

Original Research

Spatio-Temporal Variations and Driving Factors of Greywater Footprint in the Yangtze River Economic Belt, China

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Abstract

The Greywater footprint (GWF) is the natural water volume required to dilute pollutants to a standard concentration, to achieve the unification of water quality and quantity, and is one of the important methods to evaluate regional water pollution. Taking the Yangtze River Economic Belt as the research object, this paper calculated the GWF of 11 provinces in the region from 2005 to 2015, analyzed and summarized the changes and characteristics of GWF of the Yangtze River Economic Belt in time, space, social and economic dimensions, and used the driving factor model of GWF constructed by LMDI decomposition method to analyze the effects of the population, economic and technical driving factors on the change of grey water footprint. The results showed as follows. (1) From 2005 to 2015, the average grey water footprint of the Yangtze River Economic Belt reached 2.4 trillion m³, with agricultural sources, urban living sources and industrial sources accounting for 73%, 21% and 6%, respectively. In terms of distribution, the grey water footprint of provinces in the Yangtze River Economic Belt is less in the east and more in the west (2) Under the same condition of total water resources, the water pollution pressure index of Zhejiang and Jiangxi is relatively small, about 1.1 and Shanghai is at the high level of water pollution pressure index, which can reach 14 (3) Along the Yangtze River, the grey water footprint efficiency increases gradually from the upper reaches to the lower reaches. The average grey water footprint efficiency of Yunnan province in the upper reaches is about 2.7 ¥/m³, and the average grey water footprint efficiency of Shanghai in the lower reaches 36¥/m³ (4) Economic factors and technical factors played a major positive and negative driving role on the grey water footprint, accounting for 49% and -48%, respectively.

Keywords: greywater footprint, spatio-temporal variation, driving factor, Yangtze River economic belt

Introduction

Water resource is an important basic material on which human society depends for living. With the aggravation of the fresh water resource crisis, the water crisis will become the world's top risk in the foreseeable future [1, 2], many countries in the world are suffering from serious water shortage [3, 4]. Although China is relatively rich in water resources, its per capita water resources are almost at the bottom of the world rankings due to its large population [5]. At the same time, economic development often comes at the expense of the environment, leading to overexploitation, waste, and pollution of water resources, all of which are increasing the pressure on China's water resources [6]. In the 14th Five-Year Plan, the Chinese government pointed out that "we will intensify the battle of pollution prevention and control, establish a sound environmental governance system, and constantly improve the quality of water environment". Yangtze river economic belt across China features three major areas, including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan and Guizhou 11 provinces, relying on the advantage of the Yangtze river water transportation, become one of the most rapid regional economic development of China, the Yangtze river economic belt also bearing the weight of the ecological security barrier of protection of the Yangtze river important district, stores a lot of water, It is an important part of water resources allocation in China. The Yangtze River Basin, including the Yangtze River Economic Belt, has been under increasing population pressure, intensive development of water and soil resources, as well as various impacts of climate change. As a major national development strategy and an important part of the Yangtze River Basin, it is urgent to protect its water environment and water resources while developing its economy. Considering the important impact of government policies on environmental quality improvement [7, 8], this paper chooses them as the research object and tries to provide ideas for alleviating this contradiction through grey water footprint method and driving factor analysis model.

To improve the quality of water resources in the Yangtze River Economic Belt, it is necessary to determine the situation of water pollution. Falkenmark and Lindh (1974) first proposed the idea of expressing water pollution in terms of the amount of water needed to dilute waste: the amount of water used to dilute a factor by a factor of 10 to 50 represents the amount of effluent [9]. Later, in further studies, Chapagain et al. (2006) found that what dilution factor to choose depending on the type of pollutant, and the water quality standard of a pollutant was used as the standard to determine the dilution requirements [10]. Hoekstra and Chapagain first proposed the concept of "grey water footprint" in 2008 [11]. Grey water footprint (GWF) refers to the volume of natural water that

