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Studies on water resources carrying capacity in Tuhai river basin based on ecological footprint

Chengshuai Wang, Lirong Xu* and Xin Fu
School of Resources and Environment, University of Jinan, Jinan 250022, China

*Corresponding author e-mail: stu_xulr@ujn.edu.cn

Abstract. In this paper, the method of the water ecological footprint (WEF) was used to evaluate water resources carrying capacity and water resources sustainability of Tuhai River Basin in Shandong Province. The results show that: (1) The WEF had a downward trend in overall volatility in Tuhai River Basin from 2003 to 2011. Agricultural water occupies high proportion, which was a major contributor to the WEF, and about 86.9% of agricultural WEF was used for farmland irrigation; (2) The water resources carrying capacity had a downward trend in general, which was mostly affected by some natural factors in this basin such as hydrology and meteorology in Tuhai River Basin; (3) Based on analysis of water resources ecological deficit, it can be concluded that the water resources utilization mode was in an unhealthy pattern and it was necessary to improve the utilization efficiency of water resources in Tuhai River Basin; (4) In view of water resources utilization problems in the studied area, well irrigation should be greatly developed at the head of Yellow River Irrigation Area(YRIA), however, water from Yellow River should be utilized for irrigation as much as possible, combined with agricultural water-saving measures and controlled exploiting groundwater at the tail of YRIA. Therefore, the combined usage of surface water and ground water of YRIA is an important way to realize agricultural water saving and sustainable utilization of water resources in Tuhai River Basin.

1. Introduction

It is necessary to study water resources carrying capacity in order to resolve the contradiction between water supply and human needs, and the research on water resources carrying capacity has attracted great attention and become a key and hot research topic in the field of water resources science. The water resources carrying capacity, the organic combination of carrying capacity, water environment and water ecology, can reflect the social and natural attributes and environmental value of water [1]. Studies on water resources carrying capacity are popular in China, which is, however, likely taken into the theory of sustainable development in other countries. The concept of water resources carrying capacity was firstly put forward by Shi et al in the studies on water resources carrying capacity of Urumqi River Basin in Sinkiang based on conventional tendency method [2]. Since then the connotation of water resources carrying capacity has been enriched and improved and many methods, such as fuzzy synthetic evaluation, system engineering theory, multi-objective analysis, have been widely used in the study of regional water resources carrying capacity [3].
Compared with other evaluation methods of sustainable development, the method of ecological footprint is more closely linked with the sustainable development theory, with more simple and operable calculation [4]. Accordingly the water ecological footprint (WEF) method is quite useful in assessment on water resource utilization. The constructed water resources account can be integrated into the total ecological footprint and used to evaluate not only the sustainable development of water resources, but also regional sustainable development [5, 6]. Since its introduction, the WEF method has been used in assessing the water resources carrying capacity in some administrative regions [7-9]. It is clear that the integrity of the basin was ignored in the case of evaluating the regional water resources carrying capacity from administrative regionalization standpoint. However, there is little research about the application of WEF for water resources carrying capacity in the basin scale, besides in typical watershed of Liaohe Basin, Shulehe Basin, Shiyanghe Basin, Hunhe Basin and other typical basins [10-13].

Tuhai River Basin in Shandong Province is a typical basin with severe water shortage, large water consumption, high degree exploitation and utilization, and rapid adjustment of industrial structure. It is necessary and practical to assess and analyze water resources carrying capacity under the new context of the full implementation of the most stringent water management system and the optimal allocation of water resources in Shandong Province. Therefore, the method of the WEF was used to analyze and calculate water resources carrying capacity and ecological deficit in this paper to provide scientific basis for sustainable development of Tuhai River Basin in Shandong Province.

### 2. Data sources and Research Methods

#### 2.1. General situation of Study Area

![Figure 1. The Geographical Location Map of Tuhai River Basin.](image)

Tuhai River Basin in Shandong Province was used as the research zone (Figure 1). Tuhai River, located to the south of the Haihe River Basin, flows through four cities, such as Liaocheng, Dezhou, Jinan and Binzhou, from upstream to downstream, and the catchments area of Tuhai River basin, with the main channel 406 km long, is 13296 km² in Shandong Province, including Shenxian, Yanggu, Dongchangfu, Chiping and so on 13 counties (or cities). Our research zone has a transitional zone of
warm temperate semi-humid and semi-arid temperate monsoon climate, where the precipitation is mostly distributed in the flood season from June to September and the average annual precipitation is 564mm. The conflict of water supply and demand is more obvious in the spring due to less precipitation, more evaporation and water demand for irrigation.

