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Zoning assessment of county water environment carrying capacity in typical river network areas — a case study of Changxing County in the Taihu Lake Basin

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ABSTRACT

Assessment of county water environmental carrying capacity (WECC) is one of the target requirements of the action plan for prevention and control of water pollution. By combining the theory of the WECC and an analytic hierarchy process (AHP), an evaluation index system for WECC in the 7 aquatic eco-functional zones in Changxing County was developed that considers multiple interaction among water resources, water environment, water ecology, and land ecological functions. The model was tested with data including 14 indicators observed for 2018. The results indicated that the spatial distribution of WECC in each aquatic eco-functional zone manifested some geographical regularity, the water environment is in good status in zones 1, 2, fair status in zones 5, 7, and poor status in zones 3, 4 and 6. In four WECC subsystems, water environment and water ecology subsystem had significant impact on the WECC. By analysis the evaluation results, the degradation of river water ecology, the failure of water quality in aquatic eco-functional zones, and point and non-point source pollution were the main factors that restrict the WECC of Changxing County, and they were also the key to improving the WECC of Changxing County.

Keywords: Changxing County; River network areas; Water environment carrying capacity; Aquatic eco-functional zone; Index system

1. Introduction

As the basic factor affecting social and economic development, the water environment plays an important role in the regional development [1,2]. With the rapid development of socio-economy and population growth, the problems of water environment (caused by the rapid increase of water consumption in agriculture, industry, cities, and lack environmental protection measures) have been a key issue for reginal sustainable development [3–5]. In recent years, many scholars have explored the capacity and maximum limits of the regional water environment for supporting socio-economic development by assessing the carrying capacity of the water environment, and provide a scientific basis for the sustainable and coordinated development of regional social economy and water environment [6–10]. Water environment carrying capacity (WECC) is defined as the largest population and economic scale that the water environment can support in a specific region for some period of time without obvious adverse effect on the local water environment [7,11]. Scientifically evaluating the carrying capacity of water environment and formulating a reasonable water environment management plan are keys to coordinate the relationship between economic development and water environment [12].

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Recently years, Researchers have conducted a lot of research on the theory and practice of water environment carrying capacity by conducting field research, such as Taihu Lake Basin [13], Huaihe River Basin [14], Dianchi Lake Basin [15], Yunnan Province [16], Wuhan City [11]. However, literatures which study WECC most focus on large-scale studies, as province, cities or a certain river basin [17–19], their results is meaningful in sciences but difficult to apply on specifical regions to achieve a scientific and meticulous management of a regional water environment. The zoning assessment, an evaluation method based on aquatic eco-function zoning, plays a key role in the use of basin water resources, protecting the water environment, and regional economic development [20]. The zoning assessment of the water environment of county levels, which could realize refined management of regional water environment, is convenient for decision makers to distribute limited resources to different sub-areas in the policy development [21–23].

Changxing County is a typical river network area in the Taihu Lake Basin, with complex water system characteristics (slow flow, poor self-purification capacity of a water body, prone to backflow), the water environment management work urgently needs to be strengthened [24,25]. Therefore, taking Changxing County as the research object, the paper divides it into seven aquatic eco-functional zones, and constructs a regional water environment carrying capacity evaluation index system to reflect the concerted degree between socio-economic development and water environment system. The Analytic Hierarchy Process was used to evaluate the carrying capacity of Changxing County water environment. Through analyzing the evaluation results, it provides a scientific theoretical basis for scientific and meticulous management of water environment in Changxing County, and provides a reference for research carrying capacity of water environment in other districts and counties in the river network area. Fig. 1 shows a flow chart of the methods in this study.

2. Case study

2.1. Study area

The Changxing County is affiliated with Zhejiang Province in China, is located on the southwestern shore of Taihu Lake (Fig. 2). It has jurisdiction over 4 streets, 9 towns and 2 townships, with a total area of 1,431 km^2. In 2018, the permanent population was 0.6364 million and a GDP of 609.78 billion CNY. It is a county with highly developed industry and is especially advanced in the industries of manufacturing, textile, chemicals, etc. It is a subtropical maritime monsoon climate with an average annual precipitation of 1,309 mm. The rivers and harbors in the study area are intertwined and the lakes are densely covered. There are 550 rivers in the territory, with a total length of 1,631.6 km and a water area of 42.6 km^2. 20 rivers in the territory can be navigable, with a total length of 59 km. The main water system is Xitiao River water system and Sian River water system, the Changxing plain water system, the eastern plain river network and the canal.