is required to dilute certain pollutants based on natural background concentration and existing environmental water quality standards [12]. The researchers found that this method is one of the important indicators for the evaluation of water resource pressure. Meanwhile [13, 14], by analyzing the relationship between the grey water footprint and the pollutants and water environment and their existence, it can also provide useful value for pollution control decisions [15, 16]. Just as scholars have found that water footprint index is getting more and more attention [17]. Some scholars have found that there are certain differences in the grey water footprint between different countries and regions, different products, and even different production processes of the same product. Researcher think such differences provide an important basis for finding key pollution sources and solving environmental problems [18]. The assessment of water resources by the grey water footprint can be made from three different perspectives. For example, research experts will try to explore the pollution situation of the pollution source and its change rules, to provide targeted suggestions [19]. However, some scholars comprehensively calculate the grey water footprint of different pollution sources to analyze and study the sustainable development of urban water resources [20]. In addition, some scholars also combine the grey water footprint with other relevant data and methods. The grey water footprint efficiency formula is constructed by combining the grey water footprint and GDP, to link water pollution with social development [21]. Or, based on the grey water footprint, a water resources ecological compensation model is constructed to provide ideas for solving the interest disputes of river basin water pollution [22]. Or explore the driving factors behind the grey water footprint and analyze the differences and rules of influence caused by different driving factors [23, 24].

Grey water footprint is an important ecological indicator, which has an important advantage: it can unify water quality and quantity in analyzing water pollution. The purpose of this paper is to take advantage of this advantage to intuitively show the pollution change and spatial distribution of water pollution in the Yangtze River Economic Belt during the study period. At the same time, combined with the driving factor analysis model, the driving factors behind water pollution are decomposed into population, economy and technology, so as to make the water pollution situation can be associated with social and economic development, analyze the important causes of water pollution, and provide inspiration and suggestions for the government to further solve water pollution and improve the quality of water resources [25]. Since China Statistical Yearbook revised the statistical caliber of some data after 2015, in order to ensure the comparability and integrity of data, the reference data in this paper are from 2005 to 2015, so there are certain limitations in comparison with the latest data.

Material and Methods

The grey water footprint is the volume of natural water needed to dilute the total amount of water pollutants released into nature by human activities. Under the condition that the water body's self-purification capacity is not exceeded, the standard water quality concentration of pollutants is ($C_{TN, max}$, mg /L) and the natural background concentration of the receiving water body ($C_{TN, nat}$, mg /L). Then, the discharge amount is divided by the concentration difference ($C_{TN, max} - C_{TN, nat}$) to obtain the grey water footprint [11].

The Agricultural Grey Water Footprint

The grey water footprint of agriculture is mainly composed of two parts. One part comes from the farming industry, i.e. the pesticides and fertilizers used in farming are lost into the water, and the other part comes from the farming industry, i.e. the excrement discharged by raising livestock and poultry.

In addition to being used by plants, some of the chemical fertilizers and pesticides applied in agriculture will enter water bodies under the action of precipitation or irrigation, thus causing After calculating all kinds of main pollutants, nitrogen is the biggest pollutant that causes agricultural grey water footprint. There is a certain loss of nitrogen fertilizer in the process of use, and the ratio of the amount of nitrogen fertilizer into the water and the total amount of nitrogen fertilizer applied is a fixed value, namely, the leaching rate of nitrogen fertilizer. Total nitrogen (TN) was selected as the calculation standard of the grey water footprint of the planting industry.

$$GWF_{pla-grey(TN)} = \frac{\partial \times Appl}{C_{TN,max} - C_{TN, nat}}$$

In the formula, $GWF_{pla-grey(TN)}$ represents the agricultural grey water footprint, m^3 ; ∂ is leaching rate; $Appl$ Is application dosage, kg/a; $C_{TN, max}$ is the standard concentration of pollutant water quality, kg/m³; $C_{TN, nat}$ is the natural initial concentration of the receiving waterbody, kg/m³.

Livestock and poultry are to point to the cattle that breed, pig, sheep, fowl (chicken, duck) wait. The nitrogen, phosphorus, and other pollutants in the feces and urine of livestock and poultry were used to estimate the contents of the feces and urine, nitrogen and phosphorus, and other pollutants produced by livestock and poultry in each area [26].

$$GWF_{bre-grey(i)} = \frac{L_{bre(i)}}{C_{i,max} - C_{i, nat}}$$

$$GWF_{bre-grey} = \max(GWF_{bre-grey(COD)}, GWF_{bre-grey(TN)})$$

where: $GWF_{bre-grey}$ is the grey water footprint of aquaculture, $GWF_{bre-grey(i)}$ is the grey water footprint of class i pollutants (i is COD or total nitrogen); $L_{bre(i)}$ is the emission of Class i pollutants; a is for pigs, poultry, cattle, sheep; N_a is the number of livestock and poultry of type a ; $C_{i, max}$ represents the water quality standard concentration of Class i pollutant, and $C_{i, nat}$ represents the natural background concentration of Class i pollutant.

