

Article

Analysis of Ningxia Hui Autonomous District's Gray Water Footprint from the Perspective of Water Sustainability

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Abstract: Gray water footprint (GWF) is an effective method to evaluate the degree of water pollution and water quality. It is the amount of freshwater needed to dilute water pollutants to meet ambient water quality standards. Accounting and analyzing the GWF will be significant for promoting an improved water environment and sustainable water ecology in Ningxia Autonomous District. We accounted for the GWF of all cities in Ningxia from 2012 to 2020 and evaluated its spatial-temporal variations by the GWF accounting method proposed by Hoekstra. Then, the Logarithmic Mean Divisia Index (LMDI) method was applied to investigate the contributions of four driving factors: the population scale effect, economic development effect, technological effect, and industrial structure effect. And then, the changes in the GWF in the Ningxia region were analyzed. The results showed that the GWF in the Ningxia region changed from 79.21×10^8 to 29.09×10^8 m³/yr during 2012–2020, making a significant decreasing trend. Among all cities, Wuzhong City contributes the most in terms of the GWF. More specifically, economic development and technology structure are the positive and negative drivers of the GWF, respectively. The water pollution levels in Ningxia (0.49–1.3) indicated that the waste assimilation capacity has fallen short of taking up the pollutant load, which had an unfavorable impact on the groundwater according to actual water quality data. NO₃-N and NH₃-N are detected in the groundwater throughout the Ningxia region, with the highest NH₃-N content in the groundwater in Yinchuan, which almost exceeded the groundwater quality standard of category III. Above all, this study reflected the current water pollution situation better by combining the GWF with actual water quality data in Ningxia. The finding of this study is valuable for addressing water quality threats and developing sustainable development.

Keywords: gray water footprint; groundwater; actual water quality data; Logarithmic Mean Divisia Index (LMDI) method



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1. Introduction

Water is an irreplaceable natural resource for human survival and development, an important guarantee for social and economic development, and one of the main controlling factors of the ecological environment. With the advent of industrialization and urbanization, the water crisis, represented by water shortage and water environment pollution, has become an important issue limiting sustainable development [1–3]. By 2050, over 40% of the global population will be affected by the water crisis [4]. In contrast, the 2015 China State of the Environment Bulletin reported that 35.50% of 967 surface water quality monitoring sites are below Class III quality, and 61.30% of 5118 groundwater quality monitoring sites have poor and very poor grades, making the water crisis in China not optimistic either [5].

In 2011, Hoekstra and Chapagain proposed the concept of “gray water footprint”, which is defined as the water volume required for assimilating the pollutants [6]. It is a new method for evaluating water resource use and water pollution. Mekonnen and

Hoekstra first estimated the global anthropogenic nitrogen loads to freshwater by the GWF in 2015 and pointed out that three-quarters of the GWF related to N loads came from diffuse sources (agriculture), with the rest coming from domestic point sources [7]. Li assessed the water footprint of the Haihe River Basin (China) by blue footprint and gray footprint, revealing that the agricultural GWF of the HRB accounted for 54% of the total [8]. Zhang analyzed the provincial gray water footprint of provinces in China from 2003 to 2015. The results showed that domestic GWF was the dominant component in China, particularly in the developed provinces [9]. Sun calculated the values of the driving effects of per capita gray water ecological footprint change in 31 provinces in China and found that capital deepening and economic activity were obvious in the input efficiency, and capital efficiency, footprint intensity, and environmental efficiency were in decline in the output efficiency [10]. Currently, most of the research focuses on national or regional differences in GWF, and there is a lack of research on the regional GWF, especially on the spatial and temporal drivers of the GWF. The integration with GWF and the actual water quality data are also lacking [11,12].

With economic growth, the pollution-induced water shortage has further exacerbated the water scarcity in the Ningxia region. A scientific evaluation of the water environment pollution state is an essential premise for improving the overall level of water use and guarantees the sustainable development of one region. Improvement of water environment quality can alleviate the pressure of water scarcity in Ningxia to a certain extent. It aims to (1) analyze the variation of the GWF in Ningxia region, (2) identify the driving forces of the GWF, and (3) address the challenges of water sustainability by combining the GWF with the actual water quality in Ningxia region. There is a complex relationship between contaminant properties and economic development in a region, and the quantitative calculation of the GWF and its driving factors provides a good method to analyze this relationship. This paper combined GWF and traditional water quality data to study the sustainability of water resources in Ningxia, which can reflect water pollution more accurately than in the previous studies. The results of this study may provide useful guidance for the local future water resource management and water security analysis.

