrial zones, showed a gradual growing trend, but their efficiency values were lower overall. Significant increases in FEW efficiency values were observed in Futian and Longgang, while a decrease only occurred in Guangming district, where they were experiencing rapid industrialization with areas of built-up land increasing by 18.26% during 2012–2020.

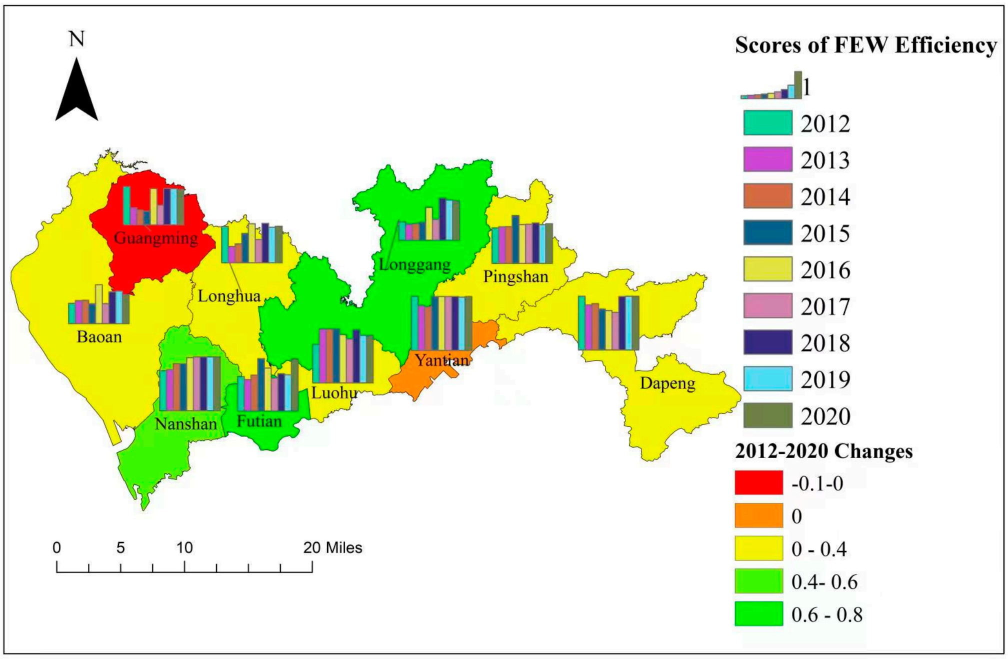

Figure 3. The temporal and spatial characteristics of regional coupling FEW efficiencies across the districts within Shenzhen City.

Table 4. Values for coupling FEW efficiency levels of Shenzhen City from 2012 to 2020.

Regions	2012	2013	2014	2015	2016	2017	2018	2019	2020
Futian	1.278	1.170	1.334	1.940	1.596	1.224	1.385	1.343	1.930
Luohu	1.427	2	2	2	1.795	1.633	1.970	1.762	1.755
Nanshan	1.483	1.526	1.748	1.738	1.967	2	2	2	2
Yantian	2	1.666	1.617	2	2	2	2	1.980	2
Baoan	0.753	0.857	0.867	0.737	1.443	0.741	1.183	1.209	1.080
Longgang	0.678	0.583	0.609	0.666	1.217	0.770	1.556	1.492	1.457
Longhua	1.347	0.604	0.701	1.089	1.450	0.859	1.464	1.315	1.354
Pingshan	1.318	1.357	1.365	1.779	1.447	1.454	1.503	1.436	1.473
Guangming	1.418	0.631	0.553	0.509	1.349	0.727	1.355	1.350	1.316
Dapeng	1.999	1.678	1.722	1.527	1.467	1.400	1.988	2	2
Shenzhen City	1.219	1.158	1.242	1.386	1.582	1.246	1.602	1.561	1.645

Overall, the value for the FEW efficiency level of Shenzhen megacity rose from 1.219 to 1.645 with fluctuations (Table 4), thus rising by 35% from 2012 to 2020, which has significant positive correlations with municipal GDP (r^2 = 0.648). This demonstrates that efficient FEW consumption does not hinder economic growth but contributes to a sustainable path of economic development. Considering the different contributions of regional FEW systems to municipal FEW efficiency, the energy efficiency values of most districts presented substantial rises as the main reason for high efficiency in the entire FEW system and the key reasons for regional difference because higher weight coefficients for the energy subsystem were found while evaluating coupling FEW efficiency.