Because water can dilute COD and nitrogen at the same time, the agricultural grey water footprint identifies the pollutant with the maximum value calculated as the decisive pollutant.

$$GWF_{agr-grey} = \max[GWF_{bre-grey(COD)}, (GWF_{pla-grey(TN)} + GWF_{bre-grey(TN)})]$$

Where, $GWF_{bre-grey}$ represents the total agricultural grey water footprint.

The Industrial Grey Water Footprint

Industrial water pollution is a kind of point source pollution, and COD and ammonia nitrogen (NH₃-N) are the main pollutants in sewage discharge, so we can directly calculate COD and ammonia nitrogen in sewage [22].

$$GWF_{ind-grey(i)} = \frac{L_{ind(i)}}{C_{i, max} - C_{i, nat}}$$

$$GWF_{ind-grey} = \max(GWF_{ind-grey(COD)}, GWF_{ind-grey(NH_3-N)})$$

The formula: $GWF_{ind-grey}$ represents the industrial grey water footprint; $GWF_{ind-grey(i)}$ represents the grey water footprint of Class I industrial pollutants; $L_{ind(i)}$ Represents the emission of class I pollutants from the industry.

The Domestic Greywater Footprint

Domestic sewage not only belongs to the type of point source pollution but also COD and ammonia nitrogen are the main pollutants in the discharged sewage. Therefore, the calculation of domestic greywater footprint is the same as that of industrial grey water footprint.

$$GWF_{dom-grey(i)} = \frac{L_{dom(i)}}{C_{i, max} - C_{i, nat}}$$

$$GWF_{dom-grey} = \max(GWF_{dom-grey(COD)}, GWF_{dom-grey(NH_3-N)})$$

Where $GWF_{dom-grey}$ represents the domestic grey water footprint; $GWF_{dom-grey(i)}$ Represents the grey water footprint of class i household pollutants; i Denotes the emission of class i pollutants.

The regional grey water footprint is composed of the above three parts: agricultural grey water footprint, industrial grey water footprint, and domestic grey water footprint, namely the sum of the three.

$$GWF_{\text{grey}} = GWF_{\text{agr-grey}} + GWF_{\text{ind-grey}} + GWF_{\text{dom-grey}}$$

Water Pollution Pressure Index

The water pollution pressure index is designed to measure the degree of water resource pollution in a certain region and water resource pressure, namely the ratio of grey water footprint to total water resources. The higher the pressure index is, the greater the degree of water resource pollution in the region will be.

$$\lambda_j = \frac{GWF_{j,\text{grey}}}{Q_j}$$

Where: λ_j is the water pollution pressure index in region j; $GWF_{j,\text{grey}}$ is the grey water footprint in region j; Q_j is the total amount of water resources in region j.

Grey Water Footprint Efficiency

Efficiency refers to the ratio of input and output, while GWF refers to GDP output per unit GWF, so as to reflect the relationship between regional GWF and local economic development, as well as to evaluate water resource utilization efficiency in different regions.

$$E = \frac{GDP}{GWF_{\text{grey}}}$$

Where GWF_{grey} represents the total grey water footprint of a region, and GDP represents the gross product of the region

MDI Index Decomposition of Grey Water Footprint

LMDI model is a logarithmic decomposition method proposed by Ang [27], which can divide the research object into several impact factors. Transform the identity A of the impact of human activities on the environment into the identity of the total gray water footprint [28]:

$$GWF = P \cdot \frac{GDP}{P_i} \cdot \frac{GWP}{GDP} = P \cdot Q \cdot E$$

GWF is the total gray water footprint; P is the total population, which is the population factor; $Q = \frac{GDP}{P}$ Represents GDP per capita, which is an economic

factor; $E = \frac{GWP}{GDP}$ Represents the intensity of grey water

footprint, which is a technical factor. Then using LMDI method, factor decomposition of the model can be obtained as follows:

$$\Delta P = (GWF_i - GWF_0) \cdot \frac{\ln(P_i / P_0)}{\ln(GWF_i / GWF_0)}$$

$$\Delta Q = (GWF_i - GWF_0) \cdot \frac{\ln(Q_i / Q_0)}{\ln(GWF_i / GWF_0)}$$

$$\Delta E = (GWF_i - GWF_0) \cdot \frac{\ln(E_i / E_0)}{\ln(GWF_i / GWF_0)}$$

$$\Delta GWF = \Delta P + \Delta Q + \Delta E$$

where, ΔP , ΔQ and ΔE respectively represent their contributions to the change of the total GWF ΔGWF in a period of time.