2. Materials and Methods

2.1. Study Area

Ningxia Hui Autonomous District is located in the arid region of northwest China, in the middle and upper reaches of the Yellow River, and is an important autonomous region for ethnic minorities in China; it has the geographical coordinates $104^{\circ}17'$ – $107^{\circ}39'$ east longitude and $35^{\circ}14'$ – $39^{\circ}23'$ north latitude (Figure 1). Yinchuan is the provincial capital. The topography is characterized by a long north–south direction and a short east–west direction, covering an area of 66,400 square kilometers. The terrain is high in the south and low in the north, with a variety of terrains including plateaus and mountains and complex geological formations [13]. The Ningxia region straddles the Inner Mongolia Plateau and the Loess Plateau, with plains accounting for 26.8%, mountains, hills, and terraces accounting for 71.4%, and deserts accounting for 1.8% [14]. The climatic characteristics are differentiated and generally belong to an arid semi-climate with large diurnal temperature differences and long sunshine hours. The average evaporation is 1748.44 mm/yr, and the average precipitation is about 184.73 mm/a. Precipitation decreases from south to north, with the largest average annual water surface evaporation in Guyuan City and the smallest in Shizuishan City [15].

The Ningxia region is one of China's most water-poor provinces, with a multi-year (1956–2016) average water resource total of 1212 million m^3 [16]. The amount of freshwater available per capita in the region is 430 m^3 /yr, which is less than half of the global average for water-scarce regions [17]. The Yellow River is the main water supply source, and groundwater resources are also limited and unevenly distributed in Ningxia [18]. Ningxia region is an important agricultural production area in China and which is located in the upper reaches of the Yellow River [13]. The Ningxia region is one of the commercial grain

production bases in China, with developed agricultural production and high agricultural inputs affecting the environment of the Yellow River's water bodies. The regional water quality in the Ningxia region has a significant impact on itself and the downstream areas of the Yellow River. At present, the Yellow River and the groundwater in the Ningxia region are all polluted. In this paper, we carried out a study on the GWF of Ningxia Autonomous District, combining the actual water quality data, and assessed the driving factor of the GWF, aiming to provide guidance for the sustainable development and utilization of water resources in this region. This paper also indicates that the water quality is greatly affected by agricultural irrigation, industrial discharge, and domestic wastewater discharge [19].

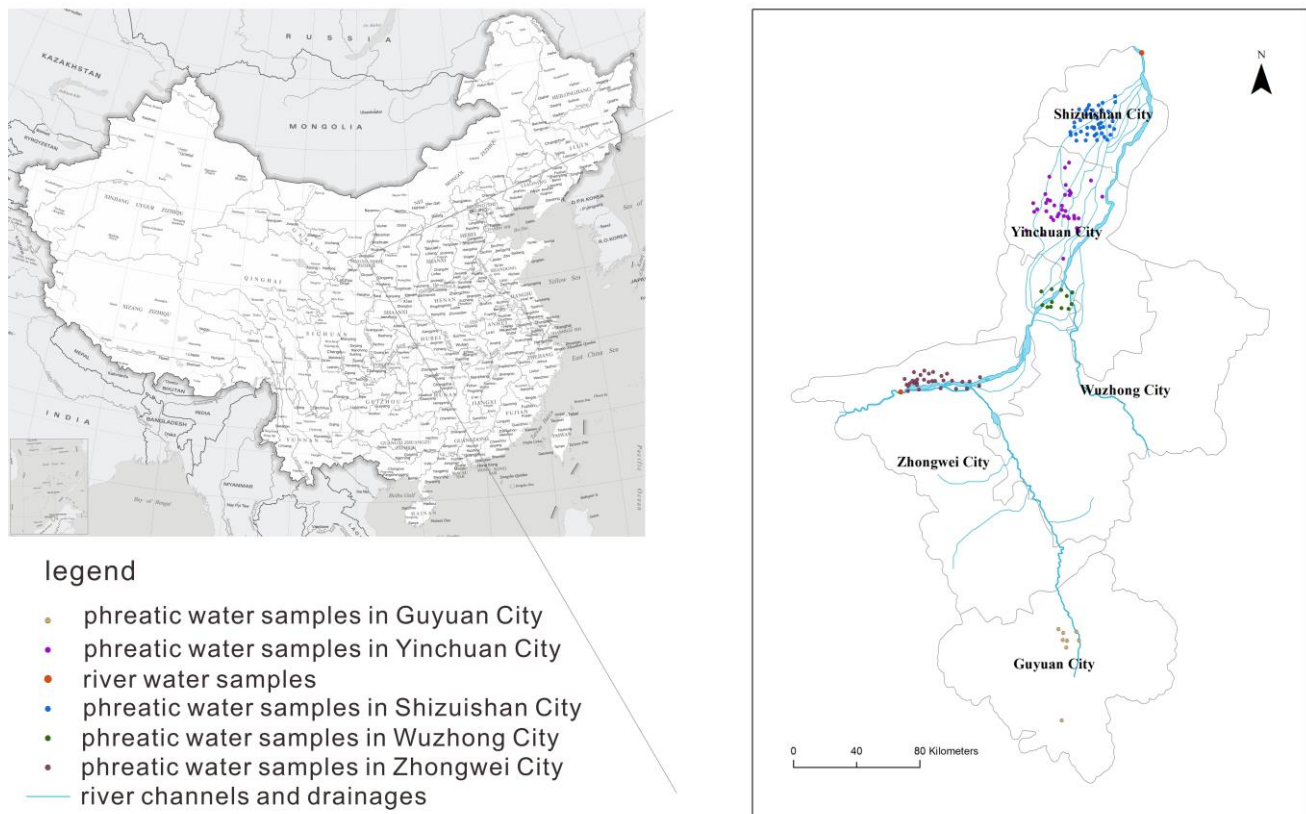


Figure 1. Geographical location map of the study area and distribution of sampling points.

