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Evaluation of urban water ecological civilization: A case study of three urban agglomerations in the Yangtze River Economic Belt, China

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A R T I C L E I N F O

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A B S T R A C T

Urbanization and economic development pose a challenge to the water ecological environment of cities. “Ecological Civilization” is a term that demonstrates the strategy to achieve the win-win goal of economic development and eco-environment protection. “Water Ecological Civilization” is a vital part of “Ecological Civilization”. This paper introduced a composite index to characterize the Urban Water Ecological Civilization (UWEC) and established an evaluation index system for UWEC based on a multicriteria analytical framework. The evaluation system contains 20 indicators selected from six criterion layers: *water resources utilization* (A, evaluating the efficiency of industrial, agricultural, domestic and public water use), *water security assurance* (B, evaluating the flood control, drainage and drinking water safety), *water environmental protection* (C, evaluating the water environment quality and water pollution prevention), *water ecological restoration* (D, evaluating the health of regional water ecosystem), *water culture system* (E, evaluating the inheritance of water culture and the popularization of UWEC awareness) and *water management institution* (F, evaluating the implementation of management systems). In our research, three major urban agglomerations (UAs) in Yangtze River Economic Belt (YREB) were chosen to be the study area. The results presented that the UWEC level of UAs gradually increased along the Yangtze River from west to east, showing obvious spatial differences. The main criteria restricting the UWEC level of UAs in the Yangtze River Delta were D and E, while E and F were the main restricting criteria for the UWEC level of UAs in the Middle Reaches of the Yangtze River and Cheng-Yu District. The indicator of “drainage compliance rate” got the lowest score among all indicators for three UAs. In addition, targeted measures for improving the UWEC level of UAs in YREB were proposed. Our study is supposed to provide a scientific reference to the improvement of UWEC level for UAs in YREB and trigger further research in the field of water ecological civilization.

1. Introduction

Industrial civilization has created huge wealth for human society while also led to a series of eco-environment issues (Beck, 1992; Martinez, 2005; Gare, 2010). Environmental pollution, resource shortages, species extinctions, natural disasters, diseases and ecological imbalances constantly threaten the survival and development of humans (Yang and Li, 2011; Bentley, 2013). Thus, the international community has been committed to find a sustainable development path which is incorporating economic development, social progress, and eco-environmental protection (Handl, 2012). China, as the world’s largest developing country, has made important contributions to the international implementation of sustainable development (Hanson, 2019). However, rapid industrialization and urbanization have triggered eco-environmental problems, which are impeding China’s sustainable development (Day, 2005; Wang et al., 2018). Under such circumstance, “Ecological

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Civilization", formally proposed by the Chinese government in 2007, has become an explicit goal to address China's serious eco-environmental issues (Gare, 2012; Zhang et al., 2018). Ecological civilization emphasizes respecting nature, conforming to nature and protecting nature (Hansen et al., 2018). The ecological civilization construction aims to create a civilized society with productive forces developed, rich life and ecological health on the basis of sustainable resources and environment (Frazier, et al., 2019).

Water plays an important role in the eco-environment system, affecting the balance and evolution of the ecosystem (Grizzetti et al., 2016; Chen et al., 2016). In the past few decades, China has experienced rapid urbanization processes, resulting in severe pressure on the urban water ecosystem, such as shortage of water resources, eutrophication of water bodies and water pollution (Han et al., 2019; Marinelli, 2018). Therefore, there is an urgent need to balance the relationship between the urban development and the urban water ecosystem. To address this issue, in 2013, the Ministry of Water Resources of China proposed the concept of "Water Ecological Civilization", referring to the harmonious development of water environment and human activities (Liu and Wang, 2018). The city is the carrier of the construction of water ecological civilization, and a high-quality water eco-environment is an important symbol of modern urban civilization (Priscoli, 2000). Urban water ecological civilization (UWEC[1]) refers to the coexistence between humans and water for a city with a complete water system, natural water flow, good water quality, diverse aquatic life, and rich water culture inheritance (Douglas, 2012; Pow, 2018).

For research related to UWEC, some scholars focused on the health state of a city from the perspective of ecology and environment (Wheeler et al., 2015). Neumann et al. (2014) conducted a household survey and found that the illness rate was highly associated with different water supply in Can Tho City, Vietnam. Han et al. (2019) used the water ecosystem health integrated index to evaluate the health status of the water ecosystem in Zhengzhou from 2007 to 2016. Shen et al. (2016) evaluated the vulnerability of the urban ecosystem health of Beijing from the comprehensive perspectives of humans' health, groundwater, surface water and atmospheric environment. Van Leeuwen et al. (2012) applied 24 indicators which were subdivided into eight categories to evaluate the sustainability of the city water cycle in Rotterdam, Maastricht and Venlo. Liu and Wang (2018) explained the relationship between the construction of water ecological civilization and the health status of urban water ecosystem by Water-Human-Health evaluation model. Considering the carrying capacity of water, land, atmosphere, energy and solid waste, Zhang et al. (2018) selected 18 indicators to establish the index system of urban resources and environment carrying capacity.

In addition, some scholars integrated the index system of UWEC from water management, water culture, water ecology and other relevant aspects (Liu et al., 2016). Zhang et al. (2017) established an optimized UWEC index system for water-shortage cities based on the rough set model and evaluated the water-shortage level of Xi'an. Liu et al. (2016) introduced the fuzzy comprehensive evaluation method to establish an evaluation system of UWEC for China's irrigation area and took Huai'an irrigation districts as a case study.

The current evaluation of UWEC is mostly based on subjective weight determination methods, such as the Delphi method and analytic hierarchy process (Liu et al., 2016; Minatour et al., 2016; Zhang et al., 2018), while objective weighting determination methods are rarely mentioned in this field (Tian et al., 2016; Wang, 2017). Minatour et al. (2016) took Nohoor village in Northeast Iran as an example to evaluate the water resources rating by the fuzzy Delphi analytic hierarchy process. The results obtained by the subjective weight determination method are greatly affected by the knowledge and experience of experts (Raju et al., 1995). Furthermore, the evaluation process usually lacks the support of mathematical theory, probably leading to unreliable conclusions (Zhao et al., 2016). The entropy method is an objective weight determination method based on the information entropy theory which considers the variability of information, thereby reducing the influence of decision-makers in the calculation of the index weight (Sahoo et al., 2016). In recent years, some scholars have begun to introduce the entropy method for the evaluation of water ecological civilization. For instance, Wang (2017) applied the entropy method to build an evaluation index system for the water ecological civilization of cross-border river cities in China. Tian et al. (2016) used the entropy method to evaluate the UWEC level of cities in the Pearl River Delta region and found that the UWEC level of these cities is significantly different.