2.2. Data Sources
Data of water consumption sub-accounts such as agricultural water consumption, industrial water consumption, and so on, were collected from “Water Resources Bulletin in Shandong Province” from 2003 to 2011, social and economic data from “Shandong Year Book”, the cultivated area and annual rainfall data of each county from “Statistical Yearbook of Jinan”, “Statistical Yearbook of Liaocheng”, “Statistical Yearbook of Binzhou” and “Statistical Yearbook of Dezhou” from 2003 to 2011, and Table 1 was obtained through the analysis and calculation of collected data.

| Population / 10⁴ | 2003  | 2004  | 2005  | 2006  | 2007  | 2008  | 2009  | 2010  | 2011  |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| GDP / 10⁵ RMB Yuan | 82.9  | 99.3  | 123.1 | 145.1 | 175.1 | 217.5 | 235.4 | 274.0 | 314.9 |
| Annual Precipitation / mm | 638.4 | 614.5 | 584.3 | 413.8 | 516.0 | 441.1 | 631.0 | 566.8 | 549.1 |
| Cultivated Land Area/10⁴ km² | 10.08 | 10.21 | 10.18 | 10.11 | 10.10 | 10.78 | 10.51 | 10.44 | 10.15 |
| Water Availability / 10⁵ m³ | 27.3  | 18.7  | 21.9  | 9.3   | 121  | 8.9   | 23.0  | 32.8  | 15.4  |
| Water Consumption / 10⁶ m³ | | | | | | | | | |
| Agricultural | 36.2  | 30.7  | 34.2  | 39.1  | 36.3  | 35.1  | 34.3  | 33.9  | 29.9  |
| Industrial | 1.75  | 1.80  | 1.92  | 2.03  | 2.29  | 2.36  | 2.69  | 2.55  | 2.86  |
| Domestic | 1.95  | 2.29  | 2.30  | 2.21  | 2.45  | 2.52  | 2.38  | 2.36  | 2.14  |
| Urban Public | 0.26  | 0.23  | 0.20  | 0.42  | 0.35  | 0.31  | 0.39  | 0.38  | 0.34  |
| Ecological | 0.10  | 0.14  | 0.18  | 0.19  | 0.29  | 0.34  | 0.28  | 0.38  | 0.37  |

2.3. Research Methods
The WEF method is widely used to measure the degree of sustainable utilization of water resources by comparing ecological surplus with ecological deficit of water resources. Water ecological surplus will appear when ecological carrying capacity is more than regional WEF, which indicates that the utility condition of water resources is in sustainable state. On the other hand, water ecological deficit will appear when ecological carrying capacity is less than regional WEF, which indicates that the utility condition of water resources is in unsustainable state.

2.3.1. Calculation Method of Water Resources Carrying Capacity. The calculation model of water resources carrying capacity [5] is:

$$ EC_ω = 0.4γ_ω φ_ω W / p_ω $$ (1)

where $EC_ω$ is the regional water resources carrying capacity, $φ_ω$ is the water resources yield factor in the study area, $γ_ω$ is a global water balance factor, W is the total amount of water resources in the study area, and $p_ω$ is the world’s average production capacity of water resources.

(1) Water resources yield factor ($φ_ω$)

The water resources yield factor in various regions can be obtained by the ratio of the average production capacity of water resources in the study area to that in the world, under the assumption that the water yield factor is one in the world. In this paper, the calculation formula of regional water resources yield factor is:

Table 1. Socioeconomic Status and Water Consumption in Tuhai River Basin from 2003 to 2011.
\[ \varphi_{ao} = P / p_{ao} \]  

(2)

where \( \varphi_{ao} \) and \( p_{ao} \) are the same as in Formula (1), \( P \) is the yield per unit area. The average production capacity of water resources is \( 29.46 \times 10^3 \text{m}^3/\text{km}^2 \) in the world and \( 12.01 \times 10^4 \text{m}^3/\text{km}^2 \) in Tuhai River Basin, so \( \varphi_{ao} \) of Tuhai River Basin is 0.41.

(2) Global water resources balance factor (\( \gamma_{ao} \))

Global water resources balance factor is the ratio of the average ecological productivity of water resources in regional biological production to the average ecological productivity in the world, and this paper followed 5.19 as its value for comparative purpose [5].