2.2. Assessment of the Gray Water Footprint

2.2.1. Gray Water Footprint

Currently, the calculation and evaluation of the GWF are mainly guided by the *Water Footprint Evaluation Manual* published by the International Water Footprint Network [6]. To be specific, the quantitative calculation of the GWF looks at the amount of water required to dilute pollutants to meet the ambient water quality standards, which is calculated as follows [20]:

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

where WF_{gray} is the GWF (m^3/yr), L is the pollutant discharge load (kg/a), C_{max} is the highest acceptable concentration of pollutant (mg/L), and C_{nat} is the background concentration of the pollutant (mg/L).

According to the recommendations of the *National Standard for Water Quality* [21,22], the maximum allowable concentration of N (C_{max}) was set to 10 mg/L , and the value of COD to 20 mg/L [23]. C_{nat} is the concentration of the water body in its original state before human disturbance. Therefore, a value of 0 mg/L was chosen as the natural background concentration of N and COD [24,25].

(1) Gray water footprint calculation of industrial and domestic sectors

The GWF is determined by the most critical pollutants; the most critical pollutants means the most pollution to the GWF. According to the *Statistical Yearbook of Ningxia*, the COD discharge in the industrial sector and the domestic sector is far greater than the N discharge. Chemical oxygen demand (COD) is the most abundant pollutant in the Industrial and domestic sectors [26], so COD is used as an indicator to evaluate the GWF of the industrial and domestic sectors. The GWFs ($WF_{ind-gray}$ and $WF_{dom-gray}$) of the industrial and domestic sectors are calculated using Equation (1).

(2) Gray water footprint calculation of the agricultural sector

Globally, agricultural nitrogen (N) inputs for crops and livestock account for approximately 85% of total anthropogenic N inputs [27]. Pollutants in the agricultural sector include fertilizers and pesticides applied in agricultural fields. Therefore, N is the main pollutant when calculating the agricultural GWF. So, the formula for calculating the agricultural GWF is as follows:

$$WF_{agr-gray} = \frac{L}{C_{max} - C_{nat}} = \frac{\alpha \times Appl}{C_{max} - C_{nat}} \quad (2)$$

where $WF_{agr-gray}$ is the GWF of the agricultural sector, $Appl$ refers to the pollution load of nitrogen from fertilizer application (kg/yr) [28], and α is the fraction of applied chemicals reaching surface water and groundwater, which in this case is 4%, using previous research results [25].

(3) Regional gray water footprint

The regional GWF mainly contains three sectors: agriculture, industry, and domestic. Therefore, the regional GWF is calculated as follows [12]:

$$WF_{gray} = WF_{ind-gray} + WF_{dom-gray} + WF_{agr-gray} \quad (3)$$

(4) Gray water footprint intensity

The gray water footprint intensity is the ratio of the gray water footprint of the region to the gross domestic product (GDP) of the region (in m^3 /million yuan); it is the gray water footprint per unit of GDP, which is calculated using the formula below [12]:

$$WF_{int-gray} = \frac{WF_{gray}}{GDP} \quad (4)$$

$WF_{int-gray}$ is the gray water footprint intensity and GDP is the gross domestic product using 2012 as the base year.

(5) Remaining gray water footprint

The remaining gray water footprint is the difference between the gray water footprint of the region and the volume of water resources in the region [12], which can be evaluated for regional water sustainability, and is given as follows:

$$AWF_{gray} = WF_{gray} - WR \quad (5)$$

AWF_{gray} is the remaining gray water footprint and WR is the water resource volume.

(6) Water pollution level

Water pollution levels are generally used to indicate the severity of freshwater pollution as follows [25]:

$$WPL = GWF / WR \quad (6)$$

When the WPL value > 1 , the waste assimilation capacity of the area is not sufficient to carry the pollutant load, while a WPL value < 1 means that there is an acceptable assimilation capacity.