The Yangtze River Economic Belt (YREB[2]) is one of the most densely populated areas in China, including three major urban agglomerations (UAs[3]), urban agglomeration in Yangtze River Delta (UAD), urban agglomeration in Middle Reaches of the Yangtze River (UAM) and urban agglomeration in Cheng-Yu District (UAC[4]). The UWEC level of the three UAs will affect the overall ecological civilization status of YREB. Facing the severe challenges for the water eco-environment in YREB (Heikkila and Xu 2014), it is of great significance to construct a scientific and reasonable evaluation index system for the quantitative assessment of UWEC level of the UAs in the YREB. Currently, the relevant research mainly focuses on the water ecosystems, water resources allocation, and wastewater discharge of YREB. Yao et al. (2019) analyzed the spatial–temporal differences and explored the driving factors of water intensity from the two dimensions of intensity effect and structure effect in YREB. Few scholars have systematically evaluated the UWEC level of the three major UAs in YREB (Ren et al., 2016).

In summary, there are few universally acknowledged evaluation index systems for the assessment of the UWEC level and the objective weight determination method is rarely applied to the UWEC evaluation of the UAs in YREB. To solve this problem, this paper developed an evaluation index system for the assessment of UWEC for cities and urban agglomerations and selected three major UAs of YREB as a case study. The differences and spatial distribution of the UWEC level of 18 pilot cities and three UAs in YREB were analyzed and targeted countermeasures for improving the UWEC level of YREB were proposed. The evaluation index system and determining weight by entropy method in this study can provide a reference for further research on the UWEC assessment. Furthermore, the case study of YREB is of great significance for guiding the UWEC construction and sustainable development of UAs in YREB, China.

2. Evaluation methods of urban water ecological civilization

2.1. A multicriteria analytical framework for assessing UWEC

In this study, the urban water ecological civilization (UWEC) is evaluated based on a multicriteria analytical (MCA[5]) framework (Opon and Henry, 2020), which involved six criteria of the water ecosystem, including water resources utilization, water security assurance, water environmental protection, water ecological restoration, water culture system and water management institution. The MCA framework is often used to solve complex indicator evaluation problems (Sala et al., 2015), such as sustainable problems (Vassoney et al., 2017, Opon and Henry, 2019). UWEC needs to consider the two systems of city and water, which is a complex evaluation system, suitable for MCA framework. The MCA

[1] UWEC is the abbreviation of "urban water ecological civilization".

[2] YREB is the abbreviation of "the Yangtze River Economic Belt, China".

[3] UA is the abbreviation of "urban agglomeration", and UAs are the plural form of UA.

[4] UAD, UAM, UAC are the abbreviation of "urban agglomeration in the Yangtze River Delta", "urban agglomeration in the Middle Reaches of the Yangtze River" and "urban agglomeration in Cheng-Yu District", respectively.

[5] MCA is the abbreviation of "multicriteria analytical".

framework can achieve scientific goal based on a set of methods (Cinelli et al., 2014; Miller et al., 2017), which contains two structures: analytical and result interpretation. The analytical structure includes five steps: indicator selection, data characterization, data normalization, indicator weighting, and aggregation indicators (Opon and Henry, 2020). Fig. 1 shows the MCA framework and the specific method applied in this research.

2.2. UWEC evaluation index system

The evaluation indicators need to be selected systematically and hierarchically. Besides, the selected indicators should be common and can reflect the current status and essence of UWEC. That is based on the *Evaluation guide of water ecological civilization construction* (2016) and high-frequency indicators introduced in papers (Wang, 2017; Sun et al., 2018; Han et al., 2019), and relevant literatures involved are listed in Table 1. Table 1 shows the UWEC evaluation index system established in this study. Criterion layer[6] is a category that can evaluate the system, and the choice of the criterion layer directly determines the scientific meaning of the evaluation result (Akbar et al., 2007). In this study, the criterion layer is established from the perspectives of water resources utilization (A), water security assurance (B), water environmental protection (C), water ecological restoration (D), water culture system (E) and water management system (F), which embodies both natural and social attributes of the UWEC. Each criterion layer includes 3–5 representative indicators, which can indicate the UWEC level.

A criterion layer represents the efficiency of water resources utilization and the degree of water saving in industry, agriculture and public water use, including five indicators: A_1 refers to the ratio of the target value of the total water consumption to the complete value which presents the degree of water saving for a city. The larger the value of A_1, the lower the water-saving efficiency of the city. An increment for A_1 value leads to the decrease of the UWEC level, thus, it is thought as a negative indicator. A_2 refers to the water consumption of 10,000 yuan of industrial value added. Under certain conditions of industrial added value, the larger the value of A_2, the more water is consumed, which is thought A_2 as a negative indicator; A_3 refers to the difference between the total water supply and the charged water accounted for the total water supply. The higher the leakage rate of the water supply network, the lower water use efficiency. An increment for A_3 value leads to the decrease of the UWEC level, which is thought A_3 as a negative indicator. A_4 refers to ratio of actual net irrigation water to gross irrigation water; A_5 refers to proportion of the number of water-saving appliances used by residents.

B criterion layer refers to the degree of regional flood and drainage control and drinking water security, including three indicators: B_6 refers to the proportion of the number of safety guarantees in centralized drinking water sources that meet the standards; B_7 refers to the ratio of the length of the flood dike meeting the flood control standard to the total length of the existing dikes; B_8 refers to the ratio of drainage area to the total urban area.

C criterion layer represents regional water environment quality and water pollution prevention level, including three indicators: C_9 refers to the proportion of water function area that meets water quality standards; C_{10} and C_{11} represent the ratio of the urban and industrial sewage compliance treatment volume to the total waste water discharge, respectively.

D criterion layer focuses on the health of the regional water ecosystem and involves three indicators: D_{12} refers to the proportion of ecologically revetment length in all artificially constructed revetments; D_{13} refers to the ratio of forest area to the total urban area; D_{14} refers to the proportion of water and soil loss treatment area to the total area of regional water and soil loss.

E criterion layer refers to the popularization of the UWEC from the related publicity and training frequency, public awareness of water ecological civilization, news and publications related to water ecological civilization, including three indicators. E_{15}, E_{16} and E_{17} represent the publicity and training related to UWEC and citizens' attitudes towards UWEC, respectively.

F criterion layer focuses on the completeness of the water-related laws and regulations, and the guidance of technical standards, including three indicators. F_{18}, F_{19} and F_{20} represent documents, policies and technical standards published by the government and related departments, respectively.

The index layer contains both positive (+) and negative (-) indicators, which have opposite impact on contribution to the UWEC level. The value of the indicators follows the rule that the higher positive value, the more contribution to the UWEC level, conversely, the higher negative value, the less contribution to the UWEC level (Han et al., 2019). A_1, A_2, A_3 are negative indicators and other indicators are positive.