3.2. Correlations between Regional FEW Efficiencies

The results of Pearson correlation analysis explore the regional synergies of FEW efficiencies among districts. If the dynamic of the FEW efficiency level for one district has strong synergetic correlations with others, then it can be regarded as relatively dominant in the whole FEW system, which can easily influence others or be affected by others. As Figure 4 shows, no negative mutual correlations among districts were observed and regional FEW efficiencies kept synergetic improvements during the study period. Longhua, Guangming and Longgang were regarded as important nodes in municipal FEW efficiency, each of which had stronger correlations with more than one other district during FEW consumptions towards economic development. As the FEW efficiency level has shrunk in Guangming, it is crucial to improve the resource efficiency of this key node in case it threatens the efficient FEW of other districts. In terms of geographical location, these three districts are all located in northern Shenzhen city and are adjacent to Dongguan city where the manufacturing industries of Guangdong province are concentrated. The industrial structure adjustments for the regional economic developments of these districts mainly benefited from the enforced industrial chains of Dongguan city, and the regional FEW resource consumption for industries were therefore influenced by the similar interference from Dongguan city, causing stronger correlations with each other. Conversely, the FEW efficiencies for Luohu and Dapeng districts, the average levels of which were relatively higher, had no synergetic correlations with others, indicating regional FEW efficiency could also be achieved by optimizing endogenous resource consumption.

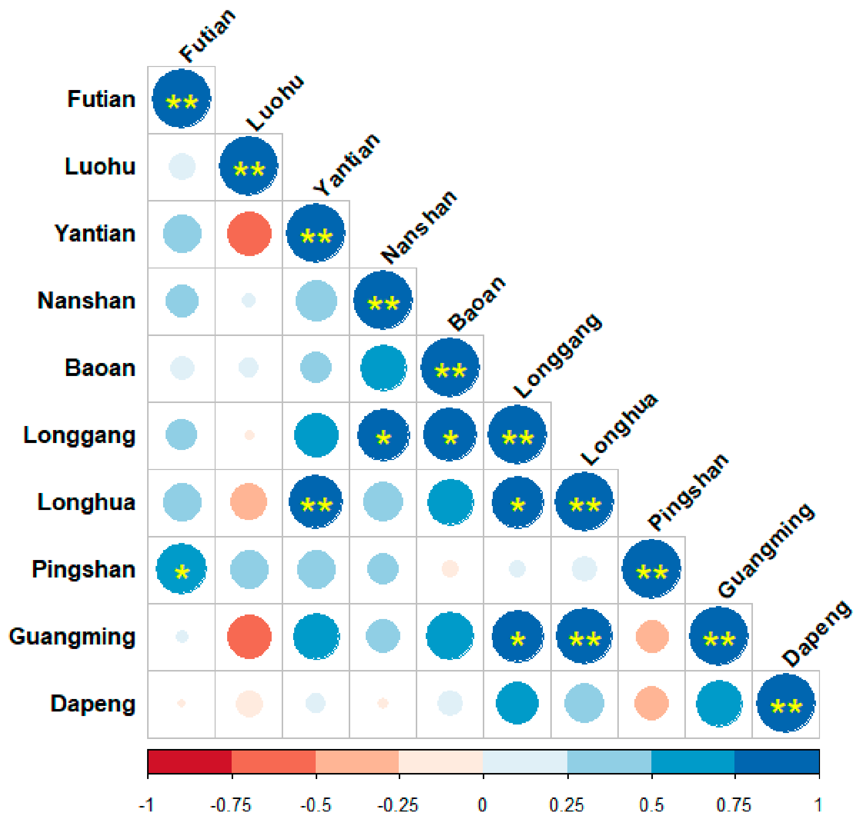

Figure 4. The correlations between FEW efficiencies among districts within Shenzhen City during 2012–2020 (The size of circle in different color indicates Pearson correlation coefficient with "*" indicating $p < 0.05$ and "**" indicating $p < 0.01$).

3.3. Driving Factors of Regional FEW Efficiencies

The results of multiple linear regression were used to reflect the impacts of urbanization on regional FEW efficiencies (Table 5). The standardized coefficient was calculated to determine which factor explained most of the variations in the values. The overall results showed that per capita GDP was the main driving factor of regional FEW efficiencies within Shenzhen city. It is acknowledged that GDP may have a strong impact on

FEW relationships, but GDP per capita is a much better index than GDP itself to indicate the positive impact of FEW resource consumption on regional economic development for improving the living standard of regional citizens [13,15]. Our findings support this statement. Concerning population and land urbanization, population density and the percentage of built-up land had limited impacts on regional FEW efficiencies, while economic urbanization, indicated by GDP per capita, drove the regional FEW efficiencies in Shenzhen city.

Table 5. Summary for multiple linear regression.

