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Water environment carrying capacity assessment of Yangtze River Economic Belt using grey water footprint model

Peigui Liu[a,b], Xingyuan Yi[a], Yuan Feng[c], Manting Shang[d,*] and Zhenxin Bao[b,e]

[a] School of Civil Engineering, Hefei University of Technology, Hefei 230009, China
[b] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing 210029, China
[c] Anhui Urban Construction Design Institute Corp., Ltd, Hefei 230051, China
[d] School of Transportation Engineering, Hefei University of Technology, Hefei 230009, China
[e] Research Center for Climate Change, MWR, Nanjing 210029, China
*Corresponding author. E-mail: hfut_smt@163.com

ABSTRACT

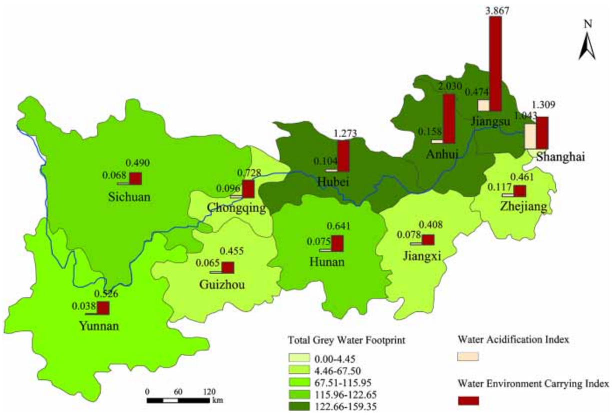
Based on grey water footprint theory and the characteristics of the water resources system, this paper constructs the evaluation index of the water environment carrying capacity of the Yangtze River Economic Belt, and calculates the point-source grey water footprint, non point-source grey water footprint, and water environment carrying capacity of the study area from 2012 to 2017. The results show that the non point-source grey water footprint is much larger than the point-source grey water footprint. The non point-source grey water footprint decreased from 1,089.75 billion m^3 in 2014 to 1,038.7 billion m^3 in 2017, indicating that the pollutants discharged into the water were decreasing in those four years. In addition, the water environment carrying capacity of the western and middle sections of the Yangtze River Economic Belt are in a good state, but the eastern section is overloaded.

Key words: grey water footprint, non point-source pollution, water environment carrying capacity, Yangtze River Economic Belt

HIGHLIGHTS

- This study selects strong representative indicators from the root of water environment problems.
- It introduces grey water footprint theory into the assessment of WECC.
- It provides a basis for analyzing the relationship between production system and water environment.

GRAPHICAL ABSTRACT



INTRODUCTION

Water environment carrying capacity (WECC) is a kind of recognition of environmental value under the conditions of social and economic development, improvement of human living standards and scientific and technological progress. With rapid economic development, environmental problems have become increasingly prominent, and the consumption of water resources is also increasing. A large number of pollutants are produced and deposited in water bodies, which seriously threaten the water environment. Therefore, how to promote economic development along the Yangtze River while ensuring the healthy and sustainable development of the water environment has become an urgent issue that requires in-depth research. The carrying capacity of the water environment is an important indicator to measure the state of the water environment and whether water resources are sustainable. It is also a key factor that links water resources with social and economic development, and is of great significance to the overall planning of regional sustainable development (Graymore *et al.* 2010; Liu & Borthwick 2011).

Furuya (2004) conducted related research on the environmental carrying capacity of the aquaculture industry in northern Japan from the perspective of biological production capacity. Dewata & Adri (2018) used water quality evaluation to determine the pollution load carrying capacity of Batang Kuranji River. Marganingrum (2018) tried to use the dynamic system method to evaluate the carrying capacity of the Bandung Basin. With the development of technology, the research content of water environment carrying capacity is constantly enriched, and the research methods are also increasing. For example, Ding *et al.* (2015) used a multi-objective model representing the carrying capacity of the water environment to establish a quantitative evaluation framework for the sustainability of urban lake development, and selected indicators from the urban social economic system and natural elasticity, adopted the structural entropy weight method to determine the indicator weights, and comprehensively evaluated and compared the dynamic changes of the water environment carrying capacity. This assessment method considers the relationship between the social and economic carrying capacity and the water environment carrying capacity, and provides a way and control direction for water environment early warning. Yang *et al.* (2015) developed a WECC assessment method (WECC-SDM) based on the system dynamics framework. Through the co-evolution and system simulation of the social–economic–water environment interaction, this WECC-SDM could dynamically calculate the water environment carrying capacity under different social and environmental scenarios. This achievement introduces the theory of system dynamics into the study of water environment carrying capacity, creating a new research idea. However, in the modeling process of this study, table functions need to be used to determine the relationship of variables. The establishment of table functions itself contains strong guessing and empirical factors, so the model constructed in this way is very subjective. Zhou *et al.* (2017) proposed an integrated model based on system dynamics (SD) and cellular automaton (CA) models, and carried out spatiotemporal analysis of the water environment carrying capacity in urban evolution. This integrated model combines the advantages of the SDM in the response of macro-factors and the advantages of the CAM in the response of the micro-factors, which can better make up for the shortcomings of the previous simplex evaluation models. Wang *et al.* (2018) combined a system dynamics (SD) model and the analytic hierarchy process (AHP) to establish the evaluation index system of water environment carrying capacity in the Bosten Lake basin, taking into account the mutual interactions among the six subsystems of industry, agriculture, population, water supply, water ecology and water pollution. The combination of SDM and AHP improves the objectivity of the research and is more scientific.