2.2. Data sources

The original data is mainly available from the Changxing County Statistical Yearbook and the Huzhou Water Resources Bulletin from 2018. In addition, other information was collected from the Water Control Office of Changxing County and river water ecological investigation, these data included information on the meteorological and hydrological, water quality, pollutant discharge, water ecology.

3. Methodology

3.1. Division of aquatic eco-functional zones

The regional division study can clarify the spatial difference of regional water environment carrying state, formulate

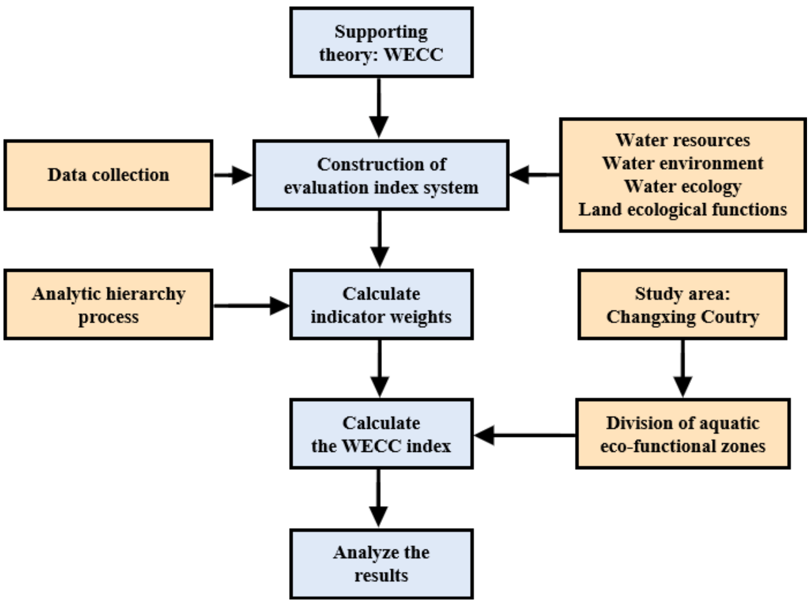

Fig. 1. Flowchart of the WECC evaluation study in Changxing County.