	Unstandardized Coefficients		Standardized Coefficients	T	Sig. (p)	Confidence Interval	
	B	Std. Error	Beta			Lower Limit	Upper Limit
Constant	1.016	0.143		7.109	0.000	0.732	1.300
PU (population density)	0.024	0.082	0.030	0.291	0.771	−0.139	0.187
EU (per capita GDP)	0.037	0.005	0.634	7.690	0.000	0.028	0.047
LU (percentage of built-up land)	−0.506	0.275	−0.192	−1.840	0.069	−1.053	0.041

Based on the aforementioned results, the districts in Shenzhen city need to maintain high-quality growth in GDP per capita with urbanization, which demonstrates that more GDP can be produced without consuming more FEW resources from the perspective of individual behavior, leading to FEW resource savings. The GDP of Shenzhen reached USD 366 billion and surpassed Hong Kong's GDP from 2018, resulting in the GDP per capita of Shenzhen is highest among Chinese cites [35]. It is acknowledged that intensive manufacturing industries, which have played a key role in the rapid economic growth of Shenzhen over the past forty years [5], cost more FEW resources due to the higher resource demand for constant mechanical operation, industrial cleaning and labor-intensive food consumption. As a technological and innovation hub in China, the secondary sector of Shenzhen gradually shifted from labor-intensive manufacture to high-technology industry through industrial restructuring, which promoted higher GDP per capita than traditional manufacturing industries and therefore reduced FEW consumptions while pursuing greater GDP. Taking energy consumption for instance, the improvements in the energy efficiencies of computer, communication and electronic product manufacturing in Shenzhen city not only contributed energy saving, but also sustained the GDP growth during 2012–2019 by the export of high value-added products (e.g., semiconductor integrated circuits) [5]. Consequently, GDP per capita should encourage resource-saving trends [56] and FEW efficiencies towards a greener GDP during the urbanization process.

4. Discussion

4.1. Urban FEW Situation and Sustainability

The recent trends in growing FEW resource utilizations have contributed to delivering significant economic development in Shenzhen city. By 2020, only Guangming district had failed to deliver significant improvements in FEW efficiencies. Among the 17 SDGs, SDG 2 (zero hunger), SDG 6 (clean water and sanitation) and SDG 7 (affordable and clean energy) are directly aimed at promoting FEW sustainability [57]. The integration of food, energy and water in a nexus framework to increase resource efficiency can be proposed as a necessary way to achieve the relevant SDGs [2–4]. From the perspective of the FEW nexus, regional water sustainability should be a particular concern, with a focus on the districts without water efficiency annually (e.g., Baoan, Longgang, Longhua, Pingshan and Guangming). It can also be seen that energy sustainability performs best with the highest level of FEW efficiencies among all districts, especially after 2016 (Table 3). The urban FEW situation demonstrates that no significant trade-offs and synergies exist between food, energy and water sustainability in the FEW system within Shenzhen city. For example, regional water sustainability did not always improve when the energy sustainability of a district improved.

Considering regional heterogeneity during economic development, the eastern districts (Yantian and Dapeng), which are key zones for ecological conservation with the highest percentage of forest land (more than 60%) (Table 1), did not achieve higher annual GDP levels compared to other districts, but they still showed higher FEW effective levels throughout the study period. This situation demonstrates that, within the megacity, it is possible to balance ecological conservation and resource efficiency in inner regions while focusing on overall municipal economic development, benefiting from the optimization of land planning that restricts the limited land occupation by industries. The promotion of ecological industries (e.g., outdoor tourism, leisure and entertainment) based on mountain and beach resources played an essential role in maintaining regional GDP and FEW efficiency. The northern districts (Longhua, Guangming and Longgang), which are the important nodes in municipal FEW efficiency, achieved lower FEW efficiencies compared to other districts. These regions, where most of the industrial zones are located, should be the hotspots for improving regional FEW efficiencies by municipal resource management.

4.2. Urban FEW Management towards Sustainability

As the city piloting the SDGs' implementation in China, Shenzhen should serve as a demonstration case of sustainable economic development, eventually realizing synergistic improvements in regional FEW efficiencies, which ensures the FEW security that is viewed by most citizens as a barometer of good governance towards sustainability [58]. In particular, the "14th Five-Year Plan for National Economic and Social Development of Shenzhen and the Outline of Long-term Goal for 2035" [59] addressed the priority of future FEW efficiencies for regional economic development, including the improvements in energy resource efficiency for mitigating climate change, water resource efficiency for leading municipal water saving and food resource efficiency for minimizing food waste. Thus, further improvements in the FEW resource management of Shenzhen city are warranted.