Even though there are many research methods to determine water environment carrying capacity, none of them can evaluate water environment carrying capacity from the source of water environment problems. In addition, the evaluation indicators constructed by these methods are highly subjective and independent, and are prone to problems such as weak representativeness of indicators and information overlap among indicators, thus affecting the accuracy of WECC evaluation results. To avoid the impact of subjective index selection on the evaluation results, this study started from the source of water environment problems and selected the perspective of pollutants affecting water environment quality. Taking the Yangtze River Economic Belt as an example, this paper studies the carrying capacity of the water environment based on grey water footprint theory. By calculating the grey water footprint of the Yangtze River Economic Belt, the water environment carrying capacity of the Yangtze River Economic Belt was evaluated in terms of time and space. It is expected to provide a scientific reference for the economic development of the Yangtze River Economic Belt and the healthy and sustainable development of the water environment. It is also expected to introduce grey water footprint theory into the evaluation method of water environment carrying capacity.

METHODOLOGY

Grey water footprint theory

The concept of grey water footprint was first proposed by Chapagain & Hoekstra (2008), and was defined as the pollution load discharged into the water body divided by the maximum allowable concentration. Through practical application, people gradually realized that it is more scientific and reasonable to replace the maximum allowable concentration in the original definition with the difference between the maximum allowable concentration and the natural background concentration (Hoekstra 2009) and it is also more convenient to calculate. That is, first, obtain the pollutant concentration that does not exceed the self-purification capacity of the water body and the natural background concentration of the receiving water body. Then, calculate the difference between the pollutant concentration and the natural background concentration. Finally, divide the concentration difference by the pollutant emissions to get the grey water footprint. In 2010, the Grey Water Footprint Working Group of the Water Footprint Network further refined the grey water footprint concept. They considered intake water quality in their calculations and adopted a multi-level approach to assess the grey water footprint of non-point-source pollution to meet the requirements of different levels of detail (Zarate 2010). The specific grey water footprint calculation formula is shown in Equations (1)–(3).

Point-source grey water footprint

Pollutants are discharged into surface water in the form of points, that is, point-source pollution. The point-source grey water footprint was estimated by calculating the pollutant discharge and pollutant concentration in sewage. The calculation formula is:

$$WF_{\text{grey-point}} = \frac{L}{C_{\max} - C_{\text{nat}}} \quad (1)$$

where $WF_{\text{grey-point}}$ is the grey water footprint of the point source (billion m^3); $C_{\max}$ is the standard environmental water quality, which is the maximum acceptable mass concentration of discharged pollutants (mg/L); C_{nat} is the background mass concentration of pollutants in the water (mg/L); and L is the total amount of pollutants (million kg).

Surface source grey water footprint

When chemicals are applied to the soil surface or soil, under the influence of factors such as dissolution and adsorption, some chemicals will seep into groundwater or enter rivers through surface runoff, thus causing nonpoint-source pollution. In this case, the pollution load can be expressed as the amount of chemical substances entering the groundwater or surface water. The total amount of chemical substances can be measured, but the portion that enters the groundwater and surface water cannot. Therefore, assuming a ratio, the chemical substances that account for this ratio will eventually reach surface water or groundwater, and the ratio is related to the underlying surface conditions, hydrological conditions, and so on (Hoekstra *et al.* 2011). Non point sources of water pollution are mainly agricultural sources. Pollutants entering the soil are predominantly nitrogen, phosphorus, and potassium, among which nitrogen fertilizer accounts for the highest proportion. In addition, compared with phosphorus and potassium, nitrogen is more mobile and easily enters surface water and groundwater. Therefore, the amount of nitrogen fertilizer applied was taken as representative in this study. The calculation formula of the grey water footprint of nonpoint sources is:

$$WF_{\text{grey-surface}} = \frac{\alpha \times Appl}{C_{\max} - C_{\text{nat}}} \quad (2)$$

where $WF_{\text{grey-surface}}$ is the grey water footprint of a nonpoint source (billion m^3); α is the leaching rate, which is the proportion of used chemicals entering the water; and $Appl$ is the fertilizer application amount (million kg).