2.3. Assessment procedure of UWEC

There are three steps to execute the proposed model: (1) data normalization, (2) weight determination by entropy method, and (3) accumulating aggregation. The following section introduces the details of each step and goal.

The first step is data normalization. The selected indicators contain different dimensions, such as "%", "m^3", and some indicators have no dimensions (Table 1). In order to eliminate the influence of dimensions, the min–max normalization method is adopted to normalize the values of 20 indicators for each pilot city (Saranya and Manikandan 2013). The normalization formula for both positive and negative indicators is shown as follows:

$$\begin{cases} \text{Positive indicator: } x'_{i,j} = \dfrac{x_{i,j} - x_j^{\min}}{x_j^{\max} - x_j^{\min}} \\ \text{Negative indicator: } x'_{i,j} = \dfrac{x_j^{\max} - x_{i,j}}{x_j^{\max} - x_j^{\min}} \end{cases} \tag{1}$$

where i denotes the pilot city i, $i = 1, 2, \ldots 18$; j denotes the indicator j, $j = 1, 2, \ldots 20$; $x_{i,j}$ is the initial data of the indicator j value of the city i; $x'_{i,j}$ is the normalized indicator j value of the city i; $x_j^{\min}$ is the minimum value of the indicator j; $x_j^{\max}$ is the maximum value of the indicator j.

After data standardization, some extreme values of the indicators that lead to abnormal values will be normalized, which the traditional entropy method is incapable to consider (Chen et al., 2015). In this study, the normalized data (Formula (1)) is translated to amend the influence of these extreme values.

$$x''_{i,j} = H + x'_{i,j} \tag{2}$$

where $x''_{i,j}$ is the translated standardization data; H is the value of translation and the general value is 1.0.

The second step is to determine weight of indicators through entropy method. Entropy method is an objective weighting method determining the weight by overall impact of the relative variation of indicators, which can exclude humans' interference and reflect the internal differences between the data (Wang et al., 2018). Therefore, the entropy method was applied to calculate the index weight. The smaller the entropy value, the higher the weight (Guiau, 1971; Wang, et al., 2018). The normalized indicator values are used to calculate the weight of the indicators by the entropy method and the specific procedure of the calculation is summarized as Formulas (3) - (5).

[6] The criterion layer contains six criteria, which are "water resources utilization", "water security assurance", "water environmental protection", "water ecological restoration", "water culture system" and "water system construction" and the abbreviation of six criteria are A, B, C, D, E, F respectively.

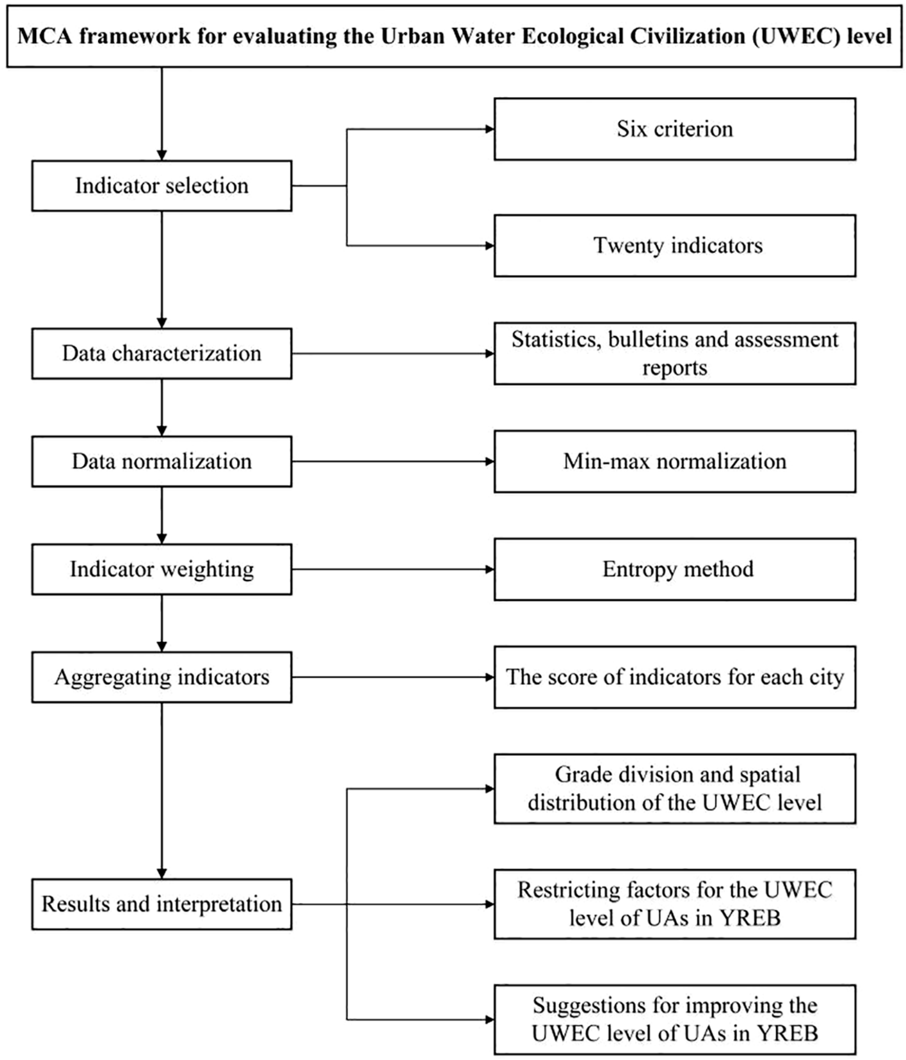

Fig. 1. The MCA framework for Urban Water Ecological Civilization evaluation in the Yangtze River Economic Belt.

$$y_{i,j} = \frac{x''_{i,j}}{\sum_{i=1}^{18} x''_{i,j}} \tag{3}$$

$$g_j = 1 + \frac{1}{\ln 18}\sum_{i=1}^{18} y_{i,j}\cdot \ln y_{i,j} \tag{4}$$

$$w_j = \frac{g_j}{\sum_{j=1}^{20} g_j} \tag{5}$$

where $y_{i,j}$ is the indicator j proportion of the city i to the summation of all cities; g_j is the difference coefficient of indicator j, the larger value of the g_j, the greater importance of the indicator j in the UWEC evaluation index system; w_j is the weight of indicator j.

The third step is to calculate the scores of indicators and criterion layers by accumulating aggregation. The A criterion layer and its indicators of the pilot city i are taken as an example to present the calculation procedure of the scores of indicators and criterion layers.

The scores of indicators A_1, A_2, A_3, A_4 and A_5 are calculated according to Formula (6).

$$Z_{i,j} = \sum_{j=1}^{5} w_j \cdot x''_{i,j} \tag{6}$$

where $Z_{i,j}$ is the score of indicator j of city i.