However, the urban characteristics of Shenzhen city increase the complexity of FEW resource management. First, the FEW resources of Shenzhen are scare. The self-sufficiency rates of the FEW resources of Shenzhen are extremely low and this megacity has long relied on Guangdong province to supply FEW resources. Cross-regional resource allocation makes it more difficult for Shenzhen to coordinate FEW management. Furthermore, within Shenzhen city, the different population densities and industrial structures in the administrative districts make it challenging to implement municipal FEW-related policies. With further urbanization, population agglomeration and economic development are presenting huge challenges to regional FEW sustainable management. This case study evaluated urban FEW efficiencies and revealed the complex interactions towards economic development among inner city areas, which could provide information for FEW management to address this challenge as follows.

With high external dependence on FEW supply, self-sufficiency in Shenzhen is a major concern. It is recommended from a nexus perspective that energy policy should be equally integrated into the Shenzhen water and food issues. Considering governmental investment is the main approach for governmental intervention in the economy, FEW subsystems should be treated equally overall for synergistic improvements in FEW efficiencies. During the study period, annual investments to support regional energy systems were normally higher than those for the water and food systems across the districts, which to some extent promoted the higher energy efficiency through structural reform and technical improvements for regional economic development. In the future, on one hand, the investments for regional water systems should be strengthened in terms of the fiscal amounts since they generally occupied smaller proportions of governmental investments compared to those for energy systems, especially in Guangming (average 1.31%) and Dapeng (average 0.31%). The aquatic nitrogen pollutants (mainly ammonia nitrogen embedded in discharged effluents) were the main cause of urban water pollution [43], which should be addressed by improvements in nitrogen removal technology used for sewage treatment supported by more financial support. On the other hand, the scope of governmental investments for food systems should cover all the districts in Shenzhen because some districts received less relevant investments during the study period, including Futian (2 years), Luohu (1 year) and Pingshan (never). These investments in the future can focus on improvements in the facilities of food storage and transportation to avoid food decay, as well as the communal propaganda for residential food saving. In the process of promoting municipal investments for FEW efficiencies, the municipal government should avoid setting a "one-size-fit-all" task benchmark, and step by step investments should be taken to suit the regional advantages of every districts. An appropriate proportion of "FEW-based investments" can effectively maintain the driving forces of economic development towards sustainability, which should include district-level targets for sustainable resource consumption being implemented by district governments.

4.3. Research Highlights and Limitations

Quantification of the FEW nexus is important for the development of FEW nexus research, but the qualitative approach was limited to further explanation of the interconnections in the FEW nexus [13]. Our exploration of urban FEW input–output efficiencies with DEA application can broaden this research method and facilitate the decision making for resource governance. Moreover, we built an index system for coupling FEW efficiency assessments, based on the local data that is much more suitable than the provincial or national data for the DEA model. Li et al. [39] investigated the synergies of FEW resource consumptions in Shenzhen city, but did not further explore the FEW characteristics within the city and failed to reveal the FEW synergies among inner regions towards whole city development. This study overcomes the relevant shortcomings. With more accurate results conducted by DEA, we can compare the various regions within the city in a horizontal dimension to better understand their statuses and the interactive relationships in efficient resource consumptions, and also to learn about their trends during a specific period on a vertical dimension. These may provide useful information for achieving cross-regional joint FEW management and FEW-related SDGs in Shenzhen city.

The research on tracking regional FEW sustainability on the city level is still preliminary. This paper downscaled the evaluation framework of regional FEW sustainability within a city and inevitably introduced some limitations. For example, the framework lacks indicators that can reflect the flow of physical and embodied FEW resources between administrative districts within the city. Thus, such an indicator system can be further optimized in the future from the following two aspects. On the one hand, based on the statistics of data availability, indicators that can reflect the mobilization of FEW resources across administrated districts or cities can be included in the indicator system. On the other hand, the FEW resources embodied in population mobility and industry chain expansion could also be considered in the indicator system. Uncertainty also exists in the coupling FEW efficiency assessment that may result from the selection of specific weight coefficients. It should be noted that a more comprehensive method for determining weight coefficients for composite FEW efficiency calculation, rather than merely depending on the ratio of regional investment to municipal amount, should be considered in future research.

5. Conclusions

The water–energy–food (FEW) nexus is a key concept to address the issues of population boom, resource scarcity and environmental degradation [2]. Cities are critical carriers of the population and economic activities, and are also important contributors to FEW consumption. This study attempted to employ the DEA model to consider the coupling efficiency of the FEW nexus in the typical urbanized Shenzhen city, from the perspectives of resource consumption, and also to illustrate a scheme for emphasizing how economic development can be a factor influencing the urban FEW nexus. The results provide suggestions for sustainable FEW resource consumption throughout the typical megacities in China. The main conclusions of this study respond to the three study objectives aforementioned and can be summarized as follows:

(1) In terms of food subsystem efficiency, 60% of administrative districts increased their values of efficiency during the study period, while 30% of administrative districts remained stable. Concerning energy subsystem efficiency, 70% of the districts of Shenzhen reached an energy efficient level (value = 1) in 2020, and half of the total districts achieved an improvement in energy resource efficiency. The annual energy efficiency achieved by Nanshan played a key role in achieving the overall energy efficiency of Shenzhen city. More than half of the total districts did not achieve water resource efficiency throughout the period, which demonstrates that the water resource issue is still the main obstacle to overall FEW improvement in Shenzhen city. In total, 80% of districts increased their relevant FEW efficiency values by 2020, the averages of which were higher for Yantian, Nanshan, Luohu and Dapeng, and lower for Baoan, Longgang and Guangming, along with a downtrend only being observed in Guangming. Overall, the FEW efficiency value of Shenzhen megacity rose by 35% from 2012 to 2020.

(2) The Pearson correlation analysis revealed that no negative mutual correlations among districts were observed, and regional FEW efficiencies maintained synergetic improvement during the study period. Longhua, Guangming and Longgang, as concentrated industrial zones, were regarded as important nodes in municipal FEW efficiency, while Luohu and Dapeng with higher percentages of forest land achieved FEW efficiencies without synergetic correlations with others districts. Considering the regional heterogeneity within the city, it is possible to balance ecological conservation and resource efficiency in inner regions while working towards overall municipal economic development.

(3) The multiple linear regression demonstrated that per capita GDP was the main driving factor of the regional FEW efficiencies of Shenzhen City. Rising GDP per capita could encourage resource-saving fashions and advanced greener economic structure adjustment during the urbanization process. From a nexus perspective of governmental intervention, there still exist potential improvements in Shenzhen to realize coordinated FEW resource management. It is recommended that energy investments should be equally integrated into the Shenzhen water and food issues; an appropriate proportion of "FEW-based investments" can effectively maintain the driving forces of economic development towards sustainability, the guidance of which is also suitable for the integrative FEW resource governance of other megacities in China.

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Appendix A

Table A1. The characteristics in numerous input and output indicators of DEA for coupling FEW efficiency assessments.

FEW Subsystems	Items	Units	Maximum	Minimum	Mean	Median	Standard Deviation
Futian							
Energy system	Energy input	Million ton of SCE (Standard Coal Equivalent)	15.794	10.715	13.977	13.977	1.659
	Water input	Million m^3	21.202	10.582	15.850	15.295	3.366
	Investment input	Million Yuan	1111.202	7.910	368.741	318.000	308.496
	Desired output (GDP)	Million Yuan	38,768.090	18,648.540	24,561.560	21,711.790	6598.583
	Undesired output (NO_x)	Ton	646.800	108.700	393.467	415.600	195.870
Water system	Energy input	Ton of SCE (Standard Coal Equivalent)	134.105	0	41.649	38.479	45.088
	Water input	Million m^3	257.765	223.659	240.436	240.670	8.359
	Investment input	Million Yuan	29.600	7.728	17.991	19.272	7.519
	Desired output (GDP)	Million Yuan	475,416.260	237,572.570	355,773.431	357,456.120	76,360.840
	Undesired output (wastewater)	Million m^3	237.673	204.596	219.992	220.305	7.990
Food system	Energy input	Million ton of SCE	3.025	1.611	2.306	2.348	0.446
	Water input	Million m^3	110.357	97.004	102.017	98.785	5.413
	Investment input	Million Yuan	295.000	0	43.966	0	94.143
	Food input (food-source protein)	Million ton	0.061	0.038	0.052	0.058	0.010
	Desired output	Million Yuan	216,697.488	78,512.805	138,455.606	133,980.274	46,292.394
	Undesired output (ammonia nitrogen)	Ton	73.097	1.280	26.774	6.288	29.014
Luohu							
Energy system	Energy input	Million ton of SCE (Standard Coal Equivalent)	8.314	6.126	7.435	7.782	0.778
	Water input	Million m^3	13.400	6.236	9.828	9.901	2.217
	Investment input	Million Yuan	971.691	0	400.815	396.320	383.826
	Desired output (GDP)	Million Yuan	17,264.910	7576.520	10,929.758	10,720.040	3169.702
	Undesired output (NO_x)	Ton	134.000	5.300	46.944	40.400	37.260