2.2.2. Decomposition Analysis

In this study, the Logarithmic Mean Division Index (LMDI) decomposition method is used to analyze the changes in the water footprint in Ningxia Hui Autonomous District and the water footprint is analyzed from four aspects, the industrial structural effect, technology effect, economic development effect, and population scale effect, to explore the main influencing factors of the changes of the water footprint in Ningxia and their mechanisms of action [29,30]. The water footprint index decomposition model is constructed using the LMDI model as follows:

$$WF_t = \sum_{i=1}^4 \frac{WF_{it}}{WF_t} \frac{WF_t}{Y_t} \frac{Y_t}{P_t} P_t \quad (7)$$

$$\Delta WF = WF_t - WF_0 = \sum_{i=1}^4 S_{it} I_t R_t P_t - \sum_{i=1}^4 S_{i0} I_0 R_0 P_0 = \Delta WF_s + \Delta WF_I + \Delta WF_R + \Delta WF_P \quad (8)$$

$$S_{it} = \frac{WF_{it}}{WF_t} \cdot I_{it} = \frac{WF_t}{Y_t} \cdot R_t = \frac{Y_t}{P_t} \quad (9)$$

where WF_{it} represents the category i water footprint in period t ; WF_t represents the water footprint in period t ; Y_t is the GDP in period t ($\text{¥} 10^4$); P_t is the resident population in period t (10^4); S_{it} is the share of water use of category i in the water footprint in period t , indicating the structural effect; I_t is the water footprint per unit of GDP in period t , representing the technological effect; R_t is the GDP per capita in period t , representing the economic effect; P represents the population effect; ΔWF is the change in the water footprint; WF_t and WF_0 represent the water footprint in year t and the base year; and ΔWF_s , ΔWF_I , ΔWF_R , and ΔWF_P are the amounts of water footprint change due to structural, technological, economic, and resident population factors of the water footprint.

The above equation is decomposed using the LMDI, and the results are as follows:

$$\Delta WF_s = \sum_{i=1}^4 \frac{WF_{it} - WF_{i0}}{\ln WF_{it} - \ln WF_{i0}} \ln \frac{S_{it}}{S_{i0}} \quad (10)$$

$$\Delta WF_I = \sum_{i=1}^4 \frac{WF_{it} - WF_{i0}}{\ln WF_{it} - \ln WF_{i0}} \ln \frac{I_t}{I_0} \quad (11)$$

$$\Delta WF_R = \sum_{i=1}^4 \frac{WF_{it} - WF_{i0}}{\ln WF_{it} - \ln WF_{i0}} \ln \frac{R_t}{R_0} \quad (12)$$

$$\Delta WF_P = \sum_{i=1}^4 \frac{WF_{it} - WF_{i0}}{\ln WF_{it} - \ln WF_{i0}} \ln \frac{P_t}{P_0} \quad (13)$$

2.2.3. Data Sources

In this study, the data covered the period from 2011 to 2021, including the data on nitrogen fertilizer application, the data on the industrial and domestic sectors from the *Ningxia Statistical Yearbook* [26], and the data on water resources from the *Ningxia Water Resources Bulletin* [31]. The main data are shown in Table 1.

Table 1. Main annual average statistics of the Ningxia region from 2012 to 2020.

Region	Nitrogen Fertilizer Application (t)	Industrial Wastewater COD Discharge (t)	Domestic Wastewater COD Discharge (t)	GDP ($\text{¥} 10^4$)	Water Resource (10^8 m^3)	Population
Total	519,202.56	46,864.64	29,007.17	30,748,826.50	11.10	6,842,416
Yinchuan City	127,878.89	7896.84	8198.84	14,763,377.33	1.51	2,408,675
Shizuishan City	102,421.89	2878.94	6784.06	4,669,425.40	1.34	765,032
Wuzhong City	135,392.78	12,665.77	5465.49	4,479,482.78	1.24	1,364,507
Guyuan City	49,712.78	9064.69	3598.64	2,383,784.10	5.53	1,197,406
Zhongwei City	103,796.22	14,358.40	4960.14	3,368,340.20	1.49	1,106,796

2.2.4. Sample Collection

A total of 138 groundwater samples were collected from the study area in August 2013, including 47 groundwater samples from Shizuishan, 37 from Yinchuan, 32 from Zhongwei, 12 from Wuzhong, and 8 from Guyuan (Figure 1). The $\text{NO}_3\text{-N}$ and $\text{NH}_3\text{-N}$ concentrations in the groundwater samples were analyzed by the standard methods recommended by the National Standardization Administration [21,22]. In addition, the 2013 data on $\text{NO}_3\text{-N}$ and COD concentrations in the Yellow River from the local hydrological bureau can be used as a supplement (Figure 1).