Total grey water footprint

From the perspective of sewage sources, the total grey water footprint of the region has three parts: agricultural, industrial, and domestic grey water footprint. Between them, industrial and domestic sewage are mainly discharged in the form of point sources, which can be calculated by the point-source grey water footprint formula (Equation (1)). The agricultural grey water footprint was calculated by using the nonpoint-source grey water footprint formula (Equation (2)). Pollutants from point and nonpoint sources are discharged into surface water. Here, assuming that the surface water dilutes pollutants from both point and nonpoint sources, the total grey water footprint in the region is calculated by the equation:

$$WF_{grey} = \max\{WF_{grey-point}, WF_{grey-surface}\} \tag{3}$$

where WF_{grey} is the total grey water footprint (billion m^3).

Evaluation index system

Water eutrophication index

Water eutrophication refers to the phenomenon of water pollution caused by excessive nitrogen, phosphorus, and other nutrients in the water, and is mainly affected by nonpoint-source pollutants. It is expressed by the ratio of nonpoint-source grey water footprint to total regional water resources, and the calculation formula is:

$$EW = \frac{WF_{grey-surface}}{WA} \tag{4}$$

where EW is the water eutrophication index, and WA is the total amount of water in the area (billion m^3).

Water acidification index

Water acidification refers to the oxygen equivalent of substances that can be oxidized by strong oxidants, reflecting the degree of pollution by reducing substances in the water. It is mainly generated by the discharge of industrial and domestic sewage, so it is expressed by the ratio of the point-source grey water footprint to the total regional water resources, and the calculation formula is:

$$AW = \frac{WF_{grey-point}}{WA} \tag{5}$$

where AW is the water acidification index.

Water environment carrying-degree index

This refers to the ratio of the consumed pollution-receiving capacity to the total pollution capacity. According to the physical meaning of Equation (3), the total grey water footprint can indirectly reflect the consumed pollution-receiving capacity, and the total water resources can reflect the total pollution-receiving capacity of the region. Therefore, the water environment carrying-degree index is expressed by the ratio of the total grey water footprint to the total water resources of the region and is used to evaluate the water environment carrying status of the region. The calculation formula is expressed as:

$$I = \frac{WF_{grey}}{WA} \tag{6}$$

where I is the water environment carrying-degree index.

The regional water environment carrying capacity can be classified according to the size of the water environment carrying degree, as shown in Table 1 (Cao *et al.* 2008). $I \leq 1$ indicates that the system is in an unloaded state. The smaller the value of I is, the greater the carrying capacity of the water environment. $I > 1$ indicates that the system is in an overload state. The greater the value of I is, the greater the carrying pressure of water resources.

Table 1 | The WECC classification

Value	$I \leq 0.6$	$0.6 < I \leq 1$	$1 < I \leq 2$	$I > 2$
WECC	Well-loaded	Loadable	Overloaded	Severely overloaded

CASE STUDY IN THE YANGTZE RIVER ECONOMIC BELT

Study area

The Yangtze River Economic Belt traverses China's eastern, central, and western regions, covering 11 provinces: Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and Guizhou (Figure 1). According to the reference of the *2018 Statistical Yearbook of Yangtze River Economic Belt* (Yangtze River Economic Belt Development Statistics Monitoring Coordination Leading Group Office 2019), the area is about 2.05 million km^2 in size, accounting for 21% of China's total area with 30% of its population and 40% of its GDP. The Yangtze River Economic Belt is one of the regions with the strongest comprehensive strength and strategic support in China. It is also the economic belt of the Inner River Basin with the largest developable scale and the widest impact in the world.

The climate of the Yangtze River is warm and humid with abundant rain and four distinct seasons. From topographic analysis, in addition to 65% of mountains and 24% of hills, plains and lakes in the Yangtze River Basin account for 10.4% of the total area. Moreover, the distribution of plains and lakes is relatively concentrated, mainly in the middle and lower reaches of the Yangtze River and the Sichuan Basin, which is suitable for centralized farming development. The area of cultivated land in the basin accounts for about a quarter of China's total area. Therefore, the Yangtze River Economic Belt has a variety of food crops, including rice, corn, sorghum, barley, and sweet potato, as well as cash crops such as cotton, silk, sesame, and pepper. So, it is an important agricultural base in China.

