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Temporal Variation of Water Environment Carrying Capacity in a Highly Urbanized Region of China

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Abstract: China has experienced an unparalleled urbanization process in recent decades, which has dramatically changed the water environment. Quantification of the water environment carrying capacity (WECC) is crucial given its importance to sustainable development. Existing studies have typically focused on the overall WECC system and lacked analysis of its internal features. In this study, the concepts, calculations, and classifications of the WECC were further developed. Using Nanjing, China, as a case study, we developed a hierarchical evaluation indicator system including three system layers (social, environmental and economic subsystems). We applied the entropy weight and fuzzy comprehensive evaluation method to evaluate the temporal variation tendency of WECC, and explored the deep-seated problems stemming from urbanization. The results indicated that WECC in Nanjing was 0.3045–0.5302 during 2006–2017, thus approaching a moderate grade with a relatively slow growth rate. Social, environmental, and economic subsystems increased by 29.3%, 83.1%, and 97.2%, respectively. Overall, Nanjing had a solid foundation regarding its economic subsystem, but its social and environmental subsystems were under pressure. Factors such as slow population growth as well as reduced energy and water use intensity improved WECC, whereas factors such as increased population density and excessive water consumption blocked WECC. Practical suggestions were proposed to resolve the primary problems of the WECC under urbanization. This holistic approach is urgently needed to achieve water environmental sustainability, both for Nanjing and for other emerging cities.

Keywords: water environment carrying capacity; entropy weight; fuzzy comprehensive evaluation; Nanjing City

1. Introduction

Urbanization has been increasing globally, especially in developing countries, and is characterized by high population densities [1]. Human activities, especially in megacities, have led to a fast-growing economy and a rapidly developing society but have also caused various environmental problems worldwide [2]. One of the most severe environmental impacts is the deterioration of water quality, which can lead to an imbalance in river ecosystems, while concurrently threatening socioeconomic

sustainability [3]. At present, the conflict between economic development and water environment protection is becoming increasingly intense [4]. This is especially true in rapidly growing large cities in developing countries [5]. To provide guidance for policy makers in sustainable development, a scientific method that can measure progress towards coordinated development of the economy and the water environment is an urgent requirement.

Water environment carrying capacity (WECC) is often used to assess sustainable socio-ecological development. It can be defined as “the largest population and economic scale that the water environment can support in a specific region during a period of time without an adverse impact on the local water environment” [6]. In the late 1960s and the early 1970s, a carrying capacity problem of the environment was noted when resource depletion and environmental degradation caused by rapid growth of the population and the economy began receiving attention [7,8]. In the early 1980s, the concept of WECC was proposed when the management of the water environment became increasingly important for ecosystem health and human health, as the impacts of human activities were further exacerbated [9]. Subsequently, based on a profound understanding of the mutual relationships between socio-economic development and the water environment, the carrying capacity of the environment has been further studied since the 1990s [10]. At present, most studies have integrated the carrying capacity theory into sustainable development research [6,11,12]. Wang et al. made policy recommendations to guarantee sustainable utilization of water resources, based on analysis of the wetland water resources carrying capacity in Beijing city [13]. Jia et al. provide a scientific reference to the management of sustainable economic and social development in China according to the spatial similarities and variations of the WECC [14]. Meng et al. regarded environmental carrying capacity as one of their sustainable development categories [15]. Peng and Deng calculated the resource carrying capacity of Guiyang from 2003 to 2017, in order to put forward corresponding countermeasures for sustainable development [16]. WECC has become an important means for assessing whether the social economy coordinates with water environment systems, and it plays a crucial role in helping cities to make informed decisions concerning sustainable development.