The score of A criterion layer for city i is the accumulation of the scores of indicators A_1, A_2, A_3, A_4 and A_5, which is shown in Formula (7).

$$S_{i,A} = \sum_{j=1}^{5} Z_{i,j} \tag{7}$$

where $S_{i,A}$ is the score of A criterion layer of city i.

The composite score of city i is the accumulation of criterion scores of A, B, C, D, E and F after getting the scores for each criterion layer of the pilot city i. In this study, the composite score of city i represents the UWEC level of city i. Similarly, the average composite score of six pilot cities in a UA is used to represent the overall level of UWEC of this UA.

Furthermore, in order to better reflect the overall level of UWEC in the UAs, in this study, we use the average composite score of UAs to represent the UWEC construction situation which is the average of the accumulation of the composite score of criterion layer of A, B, C, D, E and F for three UAs.

3. Application of the evaluation model – A case study in three UAs of YREB

3.1. Study area and data sources

The YREB stretches across the eastern, central and western of China, covering 9 provinces (Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan,

Table 1
The evaluation index system for urban water ecological civilization (UWEC) level of urban agglomerations (UAs) in the Yangtze River Economic Belt (YREB) and the descriptive statistics of indicators.

Criterion layer	Index layer		Unit	References
A	A_1	Completion rate of total water control index	%	Lundin and Morrison, 2002; Molden, and Bos, 2005; Liu et al., 2016;
	A_2	Water consumption of 10,000 yuan industrial added value	m^3	
	A_3	Leakage rate of urban water supply network	%	
	A_4	Effective utilization coefficient of agricultural irrigation water	%	
	A_5	Popular rate of water-saving apparatus	%	
B	B_6	Safety compliance rate of centralized drinking water sources	%	Mark et al., 2015; Tian et al., 2016; Wang, 2017
	B_7	Flood control compliance rate	%	
	B_8	Drainage compliance rate	%	
C	C_9	Water quality compliance rate of the water function area	%	Parker, 1932; Weston, 1948; Zhang et al., 2017; Meshesha et al., 2020
	C_{10}	Compliance rate of municipal sewage	%	
	C_{11}	Compliance rate of industrial wastewater discharge	%	
D	D_{12}	Proportion of river and lake ecological revetment	%	Cooper et al., 2017; Wang, 2017; Tian et al., 2016; Wang, et al., 2018
	D_{13}	Forest coverage rate	%	
	D_{14}	Soil and water loss treatment degree	%	
E	E_{15}	Related publicity and training frequency	/	Wang, 2017; Tian et al., 2016; Poustie et al., 2014;
	E_{16}	Public awareness of water ecological civilization	%	
	E_{17}	News and publications related to water ecological civilization	/	
F	F_{18}	Policies of water ecological civilization by government	/	Rietveld et al, 2016; Zhang et al., 2018; Lane et al., 2020
	F_{19}	System of water ecological civilization by related departments	/	
	F_{20}	Technical standards for water ecological civilization by departments and markets	/	

Note: A, B, C, D, E, F represent the criterion layers of water resources utilization, water security assurance, water environmental protection, water ecological restoration, water culture system, water management institution, respectively. e.g., A criterion layer contains indicators of A_1, A_2, A_3, A_4 and A_5.

Sichuan, Guizhou and Yunnan) and 2 municipalities (Shanghai and Chongqing), which is shown in Fig. 2. It occupies approximately 2.05 million km^2 land and generates 44.28% of China's GDP and 42.74% of the population resides. Since 2016, YREB has been officially established as one of China's key strategic development regions, and it is a prior region for achieving China's strategic development with both economic and ecological goals (Sun et al., 2018). With the development of urbanization, the interconnection of the cities in YREB is tightly bounded, making YREB one of the rapidly developing regions in the world (Ren et al., 2016). Moreover, YREB is the prior region for achieving China's strategic development with both economic and ecological goals (Sun et al., 2018). This study selected 18 pilot cities in YREB which have detailed and reliable data related to UWEC, including Hefei, Nantong, Taizhou, Minhang, Jiaxing, Wenzhou (in UAD); Xiangyang, Qianjiang, Xianning, Wuhan, Zhuzhou, Pingxiang (in UAM); Chengdu, Leshan, Luzhou, Suining, Bishan, Liangping (in UAC) (Fig. 2).

The data for this study includes text data and statistical data, which are from the reports of Water Resources Bulletin, Soil and Water Conservation Bulletin, Report on the State of the Environment in China, China City Statistical Yearbook and National Bureau of Statistics of China for each city, the Technical Assessment Report of Pilot Cities for Water Ecological Civilization Construction in China and part of the data comes from Internet News Reports. The data of indicators used in this study are statistics of 2017.

3.2. The descriptive statistics and weight for indicators

All the descriptive statistics of 20 indicators are shown in Table 2. The statistics were processed by Formula (1) and (2). The weight of each indicator was calculated according to Formula (5) and the results are shown in Table 2.

Table 2 shows the descriptive statistics and weight of 20 indicators of the UWEC evaluation system. The value of E_{17} varies greatly among different cities, followed by E_{15}. The numerical difference of A_4 is the smallest. Among all indicators, the weight of E_{17} is the largest, which is 0.0822 and the weight of B_8 is the smallest, which is 0.0253. From the perspective of the criterion layer, A criterion layer accounts for the largest weight, which is 0.2462. A_5 accounts for the largest weight (0.0753) in A criterion layer, and A_3 accounts for the minimum weight (0.0330). The B criterion layer accounts for the smallest weight, which is 0.1191. B_7 has the largest weight (0.0667). Both the weight of B_6 and B_8 are relatively small, which is 0.0271 and 0.0253, respectively. The weight of the C and D criterion layers is 0.1380 and 0.1305 respectively, and the weight of the E and F criterion layers is similar, both around 0.1855.

3.3. The UWEC level for cities and UAs in YREB

The criterion layer scores of UWEC for pilot cities are calculated based on index weight according to Formula (7) in *Section 2.3. Assessment procedure of UWEC* and the results are shown in Table 3 and Fig. 3.