In the upper reaches of the Yangtze River, the status for an economic base and opening up are relatively limited. Most of its resource endowments lie in natural and labor resources. Therefore, primary industry in the upper-basin region is dominant, and secondary industry is dominated by energy. For example, Guizhou's main industries include coal mining and metallurgy. In the middle reaches of the Yangtze River, agricultural and sideline products are the main resources, and labor resources are also abundant. Therefore, primary industry is mainly composed of economic crops, and manufacturing and heavy industries in secondary industry are relatively well developed. Midstream areas represented by Hubei mainly include automobile manufacturing, steel refining, electric power, and chemical industries. In the lower reaches of the Yangtze River, natural resources are also abundant. However, under the encouragement of economic development and opening up, the industrial structure has developed into a productive service industry. The secondary industry in the lower reaches comprises high-tech and capital-intensive industries. For example, Shanghai's leading industries include finance, real estate, and equipment manufacturing.

Figure 1 | Study area.

The Yangtze River has an annual runoff of about 975.5 million m^3, accounting for 36% of the total annual runoff of Chinese rivers, second only to the Amazon and Congo rivers. There are many lakes in the area, the water quality is generally good, and only a few small areas have serious pollution. Among the 148 sections involved in the evaluation, there were 127 sections with a water quality level of I–III, accounting for 85.8% of the total evaluated sections; 13 sections had a water quality level of IV, accounting for 8.8%; and eight sections had a water quality level of V, accounting for 5.4%. The total wastewater discharge is about 29.84 billion m^3/a in the study area, and the chemical oxygen demand emission concentration of industrial wastewater is about 167.7 mg/L.

Data sources

Total wastewater discharge and water resource data in the study area were obtained from the *China Statistical Yearbook* from 2013 to 2018, and fertilizer application data were obtained from the *China Environmental Statistical Yearbook* from 2013 to 2018, as shown in Tables 2–4.

Table 2 | COD emissions in the provinces of the Yangtze River Economic Belt from 2012 to 2017

	COD emissions (million kg)					
Province	2012	2013	2014	2015	2016	2017
Yunnan	548.60	547.20	533.80	510.00	373.80	330.70
Sichuan	1,268.70	1,232.00	1,216.30	1,186.40	676.80	675.10
Guizhou	333.00	328.20	326.70	318.30	255.90	272.50
Chongqing	402.80	391.80	386.40	379.80	255.70	252.70
Hunan	1,263.40	1,249.00	1,229.00	1,207.70	602.60	575.80
Hubei	1,086.60	1,058.20	1,033.10	986.10	519.90	519.30
Jiangxi	748.30	734.50	720.10	715.60	554.70	519.50
Anhui	924.30	902.70	885.60	871.10	496.30	495.60
Jiangsu	1,197.00	1,148.90	1,100.00	1,054.60	746.50	744.20
Zhejiang	786.20	755.10	725.40	683.20	461.50	418.60
Shanghai	242.60	235.60	224.40	198.80	147.50	141.80

Table 3 | The amount of fertilizer used in farmland in provinces of the Yangtze River Economic Belt from 2012 to 2017

	The amount of fertilizer used in farmland (million kg)					
Province	2012	2013	2014	2015	2016	2017
Yunnan	2,102.00	2,190.00	2,269.00	2,319.00	2,356.00	2,319.00
Sichuan	2,530.00	2,511.00	2,502.00	2,498.00	2,490.00	2,420.00
Guizhou	982.00	974.00	1,013.00	1,037.00	1,037.00	957.00
Chongqing	960.00	966.00	973.00	977.00	962.00	955.00
Hunan	2,491.00	2,482.00	2,478.00	2,465.00	2,464.00	2,453.00
Hubei	3,549.00	3,519.00	3,483.00	3,339.00	3,280.00	3,179.00
Jiangxi	1,413.00	1,416.00	1,429.00	1,436.00	1,420.00	1,350.00
Anhui	3,335.00	3,384.00	3,414.00	3,387.00	3,270.00	3,187.00
Jiangsu	3,310.00	3,268.00	3,236.00	3,200.00	3,125.00	3,039.00
Zhejiang	922.00	924.00	896.00	875.00	845.00	826.00
Shanghai	110.00	108.00	102.00	99.00	92.00	89.00

Table 4 | Water resources of provinces in the Yangtze River Economic Belt from 2012 to 2017

	Water resources (billion m^3)					
Province	2012	2013	2014	2015	2016	2017
Yunnan	168.98	170.67	172.66	187.19	208.89	220.26
Sichuan	289.24	247.03	255.77	222.05	234.09	246.71
Guizhou	97.40	75.94	121.31	115.37	106.61	105.15
Chongqing	47.69	47.43	64.26	45.62	60.49	65.61
Hunan	198.89	158.20	179.94	191.93	219.66	191.24
Hubei	81.39	78.01	91.43	101.56	149.80	124.88
Jiangxi	217.44	142.40	163.18	200.12	222.11	165.51
Anhui	70.10	58.56	77.85	91.41	124.52	78.49
Jiangsu	37.33	28.35	39.93	58.21	74.17	39.29
Zhejiang	144.67	93.13	113.21	140.71	132.33	89.53
Shanghai	3.39	2.80	4.71	6.41	6.10	3.40