Most previous studies have focused on quantitative analyses of WECC using different evaluation approaches [17]. These methods include comprehensive evaluation methods, ecological footprints, and multi-objective programming [18–20]. In recent years, more methods have been developed to evaluate carrying capacity including the BP (Back Propagation) neural network algorithm, matter element analysis method, and a grid search method based on GIS (Geographic Information System) [21,22]. Among these, comprehensive evaluation methods are commonly used to evaluate WECC. These methods can combine many individual indicators into a single comprehensive index. Comprehensive evaluation methods can be classified into four primary types: fuzzy comprehensive evaluation, analytic hierarchy process (AHP), principal component analyses (PCA), and the system dynamics method (SD). Lu et al. studied WECC in Huai'an from 2005 to 2014 using AHP [23]. Zhang et al. applied PCA to evaluate temporal variation trends in the water resources–water environment carrying capacity from 2005 to 2015 [24]. Yang et al. constructed a multi-criteria evaluation system of water resources carrying capacity for Xi'an to predict the developmental trends from 2015 to 2020 by SD models [25]. AHP allocates weights by allowing experts to evaluate the relative importance of indexes in pairs, which makes it more subjective than other methods. PCA can turn an original dataset into principal components, but the principal components are not as readable and interpretable as the original dataset. SD requires a substantial amount of historical data, such as population, pollution emission and other socio-economic information, thus has not been widely used due to higher costs and difficulties in data acquisition.

At present, the main challenge facing WECC evaluation is the fuzziness and uncertainty of carrying capacity and the complicated relationships between indicators and WECC [26]. The aforementioned three methods cannot efficiently handle the uncertainty and ambiguity of the evaluation process. To solve this problem, we proposed a fuzzy comprehensive evaluation method based on entropy weight. Fuzzy comprehensive evaluation method uses the fuzzy logic theory and membership function

to make an overall evaluation of complicated items affected by multiple factors [27,28]. For this method, the characteristics of each influential factor are considered comprehensively, and fuzziness or uncertainty in WECC evaluation can be efficiently tackled, which makes the evaluation process more accurate and reliable.

As for the assignment of indicator weights, there are two current primary weighting methods: subjective weighting and objective weighting. The entropy weight method is typically representative of objective weighting methods, which depends excessively on the objective data of indicators [29]. Therefore, to avoid the weights affected by researchers' perception, the entropy weight method was applied in this research.

As the largest developing country, China has experienced both rapid urbanization and prosperous economic growth in recent decades. The proportion of the urbanized population is expected to increase at an unprecedented rate in the upcoming decades, thereby increasing the importance of WECC evaluations in ensuring sustainable development. To better understand the changes in WECC, it is necessary to obtain accurate information about the performance of indicators. In this study, we selected Nanjing City as a test case because this area has been highly urbanized in recent years. Our objectives were to: (1) establish an evaluation indicator system for WECC; (2) detect the temporal dynamics of WECC for the 2006–2017 period, (3) provide the first quantification of the changes in indicators to identify the improving and blocking factors of WECC via the fuzzy comprehensive evaluation method, and (4) identify problems and provide suggestions for promoting the regional WECC. The results of the present study can provide important guidance for improving WECC and may be of considerable importance to further work on sustainable development both in China and in other countries.

2. Materials and Methods

2.1. Study Area

The study was performed in Nanjing (Figure 1). Nanjing ($118^{\circ}22''$ – $119^{\circ}14''$ E; $31^{\circ}14''$ – $32^{\circ}37''$ N), the capital city of Jiangsu Province, is situated in the eastern part of China. It has a total population of 8.30 million and an area of 6587 km². The region has a subtropical monsoon climate with an average annual temperature of 15.4 °C and rainfall of 1106 mm. Within the city limits, more than 11% of the area is occupied by water. The Yangtze River flows through Nanjing, and exits the city to the northeast, thus its water quality is exceedingly important to downstream cities such as Shanghai.

The urbanization rate of Nanjing increased from 76.4% in 2006 to 82.1% in 2017, while an urbanization rate of more than 70% is defined as highly urbanized in the “City Blue Book: China Urban Development Report no.12” published in 2019. The GDP of Nanjing reached 170.2 billion dollars, and the per capita GDP has been 20,508 dollars since 2017; both values are above the average statistics for moderately developed countries. The regional urbanization rate is 82% and has reached a mature stage. Nanjing supports important heavy industrial activities (petrochemical production, electricity generation, steelmaking, and shipbuilding) that account for poor water quality in many rivers. Additionally, rapid population expansion in recent decades has also increased wastewater discharge. Over 30 plants are distributed throughout Nanjing to treat municipal and industrial wastewater using different approaches. These statistics are mainly from the Nanjing statistics yearbook.

Figure 1. Administrative map of Nanjing.