3. Results

3.1. Analysis of the GWF

3.1.1. Changes in the GWF

Due to the lack of corresponding data after 2020, we analyzed the changes in the GWF of each industry and region in Ningxia Autonomous District from 2012 to 2020, and the statistical results are shown in Table 2 and Figure 2. Over the study period, the GWF of Ningxia decreased from 7.92 billion m^3 in 2012 to 2.91 billion m^3 , which is a decrease of 63.28%. Considering the national economic and social development, Ningxia's GWF has experienced three stages of slow decline, rapid decline, and slow decline again (Figure 2a). More specifically, from 2012 to 2014, Ningxia began to implement the strictest water resource management system, and the GWF showed a slow decline stage. The industrial sector has the most impact on the GWF, which is mainly due to the highly polluting and emitting enterprises. And the government has realized that the regulation of industrial pollution should be strengthened. From 2015 to 2017, the rapid development of urbanization in the Ningxia region caused a large fluctuation in the domestic sector. Due to the implementation of the *Action Plan for Prevention and Control of Water Pollution* [32], a cleaner transformation of key industries and the centralized management of pollution in industrial agglomerations have been strengthened, and industrial wastewater emissions have been reduced. The quality of the water ecosystem and the environment has been greatly improved, and the GWF has decreased significantly. From 2018 to 2020, with the increase in municipal wastewater treatment rates and the green transformation of industries, the GWF showed low fluctuation and a downward trend. Especially since 2019, centralized wastewater treatment and key discharging enterprises were strengthened in the Ningxia region. The GWF decreased significantly in 2020. In specific, the industrial sector has the largest variation in gray water footprint, and the overall decline trend is consistent with the variation of the GWF. The gray water footprint of the agricultural sector has the smallest variation and is basically in a stable state. The domestic sector has the smallest proportion of the GWF.

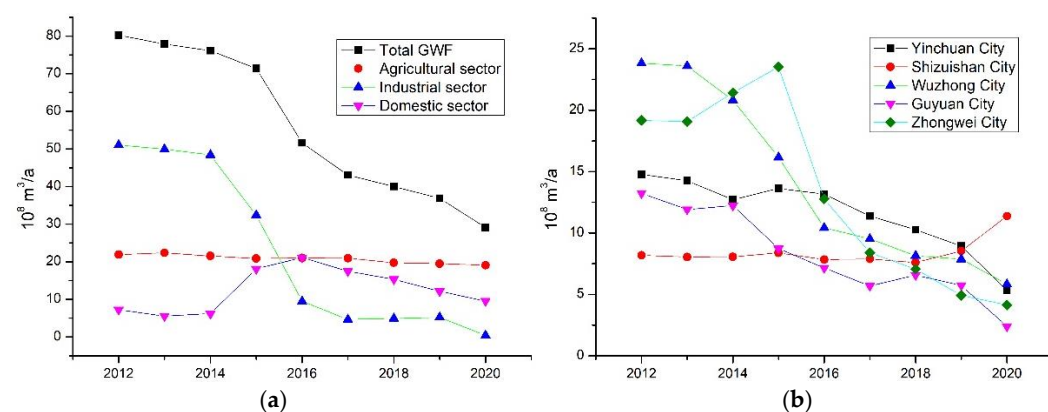


Figure 2. The total gray water footprint of Ningxia by sector and city. (a) GWF of sectors in Ningxia region; (b) GWF of cities in Ningxia region.

Table 2. The total gray water footprint of Ningxia by sector and city from 2012 to 2020; units: 10^8 m^3 .

Sector	Year	Total	Yinchuan City	Shizuishan City	Wuzhong City	Guyuan City	Zhongwei City
Agricultural sector	2012	21.89	6.20	3.97	5.60	1.78	4.34
	2013	22.36	6.39	4.08	5.66	1.88	4.34
	2014	21.52	5.63	4.08	5.51	1.98	4.32
	2015	20.88	5.12	4.15	5.36	2.00	4.25
	2016	20.99	5.13	4.13	5.48	2.06	4.20
	2017	20.93	5.17	4.19	5.53	1.99	4.05
	2018	19.73	4.36	4.10	5.25	2.13	3.89
	2019	19.51	4.11	4.12	5.21	2.07	4.00
	2020	19.09	3.93	4.05	5.14	2.01	3.97
Industrial sector	2012	51.06	7.74	2.61	16.56	9.93	13.23
	2013	49.97	7.74	2.43	16.58	8.78	13.43
	2014	48.40	6.45	2.42	14.12	8.80	15.75
	2015	32.39	4.48	1.82	6.05	3.77	15.32
	2016	9.50	1.98	0.61	0.50	2.23	3.91
	2017	4.68	1.00	0.73	0.48	1.84	0.42
	2018	4.92	0.83	0.45	0.54	2.60	0.12
	2019	5.24	0.73	0.40	0.57	2.56	0.08
	2020	0.46	0.02	0.17	0.08	0.11	0.08
Domestic sector	2012	7.25	0.84	1.61	1.66	1.53	1.61
	2013	5.57	0.12	1.54	1.35	1.26	1.30
	2014	6.20	0.64	1.57	1.18	1.45	1.35
	2015	18.12	4.03	2.42	4.75	2.97	3.95
	2016	21.12	6.06	3.09	4.44	2.87	4.67
	2017	17.49	5.22	2.96	3.52	1.87	3.92
	2018	15.37	5.07	3.05	2.36	1.85	3.05
	2019	12.15	4.09	4.01	2.08	1.10	0.86
	2020	9.54	1.40	7.15	0.62	0.27	0.10
Total	2012	80.20	14.78	8.19	23.83	13.24	19.18
	2013	77.90	14.26	8.05	23.60	11.92	19.08
	2014	76.11	12.72	8.07	20.81	12.23	21.42
	2015	71.38	13.63	8.39	16.16	8.73	23.52
	2016	51.62	13.17	7.83	10.42	7.15	12.77
	2017	43.09	11.38	7.88	9.52	5.69	8.39
	2018	40.03	10.25	7.60	8.15	6.58	7.06
	2019	36.90	8.94	8.53	7.86	5.73	4.93
	2020	29.09	5.34	11.37	5.84	2.39	4.14