It can be seen from Table 3 and Fig. 3 that in A criterion layer, the scores of the cities in UAD are higher and in UAC are lower. The scores of cities in UAM range from 0.073 to 0.122. The scores of A for each city show that Minhang has the highest score (0.230) and Liangping has the lowest score (0.064). The difference in B criterion layer for cities in each UA is relatively small. The scores of B show that Qianjiang has the highest score (0.119) and Suining has the lowest score (0.026). The low-lying terrain and imperfect urban drainage network facilities of Suining have contributed to the risk of increasing the magnitude and frequency of floods and drainage. The scores of C for each city show that Zhuzhou has the highest score (0.126) and Liangping has the lowest score (0.049) with the smallest difference (0.077). In terms of D, the scores for each city show that Pingxiang has the highest score (0.118), while Taizhou has the lowest score (0.031). However, the difference between the scores of Pingxiang and Taizhou is only 0.087, which is small as well. The scores of E criterion layer show that Wuhan has the highest (0.141) and Xianning has the lowest (0.003), with a difference of 0.138. The high score of E criterion in Wuhan is primarily due to the fact that the local government attaches great importance to the construction of water culture. The government of Wuhan released>5,000 various water affairs news during 2013 ~ 2018. While with the rapid development of the economy in Xianning, the protection of traditional water culture carriers and the excavation of cultural connotations have not received enough attention. Some cultural relics, ancient bridges and ancient weirs were destroyed during the urban expansion in Xianning. The scores of F criterion layer present that Jiaxing is the highest (0.183). Chengdu and Luzhou are the lowest (both 0.010), with the largest difference (0.173) among all pilot cities. It can be seen from Fig. 3 that the score of pilot cities vary greatly, indicating that each pilot city has its own merits and demerits of UWEC.

The UWEC level is classified with five sub-levels based on composite

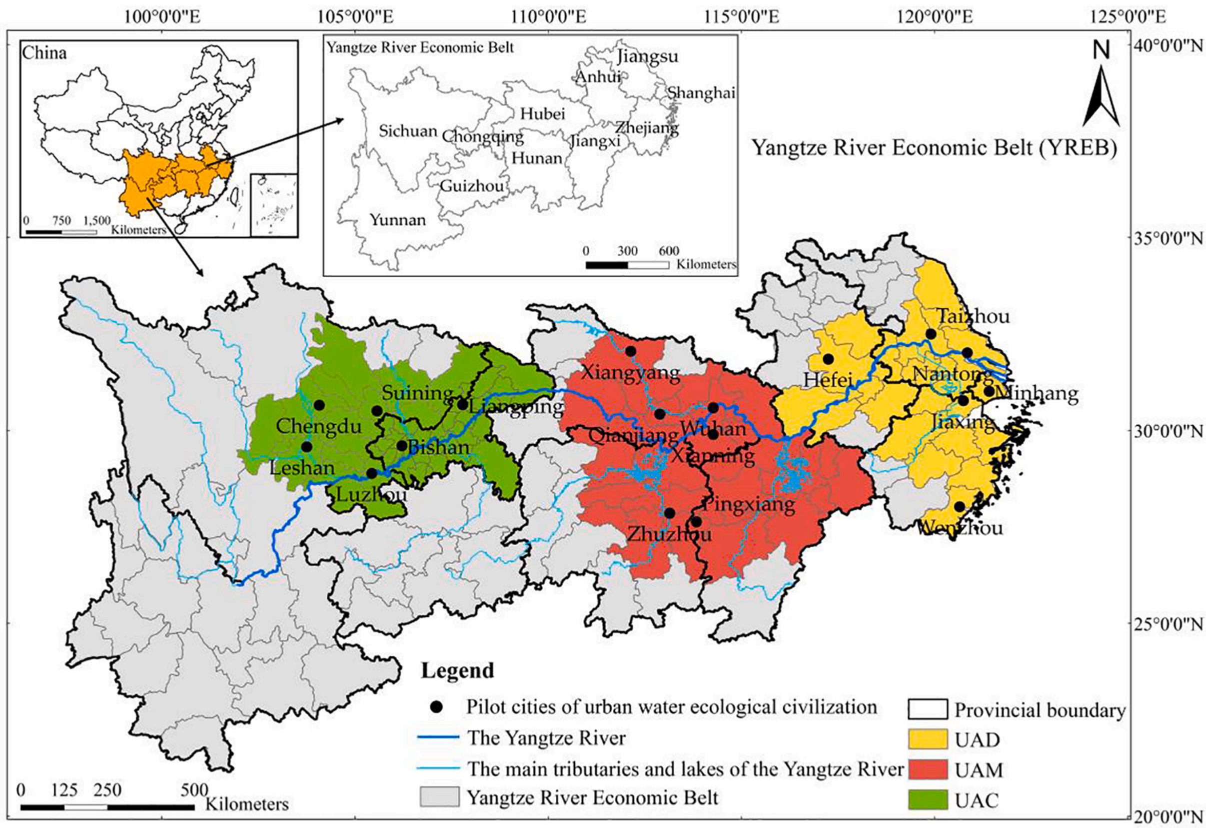

Fig. 2. The location of three major urban agglomerations (UAD, UAM, UAC) and 18 pilot cities for water ecological civilization construction in the Yangtze River Economic Belt (YREB). UAD, the urban agglomeration in the Yangtze River Delta; UAM, the urban agglomeration in the middle reaches of the Yangtze River; UAC, the urban agglomeration in Cheng-Yu district.

Table 2
The descriptive statistics and weight for indicators of the urban water ecological civilization evaluation system.

Index layer	Unit	Min	Max	Mean	S.D.	Weight
A_1	%	66.21	100	88.06	8.67	0.0467
A_2	m^3	5.87	88	32.37	20.60	0.0325
A_3	%	9.81	16.9	12.07	1.80	0.0330
A_4	%	0.47	0.73	0.55	0.07	0.0587
A_5	%	74	100	91.17	9.81	0.0753
B_6	%	80.14	100	98.27	4.95	0.0271
B_7	%	80	100	91.60	6.86	0.0667
B_8	%	37	100	86.21	14.49	0.0253
C_9	%	55.77	100	81.63	13.10	0.0499
C_{10}	%	89	97.02	93.42	2.38	0.0510
C_{11}	%	80	100	95.47	5.60	0.0371
D_{12}	%	39.4	100	80.13	15.32	0.0330
D_{13}	%	17.14	67.24	40.96	15.38	0.0597
D_{14}	%	20.5	100	69.35	20.90	0.0378
E_{15}	/	2	526	52.44	117.73	0.0472
E_{16}	%	80	98.82	89.89	5.56	0.0533
E_{17}	/	4	5000	614.61	1502.01	0.0822
F_{18}	/	0	70	18.61	20.38	0.0653
F_{19}	/	0	70	15.67	15.92	0.0424
F_{20}	/	0	26	5.33	7.82	0.0757

Note: Min, the minimum value of descriptive statistics for pilot cities; Max, the maximum value of descriptive statistics for pilot cities; S.D., the standard deviation of descriptive statistics for pilot cities; For the detailed description of abbreviation of A_1 to F_{20}, please see Table 1.

score: I (>0.6), II (0.5 ~ 0.6), III (0.4 ~ 0.5), IV (0.3 ~ 0.4), V (<0.3), shown in Table 3. Jiaxing and Minhang belong to I level; Taizhou, Xiangyang and Wuhan rank II level, Liangping belongs to V level; and all other cities are rated as III level. The result indicates that the UWEC level of pilot cities in YREB is imbalanced.