2.3.2. Calculation Method of WEF. In the current paper, the WEF was divided into five sub-accounts based on the characteristics of water utilization: domestic WEF, agricultural WEF, industrial WEF, urban public WEF and ecological WEF, in which domestic WEF resulted from water for urban and rural domestic, agricultural WEF mainly from water for farmland irrigation and forestry, animal husbandry and fishery, urban public WEF mainly from water for commercial and service industry, ecological WEF mainly from water for green area and dilution pollution. The WEFs of different sub-accounts are calculated as follows:

\[
\begin{align*}
EF_i &= \gamma_{ao} W_i / p_{ao} \\
EF_a &= \gamma_{ao} W_a / p_{ao} \\
EF_i &= \gamma_{ao} W_i / p_{ao} \\
EF_c &= \gamma_{ao} W_c / p_{ao} \\
EF_e &= \gamma_{ao} W_e / p_{ao}
\end{align*}
\]

(3)

where \( EF_i \) is the domestic WEF(\( \text{km}^2 \)), \( W_i \) is domestic water consumption, \( EF_a \) is the agricultural WEF, \( W_a \) is agricultural water consumption, \( EF_i \) is the industrial WEF, \( W_i \) is industrial water consumption, \( EF_c \) is the urban public WEF, \( W_c \) is urban public water consumption, \( EF_e \) is the ecological WEF, \( W_e \) is ecological water consumption. \( \varphi_{ao} \) and \( p_{ao} \) are the same as in Formula (1).

3. Results and Discussion

3.1. The Dynamic Characteristics of WEF in Tuhai River Basin

The WEF in Tuhai River Basin can be obtained by formula (3) as shown in Table 2.

### Table 2. Water Resources Carrying Capacity and WEF in Tuhai River Basin. \( \text{km}^2 \)

| WEF            | 2003    | 2004    | 2005    | 2006    | 2007    | 2008    | 2009    | 2010    | 2011    |
|---------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Agricultural  | 44087.8 | 36734.3 | 41172.4 | 48909.9 | 44277.2 | 42738.5 | 41508.9 | 40575.6 | 35662.5 |
| Irrigation    | 37673.5 | 30633.4 | 35600.8 | 43466.0 | 38203.4 | 37503.3 | 36339.1 | 35614.7 | 31530.7 |
| Industrial    | 2174.6  | 2223.1  | 2453.1  | 2579.8  | 3172.0  | 2967.1  | 3441.5  | 3106.6  | 3523.8  |
| Domestic      | 2312.6  | 2751.2  | 2814.0  | 2657.0  | 3041.6  | 3100.3  | 2874.5  | 2879.1  | 2687.6  |
| Urban Public  | 330.7   | 298.3   | 241.4   | 546.8   | 474.5   | 399.2   | 525.1   | 477.3   | 429.3   |
| Ecological    | 124.0   | 183.9   | 176.3   | 190.3   | 327.7   | 424.6   | 343.5   | 400.5   | 372.0   |
| Total WEF     | 49029.7 | 42191.7 | 46857.2 | 54883.8 | 51293.0 | 49629.7 | 48695.3 | 47349.1 | 42675.2 |
| WCC           | 7875.1  | 5416.5  | 6323.0  | 2686.1  | 3507.7  | 2566.1  | 6651.6  | 9489.2  | 4456.1  |
| WED           | 41154.6 | 36775.2 | 40534.2 | 52197.7 | 47785.3 | 47063.6 | 42043.7 | 37949.9 | 38219.1 |

Note: WRCC is water resources carrying capacity; WRED is water resources ecological deficit.
The total WEF in Tuhai River basin decreased from 49029.7 km$^2$ in 2003 to 42675.2 km$^2$ in 2011, with a downward trend in overall volatility, in which the upward trend from 2003 to 2006 is more significant, reaching the highest value of 54883.8 km$^2$ in 2006, followed by a downward trend. Agriculture is the primary water consumer in Tuhai River basin, accounting for more than 83% of the total water consumption. Though the proportion of agricultural water consumption has been decreasing from 89.9% in 2003 to 83.6% in 2011, it is still too high due to its slow declining, consequently, the contradiction of WEF lies in water utilization structure in view of the fact that agricultural water is the main contributor to WEF in Tuhai River Basin.

The average agricultural WEF was 41740.79km$^2$, accounting for 86.8% of the total WEF, in which 86.9% is used for irrigation. The analysis showed that WEF was positively correlated with irrigation WEF while negatively correlated with annual precipitation. The precipitation of Tuhai River Basin is 18.2% less than the average annual precipitation in 2006, when different degrees of droughts were popular throughout China, so there was a sudden increase in irrigation water, leading to the highest value of WEF during the study period.