RESULTS AND ANALYSIS

Analysis of the time variation characteristics of the grey water footprint in the Yangtze River Economic Belt

According to China's *Environmental Quality Standards for Surface Water* (State Environmental Protection Administration 2002), from the perspective of water function, class V water is generally for agricultural water and landscape water, meeting the water quality requirements of the water environment in the Yangtze River Basin. Therefore, the standard limit value of class V water was selected as the maximum acceptable mass concentration of pollutants in water (C_{max}). C_{nat} is the original concentration of pollutants in water, usually assumed to be zero (Hoekstra & Chapagain 2008). According to field data, the leaching rate of nitrogen in the area is 10% (Chapagain *et al.* 2006).

The grey water footprint of the Yangtze River Economic Belt from 2012 to 2017 was calculated using Equations (1) to (3), as shown in Figure 2. Figure 2 shows that the overall change in the total grey water footprint of the Yangtze River Economic Belt was a gradually decreasing trend. Specifically, the grey water footprint of point sources decreased by nearly 44%, from 220.04 billion m^3 in 2012 to 123.65 billion m^3 in 2017, reflecting a decrease in pollutant discharged from point sources in the Yangtze River Economic Belt since 2012. The fluctuation range of the grey water footprint of nonpoint sources was small, with the maximal value being 1,089.75 billion m^3 in 2014, and the minimal value being 1,038.70 billion m^3 in 2017, a

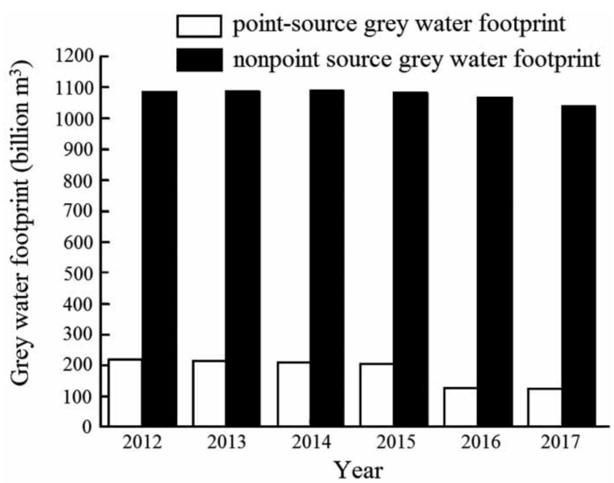


Figure 2 | Grey water footprint of the Yangtze River Economic Belt from 2012 to 2017.

difference of only 51.05 billion m^3. In addition, the nonpoint-source grey water footprint was more than fivefold that of the point-source grey water footprint, indicating that the main cause of water pollution is nonpoint-source pollution in the Yangtze River Economic Belt. Moreover, since the annual agricultural planting area in cities of the Yangtze River Economic Belt is basically unchanged, the crop-planting structure was relatively stable, and the amount of applied fertilizer varied little from year to year; the annual variation range of nonpoint-source pollutants was also small. The calculated results are consistent with the actual situation, which indicates that they are reasonable.

Analysis of the spatial differences of the grey water footprint in the Yangtze River Economic Belt

Due to differences in the cultivated land areas, planting structure, water resource status, industrial layout, and development level among different cities in the Yangtze River Economic Belt, spatial differences in the grey water footprint of different cities were observed. In addition, the agricultural planting area of cities in the Yangtze River Economic Belt was basically consistent over the years and the crop-planting structure was relatively stable, as reflected by the small change in the total grey water footprint between different years in the same province or city. The spatial difference of the grey water footprint between cities in the Yangtze River Economic Belt was analyzed by taking 2017 as an example.

Using the data shown in Tables 2–4 and Equations (1) to (3), the point-source, nonpoint-source, and total grey water footprints of 11 provinces along the Yangtze River Economic Belt in 2017 were obtained, as shown in Figure 3. In 2017, Jiangsu had the largest point-source grey water footprint with 18.61 billion m^3, while Shanghai had the smallest with 3.55 billion m^3. Considering Jiangsu's current economic development, it is the second strongest economic province in China, ranking first in terms of gross GDP as well as industrial wastewater emissions among provinces in the Yangtze River Economic Belt. Therefore, the total point-source grey water footprint of Jiangsu is higher than that of the other provinces. In 2017, the grey water footprint of nonpoint sources, ranked from largest to smallest, was Anhui (159.35 billion m^3), Hubei, Jiangsu, Hunan, Sichuan, Yunnan, Jiangxi, Guizhou, Chongqing, Zhejiang, and then Shanghai (4.45 billion m^3). The high value in Anhui was mainly because it has the highest sowing area and grain yield among cities in the Yangtze River Economic Belt and is the fourth largest agricultural province in China. Due to its small jurisdiction area, the point-source, nonpoint-source, and total grey water footprints of Shanghai are lower than those of other cities in the Yangtze River Economic Belt.