As illustrated in Fig. 3, Jiaxing has the highest composite score (0.631) of all cities while Liangping has the lowest score (0.288). The composite score of Hefei is the lowest in UAD (0.425). In UAM, Xiangyang and Wuhan score the highest (0.563) while Xianning is the last one only with 0.373. The composite score of Bishan (0.426) is relatively high in UAC. Besides, Fig. 3 also demonstrates that the A criterion layer accounts for a large proportion of the UWEC level for most cities, which means that A criterion layer is more concerned in most cities. The proportion of other criterion layers is different, indicating that different cities attach different aspects of UWEC.

The average composite scores of each UA in YREB are calculated and are shown in Fig. 4.

The average composite score of the UAD, UAM and UAC is 0.531, 0.478, and 0.364 respectively and the standard deviation of UAD, UAM and UAC is 0.043, 0.073 and 0.092 respectively. It means that the UWEC level of UAD is higher than UAM and UAC and the cities in UAD are all in high levels while the cities in UAC have a great change.

3.4. Recommendations for improving the UWEC level

According to the evaluation results and discussions above, our instructions are summarized as follows. For the entire YREB, efforts should be made to build resource-saving and environment-friendly cities to improve the UWEC level from the perspective of the integration of the Yangtze River Basin.

UAD should improve water quality, protect the water system, and establish a forceful mechanism to eliminate water pollution. The government needs to pay more attention to urban flood and drainage control infrastructure (Maragno et al., 2018). The key industries, such as printing, agriculture and pesticides, should implement clean

Table 3
Scores for each criterion layer (A, B, C, D, E, and F) and composite scores for the urban water ecological civilization (UWEC) level of each pilot city in three urban agglomerations (UAs) in the Yangtze River Economic Belt (YREB).

UAs	Pilot cities	Scores for each criterion layer						Composite score	Grade	Overall ranking
		A	B	C	D	E	F			
UAD	Jiaxing	0.202	0.097	0.076	0.079	0.039	0.183	0.677	I	1
	Minhang	0.23	0.115	0.06	0.048	0.052	0.126	0.631	I	2
	Taizhou	0.215	0.096	0.116	0.031	0.034	0.018	0.510	II	5
	Wenzhou	0.139	0.086	0.088	0.083	0.088	0.012	0.496	III	6
	Nantong	0.175	0.081	0.053	0.07	0.011	0.06	0.450	III	9
	Hefei	0.148	0.118	0.077	0.049	0.016	0.017	0.425	III	11
UAM	Xiangyang	0.099	0.094	0.096	0.095	0.086	0.094	0.563	II	3
	Wuhan	0.179	0.065	0.101	0.052	0.141	0.025	0.563	II	3
	Zhuzhou	0.137	0.056	0.126	0.104	0.042	0.025	0.490	III	7
	Pingxiang	0.127	0.08	0.105	0.118	0.038	0.015	0.484	III	8
	Qianjiang	0.077	0.119	0.103	0.039	0.039	0.021	0.398	IV	12
	Xianning	0.12	0.085	0.064	0.084	0.003	0.017	0.373	IV	15
UAC	Bishan	0.08	0.095	0.109	0.088	0.017	0.037	0.426	III	10
	Leshan	0.073	0.094	0.064	0.085	0.039	0.043	0.398	IV	12
	Suining	0.122	0.026	0.112	0.056	0.043	0.036	0.396	IV	14
	Chengdu	0.08	0.08	0.062	0.072	0.033	0.01	0.337	IV	16
	Luzhou	0.072	0.067	0.088	0.089	0.013	0.01	0.340	IV	17
	Liangping	0.064	0.044	0.049	0.085	0.033	0.012	0.288	V	18

Note: UAD, the urban agglomeration in the Yangtze River Delta; UAM, the urban agglomeration in the Middle Reaches of the Yangtze River; UAC, the urban agglomeration in Cheng-Yu District. The UWEC level was divided into five grades according to the composite score: I (>0.6), II (0.5 ~ 0.6), III (0.4 ~ 0.5), IV (0.3 ~ 0.4), V (<0.3).

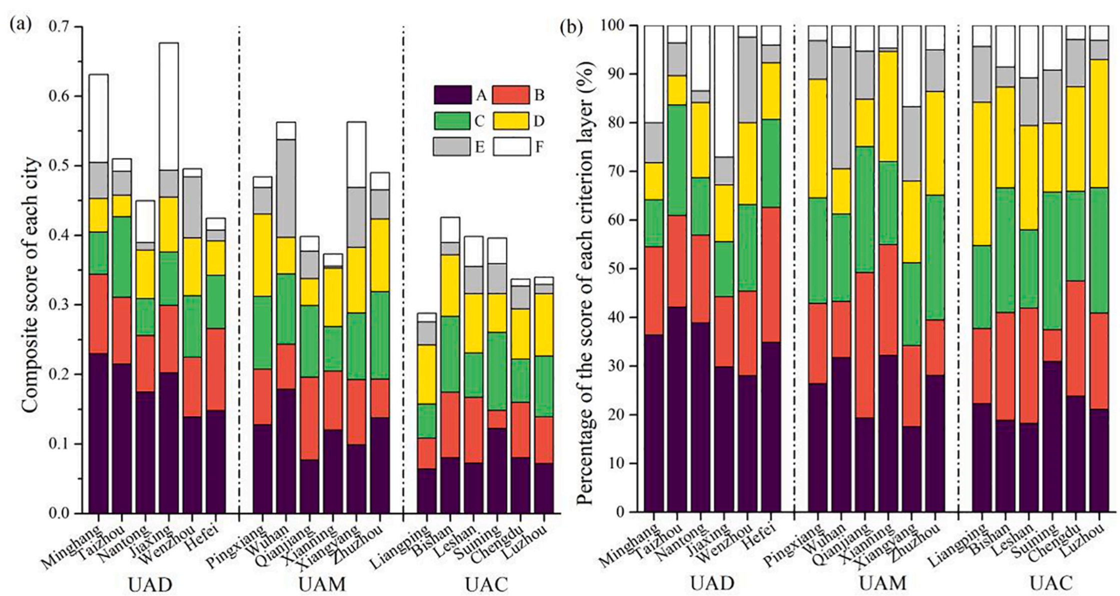

Fig. 3. (a) The composite score of urban water ecological civilization (UWEC) level of each city in three urban agglomerations (UAD, UAM, UAC); (b) the percentage of the score of each criteria layer (A, B, C, D, E, F). Composite score of each city is accumulated by the score of all criteria layers, and the calculation procedure is shown in Section 2.3. A, water resource utilization; B, water security assurance; C, water environmental protection; D, water ecological restoration; E, water culture system; F, water management institution. For the detailed descriptions of UAD, UAM and UAC, please see Fig. 2.

transformation approaches to reduce the level of pollution. Besides, the government should comprehensively strengthen the ecological construction and restoration of the forest parks and important wetlands (Issaka and Ashraf, 2017).