Data Sources

Grey water footprint is a method to convert water pollution into water volume, which is more intuitive and specific, so as to realize quantitative analysis. The collection and calculation of pollution data are particularly important. Industrial and life source of chemical oxygen demand (COD) and ammonia nitrogen ($\text{NH}_3\text{-N}$) related pollution data directly from the environment in China statistical yearbook, and as a source of agricultural non-point source pollution (TP), total nitrogen pollution data is indirectly through the China rural statistical yearbook of regional applying quantity of chemical fertilizer, regional livestock number calculation, In the calculation, the emission coefficient of livestock fecal pollutants came from the "Technical Report on Pollution Investigation of Large-scale Livestock and Poultry Industry", and the leaching rate of nitrogen fertilizer was 7%. GDP, population and water resources for each province come from the China Statistical Yearbook. Secondly, the environmental maximum allowable concentration of COD, ammonia nitrogen and TP in water is based on the Basic Project Standard Limits of Surface Water Environmental Quality Standards (GB 3838-2002), and the concentration of pollutants in class iii water is the environmental maximum allowable concentration. 0.02 kg/m³, 0.001 kg/m³, 0.001 kg/m³, and the natural background concentration was calculated as 0.

Results and Discussion

Temporal Variation of Grey Water Footprint

Fig. 1a) shows that the total GWF has little change during the period.

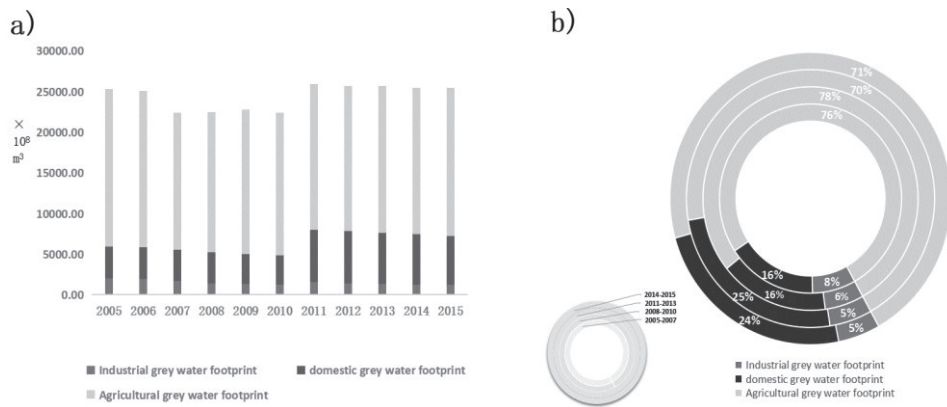


Fig. 1. Total grey water footprint a) and structural analysis b).

GWF has the lowest value, about 2.2 trillion m^3 , and in 2011, it has the highest value, about 2.6 trillion m^3 , and the average total GWF has reached 2.4 trillion m^3 . The time variation of the total GWF in the Yangtze River Economic Belt during this period can be divided into three stages. The first stage is the period from 2005 to 2008, and the total GWF of this stage shows a decreasing trend year by year. This is because this period is in the “Eleventh Five-Year Plan” stage: The Chinese government stresses the implementation of the comprehensive and scientific outlook on development to strengthen environmental protection and build an environment-friendly society, and has introduced a large number of environmental governance policies, including improving the water environment. The period from 2008 to 2010 belongs to the second stage, in which the total GWF fluctuates and increases slightly, which is related to the external environmental effects brought about by China’s deepening opening-up and rapid economic development. The third stage: From 2011 to 2015, in the third stage, the change of the total gray water footprint of the Yangtze River Economic Belt began to decline slowly again. In 2011-2015, is China’s “twelfth five-year plan”, accompanied by 2012, the party’s “18”, emphasize to play good pollution control to be completed, which involved the strictest water resources management

system as an important content of the construction of ecological civilization, is located in the Yangtze River basin of Dongting lake and Poyang lake has been as a key water pollution governance object. On the other hand, from the perspective of industrial sources, urban living sources and agricultural sources, as shown in Fig. 1b) taking 2008 as the boundary analysis and comparing 2005-2008 with 2008-2010 and 2011-2015, the proportion of GWF from industrial sources decreased by 1-3 percentage points. It can be seen that the pollution discharge control of industrial sources in the Yangtze River Basin has produced the effect. Second, with the deepening of urbanization and urban population increase, the source of life considerably increase the proportion of grey water footprint, nearly 10 percentage points, at the same time, the sewage from agricultural sources is decreasing. According to the change of time node, found in 2008 with the rural life pollution control technology policy “issued and implemented, the attention to rural environment management, reduce the unreasonable use of fertilizers in agriculture.