2.2. Construction of Evaluation Indicator System

Identifying an appropriate indicator evaluation system is crucial for WECC, as it can determine whether the current water environment is sustainable and, if not, how to address its underlying problems. A hierarchical evaluation indicator system for WECC has been established in this paper based on the study of the relationship between environmental quality, water resources and social economy [30,31]. In this evaluation system, the overall target is represented by A and the overall goal is further divided into three system layers, including social subsystem (A_1), environmental subsystem (A_2), and economic subsystem (A_3).

When selecting indicators, those frequently used in relevant studies were first clarified by the frequency statistical method. Secondly, the indicators related to social, environmental and economic studies were extracted. Thirdly, each indicator was vetted specifically against the following selection principles: accessibility, feasibility of measurement, relevance in assessing the water environment, whether the indicator was within governmental capabilities for development, and whether it was representative of the related issues to the greatest possible extent [32]. Finally, 23 indicators were selected in the evaluation system, as shown in Table 1.

Table 1. Evaluation indicator system of water environment carrying capacity (WECC).

Overall Target	System Layer	Indicator Layer	Units	Attributes
water environment carrying capacity(A)	Social subsystem (A ₁)	Population growth rate (u_1)	%	–
		Population density (u_2)	people/km ²	–
		Urbanization rate (u_3)	%	+
		Domestic water use per capita (u_4)	L/(day·person)	–
		Industrial water reuse (u_5)	%	+
		Water resources per capita (u_6)	m ³ /person	+
		Water resources utility rate(u_7)	%	–
	Environmental subsystem (A ₂)	Forest area as percent of land area(u_8)	%	+
		Arable land area as percent of land area(u_9)	%	+
		Use of fertilizers per unit of agricultural land area(u_{10})	10 ³ kg/km ²	–
		Use of pesticides per unit of agricultural land area(u_{11})	kg/km ²	–
		Compliance rate for water quality standards(u_{12})	%	+
		Wastewater treatment rate(u_{13})	%	+
		COD emission per unit of industrial added value(u_{14})	kg/10 ⁴ RMB	–
		Wastewater discharge per unit of GDP(u_{15})	kg/RMB	–
		GDP per capita(u_{16})	10 ⁴ RMB/person	+
		Industrial output per capita (u_{17})	10 ⁴ RMB/person	+
	Economic subsystem (A ₃)	The percentage of tertiary industry(u_{18})	%	+
		Annual energy consumption per capita(u_{19})	kg/person	–
		Energy consumption per unit of GDP(u_{20})	kg/10 ⁴ RMB	–
		Water consumption per unit of GDP(u_{21})	m ³ /10 ⁴ RMB	–
		Water consumption per unit of industrial added value(u_{22})	m ³ /10 ⁴ RMB	–
		Generation of industrial solid waste(u_{23})	10 ⁷ kg	–

Five indicators related to population, urbanization and water use have been chosen to represent the social subsystem situation. Population is an important contextual reference regarding WECC for decision makers evaluating the interrelationships between people, resources, and the environment. Rural–urban demographic transition increases pressure on the environment, especially in ecologically-sensitive areas. Moreover, most of the water used by industries and municipalities is often returned to watercourses degraded in quality, which makes water consumption a serious concern in environmental management.

Ten indicators reflecting the state of water resources, environmental pollution and protection are selected in the environmental subsystem. Adequate freshwater is essential to support the ecosystem and social and economic development. It also plays a pivotal role in human life, food production, industry, and hydropower generation. The quantity of available water is a measure of the vulnerability of a city to water shortages. In addition, land is becoming an increasingly scarce resource because of the expanding requirements of urban development. Many land-based issues such as agricultural land degradation, deforestation and desertification threaten the stability and resilience of water ecosystems. The use of agrichemicals while enhancing productivity also has potential impacts on the environment, including eutrophication and contamination of water supplies. Furthermore, four indicators focusing on sewage pollution and treatment are used in the subsystem, which can reflect ecosystem health and environmental governance, respectively.

Eight indicators concerning economic performance, energy use, and industrial waste generation are selected for this subsystem. Increasing economic growth and investment is critical for assisting cities in meeting the objectives of sustainable water environment. In addition, to improve the standard of living of a growing population, sharp increases in energy services will considerably compound future environmental and human health problems. Moreover, material consumption and waste production are also the major causes of the continued depletion of water resources and deterioration of the environment.