Among the Ningxia cities, the GWF shows a significant decrease in Wuzhong City, where it dropped from 2.38 billion m^3 (2012) to 584.00 million m^3 (2020). The largest fluctuation takes place in Zhongwei City, where the GWF rose from 1.92 billion m^3 (2012) to 2.35 billion m^3 (2015) and then fell to 414.00 million m^3 (2020). Shizuishan City marks the smallest variation as the GWF was on a flat trend, with a slight upward trend in 2019–2020.

It can be seen that the contribution rate of the GWF of Ningxia cities during 2012–2020 can be ranked in the following order: Wuzhong City (24.92%) > Zhongwei City (23.80%) > Yinchuan City (20.63%) > Shizuishan City (14.99%) > Guyuan City (14.55%) (Figure 3). This is presumably due to the fact that industrial sectors in both Wuzhong and Zhongwei are dominated by mining and manufacturing industries, which pollute water resources more. The contribution rate of the industrial GWF shows a decreasing trend, especially after 2016. In Wuzhong City, for example, it decreased from 69.52% in 2012 to 4.79% in 2016 and to 1.40% in 2020. The contribution rate of agricultural GWF shows an increasing trend in all cities except Shizuishan. The overall GWF contribution rate of the domestic sector shows a fluctuating growth trend.

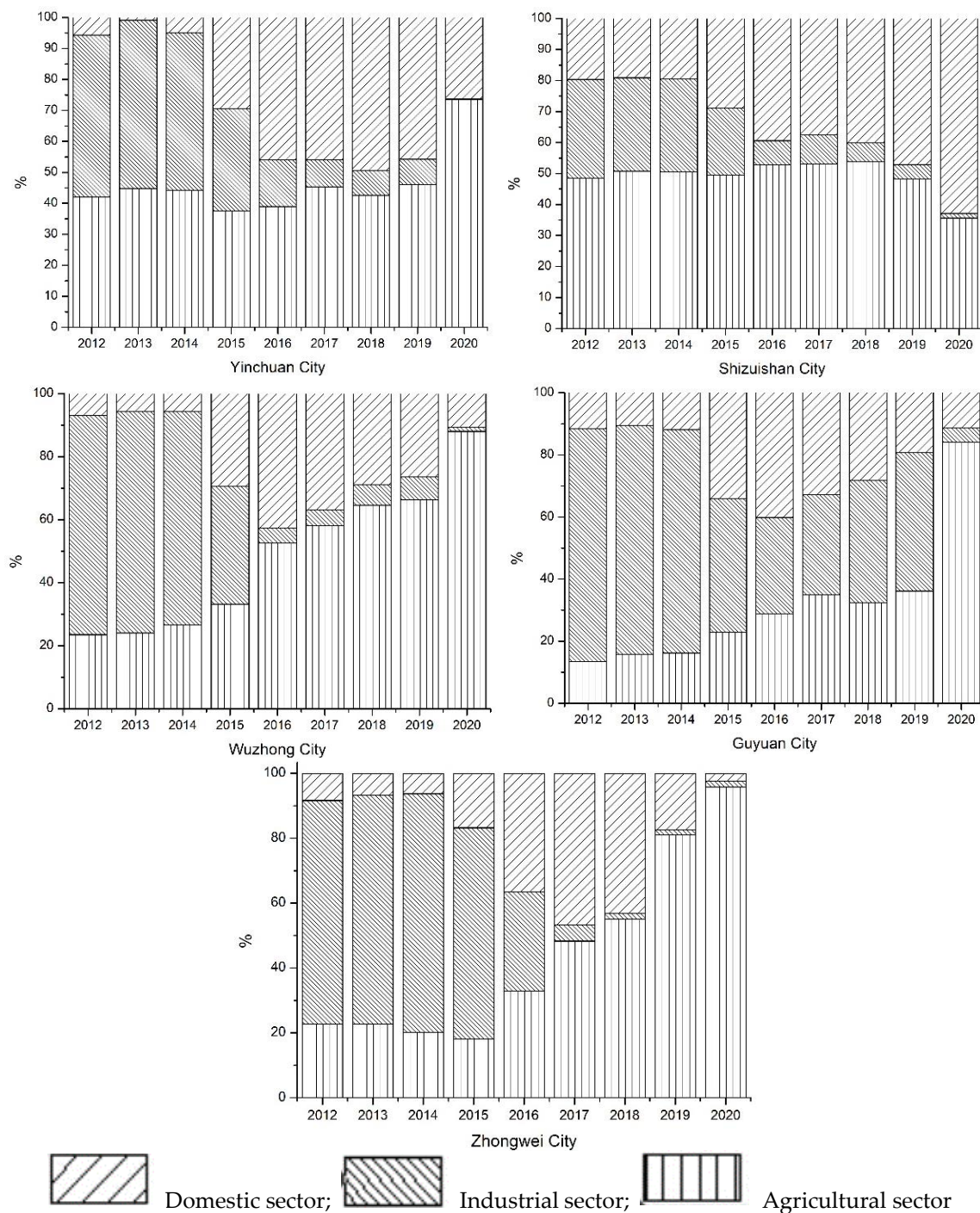


Figure 3. The contribution of the gray water footprint by sector in Ningxia cities.