Table A1. *Cont.*

FEW Subsystems	Items	Units	Maximum	Minimum	Mean	Median	Standard Deviation
Water system	Energy input	Ton of SCE (Standard Coal Equivalent)	549.692	80.182	454.566	336.530	170.362
	Water input	Million m^3	147.944	131.228	143.361	142.606	4.56038
	Investment input	Million Yuan	18.000	4.144	10.906	10.552	4.813
	Desired output (GDP)	Million Yuan	239,025.600	135,825.200	197,624.600	192,916.500	36,837.760
	Undesired output (wastewater)	Million m^3	144.079	127.127	139.521	138.643	4.654
Food system	Energy input	Million ton of SCE	1.516	0.921	1.308	1.258	0.214
	Water input	Million m^3	70.182	62.8905	64.6234	65.7313	2.452298
	Investment input	Million Yuan	80.000	0	0	8.889	25.142
	Food input (food-source protein)	Million ton	0.045	0.027	0.041	0.037	0.007
	Desired output	Million Yuan	160,002.800	55,256.960	93,356.260	98,846.140	34,842.380
	Undesired output (ammonia nitrogen)	Ton	61.185	0.126	2.772	15.706	20.160
Yantian							
Energy system	Energy input	Million ton of SCE (Standard Coal Equivalent)	2.158	1.651	2.035	1.956	0.167
	Water input	Million m^3	2.676	1.713	1.942	2.096	0.315
	Investment input	Million Yuan	978.154	70.030	259.12	481.923	366.307
	Desired output (GDP)	Million Yuan	8793.510	7498.130	8234.120	8223.874	355.498
	Undesired output (NO_x)	Ton	239.900	21.100	69.300	88.700	68.081
Water system	Energy input	Ton of SCE (Standard Coal Equivalent)	83.278	12.300	50.083	45.571	22.538
	Water input	Million m^3	38.736	36.178	37.643	37.478	0.871
	Investment input	Million Yuan	12	3.575	7.038	7.169	2.435
	Desired output (GDP)	Million Yuan	65,814.860	36,617.870	54,026.930	52,964.900	10,106.100
	Undesired output (wastewater)	Million m^3	36.952	29.191	30.409	31.355	2.559

Table A1. *Cont.*

FEW Subsystems	Items	Units	Maximum	Minimum	Mean	Median	Standard Deviation
Food system	Energy input	Million ton of SCE	0.392	0.248	0.342	0.330	0.050
	Water input	Million m^3	15.842	12.440	13.362	13.687	1.153
	Investment input	Million Yuan	63	0	16.306	24.053	24.067
	Food input (food-source protein)	Million ton	0.009	0.006	0.008	0.008	0.001
	Desired output	Million Yuan	29,881.130	12,545.530	19,818.350	20,316.130	5771.499
	Undesired output (ammonia nitrogen)	Ton	15.871	0.105	1.352	4.600	5.154
Nanshan							
Energy system	Energy input	Million ton of SCE (Standard Coal Equivalent)	20.523	12.790	14.991	16.132	2.658
	Water input	Million m^3	16.830	11.382	14.882	14.445	1.576
	Investment input	Million Yuan	1357.385	32.940	398.815	442.926	418.140
	Desired output (GDP)	Million Yuan	207,831.290	166,793.630	198,760.560	193,684.043	13,020.024
	Undesired output (NO_x)	Ton	18,436.300	1050.800	5872.600	6178.144	5307.760
Water system	Energy input	Ton of SCE (Standard Coal Equivalent)	645.500	103.208	477.296	391.997	194.204
	Water input	Million m^3	252.589	186.068	236.830	223.778	25.183
	Investment input	Million Yuan	87.200	15.120	55.104	47.463	22.779
	Desired output (GDP)	Million Yuan	650,222.270	283,600.200	397,847.580	438,445.344	120,652.463
	Undesired output (wastewater)	Million m^3	234.210	180.299	229.065	215.051	22.504
Food system	Energy input	Million ton of SCE	3.913	1.923	2.519	2.743	0.661
	Water input	Million m^3	105.261	77.271	99.182	94.852	8.642
	Investment input	Million Yuan	636.000	0.000	41.760	148.621	205.037
	Food input (food-source protein)	Million ton	0.071	0.032	0.061	0.054	0.016
	Desired output	Million Yuan	251,570.431	65,412.585	140,227.361	145,193.128	63,455.715
	Undesired output (ammonia nitrogen)	Ton	115.818	1.062	54.498	52.035	39.436