Chongqing, Guizhou, Zhejiang, and Shanghai showed a low total grey water footprint in 2017. Chongqing and Guizhou are located in the southwest of China and belong to the mountainous plateau area. The area used for agricultural sowing is small. Shanghai and Zhejiang are located in southeastern coastal areas and have small jurisdiction areas, a high urbanization rate, developed industrial industries, and less arable land, so they have relatively low pollution from nonpoint sources. According to Equation (3), the total grey water footprint is equal to the nonpoint-source grey water footprint. Therefore, the main factor affecting the total grey water footprint is the nonpoint sources, so the total grey water footprints of Chongqing, Guizhou, Zhejiang, and Shanghai are smaller than those of the other regions. There was a high total grey water footprint in Yunnan, Sichuan, Hunan, Hubei, Anhui, and Jiangsu. This is because the cultivated land areas of these provinces are foremost of all provinces in the Yangtze River Economic Belt, and because the amount of applied fertilizer is proportional to the size of agricultural land, a large area of agricultural land inevitably leads to an increase of applied-fertilizer amount.

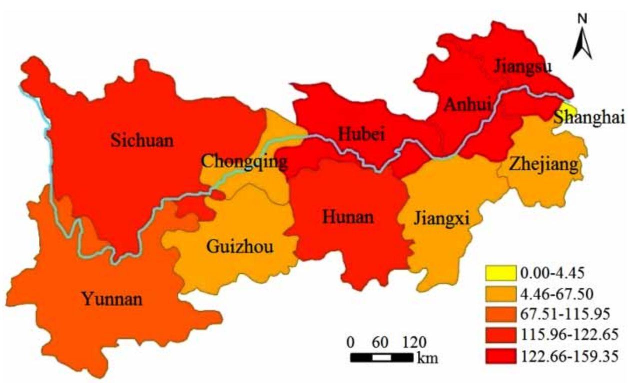


Figure 3 | The total footprint of grey water in the provinces along the Yangtze River Economic Belt in 2017.

Analysis of the water environment carrying capacity of the Yangtze River Economic Belt

Water acidification index

As can be seen from Figure 4, among cities in the Yangtze River Economic Belt, Shanghai had the highest water acidification index of 1.043, indicating that the water environment carrying capacity was overloaded. The main reason for this is that Shanghai is the economic center of China. The high population density and excessive number of industrial parks led to Shanghai's rapid economic development but also caused significant industrial and domestic wastewater discharge. The lowest water acidification index was found in the province of Yunnan with 0.038, mainly due to its abundant water resources and relatively small amount of wastewater discharge. The acidification index of the other provinces was found to be between 0.065 and 0.474.

Water environment carrying capacity

According to Equation (6), the water environment carrying capacity index values of the provinces in the Yangtze River Economic Belt in 2017 were calculated, as shown in Figure 4. Considering the relationship between the freshwater capacity required to dilute pollutants and the pollution-carrying capacity, the carrying state was divided into four levels: 'well-loaded', 'loadable', 'overloaded', and 'severely overloaded' (Table 1). The evaluation results showed that the water environment carrying indexes of Yunnan, Sichuan, Guizhou, Jiangxi, and Zhejiang are all less than 0.6, which are in the 'well-loaded' state. The water environment carrying indexes of Chongqing and Hunan are 0.728 and 0.641, respectively, between 0.6 and 1. They are in a loadable state. The worst water environment states are Anhui and Jiangsu. Their water environment carrying index is greater than 2 and they are in a 'severely overloaded' state.

In order to further analyze the spatial changes of the water environment carrying capacity of the Yangtze River Economic Belt, the Yangtze River Economic Belt is divided into three sections. The western section includes Yunnan, Sichuan, Guizhou, and Chongqing. The middle section contains Hunan, Hubei, Jiangxi, and Anhui. The eastern section has Jiangsu, Zhejiang, and Shanghai. The WECC calculation results for these three sections and the entire Yangtze River Economic Belt are shown in Figure 5.