3.1.2. Remaining Gray Water Footprint

The remaining gray water footprint can reflect the level of pollutant accumulation in water bodies and the sustainability of water ecology in each region. The overall trend of the remaining gray water footprint in Ningxia is decreasing (Figure 4), which indicates that the water environment in Ningxia has significantly improved, and ecological environmental protection has been effective in recent years. However, the sustainability of the water environment still faces serious challenges because Ningxia is located in a semi-arid and arid region with relatively few local water resources.

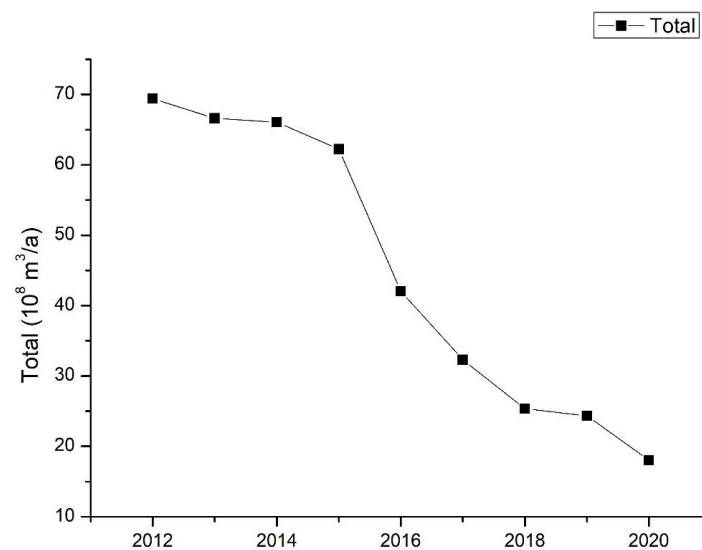


Figure 4. The remaining gray water footprint in Ningxia.

The GWF of Ningxia spatially shows the characteristics of high in the north and low in the south, and the remaining gray water footprint of Ningxia is basically positive, indicating that the regional water pollution level has exceeded the local water resource carrying capacity range, and the water resources situation is not optimistic. It can be seen through the distribution of the remaining gray water footprint of each city in Ningxia (Figure 5) that, overall, the remaining gray water footprint of Ningxia shows a significant decreasing trend, and the overall development is in a good direction. However, except for Guyuan City, other cities still show positive values, and the overall water resource status is still not optimistic. This is the result of limited total water resources in the region and the low water resource carrying capacity. The contradiction between local economic development and water protection is still prominent.