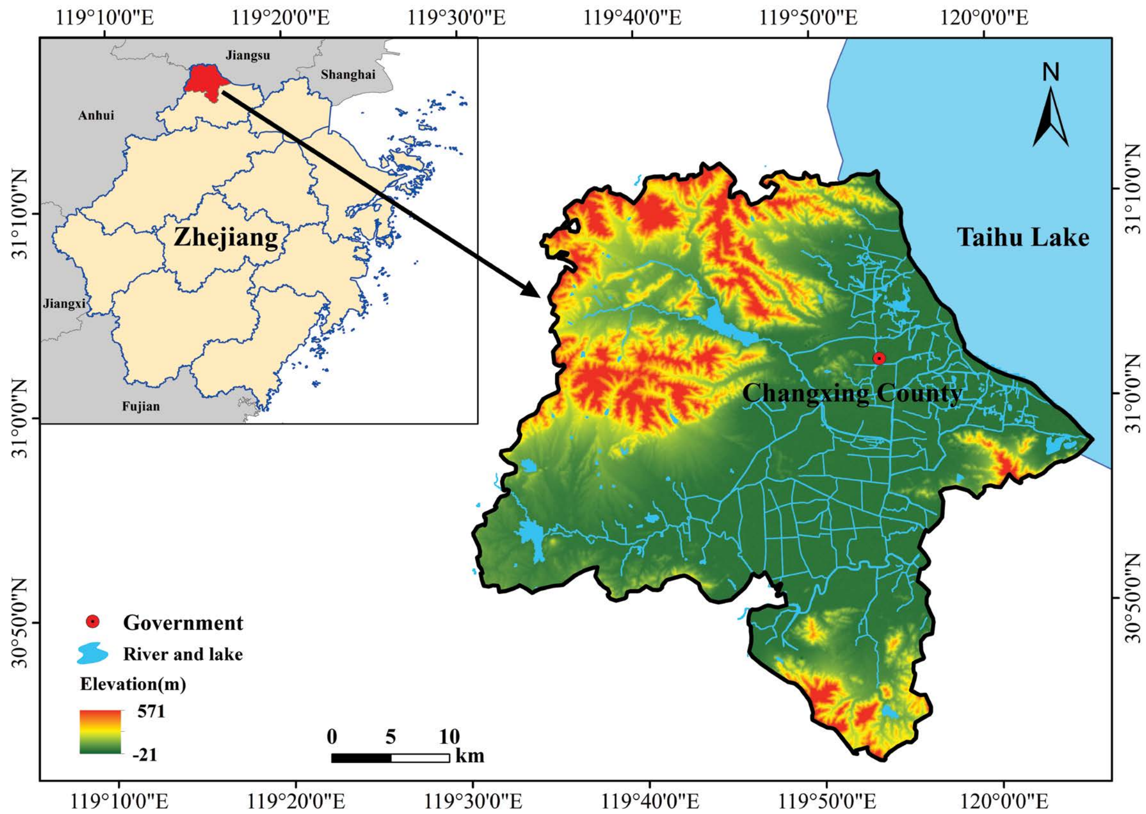

Fig. 2. The location of the study area and its distribution of water area.

policies and measures for water pollution prevention and control and water resources utilization according to local conditions, realize regional water environment differentiation and meticulous management [26]. According to the characteristics of regional water system, the primary control units sections and catchment areas are taken as the basis for division, comprehensively considering the distribution status of key pollution sources, the requirements of environmental risk management and control, the typicality and practicability of zoning, and combining with administrative divisions, the study area was divided into 7 aquatic eco-functional zones (Fig. 3).

3.2. Construction of evaluation index system

WECC is a complex system affected and restricted by various factors. The normal operation of this system not only requires water quantity and quality as a basic guarantee, but also requires the support of ecological functions. Therefore, the composition of the evaluation index system for the WECC should include three types of indicators: water resources, water environment, and ecological function elements (water and land ecological functions). The selected evaluation indicators should reflect the actual conditions of the study area and the impacts socio-economic activities on the WECC. For this purpose, we referred to both domestic and foreign water environment carrying capacity previous research results, consulted with selected experts, and considered the actual water environmental situation of the study area as well as the availability of statistical data. Eventually, an evaluation index system composed of a total of 14 evaluation indexes for the WECC in Changxing County was established, which is shown in Table 1. Furthermore, the system was divided into four major components, that is, water resources subsystem, water environment subsystem, water ecology subsystem, and land ecological functions subsystem. Additionally, the selected indicators are in accordance with established principles of scientificalness, acquisitiveness, integrity, representativeness and recognition. Table 2 lists the values of these 14 indicators for each aquatic eco-functional zone in 2018.

3.3. Analytic hierarchy process to determine index weight

In this research, the impact of indicators in the model on the WECC varies, the weight of the indicators need to be determined. At present, methods of calculating weight mainly include subjective and objective weighting method. In the former, the weight of each index is obtained based on the experts' experience, such as, AHP and expert survey method; in the latter, the weight of each index is determined by mathematical method, which does not depend on the subjective judgment of researchers. In this study, the indicators in the evaluation model involve multiple systems and elements, the AHP is highly suitable for determining the weight of each index. The AHP is a multi-objective, multi-criteria, and multi-factor decision-making method, it was originally proposed by Saaty in the 1970s [27].