It can be seen from Figure 5 that the WECC index of the entire economic belt was between 0.6 and 1, which made it 'loadable', with the maximum of 0.986 occurring in 2013. For the western section, the water environment was in the best carrying state with a small fluctuation range and showed an increasingly 'well-loaded' trend from 2015. The middle section was

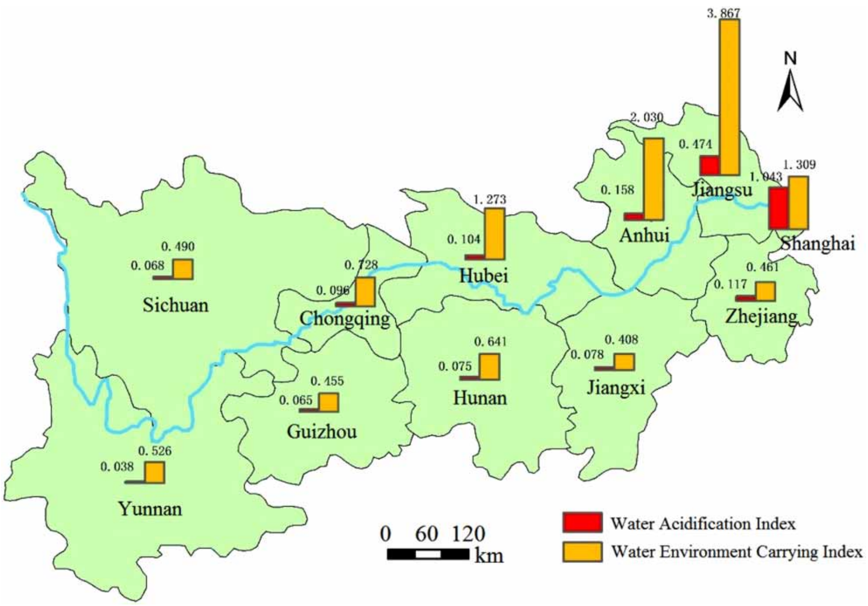


Figure 4 | The water acidification index and water environment carrying index of the provinces in the Yangtze River Economic Belt.

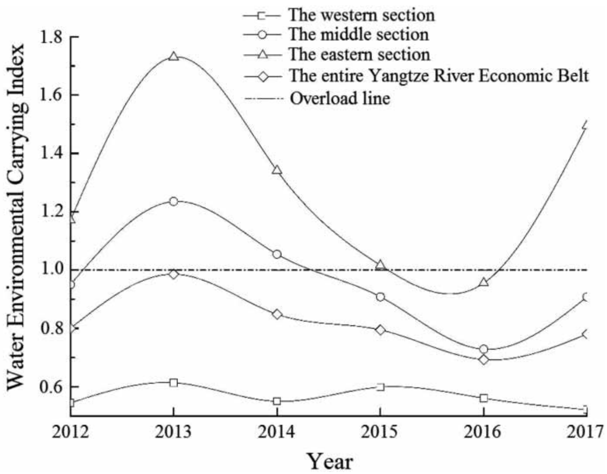


Figure 5 | Water environment carrying index of the Yangtze River Economic Belt, 2012–2017.

'overloaded' in 2013 and 2014, while it was 'loadable' in other years. The maximum of the WECC index was 1.235 in 2013, and the minimum was 0.729 in 2016. The eastern section of the Yangtze River Economic Belt had the worst carrying state and was 'overloaded' in all study years except 2016 (it was 'loadable' in 2016); and its carrying capacity index will continue to grow in the future. Therefore, for the eastern part of the Yangtze River Economic Belt, the water environment should be improved, enterprises that are not up to environmental-protection standards should be strictly checked, fertilizer application efficiency should be improved, and the amount of wastewater that is directly discharged into surface water should be reduced. Comprehensive measures should be taken to improve the water environment carrying level, and ensure that the water environment carrying status gradually improves in the future.

In summary, the grey water footprint is an indicator of freshwater pollution caused by product production throughout the supply chain, and it is usually used as an indicator of water pollution. This study introduced the grey water footprint into the assessment of water environment carrying capacity. This indicator starts from the root causes of water environment problems. It can not only reflect the consumption of freshwater resources and the types of water sources, but also reflect the amount of sewage and the sources of water pollution. It is quite representative and provides a more reasonable and broad perspective for the relationship between production systems and freshwater systems. The evaluation results can provide a scientific basis for analyzing the relationship between the production system and water resources and the water environment.

CONCLUSIONS

Based on the water environment characteristics of the Yangtze River Economic Belt, this paper uses the grey water footprint to evaluate the water environment carrying capacity of the study area from 2012 to 2017. The grey water footprint of the Yangtze River Economic Belt has undergone a gradually decreasing trend. The grey water footprint of point sources decreased from 220.038 billion m^3 in 2012 to 123.645 billion m^3 in 2017 and that of nonpoint sources decreased from 1,089.75 billion m^3 in 2014 to 1,038.7 billion m^3 in 2017. This indicates that the amount of discharged pollutants in the water was decreasing steadily for those six years in the Yangtze River Economic Belt. In addition, the western and middle sections of the Yangtze River Economic Belt had good water environment carrying conditions, but the eastern section was already overloaded, especially in Anhui and Jiangsu, where the water environment carrying index had exceeded 2, which is a 'severely overloaded' condition. The main cause of water pollution in the eastern section of the Yangtze River Economic Belt is nonpoint-source pollution, which is caused by excessive application of pesticides and fertilizers. In fact, most of the land in all the provinces of the Yangtze River Economic Belt is cultivated. Therefore, it is necessary to improve the efficiency of chemical fertilizer application, and strengthen environmental regulation and protection measures to improve the carrying capacity of the water environment.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results. The Belt and Road Special Foundation of the State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering No. 2018nkms06 collected some data for this study.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Cao, F. F., Lou, Z. H., Xu, Y. P. & Yuan, W. 2008 Research on carrying capacity of water resources and sustainable development of the Qiantang river basin. *China Rural Water and Hydropower* **2008** (4), 13–16 + 25.