Spatial Variation of Grey Water Footprint

In Fig. 2a), the GWF of 11 provinces is roughly divided into five echelons by averaging the regions from

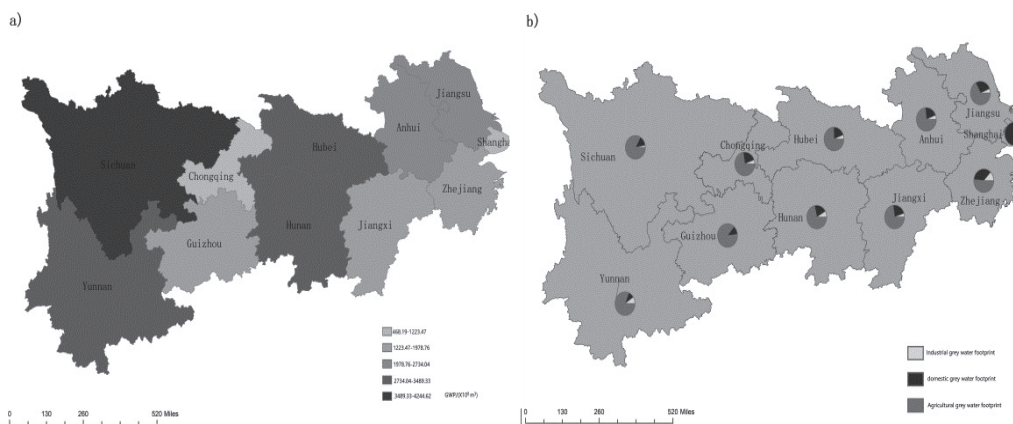


Fig. 2. The grey water footprint of each province a) and structural analysis b).

2005 to 2015. First, the GWF of the eastern provinces is less in the east and more in the west. Including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, the five provinces average volume reached 160 billion m after grey water footprint, and east of the Yangtze river, removal of Chongqing and Guizhou in the whole Yangtze river and the upstream section, including Hunan, Hubei, Sichuan and Yunnan of the four provinces belong to a larger amount of grey water footprint area, grey water footprint amount up to around 320 billion m after.

Look from Fig. 2b), the grey water footprint on the structure of the Yangtze river economic belt that the source of agriculture accounts for the main part of 11 provinces, 10 provinces except Shanghai agricultural source grey water footprint of ash ratio has exceeded 50% of the total water footprint, along the Yangtze river upstream to downstream at the same time, the agricultural source of herself and grey water footprint declining trend, the highest in Sichuan, about 83%, However, in the lower reaches of the Yangtze River, the grey water footprint of agricultural sources begins to decline, and the proportion of the grey water footprint of agricultural sources is close to 20% when it reaches Shanghai.

Water Pollution Pressure

The water pollution pressure index, as the ratio of the regional grey water footprint to the total water resources in the region, can be used to evaluate the degree of water pollution in the region and the situation of sustainable development of water resources.

In Fig. 3a), these 11 provinces can be divided into three echelons: rich water resources, good water resources and water resources shortage.

Fig. 3 shows that Shanghai is the province with the highest water pollution pressure, followed by Jiangsu, which is a province with high water pollution pressure. Hubei and Anhui are under moderate water pollution pressure, while Sichuan, Chongqing, Guizhou, Hunan, Jiangxi, Zhejiang and Yunnan are under low water pollution pressure.

In order to make the comparison of water pollution pressure data more reasonable and scientific, the comparison was made on the basis of water resources echelon division.

As can be seen from Fig. 3(c-e), in terms of time variation, although the water pollution pressure index of each province fluctuates to varying degrees, on the whole it presents a decreasing trend. For the four provinces that belong to the first echelon of rich water resources, the average water pollution pressure index of Jiangxi province is slightly lower than that of other provinces, only reaching about 1.1. Relative to the first gradient, pressure between the second and the third echelon of regional water pollution index exists different degree of difference, in the second tier as good as the average maximum and minimum of Hubei and Zhejiang, nearly two pressure difference between the two index of unit, the third echelon at the same time, the Shanghai index of average water pollution pressure up to 14, Chongqing is only about 2, a gap of nearly 7 times.