![Figure 2. The Area Curve Map of WEF in Tuhai River Basin.](image)

The average industrial WEF was 2849.1km$^2$, accounting for 5.93% of the total WEF. The industrial WEF showed a significant growth trend due to rapid increase in economic development and industrial water demand from 2003 to 2011. The average domestic WEF was 2791.0 km$^2$, accounting for about 5.81% of the total WEF. Domestic WEF showed a slow growth trend due to improvement of people's living standard, especially for rural residents. The average of urban public WEF was 562.8km$^2$, accounting for 0.86% of the total WEF, and the urban public WEF showed a fluctuating ascending trend from 2003 to 2011. Compared with other water consumptions, ecological WEF had the lowest proportion and the fastest growth, from 0.3% in 2003 up to 0.9% in 2011. The changes of WEF area can demonstrate the changes of WEF of each sub-account, as illustrated in Figure 2.

### 3.2. Dynamic Characteristics of Water Resources Carrying Capacity in Tuhai River Basin

It can be seen from Table 2 that the water resources carrying capacity in the basin changed remarkable in downward trend. The water resources carrying capacity was 7875.1 km$^2$ in 2003 and continued to decline to 2 566.1 km$^2$ in 2008, however, in high level in 2009 and 2010 mainly due to the increase of precipitation in the basin. The analysis shows that water resources carrying capacity of Tuhai River Basin have a significant positive correlation with precipitation (Figure 3). To some extent, water resources carrying capacity is mostly affected by natural factors such as hydrology and meteorology.
Figure 3. The Relationship between Water Resources Carrying Capacity and Precipitation. Figure 4. The Relationship between Ecological Carrying Capacity and Irrigation WEF.

3.3. Water Ecological Deficit in Tuhai River Basin

The fact that WEF was more than water resources carrying capacity showed that water supply was inadequate and the utility condition of water resources was in unsustainable state in Tuhai River Basin from 2003 to 2011. The water ecological deficit fluctuated upward trend from 2003 to 2006, with a peak of 53540.6 km$^2$ in 2006, followed by a decrease to 38219.2 km$^2$ in 2011, which was consistent with the trend of WEF in the basin. The analysis showed that WEF had a positive correlation to irrigation WEF of Tuhai River Basin (Figure 4), which indicated that the water ecological deficit was mainly caused by agricultural water consumption. It can be forecasted that there would be a further increase in the water ecological deficit with the increase of water consumption judging by the present economic improvement. Accordingly, it is urgent to find effective ways of rational utilization of limited water resources for the sustainable development in Tuhai River Basin.

4. Conclusions and Discussions

The WEF showed an overall downward trend, in which agricultural WEF accounted for more than 83% in Tuhai River Basin from 2003 to 2011. Agricultural water consumption is the main contributor to WEF, which proportion has decreased but not much, and about 86.9% of agricultural WEF was used for irrigation water. The water resources carrying capacity had a downward trend in general, a drop of 43.42% in 2011 compared with 2003, which was mostly affected by the hydrology, meteorology and other natural factors. The analysis of water resources ecological deficit showed that the degree of water resources exploitation in this basin is very high with little potentiality. There was a big contradiction between water demand and water supply, and the water resources utilization mode of Tuhai River Basin was in an unhealthy pattern, so it was necessary to improve the utilization efficiency of water resources.

As a major agricultural district, agricultural water is the main contribution to the water ecological deficit in Tuhai River Basin, and local agricultural irrigation mostly depends on water form Yellow River, supplemented by well-canal combined irrigation. The main problems of water utilization in the Yellow River Irrigation Area (YRIA) are: irrigation relies on water form Yellow River, with lower groundwater utilization at the head of irrigation area; On the other hand, the ecological environment has been deteriorated due to the lack of water from Yellow River and over exploitation of groundwater at the tail of irrigation area, such as Shenxian, Huimin and other counties. Therefore, the combined usage of surface water and ground water of YRIA should be an important way of water saving in the basin. Specific measures are as follows: well irrigation should be greatly developed and shallow groundwater resources should be exploited as much as possible at the head of YRIA, and more water from Yellow River should be transferred to the tail area for irrigation and supplement groundwater with lining the main channel; however, water from Yellow River should be utilized for irrigation, combined with agricultural water-saving measures and controlled exploiting groundwater at the tail of YRIA. In conclusion, combined usage of surface water and ground water of Yellow River Irrigation
District is an important way to realize agricultural water saving and sustainable utilization of water resources in Tuhai River Basin.

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