2.3. Data Analysis

In this study, the analysis consists of three steps: dimensionless standardization, weight calculation via entropy method, and fuzzy comprehensive evaluation.

2.3.1. Standardization of Raw Data

To eliminate the influences of magnitude and dimension, it is necessary to standardize the raw data. The indicators with different attributes can be divided into positive and negative indicators, as shown in Table 1. Then, all the indicators can be standardized by the following equations:

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (1)$$

$$y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (2)$$

where x_{ij} is the original value of the i th indicator in the j th sample; y_{ij} ($i = 1, 2, \dots, m$, and $j = 1, 2, \dots, n$) is the standardized value of the i th indicator in the j th sample; and m and n are the number of indicators and samples respectively. Equation (1) is for positive indicators, whereas Equation (2) is for negative indicators.

2.3.2. Entropy Weight Method

Various indicators have different impacts on WECC and thus it is critical to attribute their weights. The entropy method was applied to ensure the objectivity and rationality of weight assignment [33]. In the equation below, $Y = (y_{ij})_{m \times n}$ represents the standardized indicator matrix. The proportion p_{ij} of the i th indicator in the j th sample to the total value of the i th indicator was specified as follows:

$$p_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (3)$$

The entropy e_i of the i th indicator was calculated using the following function:

$$e_i = -\frac{1}{\ln(n)} \sum_{j=1}^n (p_{ij} \ln(p_{ij})) \quad (4)$$

The weight w_i of the i th indicator was determined by the formula below:

$$w_i = \frac{1}{\ln(n)} \sum_{j=1}^n (p_{ij} \ln(p_{ij})) \quad (5)$$

2.3.3. Fuzzy Comprehensive Evaluation

Fuzzy comprehensive evaluation is a method that uses fuzzy set theory to convert the qualitative evaluation into a quantitative evaluation. The method has been applied to carrying capacity assessment to eliminate the fuzziness or uncertainty that may exist in the assessment process [34]. Furthermore, fuzzy comprehensive evaluation has now become an effective decision-making tool, especially in multi-factor assessments [35]. The main procedure of fuzzy comprehensive evaluation is as follows [36].

The factor set U can be determined as:

$$U = \{u_1, u_2, \dots, u_m\} \quad (6)$$

where u_i is the i th indicator value and m is the number of indicators.

The evaluation criteria set V is the aggregate composed of three grading criteria, where v_1, v_2 and v_3 represents “excellent”, “moderate” and “poor”.

$$V = \{v_1, v_2, v_3\} \quad (7)$$

The following membership function was applied to determine the membership degree of each factor for three criteria.

$$r_1(u_i) = \begin{cases} 0.5\left(1 + \frac{v_1 - u_i}{v_2 - u_i}\right) & u_i < v_1 \\ 0.5\left(1 - \frac{u_i - v_1}{v_2 - v_1}\right) & v_1 \leq u_i < v_2 \\ 0 & u_i \geq v_2 \end{cases} \quad (8)$$

$$r_2(u_i) = \begin{cases} 0.5\left(1 - \frac{v_1 - u_i}{v_2 - u_i}\right) & u_i < v_1 \\ 0.5\left(1 + \frac{u_i - v_1}{v_2 - v_1}\right) & v_1 \leq u_i < v_2 \\ 0.5\left(1 + \frac{v_3 - u_i}{v_2 - u_i}\right) & v_2 \leq u_i < v_3 \\ 0.5\left(1 - \frac{v_3 - u_i}{v_2 - u_i}\right) & u_i \geq v_3 \end{cases} \quad (9)$$

$$r_3(u_i) = \begin{cases} 0 & u_i \leq v_2 \\ 0.5\left(1 + \frac{u_i - v_3}{v_2 - v_3}\right) & v_2 \leq u_i < v_3 \\ 0.5\left(1 + \frac{v_3 - u_i}{v_2 - u_i}\right) & u_i \geq v_3 \end{cases} \quad (10)$$

where $r_j(u_i)$ (or r_{ij}) ($i = 1, 2, \dots, m; j = 1, 2, 3$) is the membership degree of factor u_i to the j th criteria.