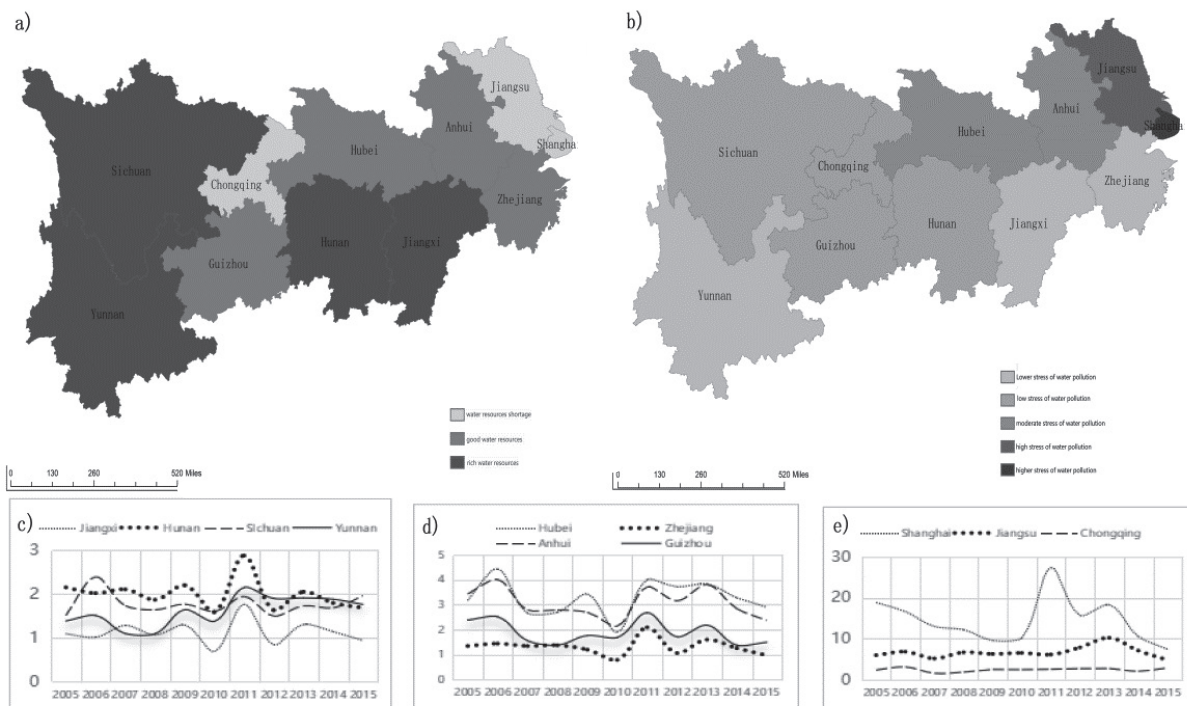


Fig. 3. Water resources distribution a) water pollution pressure of provinces b) comparison of areas in rich water resources c) comparison of areas in good water resources d) comparison of areas in water resources shortage e).

Grey Water Footprint Efficiency

Analysis of Grey Water Footprint Efficiency of the Yangtze River Economic Belt Water Footprint Efficiency refers to the GDP output per cubic meter of a region calculated by taking the grey water footprint of the region as input and the GDP of the region as output. As shown in Fig. 4a), provinces in the Yangtze River Economic Belt are divided into three efficiency areas according to their GWF, namely, high efficiency area, medium efficiency area and low efficiency area.

High efficiency area, for the “Changjiang Delta” three provinces: Shanghai, Jiangsu, Zhejiang; Medium efficiency area ranging from Anhui, Jiangxi, Hubei, Hunan and Chongqing, occupy the midsection of the Yangtze river basin mainly region, the low efficiency of the final area contains three provinces along the Yangtze river upstream, Sichuan, Yunnan and Guizhou provinces, presents the economically developed coastal areas in grey water footprint efficiency is more higher than inland economy is relatively underdeveloped regions.

In order to ensure the comparability of data, the gray water footprints of 11 provinces from 2005 to 2015 were respectively represented according to the above three regions, as shown in Fig. 4(b-d).

On the whole, China’s productivity and economic level have been continuously improved since the

reform and opening up, which is fully reflected in the continuously improved grey water footprint efficiency of the 11 provinces in the Yangtze River Economic Belt. Especially in the coastal areas with more developed productivity and economic level, the grey water footprint efficiency has a greater growth range and a faster growth rate. Shanghai, Jiangsu and Zhejiang area, can reach 20%-30% a year growth, In the second tier, the medium efficiency of the grey water footprint are growing by about 10% a year, while the low efficiency provinces of Sichuan, Yunnan and Guizhou are growing by an average of about 5%.