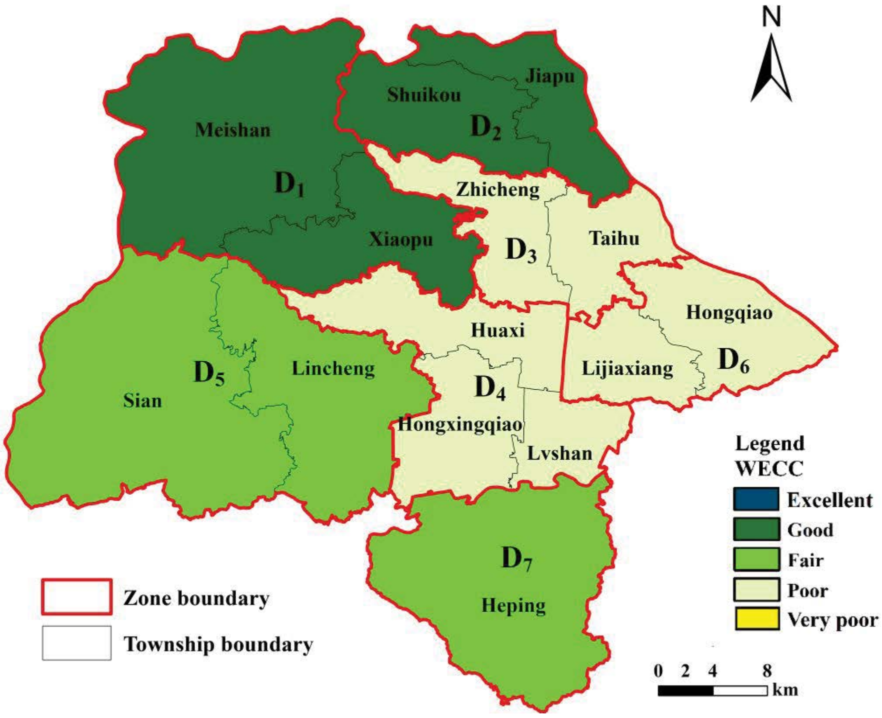

Fig. 3. Spatial distribution of WECC in Changxing County (the results of this study only included good, fair, and poor state).

The AHP model solves quantitative problems by integrating the subjective judgments of researchers and combining qualitative and quantitative data [28].

The main steps of the AHP are as follows:

- Establish a hierarchical structure model. Clarify the scope of the problem, understand the influencing factors involved in the problem, and determine the relationship between the various factors. Based on a preliminary analysis of the evaluation system, the system structure is divided into a hierarchical tree structure, which generally divided into three levels: the top is the target level, the middle is the standard level, and the bottom is the index level.
- Construct of pairwise comparison judgment matrix, as shown in Eq. (1). The hierarchical structure model determines the subordinate relationships between the upper and lower elements. For each element of the same level, pairwise comparisons are made based on the elements associated with the adjacent upper level, and the scale of judgement is shown in Table 3.

$$B = \left(b_{ij}\right)_{n\times n} \tag{1}$$

$$b_{ij} = \begin{cases} 1/b_{ji} & i \neq j \\ 1 & i = j \end{cases} \quad \left(i, j = 1, 2, 3, \cdots, n\right) \tag{2}$$

where B is the judgment matrix, n is the number of factors for the pair-wise comparison, b_{ij} is the ratio of the factor b_i to the importance of factor b_j relative to a criterion, b_{ij} has the properties of Eq. (2).

- Determine the relative weight of each element by the judgment matrix. Calculate the eigenvectors corresponding to the maximum eigenvalue (λ_{max}) of each judgment matrix. The relative weight of each element in the index (bottom) level relative to the weight of each element in the target (top) level can be obtained by normalizing the eigenvectors corresponding to the maximum eigenvalue. Then, the judgment matrix is tested based on the consistency ratio (CR). Generally, if CR < 0.1, the judgment matrix is regarded as having satisfactory consistency. The calculation formula of CR is as follows:

$$\text{CR} = \frac{\text{CI}}{\text{RI}} \tag{3}$$

$$\text{CI} = \frac{\lambda_{max} - n}{n-1} \tag{4}$$

where RI represent random consistency index (Table 4) and CI is consistency index.