The fuzzy membership matrix R can be expressed as:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{13} \\ r_{21} & r_{22} & \cdots & r_{23} \\ \vdots & \vdots & \cdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{m3} \end{bmatrix} \quad (11)$$

The fuzzy comprehensive assessment matrix B was determined as:

$$B = W \times R = (b_1, b_2, b_3) \quad (12)$$

where $W = (w_1, w_2, \dots, w_m)$ is the weight matrix; and b_j ($j = 1, 2, 3$) and is an element in matrix B .

In order to quantitatively reflect WECC, the evaluation grades, v_1, v_2 and v_3 , were scored between 0 and 1: $a_1 = 0.95, a_2 = 0.5, a_3 = 0.05$. The higher score indicates that water environment protection is more effective [26].

$$A = \sum_{j=1}^3 b_j a_j \quad (13)$$

The final assessment result A , represents the comprehensive index of WECC. The WECC improves with a higher index.

3. Results

3.1. Weight and Descriptive Statistics of Indicators

The general statistics of the 23 indicators as well as their corresponding weights are presented in Table 2. According to the entropy weight method, the weights of the indicators ranged from 0.0206–0.0763, and those of large weight were as follows: population density (0.0763) > water resources per capita (0.0731) > compliance rate for water quality standards (0.0652) > water resources utility rate (0.0622) > GDP per capita (0.0555) > urbanization rate (0.0534) > percentage of tertiary industry (0.0526) > wastewater treatment rate (0.0518) > industrial output per capita (0.0504). Comparisons of weights demonstrated that indicators representing population as well as water quantity and quality tended to

have greater impact on WECC. The weights of the three subsystems were as follows: 0.2282 (social subsystem), 0.4350 (environmental subsystem), 0.3268 (economic subsystem). Thus, the environmental subsystem had the most significant influence on WECC.

Table 2. The weights of 23 indicators and descriptive statistics.

	u_1	u_2	u_3	u_4	u_5	u_6	u_7	u_8	u_9	u_{10}	u_{11}	u_{12}
Maximum	3.10	1259	82.1	361	88.1	834	153	31.0	37.0	55.2	1502	77.8
Minimum	0.29	1092	76.4	266	64.8	290	127	22.0	35.7	30.0	675	56.2
Average	1.47	1203	79.4	308	81.5	430	142	27.0	36.3	37.7	961	67.8
Weight	0.0436	0.0763	0.0534	0.0283	0.0266	0.0731	0.0622	0.0351	0.0412	0.0225	0.0216	0.0652
	u_{13}	u_{14}	u_{15}	u_{16}	u_{17}	u_{18}	u_{19}	u_{20}	u_{21}	u_{22}	u_{23}	
Maximum	96.3	2.40	2.40	14.11	4.64	59.7	4750	1.310	162.2	143.1	2068	
Minimum	83.2	0.14	0.85	3.93	1.64	47.9	3849	0.590	36.5	30.4	1278	
Average	91.4	1.04	1.48	8.44	3.10	53.5	4253	0.874	79.7	66.4	1634	
Weight	0.0518	0.0247	0.0376	0.0555	0.0504	0.0526	0.0309	0.0463	0.0481	0.0325	0.0206	

3.2. Grading Criteria of Evaluation Indicators

According to the formulas (Equations (8)–(10)), it is necessary to acquire the grading criteria of all the evaluation factors. In this study, the grading criteria in Table 3 were obtained by classification standard from relevant research [28,31], or standards including “Eco-county, eco-city, and eco-province construction standards (Revised Draft)”, “Urban residents domestic water consumption standard (GB/T 50331-2016)” and “General rule for planning urban drainage engineering (GB 50318-2017)”.

Table 3. Grading criteria of indicators.

Indicator	Excellent	Moderate	Poor	Attributes
Population growth rate	0.3	0.9	1.5	–
Population density	400	500	600	–
Urbanization rate	75	65	55	+
Domestic water use per capita	150	225	300	–
Industrial water reuse	85	70	55	+
Water resources per capita	1700	1100	500	+
Water resources utility rate	40	50	60	–
Forest area as percent of land area	30	22.5	15	+
Arable land area as percent of land area	35	27.5	20	+
Use of fertilizers per unit of agricultural land area	15	22.5	30	–
Use of pesticides per unit of agricultural land area	300	500	700	–
Compliance rate for water quality standards	80	70	60	+
Wastewater treatment rate	95	90	85	+
COD emission per unit of industrial added value	0.8	1.2	1.6	–
Wastewater discharge per unit of GDP	1	1.5	2	–
GDP per capita	8	6	4	+
Industrial output per capita	6	4	2	+
The percentage of tertiary industry	60	50	40	+
Annual energy consumption per capita	3500	4000	4500	–
Energy consumption per unit of GDP	0.5	0.95	1.4	–
Water consumption per unit of GDP	30	50	70	–
Water consumption per unit of industrial added value	25	40	55	–
Generation of industrial solid waste	1200	1400	1600	–