For UAM, the government should build a water resources guarantee system and scientifically dispatch water resources. A flood and drainage control and disaster mitigation system should be established. Moreover, the government is supposed to ameliorate the reform and innovation of the water conservancy construction management system, strengthen the comprehensive management of water resources in both urban and rural areas.

For UAC, priorities shall be given the current key work is to strengthen water environmental protection, water ecological restoration and water management. The comprehensive management of soil erosion in key lakes and reservoirs should be carried out (Wang and Xu, 2015). The water-saving transformation technologies in industrial and agricultural production areas should be strengthened to promote the construction of a water-efficient society. Additionally, the flood and drainage control and disaster mitigation system should be improved. The material cultural heritage of UAC should be carefully excavated and protected while promoting the modern development of the water culture.

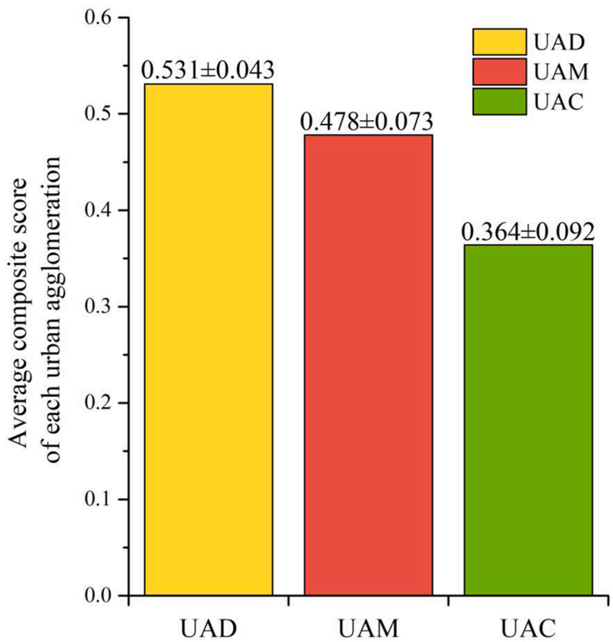

Fig. 4. Average composite score for the UWEC level of three UAs. The value labeled in the bar chart is the average composite score ± standard deviation.

4. Discussion

4.1. Comparative analysis with relevant literature

For UAM, the scores of criterion layer D (water ecological restoration) of Wuhan and Hefei are lower than those of Chengdu, which is consistent with the finding of Ren et al. (2016). However, different from the conclusion of Ren et al. (2016), the scores of criterion layers A (water resources utilization), C (water environmental protection) and D of Wuhan and Hefei are higher than those of Chengdu. This phenomenon is mainly due to the data used by Ren et al. (2016) is from the period of 2011 to 2013. During this period, the construction of UWEC had not yet begun. This also indicates that the A and C criterion layer of Wuhan and Hefei have greatly improved through the pilot construction policy of UWEC since 2013. Wang (2017) evaluated the UWEC level of cross-border river cities with four criteria layers of water ecology, water security, water management, and water culture, and the results show that most cities have relatively high scores of water ecology and low scores of water culture. While in this study, the UWEC evaluation of three major UAs shows that the score of criterion layer E (water culture system) is lower than that of other criterion layers, which indicates that the construction of water culture system in all pilot cities of YREB needs to be strengthened. In addition, the score of criterion layer D of UAD is the lowest among all criterion layers. Therefore, the UAs of YREB, especially UAD, should pay more attention to the water ecological restoration.

The uncertainty of the method chosen will lead to the uncertainty of the results (Opon and Henry, 2020). In this study, there are 18 samples, with 20 variables. Since the number of samples is less than the number of variables, it cannot pass the Kaiser Meyer Olkin (KMO) test and bartlett spherical test. The indicators with higher correlation (>0.5 or < -0.5) are fewer, only 10 indicators, accounting for 5.3% of the total number of indicators, and there is no large amount of information overlap, so it is unnecessary to do dimensional analysis. Although the method will cause uncertainty of results (Opon and Henry, 2020), according to the analysis mentioned above, the entropy method could still avoid those problems and apply to UWEC evaluation system. However, it should be noticed that the weight calculated by the entropy method is based on the data employed, thus, the weight value will change once the data changes. Due to limited research for the evaluation of the UWEC level of cities or UAs in YREB, it is difficult to compare the index weight of this study with other literature (Sun et al., 2018). Furthermore, some cities' statistics are difficult to obtain, so only the pilot cities with accurate and reliable data are selected as representatives to reflect the overall level for UWEC in three major UAs in YREB.

4.2. Spatial differences of the UWEC level in YREB

On the whole, the UWEC level of the UA in the lower reaches of the Yangtze River is higher than that in the upper reaches which is shown in Fig. 5. All the pilot cities with the overall ranking of the grade I are distributed in the UAD (Jiaxing and Minhang city). Most pilot cities with the overall ranking of grades II and III are distributed in UAD and UAM. The cities with the overall ranking of grade IV are distributed in UAC except for Xiangyang and Xianning city in UAM. Only Liangping city, distributed in UAC, has a UWEC level of grade V.

The UWEC level of Minhang, Jiaxing located in the east of UAD is higher (grade I) than other cities (grade II). The UWEC level of cities in the west and south of UAD is relatively low. Overall, the UWEC level of cities in Shanghai and Zhejiang Province is higher than that in Jiangsu Province. The UWEC level of cities in the south of UAM is grade III and in the middle of UAM is grade IV, except for Wuhan (grade II), the provincial capital city of Hubei Province. The UWEC level in the north of UAM is high (grade II). The UWEC level of Bishan, located in the east of UAC, is grade V, while the UWEC level of other cities is grade IV or III. Pilot cities in Sichuan Province have similar UWEC levels, while there are obvious differences in the UWEC level of cities in Chongqing.

4.3. Advantages and disadvantages of UWEC in three UAs

As one of the core regions with a highly developed economy in China, the local governments of UAD often have more capital investment for the construction of UWEC than less developed regions (Ren et al., 2016). The criterion score of Minhang is higher than that of other cities. Minhang fully promoted the construction of a water-saving society and strengthened the comprehensive utilization and recycling of water resources. As an important industrial base in Shanghai, the effect of industrial water saving has been obvious. The intensity of water resource consumption in Minhang has been declining in recent years.

UAD has experienced rapid industrialization and urbanization and becomes the developed industrial and agricultural production center of China (Zhang et al., 2019). There are>25 chemical parks along the lower reaches of the Yangtze River and its main tributaries and the wastewater was discharged into the lower reaches of the Yangtze River (Peng et al., 2018; Zhang et al., 2018). Thus, the water eco-environment quality of UAD is still facing great challenges.