Analysis on Driving Factors of Grey Water Footprint

The influencing factors of the change of the GWF in the Yangtze River Economic Belt are divided into population factors, economic factors and technological factors, so as to further study the GWF through the internal structure of social and economic development. The driving factors for the annual change of GWF from 2005 to 2015 were calculated to obtain the change line chart, as shown in Fig. 5, and the cumulative contribution, as shown in Table 1.

On the whole, demographic factor is the least influential factor among the three driving factors, and the change range of time dimension is the most stable.

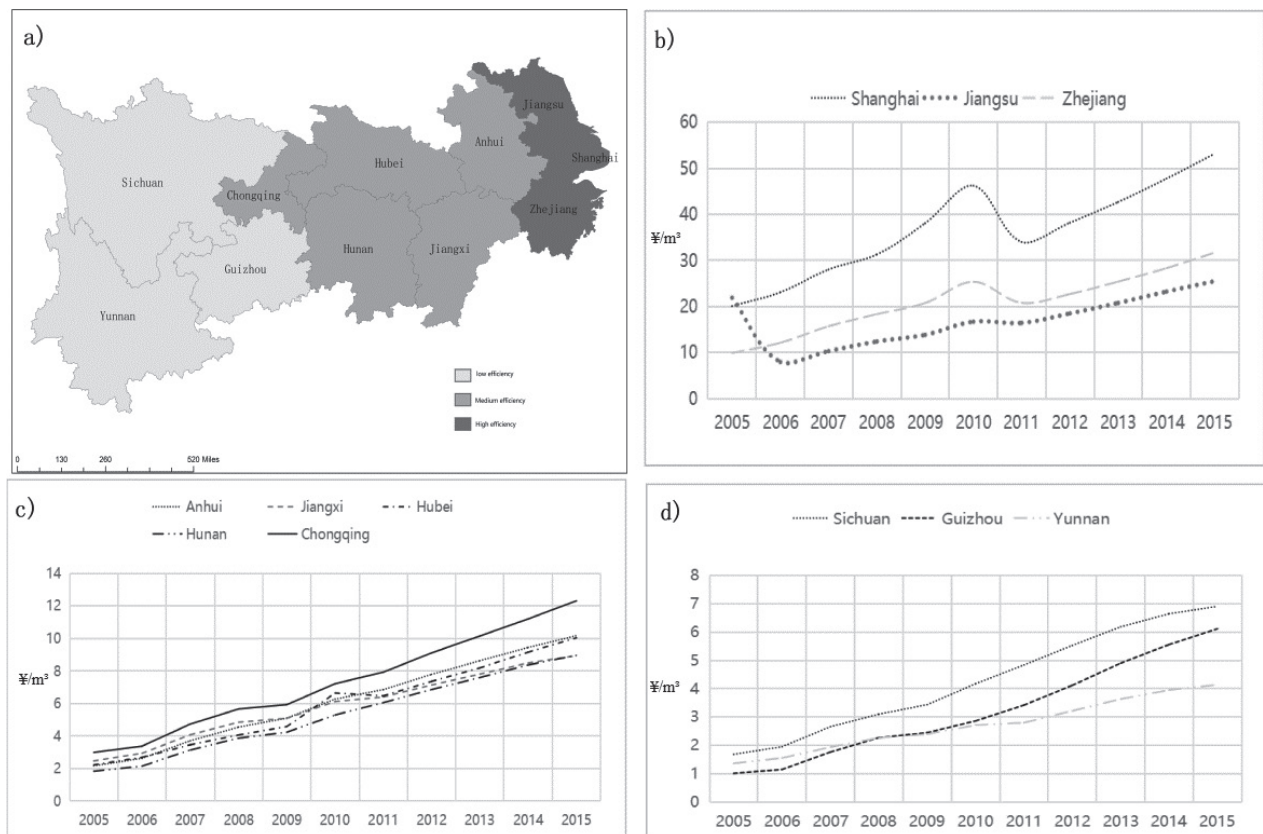


Fig. 4. Grey water footprint efficiency of provinces a) comparison of areas in high efficiency b) comparison of areas in Medium efficiency c) comparison of areas in low efficiency d).