- The judgment of each hierarchy is integrated to obtain the overall priority ranking of the alternatives. Complete the whole process from the object hierarchy to index hierarchy.

3.4. Normalization of indicators

Because the units and dimension of the selected evaluation indicators are different, the original data is processed by the method of extreme standard method [29]. The formulas were as follows:

Table 1
The index system for water environment carrying capacity

Target level	Standard level	Weight	Index level	Weight	Index interpretation
WECC in Changxing County	Water resources subsystem	0.23	Development and utilization ratio of water resources C_1 (–)	0.39	Total regional water use/Regional water resources
			Ten thousand yuan GDP water consumption C_2 (–)	0.32	Regional water consumption/Regional GDP
			Water area index C_3 (+)	0.29	Water area/Total area
	Water environment subsystem	0.36	Water environmental quality index C_4 (–)	0.31	Concentration of cross-section pollutants/Standard concentration of surface water III pollutants
			Industrial waste water discharge index C_5 (–)	0.28	Industrial waste water discharge in the assessment area
			Fertilizer application intensity index C_6 (–)	0.22	Total amount of fertilizer application in assessment area (converted to pure)/Area of cultivated land in assessment area
			Urban sewage discharge index C_7 (–)	0.19	Urban domestic sewage discharge
	Water ecology subsystem	0.23	Plant coverage shoreline ratio C_8 (+)	0.22	Riparian plant cover length/Riparian length
			Aquatic plant coverage C_9 (+)	0.31	Coverage area of aquatic plants/Total area of rivers
			River connectivity C_{10} (+)	0.18	100–100 × number of gate dams/Length of river section (km)
			Proportion of natural embankments C_{11} (+)	0.29	Length of natural bank/Total length of river course
	Land ecological function subsystem	0.18	Forest coverage C_{12} (+)	0.38	Forest area/Total area
			River sinuosity C_{13} (+)	0.34	Real length of river/Straight distance of river
			River network density C_{14} (+)	0.28	River length/Basin area

Note: (+) indicates a positive indicator, (–) indicates a negative indicator.
Coverage rate of aquatic plants is 0%~60% as a positive indicator, and 60%~100% is a negative indicator.

Table 2
Values of the 14 indicator in each aquatic eco-functional zone

Index	Unit	Areas						
		D_1	D_2	D_3	D_4	D_5	D_6	D_7
C_1	%	21.50	34.40	61.40	65.60	31.30	75.10	36.40
C_2	m^3/ten thousand Yuan	43.80	63.80	32.60	126.50	152.80	86.40	119.70
C_3	%	2.74	1.64	5.13	2.63	2.21	9.43	2.71
C_4	–	0.52	0.70	0.79	0.75	0.54	0.83	0.69
C_5	Ten thousand tons	82.40	826.40	801.30	599.90	163.10	1,091.90	168.40
C_6	kg/hm^2	292.00	415.00	388.00	384.00	176.00	348.00	477.00
C_7	Ten thousand tons	281.40	163.40	1860	335.20	244.50	186.80	127.30
C_8	%	41.90	47.20	28.50	25.10	36.80	16.20	32.10
C_9	%	10.00	20.40	8.80	8.70	7.60	10.60	16.50
C_{10}	–	89.36	95.68	96.05	97.35	98.55	97.79	100.00
C_{11}	%	27.39	78.61	21.62	20.94	16.78	18.79	33.35
C_{12}	%	66.10	58.70	23.90	11.44	55.72	20.87	46.73
C_{13}	–	1.19	1.39	1.05	1.08	1.31	1.23	1.42
C_{14}	–	0.06	0.16	0.64	0.41	0.19	0.57	0.30

Table 3
Scale of relative importance and its definition

Numerical scale	Definition
1	Equal importance between the two elements
3	Moderate importance of one element compared to the other
5	Strong importance of one element compared to the other
7	Dominance of one element over the other
9	Absolute dominance of one element over the other
2, 4, 6, 8	Intermediate values between the two adjacent judgments
Reciprocals	If index *i* has one of the above numbers assigned to it when compared with index *j*, then *j* has the reciprocal value when compared with *i*

Table 4
The value of RI

n	RI
1	0
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48

Positive indicators:

$$\overline{X}_{ij} = \frac{X_{ij} - \min(X_i)}{\max(X_i) - \min(X_i)} \tag{5}$$

Negative indicators:

$$\overline{X}_{ij} = \frac{\max(X_i) - X_{ij}}{\max(X_i) - \min(X_i)} \tag{6}$$

where X_{ij} is the initial value of the indicator, $\overline{X}_{ij}$ is the normalized indicators, the initial maximum and minimum values of the corresponding indicators are $\max(X_i)$ and $\min(X_i)$.