3.3. Changes in WECC from 2006 to 2017

The WECC and three subsystems were all divided into excellent (grade I), good (grade II) and poor (grade III) based on the calculation result. The evaluation grading criteria for WECC and subsystems in Nanjing City are shown in Table 4.

Table 4. Grading criteria of WECC and subsystems.

Grade	Comprehensive Index
excellent (I)	0.725
moderate (II)	0.55
poor (III)	0

The comprehensive index in Nanjing from 2006 to 2017 was calculated based on the fuzzy comprehensive evaluation method combined with the entropy weight of each indicator, as shown in Figure 2. WECC in Nanjing exhibited a general growth trend but did not exceed the moderate grade (II). WECC increased from 0.3045 in 2006 to 0.5302 in 2017, and the average rate of change was approximately 2.05% per year. It could be interpreted that the level of sustainable development was better during these years, but Nanjing's speed of social, environmental, and economic development was not high enough. The comprehensive index fell in 2011 and 2016. This moderate fluctuation in the long-term period means that the short-run WECC is volatile to external shocks [37].

Figure 2. Comprehensive index of WECC in 2006–2017.

Figure 3 shows the comprehensive index and variation of each subsystem in Nanjing from 2006 to 2017. Specifically, the social, environmental and economic subsystems increased by 29.3%, 83.1% and 97.2% respectively. In comparison, the comprehensive index of the economic subsystem displayed an increasing tendency throughout the study period; it surpassed the moderate grade (II) in 2013. The highest point (0.6199) of the economic subsystem appeared in 2017, whereas the lowest value was 0.3143 in 2006. The social subsystem increased slightly from 0.3438–0.4445 in 2006–2017. There were some fluctuations in this subsystem, and the largest slump was observed in 2011. The environmental subsystem exhibited a strong upward trend but was still lower than grade II. The highest point was 0.5057 in 2017, whereas the lowest was 0.2763 in 2006. Overall, Nanjing has a solid economic foundation, but the social and environmental subsystems must be strengthened.

Figure 3. Comprehensive index of the three subsystems in 2006–2017.

3.4. Evaluation of Indicators from 2006 to 2017

In the evaluation of single indicators, the higher the comprehensive index, the more beneficial to sustainable development. For a positive indicator, the comprehensive index changes in the same direction as the indicator value; for the negative indicator, the index and indicator value change inversely. The evaluation results of the indicators are shown in Figure 4 for the three subsystems in 2006–2017.

Figure 4. Comprehensive index of indicators in 2006–2017.

3.4.1. Social Subsystem

In terms of the social subsystem, the population density (u_2) exhibited consistently low indexes in 2006–2017 owing to the large population immigrating to Nanjing. Increased economic strength and more additional job options in recent years, along with the improved infrastructure, stimulated a population shift from economically backward areas to more developed regions. Although the total population grew, the growth rate declined by 81% from 2006 to 2017. Thus, the comprehensive indexes of population growth rate (u_1) increased significantly from 0.11 in 2006 to 0.61 in 2017. The urbanization rate (u_3) performed strongly with a comprehensive index of more than 0.75 throughout the period. The comprehensive index of domestic water use per capita (u_4) remained low especially in 2011. Industrial water reuse (u_5) behaved well in most of the years, but a low point was also observed in 2011. This implies that industrial water reuse and domestic water consumption played an important role in the trough in the social subsystem. Overall, the variability introduced by the slowdown in population growth was the primary driving force for the increase in the figures for the social subsystem. The results also indicated that dense population and overuse of domestic water prevented further growth of the social subsystem.

