Grey water footprint assessment of domestic wastewater in Guangdong section of the Dongjiang River Basin

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Abstract—Water pollution in river basins has become one of the main factors in restricting regional social-economic development. Water footprint assessment at river basin level is a hot issue in the research on water for sustainable development. In this study, the grey water footprint method was introduced for domestic wastewater assessment. The approach can effectively reflect the impact of water pollution on the amount of available water resources by evaluating the degree of water pollution from the perspective of water quantity. In order to verify the approach, the region of Guangdong section of the Dongjiang River Basin (GD-DRB) was selected as a case. Based on multiple pollutants (i.e., CODₐₕ, NH₃-N, BOD₅ and TP), grey water footprint of the river basin was calculated. The results showed that the grey water footprint of domestic water in the urban area of the region was higher than that in the rural area. The total amount of grey water footprint in the region was 28.41 billion m³. The main pollutants in the region were phosphorus and organic compounds.

1. Introduction

Water shortage and pollution are the main environmental problems in China [1]. Water pollution in river basins is a serious environmental problem, influencing socio-economic development. Water footprint, defined as the amount of water required to produce goods and services, has become a hot issue in the research of water resources management [2]. Water footprint represents the true amount of water that sustains human consumption [3]. It can link human activities with water consumption, and show the influence of water pollution on the environment.

Grey water footprint is one of the evaluation indexes of water footprint. Grey water footprint is defined by the amount of water required to dilute the pollutant concentration in the sewage to meet environmental quality standards for surface water [4]. Reflecting the tradeoffs between water quality and pollution discharge, grey water footprint was used to indicate the quality of the watershed environment. Evaluation of grey water footprint can support decision making for water resources management. Previously, many studies focused on multiple scales of grey water footprint (e.g., national, regional, and sector scales). In terms of the national scale, watershed grey water footprint of 31 provinces in China was estimated [5]. The intensity of grey water footprint was affected by urbanization level. In light of specific sector, the grey water footprint of agriculture was influenced by variations in available water [6]. Traditionally, chemical oxygen demand (COD), ammonia nitrogen (NH₃-N), total nitrogen (TN) and total phosphorus (TP) were chosen as indicators to quantify the grey water footprint in China [7]. On the regional scale, the amount of grey water footprint in China decreased from southeast to northwest. Liu et al. [8] evaluated water environmental carrying capacity in the Yangtze River Economic Belt based on the grey water footprint approach. Based on pollutants produced by multiple sectors, domestic wastewater was a major contributor of grey water footprint [9]. On the industrial scale, Ansorge et al. [10] analyzed the pollution load of sewage treatment plants based on the theory of grey
water footprint. The grey water footprint of the discharge of polluting substances from nuclear power plants was evaluated by Ansorge et al. [11]. Thus, grey water footprint assessment is regarded as an effective tool for protecting the watershed environment.

The objective of this study is to apply the grey water footprint approach into a typical watershed (i.e., GD-DRB). This study is expected to provide decision-making support for watershed sustainable development.

2. Case Study
Accounting for 24.3% of the Pearl River Basin in Guangdong, the watershed of Dongjiang River Basin supports water resource demands in Dongguan, Zengcheng, Huizhou, Shenzhen, Xinfeng and Heyuan of Guangdong Province (Fig. 1). Dongjiang River provides water to 30.2 million people in Guangdong Province, accounting for 30% of the province's permanent population.

In 2019, the Gross Domestic Product (GDP) of Guangdong Province supported by the Dongjiang River Basin reached 4.17 trillion yuan, accounting for about 39% of GDP in Guangdong Province. Thus, the Dongjiang River Basin plays an important role in the socio-economic development in Guangdong Province. However, with the growth of economy and population, the exploitation and utilization of water resources in the Dongjiang River Basin has become the highest among all the basins in Guangdong Province [12-13] (Fig. 2).
The conflicts between water supply and demand in GD-DRB became increasingly obvious. In addition, the development of urbanization and industrialization led to deterioration of water quality in the basin. The carrying capacity of the watershed gradually decreased. The Dongjiang River Basin was under the double pressures of seasonal water shortage and water quality deterioration, which posed a severe challenge to sustainable utilization of water resources. Thus, GD-DRB, regarded as a typical region, was selected as a case.

3. Methodology
Domestic wastewater is mainly generated from urban and rural sewage. Domestic sewage, regarded as one of the main sources of point source pollution, is discharged by sewage treatment plants. Domestic sewage contains multiple pollutants (e.g., COD$_{Cr}$, NH$_3$-N, TP and BOD$_5$). Thus, the grey water footprint of domestic wastewater was expressed as follows [14]:

\[
HGWF_i = \frac{L_i}{(C_{\text{max}} - C_{\text{nat}})} - W_{dh}
\]

(1)

where $HGWF_i$ is the grey water footprint of the $i^{th}$ pollutant (i.e., COD$_{Cr}$, NH$_3$-N, TP and BOD$_5$) (unit: m$^3$); $L_i$ is the load of the $i^{th}$ pollutant (unit: kg); $W_{dh}$ is the amount of domestic sewage (unit: m$^3$); $C_{\text{max}}$ is the maximum allowable concentration of the $i^{th}$ pollutant according to wastewater discharge standards (unit: kg/m$^3$); and $C_{\text{nat}}$ is natural background concentration of the $i^{th}$ pollutant in receiving water (unit: kg/m$^3$). The Dongjiang River Basin was required to meet the standards of class III surface water, according to SEPA and GAQS [15]. Thus, maximum allowable concentrations of pollutants (i.e., pollutants of COD$_{Cr}$, BOD$_5$, NH$_3$-N and TP) were 20 mg/L, 4 mg/L, 1.0 mg/L and 0.2 mg/L, respectively. Pollutant load (i.e., $L_i$) was obtained by the formula (2).