3.5. Evaluation model

According to the weight and standardized values of the indicators, the comprehensive evaluation model is constructed.

$$Y_k = \sum_{i=1}^{n} \overline{X}_{ij} \cdot W_{ik} \tag{7}$$

$$Y = \sum_{k=1}^{m} Y_k \cdot W_k \tag{8}$$

where n is the number of indicators in the subsystem, $\overline{X}_{ij}$ is the standardized value of the indicators, W_{ik} is the weight of the index in the subsystem, m is the number of subsystems, W_k is the weight of the subsystem, Y_k and Y are the comprehensive evaluation value of subsystems and water environment carrying capacity, respectively. According to the different index values of the WECC, the carrying states can be classified into five groups, shown in Table 5 [29].

4. Results and discussion

4.1. Results

4.1.1. Results comprehensive evaluation of WECC

Spatial distribution of water environmental carrying capacity in Changxing County was shown in Fig. 3. It's obvious of regional differences in the WECC in study area. The WECC of zones 1, 2 were all than 0.6, which were in a good state. The evaluation value of zones 5, 7 was 0.597 and 0.566, respectively, between 0.6 and 1, they were in a fair state. The worst WECC states were zones 3, 4 and 6. Their water environment carrying index is less than 0.4 and they were in a poor state. Considering Changxing's current regional characteristics, the north-western part is a drinking water source area, mostly mountainous, the south-western part is a hilly area, mainly agricultural and the central-eastern part is a plain area, mainly developing the textile printing and dyeing industry. Therefore, the assessment results are consistent with the actual situation, which indicates that the result is reasonable.

The histogram showed the spatial variation of evaluation value of each subsystem in each aquatic eco-functional zone (Fig. 4). The evaluation value of each subsystem presented different degree of variation. Compared with the evaluation value in the zone of highest value, the evaluation value in the zone of lowest value of water resources, water environment, water ecology, land ecological functions subsystem changed by 0.55, 0.76, 0.70, 0.51, respectively. The changed value of water environment and water ecology subsystem was relatively large, indicating that it affected WECC significantly.

4.1.2. Influencing factors of WECC

In order to obtain the specific factors affecting the carrying capacity of water environment, we analyzed the

Table 5
Status of the WECC in Changxing County

WECC index values	Carrying status
0.8~1.0	Excellent
0.6~0.8	Good
0.4~0.6	Fair
0.2~0.4	Poor
0~0.2	Very poor

evaluation value of each index in water resources (a), water environment (b), water ecology (c), land ecological functions and (d) subsystems.

According to Fig. 5a, the indexes evaluation value of water area index (C_3) in zone 2, ten thousand yuan GDP water consumption (C_2) in zone 6, development and utilization ratio of water resources (C_1) in zone 5 in the water resources subsystem was the lowest. Fig. 5b shows that the indexes evaluation value of urban sewage discharge index (C_7) in zone 3, water environmental quality index (C_4) and industrial waste water discharge index (C_5) in zone 6, fertilizer application intensity index (C_6) in zone 7 in the water environment subsystem were 0. In Fig. 5c, the indexes evaluation value of river connectivity (C_{10}) in zone 1, aquatic plant coverage (C_9) and proportion of natural embankments (C_{11}) in zone 5, riparian plant coverage (C_8) in zone 6 in the water ecology subsystem was the worst. Fig. 5d shows that the indexes evaluation value of river network density (C_{14}) in zone 1, River sinuosity (C_{13}) in zone 3, forest coverage (C_{12}) in zone 4 in the land ecological functions subsystem was the poorest. In which, the indicator's average evaluation values of C_4, C_6, C_9 and C_{11} were 0.456, 0.408, 0.328 and 0.231 respectively, and the low evaluation value of these four indicators was the main reason for the WECC to maintain a low level for study area. It reflected the degradation of river water ecology, the failure of water quality in aquatic eco-functional zones, and point and non-point source pollution brought great pressure on WECC of Changxing County.