Table A1. *Cont.*

FEW Subsystems	Items	Units	Maximum	Minimum	Mean	Median	Standard Deviation
Baoan							
Energy system	Energy input	Million ton of SCE (Standard Coal Equivalent)	13.545	8.665	11.711	11.311	1.463
	Water input	Million m^3	197.287	148.921	172.198	174.670	13.971
	Investment input	Million Yuan	5199.888	266.760	2105.247	2032.656	1435.362
	Desired output (GDP)	Million Yuan	185,878.590	93,614.251	151,053.310	148,280.395	35,424.409
	Undesired output (NO_x)	Ton	2931.200	227.100	916.200	1275.556	963.466
Water system	Energy input	Ton of SCE (Standard Coal Equivalent)	582.291	167.039	464.728	384.628	149.760
	Water input	Million m^3	471.434	448.330	458.365	459.788	6.473
	Investment input	Million Yuan	69.377	18.032	44.838	41.883	16.487
	Desired output (GDP)	Million Yuan	385,358.470	182,723.311	307,124.520	296,870.271	73,323.284
	Undesired output (wastewater)	Million m^3	460.193	439.563	448.442	449.891	5.878
Food system	Energy input	Million ton of SCE	2.248	1.373	2.036	1.906	0.313
	Water input	Million m^3	167.907	141.254	160.126	156.954	8.621
	Investment input	Million Yuan	31,371.840	23.530	95.970	5702.574	10,433.481
	Food input (food-source protein)	Million ton	0.176	0.076	0.157	0.136	0.043
	Desired output	Million Yuan	626,221.020	158,406.444	361,271.925	367,921.635	164,384.303
	Undesired output (ammonia nitrogen)	Ton	528.478	37.225	151.865	246.380	168.754
Longgang							
Energy system	Energy input	Million ton of SCE (Standard Coal Equivalent)	15.423	9.157	12.902	12.211	2.383
	Water input	Million m^3	135.068	104.180	114.995	117.200	9.272
	Investment input	Million Yuan	3642.382	703.730	2543.231	2369.189	1052.728
	Desired output (GDP)	Million Yuan	336,093.650	37,175.786	105,036.430	151,200.695	125,032.276
	Undesired output (NO_x)	Ton	2755.442	382.200	579.500	950.127	737.399

Table A1. *Cont.*

FEW Subsystems	Items	Units	Maximum	Minimum	Mean	Median	Standard Deviation
Water system	Energy input	Ton of SCE (Standard Coal Equivalent)	1158.848	259.323	925.761	730.572	333.931
	Water input	Million m^3	411.192	371.380	396.598	394.757	11.032
	Investment input	Million Yuan	74.800	25.312	47.520	47.375	15.471
	Desired output (GDP)	Million Yuan	474,448.510	195,823.904	347,047.250	334,766.618	104,515.869
	Undesired output (wastewater)	Million m^3	391.121	358.484	383.678	380.566	9.702
Food system	Energy input	Million ton of SCE	2.801	1.451	2.168	2.079	0.546
	Water input	Million m^3	177.730	140.425	151.465	156.086	12.598
	Investment input	Million Yuan	3108.209	157.240	302.310	1100.218	1159.821
	Food input (food-source protein)	Million ton	0.156	0.055	0.122	0.109	0.040
	Desired output	Million Yuan	557,604.564	113,706.369	280,364.965	299,380.933	153,430.519
	Undesired output (ammonia nitrogen)	Ton	426.784	2.877	84.848	164.111	164.840
Longhua							
Energy system	Energy input	Million ton of SCE (Standard Coal Equivalent)	8.393	5.304	7.148	7.006	1.092
	Water input	Million m^3	90.759	57.446	66.664	71.031	10.810
	Investment input	Million Yuan	18,761.294	247.410	1188.383	4047.146	5933.322
	Desired output (GDP)	Million Yuan	143,875.810	46,434.760	91,750.890	91,933.673	30,200.516
	Undesired output (NO_x)	Ton	461.800	36.300	173.200	266.000	155.181
Water system	Energy input	Ton of SCE (Standard Coal Equivalent)	510.697	88.613	279.109	311.995	162.162
	Water input	Million m^3	256.006	131.020	249.052	235.419	37.381
	Investment input	Million Yuan	48.400	15.008	31.416	30.613	11.377
	Desired output (GDP)	Million Yuan	251,077.240	117,603.249	188,458.200	189,497.670	48,656.320
	Undesired output (wastewater)	Million m^3	232.740	108.928	226.994	213.108	37.276