\[
L_i = \left( P_u W_{pe} n_i \gamma + P_r W_{pn} n_i \gamma \right) t
\]

(2)

where $P_u$ is the urban population; $P_r$ is the rural population; $W_{pe}$ is the quota of urban domestic water [unit: L/(d·person)]; $W_{pn}$ is the quota of rural domestic water [unit: L/(d·person)]; $n_i$ is the concentration of the $i^{th}$ pollutant in sewage; $\gamma$ is domestic sewage discharge coefficient; and $t$ is time (unit: d). Domestic water quota of cities and towns in the Dongjiang River Basin was referred to the DWRGP [16]. The sewage discharge coefficient of urban and rural residents were 0.85 and 0.80, respectively. The grey water footprint of domestic wastewater (i.e., $HGWF$) was obtained by the formula (3).
\[ HGWF = \max_i (HGWF_i) \]  

where \( HGWF \) is the grey water footprint of domestic wastewater (unit: m\(^3\)).

4. Results and Analysis

In this study, the grey water footprints of domestic wastewater in 10 districts and cities of GD-DRB in 2019 were calculated. The main pollutants of COD\(_c\), NH\(_3\)-N, BOD\(_5\) and TP were selected as indicators for grey water footprint analysis. The results are shown in Table I. The grey water footprint of residential wastewater in Shenzhen was higher than that in other cities. The grey water footprint of residential wastewater in Xinfeng was smaller than that in other cities.

| Districts and cities | The grey water footprint of pollutants\(^*\) | \( COD_c \) | NH\(_3\)-N | BOD\(_5\) | TP |
|----------------------|-----------------------------------------------|----------|--------|---------|-----|
| Zengcheng            | 4.65                                          | 8.49     | 9.60   | 11.03   |
| Huicheng             | 5.39                                          | 10.70    | 12.56  | 10.01   |
| Huiyang              | 1.99                                          | 4.48     | 4.54   | 4.57    |
| Huidong              | 2.96                                          | 6.75     | 6.47   | 4.65    |
| Boluo                | 3.41                                          | 7.73     | 7.42   | 5.34    |
| Longmen              | 1.00                                          | 2.26     | 2.17   | 1.57    |
| Xinfeng              | 0.61                                          | 1.17     | 1.47   | 1.06    |
| Heyuan               | 13.23                                         | 26.03    | 30.51  | 24.37   |
| Dongguan             | 30.60                                         | 63.18    | 67.94  | 75.80   |
| Shenzhen             | 68.56                                         | 119.61   | 114.41 | 131.43  |
| Total                | 132.40                                        | 250.40   | 257.09 | 269.83  |

\(^*\) unit: 100 million m\(^3\)

The amounts of main pollutants differentiated among cities of the region. TP was regarded as the main pollutant of domestic wastewater in Zengcheng, Huiyang, Dongguan and Shenzhen. NH\(_3\)-N was regarded as the main pollutant of domestic wastewater in Huicheng, Xinfeng and Heyuan. The grey water footprint of BOD\(_5\) in Huidong, Boluo and Longmen was higher than that of other pollutants. The total grey water footprints of BOD\(_5\) and TP were larger than COD\(_c\) and NH\(_3\)-N. Thus, the main pollutants in GD-DRB were BOD\(_5\) and TP.

![Figure 3 Proportion of grey water footprint of each district and city to the total GWF in 2019.](image)

In light of the influence from urban and rural population, the grey water footprint of urban domestic wastewater was higher than that of rural domestic wastewater. For example, the grey water footprint of urban domestic wastewater in Dongguan was thirty-five times more than that of rural domestic wastewater. The grey water footprints of urban and rural domestic wastewater in Dongguan were 70.9 billion m\(^3\) and 2.0 billion m\(^3\), respectively. The grey water footprint of domestic wastewater in Shenzhen...
was the highest (i.e., 13.14 billion m$^3$), accounting for 46.3% of total amount of grey water footprint in the region.

The total amount of grey water footprint in GD-DRB was 28.41 billion m$^3$. Domestic wastewater discharges of phosphorus and organic compounds in the region caused serious water pollution, leading to the increase of grey water footprint. The grey water footprint of domestic sewage was related to urbanization rate and population. Domestic wastewater posed challenges to aquatic ecosystem and water resources management in the Dongjiang River Basin.

Figure 4 The grey water footprint of rural, urban and total domestic wastewater (unit: 100 million m$^3$)
* The urbanization rate of Shenzhen is 100%.

5. Conclusions
Grey water footprint is an effective approach to analyze the influence of various pollutants with different concentrations on water quality. In this study, NH$_3$-N, COD$_{Cr}$, BOD$_5$ and TP were selected as the indicators for grey water footprint assessment of domestic wastewater. GD-DRB was taken as a case study. The amount of grey water footprint of the region in 2019 was 28.41 billion m$^3$. The main pollutants in the region were organic compounds and phosphorus. The development of urbanization would affect the grey water footprint of domestic sewage. On the one hand, the acceleration of urbanization is accompanied by the increase of water consumption and wastewater discharge, leading to the increase of grey water footprint. On the other hand, the development of urbanization is also conducive to improving the efficiency of water resources utilization and wastewater treatment, and it is also helpful to alleviate the environmental pressure on the river basin. Under the background of urbanization development, water pollutions and shortages need to be considered. From the perspective of grey water footprint, it can provide decision support for sustainable use of water resources.

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