4.2. Discussion

4.2.1. Accuracy analysis for the assessment

Though the method used in the case is based on subjective weighting, it overcomes complicated and difficult decision problems. The AHP models solve quantification problems by integrating the subjective judgments on researchers and by combining qualitative data with quantitative data, and reflect more accurately the characteristics of water environment system restricted by complex factors. It can fully reflect the actual situation of the water environment system in Changxing County.

4.2.2. Scope and limitations of the study

In this paper, the evaluation index system of water environmental carrying capacity was constructed by AHP. Assessment of the WECC of seven aquatic eco-functional

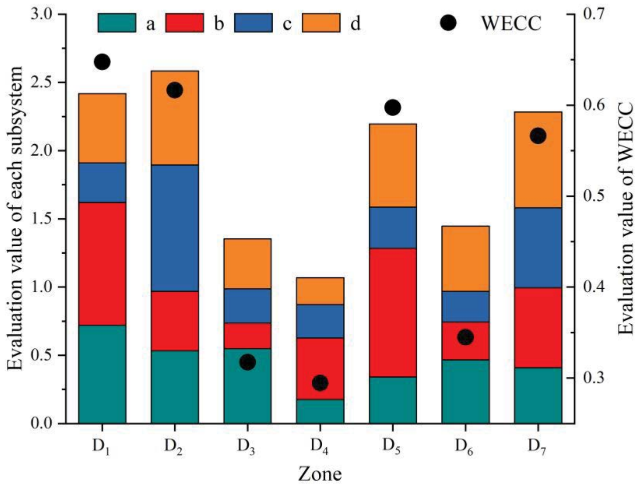

Fig. 4. Evaluation value of WECC of each subsystem in Changxing County (a) water resources subsystem, (b) water environment subsystem, (c) water ecology subsystem, and (d) land ecological functions subsystem, WECC – water environment carrying capacity.

zones in Changxing County, it provides a scientific theoretical basis for scientific and meticulous management of water environment in Changxing County, and provides a reference for research the WECC in other districts and counties in the river network area.

However, there is some limitation in the paper. Because the current evaluation system of WECC is not perfect, there is no unified standard for the selection of indicators and calculation methods, the selection, calculation and data acquisition methods of WECC indicators in this paper still need to be discussed in depth. In addition, limited by the availability of data, this study only evaluates the WECC of different zones in Changxing County in space, without considering the time trend of development of WECC. In the future, the assessment of WECC in different years should be carried out in each region, so as to realize dynamic zoning management of regional water environment.

5. Conclusion

This paper constructs a comprehensive evaluation index system of water environmental carrying capacity from four perspectives of (water resources, water environment, water ecology and land ecological functions), and evaluates the WECC of seven aquatic eco-functional zones in Changxing County by using the AHP method. The results show that the water environment carrying states of the seven zones of Changxing County has obvious regional differences. In general, the water environment carrying states in zones 1, 2 is a good status, that in zones 5, 7 is a fair status, and that in zones 3, 4, 6 is a poor status. Compared with the evaluation value in the zone of highest value, the evaluation value in the zone of lowest value of water resources, water environment, water ecology, land ecological functions subsystem changed by 0.55, 0.76, 0.70, 0.51, respectively. The changed value of water environment and water ecology subsystem was relatively large,