Chapagain, A. K. & Hoekstra, A. Y. 2008 The global component of freshwater demand and supply: an assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. *Water International* **33** (1), 19–32. doi:10.1080/02508060801927812.

Chapagain, A. K., Hoekstra, A. Y., Savenije, H. H. G. & Gautam, R. 2006 The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. *Ecological Economics* **60** (1), 186–203. doi:10.1016/j.ecolecon.2005.11.027.

Dewata, I. & Adri, Z. 2018 Water quality assessment and determining the carrying capacity of pollution load Batang Kuranji River. *IOP Conference Series: Materials Science and Engineering* **335**, 012027. doi:10.1088/1757-899X/335/1/012027.

Ding, L., Chen, K. L., Cheng, S. G. & Wang, X. 2015 Water ecological carrying capacity of urban lakes in the context of rapid urbanization: a case study of East Lake in Wuhan. *Physics and Chemistry of the Earth* **89–90**, 104–113. doi:10.1016/j.pce.2015.08.004.

Furuya, K. 2004 Environmental carrying capacity in an aquaculture ground of seaweed and shellfish in Sanriku coast, Japan. *Bulletin of Fisheries Research Agency* **2004** (supplement 1), 65–69.

Graymore, M. L. M., Sipe, N. G. & Rickson, R. E. 2010 Sustaining human carrying capacity: a tool for regional sustainability assessment. *Ecological Economics* **69** (3), 459–468. doi:10.1016/j.ecolecon.2009.08.016.

Hoekstra, A. Y. 2009 Human appropriation of natural capital: a comparison of ecological footprint and water footprint analysis. *Ecological Economics* **68** (7), 1963–1974. doi:10.1016/j.ecolecon.2008.06.021.

Hoekstra, A. Y. & Chapagain, A. K. 2008 *Globalization of Water: Sharing the Planet's Freshwater Resources*. Blackwell Publishing, Oxford, UK. doi:10.1002/9780470696224.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M. & Mekonnen, M. M. 2011 *The Water Footprint Assessment Manual: Setting the Global Standard*. Earthscan, London, UK. doi:10.4324/9781849775526.

Liu, R. Z. & Borthwick, A. G. L. 2011 Measurement and assessment of carrying capacity of the environment in Ningbo, China. *Journal of Environmental Management* **92** (8), 2047–2053. doi:10.1016/j.jenvman.2011.03.033.

Marganingrum, D. 2018 Carrying capacity of water resources in Bandung Basin. *IOP Conference Series: Earth and Environmental Science* **118**, 012026. doi:10.1088/1755-1315/118/1/012026.

State Environmental Protection Administration 2002 *Environmental Quality Standards for Surface Water*. China Standards Press, Beijing, China.

Wang, Y. M., Zhou, X. D. & Engel, B. 2018 Water environment carrying capacity in Bosten Lake basin. *Journal of Cleaner Production* **199**, 574–583. doi:10.1016/j.jclepro.2018.07.202.

Yang, J. F., Lei, K., Khu, S., Meng, W. & Qiao, F. 2015 Assessment of water environmental carrying capacity for sustainable development using a coupled system dynamics approach applied to the Tieling of the Liao River Basin, China. *Environmental Earth Sciences* **73** (9), 5173–5183. doi:10.1007/s12665-015-4230-0.

Yangtze River Economic Belt Development Statistics Monitoring Coordination Leading Group Office 2019 *2018 Statistical Yearbook of Yangtze River Economic Belt*. China Statistics Press, Beijing, China.

Zarate, E. 2010 *WFN Grey Water Footprint Working Group Final Report: A Joint Study Developed by WFN Partners*. Water Footprint Network, Enschede, The Netherlands.

Zhou, X. Y., Lei, K., Meng, W., Khu, S. T., Zhao, J., Wang, M. & Yang, J. F. 2017 Space–time approach to water environment carrying capacity calculation. *Journal of Cleaner Production* **149**, 302–312. doi:10.1016/j.jclepro.2017.02.110.

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