3.4.2. Environmental Subsystem

For the environmental subsystem, the comprehensive index of indicators representing forest area, wastewater treatment and pollution control (u_8 , u_{13} , u_{14} and u_{15}) showed consistent growth and all reached high levels (more than 0.75 in 2017). This was caused by the effective application of environmental laws and a variety of actions taken by the government to protect the environment. For instance, fewer fertilizers and pesticides were used in agricultural land, which can be ascertained from the performance of the two indicators (u_{10} and u_{11}). However, pollution discharge increased, especially in recent years as the population continued to rise and industrialization accelerated. This led to a large decline in compliance rate for water quality standards (u_{12}) in 2011–2017. Regarding the indicators related to water resources (u_6 and u_7), the comprehensive indexes were lower than 0.45 and 0.10, respectively. This minimal improvement in the two indicators was especially influential, given that those indicators accounted for 31% of the environmental subsystem. Thus, water shortage, over-exploitation of water resources, and poor water quality were likely to be the dominant factors in constraining the growth of environmental subsystems in Nanjing from 2006 to 2017. The results of the indicator analysis also demonstrated that local government tried to protect the water environment; however, the forces of environmental destruction (e.g., socioeconomic, demographic and technological) overwhelmed protection efforts [38].

3.4.3. Economic Subsystem

In the economic subsystem, GDP per capita (u_{16}), industrial output per capita (u_{17}) and percentage of tertiary industry (u_{18}) exhibited a strongly increasing trend. This was because Nanjing's economic growth in the past decades has been one of the fastest among major cities in China, a more than 10% annual increase in most years, and industrial structure has somewhat upgraded. The comprehensive index of annual energy consumption per capita (u_{19}) decreased to 0.20, whereas the index of energy consumption per unit of GDP (energy intensity) (u_{20}) has increased to 0.68. This was because, although the highest energy demand in history was driven by the economy and population, the governmental target for reducing energy intensity in its energy-conservation plan was nonetheless achieved. Indicators associated with economic water consumption (u_{21} , u_{22}) both decreased by nearly 80%, which resulted in an improvement of their comprehensive index. The index for generated industrial solid waste (u_{23}) showed an irregular fluctuation with a decreasing trend through time, indicating that there was a great increase in urban solid waste. The analysis results suggested that high levels of energy consumption and industrial solid waste generation are major problems in this subsystem. Economic

growth, energy and water use intensity reduction led to a large overall increase in the figures for the economic subsystem in Nanjing across the entire study period.

4. Discussion

4.1. Problems Underlying Changes in WECC

Nanjing's WECC presents a continuous increasing tendency from 2006 to 2017, while the increase rate remains slow. The evaluation of indicators provides an explanation for the variation of WECC and the three subsystems and helps to reveal the underlying problems of WECC.

In the social subsystem, the dense population inevitably exerts great impacts on WECC. In 2019, the population density of Nanjing reached 1290 people/km². Population gains are driven largely by migration. Nanjing is urbanized, with 6.82 million people or 82% living in urban areas. Although the city has benefited from its massive population, especially in terms of economic growth, it also faces major challenges. For example, local water resources per capita in Nanjing are less than 1000 m³, which is no more than 1/8 of the world's average. In addition, domestic water consumption increased by 34.3% during 2006–2017. If an abundant transit of water brought by the Yangtze River is not achieved, water shortage will be one of the future bottlenecks within the city [39]. The ever-expanding population will also affect Nanjing's already troublesome land degradation and water environment [40]. Nanjing lost 8110 ha arable land between 2006 and 2017 under urbanization. To ensure its food supply, Nanjing has attempted to intensify the use of land, which has consequently contributed to land degradation. Domestic wastewater increased by nearly 60%, and population growth is also viewed as one of the decisive factors.

In the economic subsystem, service industries comprised the largest part of Nanjing's GDP, while manufacturing industries accounted for 38% in 2019. Comparatively ten years ago, manufacturing industries were dominant in the overall composition of GDP. Nevertheless, despite the rapid development of service industries catching up quickly, major industries including petroleum, cement, steel and electric power still constituted approximately 35% of the industrial output value and covered more than 90% of the total emission of industrial pollutants. Because of its reliance on heavy industry, Nanjing's development has been accompanied by environmental degradation as those industries at the low end of the global value chain are energy-, resource- and pollution-intensive. Although local government announced plans to accelerate the transformation of industrial restructuring and development patterns, the proportion of pollution-intensive industries decreased only by little. This effect may be attributed to the composition of GDP, which has a strong production component and an over-reliance on investment. For years, China's central and local governments have been enthusiastic about investing in infrastructure to boost growth when the economy is vulnerable, which will directly increase the consumption of heavy industry products, thus resulting in an overcapacity problem in heavy industry [41]. This development pattern may lead to destructive ecological and environmental consequences [42].