Table A1. *Cont.*

FEW Subsystems	Items	Units	Maximum	Minimum	Mean	Median	Standard Deviation
Food system	Energy input	Million ton of SCE	1.524	0.797	1.201	1.189	0.263
	Water input	Million m^3	101.938	27.256	88.385	82.951	21.583
	Investment input	Million Yuan	124.930	0.000	0.000	55.524	62.078
	Food input (food-source protein)	Million ton	0.099	0.040	0.081	0.072	0.023
	Desired output	Million Yuan	153,867.626	29,021.118	70,782.370	77,870.406	42,092.919
	Undesired output (ammonia nitrogen)	Ton	194.827	2.716	19.467	52.344	68.064
Pingshan							
Energy system	Energy input	Million ton of SCE (Standard Coal Equivalent)	2.487	1.557	2.011	2.042	0.350
	Water input	Million m^3	39.343	28.624	33.275	33.496	2.927
	Investment input	Million Yuan	2288.990	175.620	647.048	780.275	565.958
	Desired output (GDP)	Million Yuan	262,738.930	24,846.620	137,223.220	120,790.836	78,742.709
	Undesired output (NO_x)	Ton	252.400	30.000	89.400	104.922	63.692
Water system	Energy input	Ton of SCE (Standard Coal Equivalent)	233.414	34.788	159.143	138.290	72.017
	Water input	Million m^3	87.994	43.702	77.060	74.064	11.379
	Investment input	Million Yuan	29.200	9.009	16.353	16.852	6.168
	Desired output (GDP)	Million Yuan	80,105.320	34,524.860	53,077.290	55,738.980	15,866.113
	Undesired output (wastewater)	Million m^3	84.264	39.967	72.295	70.095	11.326
Food system	Energy input	Million ton of SCE	0.475	0.234	0.338	0.347	0.084
	Water input	Million m^3	24.073	18.343	22.157	21.721	1.637
	Investment input	Million Yuan	0	0	0	0	0
	Food input (food-source protein)	Million ton	0.022	0.009	0.019	0.016	0.005
	Desired output	Million Yuan	77,289.375	18,694.368	42,562.769	43,446.214	20,014.587
	Undesired output (ammonia nitrogen)	Ton	71.085	0.566	23.767	36.424	26.772

Table A1. *Cont.*

FEW Subsystems	Items	Units	Maximum	Minimum	Mean	Median	Standard Deviation
Guangming							
Energy system	Energy input	Million ton of SCE (Standard Coal Equivalent)	3.490	2.276	2.813	2.893	0.406
	Water input	Million m^3	73.116	48.994	60.222	59.165	6.472
	Investment input	Million Yuan	7424.998	655.511	2374.873	3081.897	2553.177
	Desired output (GDP)	Million Yuan	74,144.330	27,247.040	36,154.170	44,553.237	17,000.892
	Undesired output (NO_x)	Ton	219.700	34.100	68.400	92.167	57.176
Water system	Energy input	Ton of SCE (Standard Coal Equivalent)	197.619	43.581	82.740	104.134	52.148
	Water input	Million m^3	245.546	114.865	140.367	146.054	37.297
	Investment input	Million Yuan	36.729	9.856	20.304	20.521	8.258
	Desired output (GDP)	Million Yuan	110,077.140	50,459.670	74,203.410	78,085.678	19,309.675
	Undesired output (wastewater)	Million m^3	242.471	111.500	134.468	140.828	37.417
Food system	Energy input	Million ton of SCE	0.668	0.342	0.473	0.491	0.105
	Water input	Million m^3	77.571	24.720	30.328	34.646	15.525
	Investment input	Million Yuan	289.210	0.000	0.000	62.341	90.492
	Food input (food-source protein)	Million ton	0.043	0.014	0.031	0.028	0.011
	Desired output	Million Yuan	354,613.635	83,121.486	186,048.310	196,512.882	92,659.073
	Undesired output (ammonia nitrogen)	Ton	129.747	4.727	60.889	75.034	43.975
Dapeng							
Energy system	Energy input	Million ton of SCE (Standard Coal Equivalent)	1.202	1.010	1.089	1.114	0.067
	Water input	Million m^3	9.011	4.686	6.476	6.705	1.350
	Investment input	Million Yuan	9458.722	701.010	1538.010	3584.381	3385.691
	Desired output (GDP)	Million Yuan	20,772.080	14,212.590	18,331.890	17,744.050	2071.373
	Undesired output (NO_x)	Ton	1798.758	314.000	831.600	969.851	521.395

Table A1. *Cont.*

FEW Subsystems	Items	Units	Maximum	Minimum	Mean	Median	Standard Deviation
Water system	Energy input	Ton of SCE (Standard Coal Equivalent)	63.294	8.338	28.388	35.218	20.457
	Water input	Million m^3	32.693	30.319	31.560	31.439	0.759
	Investment input	Million Yuan	7.200	2.002	4.368	4.657	1.499
	Desired output (GDP)	Million Yuan	35,143.530	3.360	30.623	8519.328	12,728.647
	Undesired output (wastewater)	Million m^3	28.963	26.576	27.751	27.710	0.787
Food system	Energy input	Million ton of SCE	0.213	0.152	0.198	0.188	0.022
	Water input	Million m^3	7.886	5.109	5.980	6.144	0.885
	Investment input	Million Yuan	10,669.791	1.000	214.888	3206.782	4369.322
	Food input (food-source protein)	Million ton	0.006	0.004	0.006	0.005	0.001
	Desired output	Million Yuan	21,877.508	7724.409	12,646.761	13,683.076	4845.435
	Undesired output (ammonia nitrogen)	Ton	39.248	0.120	16.839	15.853	12.676

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