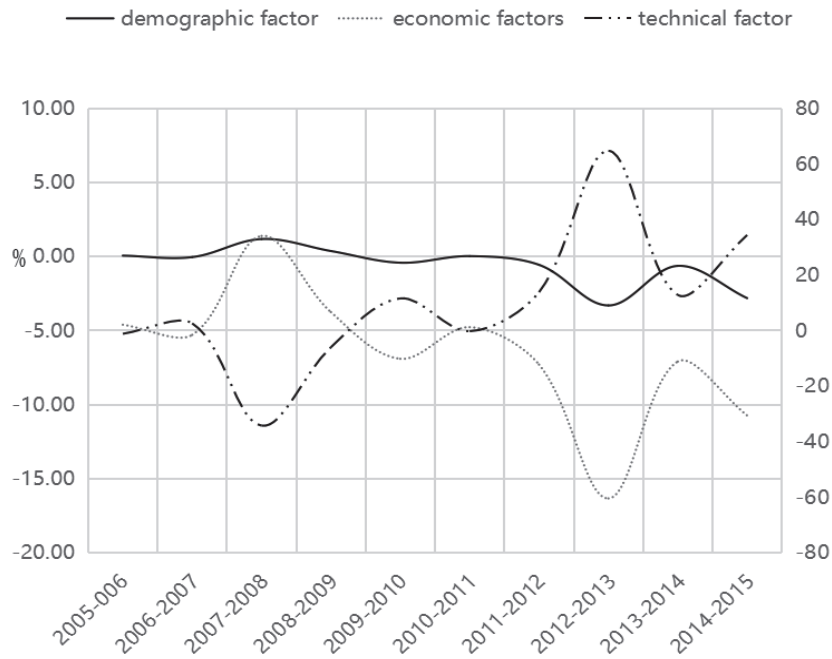


Fig. 5. Changes in the contribution of driving factors to the grey water footprint.

Table 1. Contribution of driving factors to change of grey water footprint in the Yangtze River Economic Belt.

Driving factor	Cumulative contribution (m ³)	Proportion	Effect
Demographic factor	1245.67x10 ⁸	2%	Positive effect
Economic factors	30739.5x10 ⁸	49%	Positive effect
Technical factor	-29979.1x10 ⁸	48%	Negative effect

At the same time, the influence of demographic factors constantly changes from a positive effect to a negative effect. The former stage can be explained as the increase of total population will directly lead to the increase of domestic water consumption and sewage discharge and thus have a positive effect on the GWF. However, in combination with the structural change of GWF mentioned above, reduce agricultural source grey water footprint, urban life source higher proportion of grey water footprint, after a phase can be on the population structure of it, with the continuous development of China's urbanization, the rural population to urban population, rural population decline caused by ash water footprint reduction than caused by the increase in urban population, the addition of ash water footprint. It shows that concentrated water resources management means such as water saving and water purification can more effectively improve the utilization rate of water resources and reduce pollution emission.

Economic factors become the main driving factors, and grey water footprint show state of uncertainty, and after 2008 years of the Yangtze grey water footprint is enhanced unceasingly to the driving role, its action begins to decrease gradually in the 2012 years later, on the one hand, shows that economic growth is the

main factor of increasing ash water footprint, the development process of pressing needs at the expense of the environment. On the other hand, China's bold development mode at the expense of the environment is constantly improving, and the national environmental protection policy and green economy can be realized continuously.

Technical factors as the Yangtze river economic belt grey water footprint negative effects, the main factors of grey water footprint growth inhibition of growth played a major role, and the technique of sewage treatment, green production technology, water-saving infrastructure and so on a series of measures to protect the water environment in constant development and popularization, the technical factors of negative effect also has been increasing, This indicates that the technical development of water environmental protection in China has achieved good results.

Conclusions

On the grey water footprint theory to the Yangtze river economic belt of 11 provinces industry source, the source of life and the source of water pollution after

unified convert water effective comparison and analysis of quantitative research, and through the grey water footprint respectively and the region of water resources, regional population and GDP are associated makes different parts in different parts of the water pollution can be combined with social and economic conditions, The following conclusions are drawn:

- From the time dimension, the GWF of each province shows a downward trend on the whole.
- From the spatial dimension, taking the boundary between Jiangxi and Hunan as the boundary, the total GWF of the provinces of the Yangtze River Economic Belt generally forms a pattern of less GWF in the east and more in the west.
- From the factor dimension, among the three factors of population, economy and technology, the population factor has the least influence, while the economic factor is the main positive driving factor for the GWF, while the technical factor is the main negative driving factor.

Therefore, in order to promote the sustainable development of water resources in the Yangtze River Economic Belt, the following suggestions are put forward: 1) To realize green development according to the regional characteristics [29]. 2) in view of the high degree of water pollution from agricultural sources, the provinces can carry out pollution control for agricultural sources. 3) Improving the ecological compensation mechanism in the river basin.

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Conflict of Interest

On behalf of all the authors, the corresponding author declares that there is no conflict of interest.

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