The government of UAM comprehensively improved the river and lake ecosystem. The key areas of soil erosion have been comprehensively controlled, and the lake ecosystem has also been improved in UAM (Dai et al., 2020). None of the criteria level score is the lowest for UAM, indicating that the construction of UWEC for UAM is more balanced, compared with the other two urban agglomerations. The government of UAM should also continue to attach importance to efficiency of water resources utilization, water security assurance and introduce more water relevant laws and regulations to strengthen water management further.

As a compound effect of low floodwater irrigation, low popularity of water-saving appliances and excessive use of pesticides and fertilizers, the problem of inefficient utilization of water resources and water environment pollution in UAC is particularly prominent. Some cities have undertaken the transfer of high-water-consuming enterprises from the eastern area, resulting in shortage of water resources (Sun et al., 2018). Besides, UAC is one of the areas with the most intensive geological disasters and the most serious soil erosion in China (Cheng et al., 2020). The flood control and drainage are difficult to perform, resulting in a low score of B. The public's awareness of water ecology is

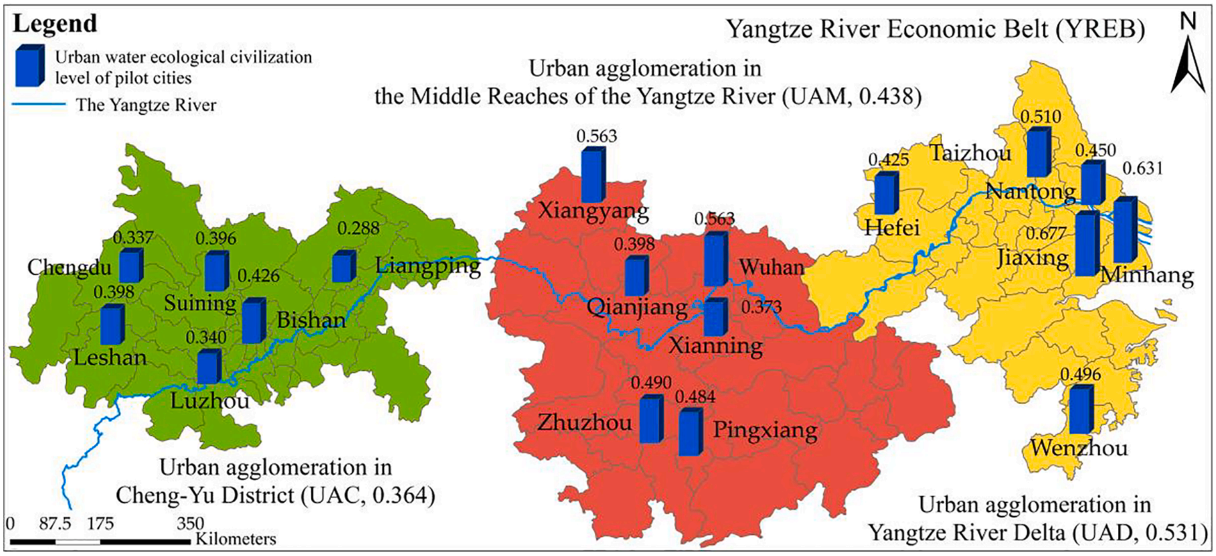

Fig. 5. The composite score for the urban water ecological civilization (UWEC) level of each pilot city in three urban agglomerations (UAs) in the Yangtze River Economic Belt (YREB).

not high and the utilization, construction and publicity of water resources have not yet formed a complete system. In recent years, industrial transfer in the eastern region was undertaken by UAC, especially from traditional manufacturing businesses to enterprises that produced heavy chemical wastes and pollutions, while consumes a large amount of energy. The changes in business have led to the deterioration of the water ecological environment. These above reasons make the overall level of UWEC in UAC lower than that in UAD and UAM.

Besides, it's worth noting that for UAD, UAM and UAM, the three UAs of YREB, B_8 (Drainage compliance rate) scores lowest among 18 indicators of UAD. This warns us that cities in YREB should pay more attention to the prevention of urban drainage.

5. Conclusions

(1) This paper introduced a composite index to characterize the Urban Water Ecological Civilization (UWEC) to characterize cities' water ecological civilization construction level and established an evaluation index system for UWEC based on a multicriteria analytical framework. The evaluation index system includes 20 indicators selected from six criterion layers of water resources utilization, water security assurance, water environmental protection, water ecological restoration, water culture system and water management institution. The entropy method can effectively eliminate the interference of subjective factors and objectively determine the index weight based on the information entropy theory which is suitable for this study.

(2) The three major urban agglomerations (UAs) in Yangtze River Economic Belt (YREB) of China were taken as the study area, and the UWEC level of 18 pilot cities of three UAs in YREB was quantitatively evaluated. The results showed that the indicator of the news and publications (0.083) related to water ecological civilization accounted for the largest weight of the UWEC evaluation, while the indicator of drainage compliance rate account for the smallest index weight (0.026). For the six criterion layers, water resources utilization accounted for a maximum weight (0.246), while the water safety assurance occupied a minimum weight (0.119). The indicator with the highest score was the popularity rate of water-saving devices for UAD and UAM, and the forest coverage rate for UAC. The drainage compliance rate is the indicator with the lowest score for all three UAs.

(3) The overall level of UWEC in UAD was the highest, followed by UAC and UAM, which indicated that the UWEC level of UAs in YREB decreased along the Yangtze River from east to west. For UAD, the UWEC level of Minhang and Jiaxing, located in the east, was higher than cities in the west and south. For UAM, the UWEC level of cities in the south and middle was relatively low except for Wuhan, while the UWEC level in the north was high. For UAC, the UWEC level of cities in the eastern area was much lower than those in the western area. Among 18 pilot cities, the UWEC level of Jiaxing and Liangping was the highest and the lowest, respectively. Generally, both the UWEC level of 18 pilot cities and 3 UAs presented obvious spatial differences.

Overall, the results of the case study were essentially consistent with the actual situation of water ecological civilization construction of three UAs in YREB, which implied that our index system was reasonable for the assessment of UWEC. In future research, with the progress of water ecological civilization construction, the interannual changes of the UWEC level in the research area could be evaluated to provide a better understanding of the dynamic changes. In addition, relevant information and data related to water ecological civilization of more cities should be considered to improve the evaluation index system for UWEC.

CRediT authorship contribution statement

Pei Tian: Conceptualization, Investigation, Methodoloy, Writing - original draft, Funding acquisition. **Huaqing Wu:** Formal analysis, Methodology, Software, Writing - review & editing. **Tiantian Yang:** Investigation, Validation, Writing - review & editing. **Faliang Jiang:** Investigation, Writing - review & editing. **Wenjie Zhang:** Writing - review & editing. **Zhanliang Zhu:** Writing - review & editing. **Qimeng Yue:** . **Muxing Liu:** Writing - review & editing. **Xinyi Xu:** Project administration, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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