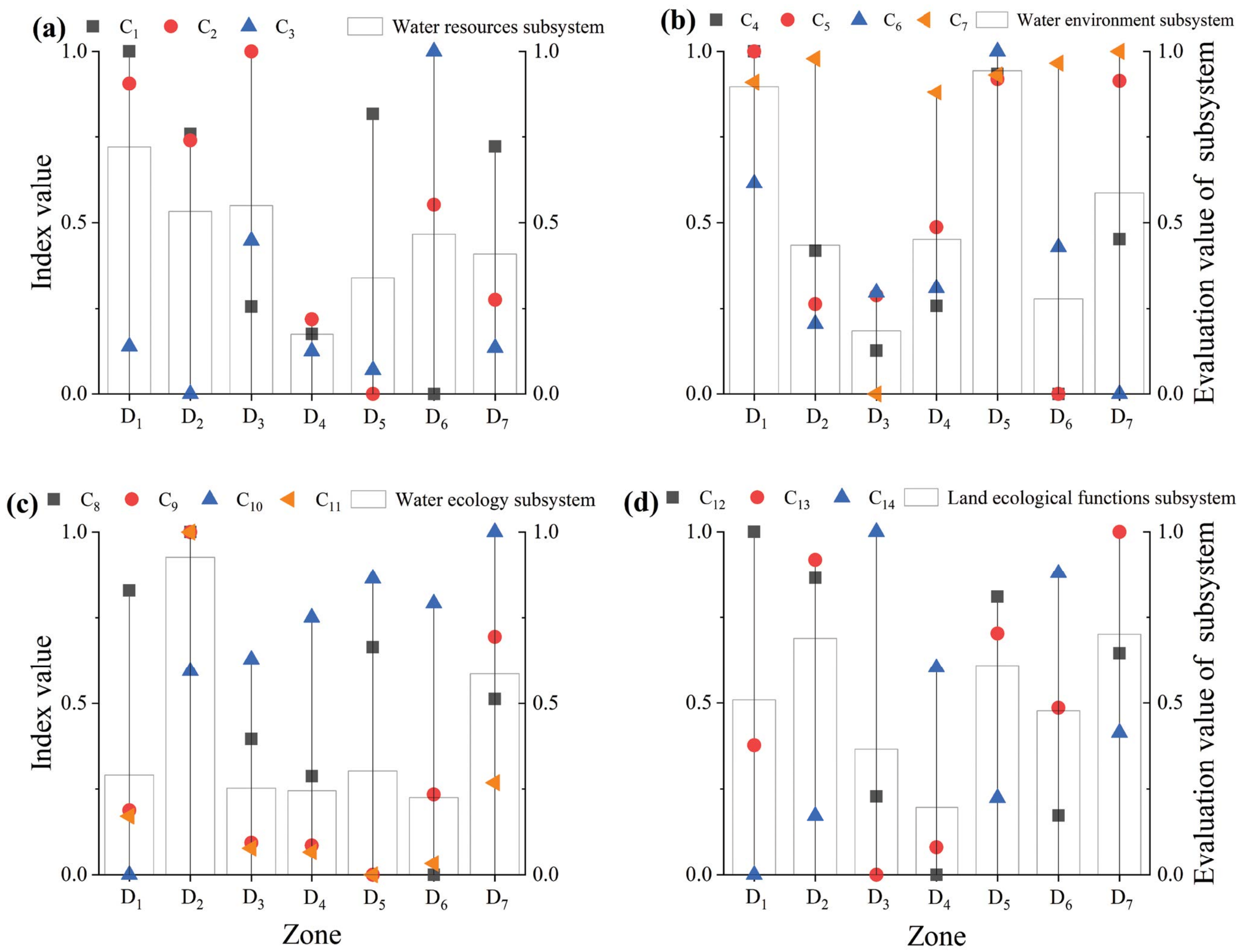

Fig. 5. The index evaluation value of water resources (a), water environment (b), water ecology (c), land ecological functions, and (d) subsystems.

indicating that it affected WECC significantly. By analysis the evaluation results, the degradation of river water ecology, the failure of water quality in aquatic eco-functional zones, and point and non-point source pollution were major constraints to the WECC in Changxing County.

This paper believes that the study on zoning of WECC at county level contributes to the study of the scientific and meticulous coordination of the relationship between socio-economic development and water environment, and it also could provide a reference opinions for policy formulation as well as further, similar studies.

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