In the environmental subsystem, the compliance rate for water quality standards in Nanjing remained lower than 80%. Moreover, pollution emissions still showed an upward tendency: wastewater discharge increased by 46.8%, and industrial solid waste increased by 56.2% from 2006 to 2017. Although Nanjing has attempted to protect the environment as claimed in its 11th, 12th and 13th Five-Year Plan, it is also pursuing rapid growth in GDP. Heavily polluting factories are still built at a rapid rate [43]. A key challenge for Nanjing is to continue strong economic growth while reversing environmental degradation. Reductions in pollutant emissions per unit of GDP are unlikely to reduce total emissions if the economy continues to grow [44]. Local governments must ensure efficient enforcement of environmental laws when they conflict with economic development. However, the main problem seems to be the inability to enforce most of the environmental regulations when facing overwhelming economic requirements [45].

4.2. Policy Suggestion

To improve WECC effectively, specific and targeted policy suggestions are proposed as follows:

(1) Strict enforcement of environmental regulations

Addressing water pollution in Chinese cities requires strategic urban planning and regulations [46]. The implementation of environmental policy objectives is also an important source for improving the overall WECC. Lax enforcement and competing policy objectives will undercut the government's efforts to avoid environmental problems. Local government should determine the balance between economic growth and environmental protection objectives and strengthen incentives to enforce environmental regulations on firms.

(2) Spatial arrangement of the urban population

Nanjing continues to encourage population growth in newly-approved plans to achieve a prosperous society. However, Nanjing's dense population places significant pressure on WECC. According to statistics, downtown residents comprise more than half of the city's population. A reasonable population distribution is needed. Nanjing should create new towns with well-developed public services including pensions, health care, and compulsory education, which would allow for more people to move from downtown. The environmental and social problems caused by overcrowding may thus be effectively alleviated.

(3) Transformation of the development model

Rapid growth in GDP has been Nanjing's central goal during the past decades. The dominant development model has achieved high GDP with low resource efficiency and high pollution. Nanjing must shift its economic development model toward efficient resource use and low pollution, which can greatly improve the local WECC. Additional efforts should be made to reduce the role of infrastructure investment in spurring growth, which has proven to be more pollution-intensive [38]. Fortunately, the Chinese government has proposed a "New Normal" economic development concept and has strongly emphasized development quality and a reasonable economic structure to prevent and mitigate pollution [42]. In line with this concept, the Nanjing government should develop more environmentally beneficial technologies, which would increase economic efficiency while reducing environmental damage [38].

(4) Optimization of the industrial structure

The transformation of industrial structure is the key factor in promoting WECC by increasing the percentage of tertiary industry and reducing pollutant emissions. Nanjing should continue to promote the upgrading of industrial structures. The government needs to accelerate the development of the service sector and high-tech industry and focus on innovation while restricting the rapid growth of energy-intensive and pollutant-intensive industries, such as steel, cement, chemicals and power plants. If these policies are carefully implemented, a more sustainable city is entirely possible.

5. Conclusions

The following conclusions can be drawn from the work described in this paper:

- (1) Based on the carrying capacity concept, this study constructed a hierarchical evaluation indicator system including three system layers (social, environmental and economic subsystems), and determined grading criteria to provide a reference for WECC assessment.
- (2) The WECC comprehensive index of Nanjing increased from 0.3045–0.5302 in 2006–2017, approaching Grade II (moderate) with a slow growth rate. The economic subsystem presented a stable and continuous growth, whereas the social and environmental subsystems were under considerable pressure.

- (3) Factors improving WECC include slow population growth, improved water environment protection, rapid economic growth, and reduced energy and water use intensity. Factors blocking WECC include increased population density, excessive water consumption, degraded water quality and an unsustainable economic development pattern.
- (4) To resolve the primary problems of WECC under urbanization, practical suggestions are proposed from the aspects of population, environmental regulation enforcement, development patterns and industrial structure.

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