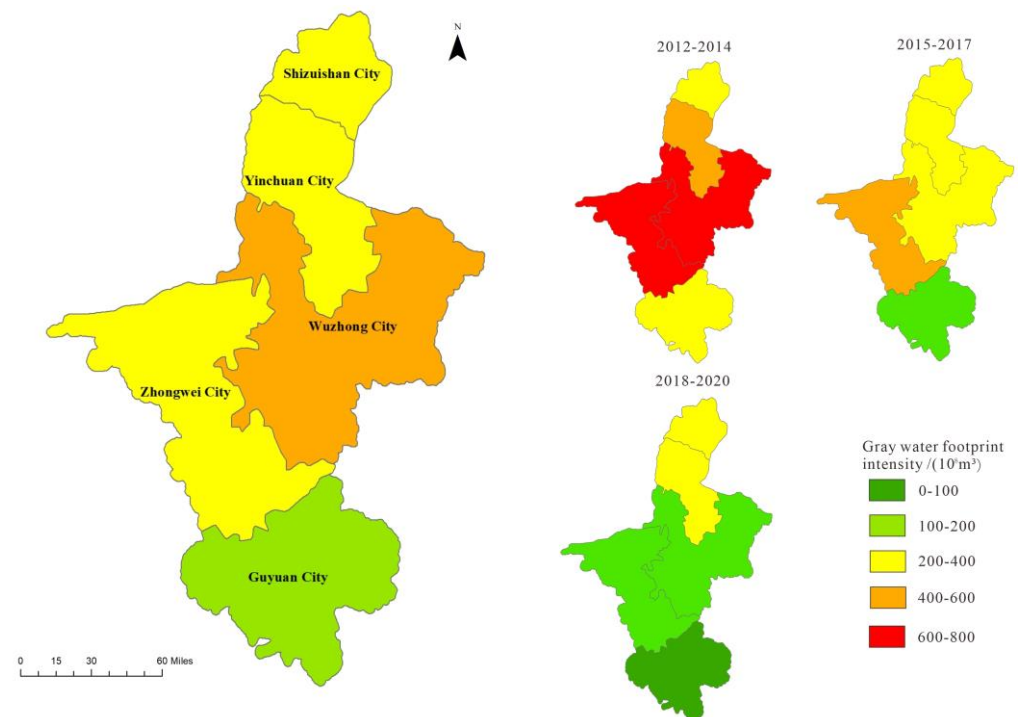


Figure 5. Spatial and temporal variations of the remaining gray water footprint in Ningxia.

3.1.3. Gray Water Footprint Intensity

Gray water footprint intensity is the GWF per unit of GDP, and the lower the intensity, the higher the GDP generated per unit of gray water footprint and the higher the efficiency of the gray water footprint. From 2012 to 2020, the gray water footprint intensity of Ningxia decreased year by year; it went down by 78.34% (Figure 6). Especially after 2015, the GWF was significantly decreased in Zhongwei, Wuzhong, and Guyuan, by 82.38%, 63.88%, and 72.65%, respectively. The efficiency of the GWF increased significantly, which is presumed to be related to the industrial structural adjustment and rapid upgrading of industrial wastewater treatment technology during this period.

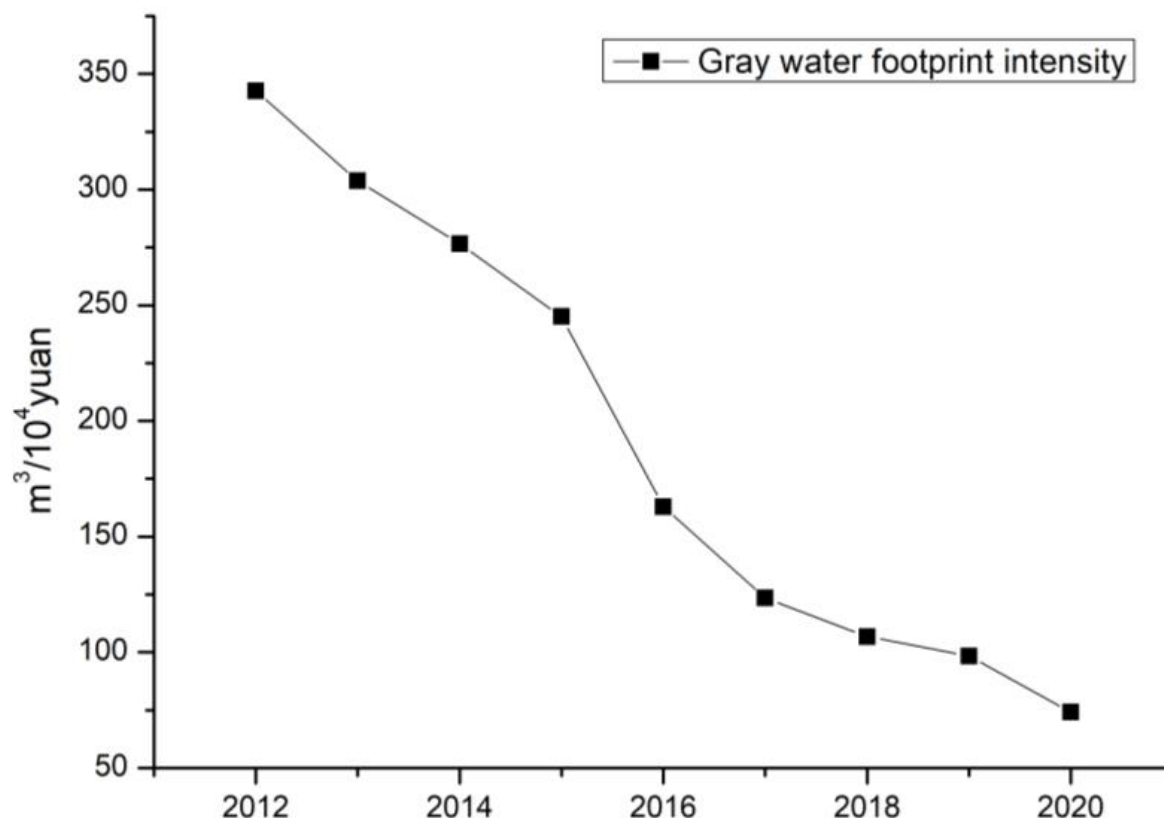


Figure 6. Gray water footprint intensity in Ningxia.

The gray water footprint intensity of the Ningxia region shows a spatial trend of low in the north and high in the south, Shizuishan and Yinchuan being low and the rest of the cities being high, which also reflects the uneven level of regional economic development and regional ecological quality. In recent years, the overall gray water footprint intensity of the whole region has been declining, especially in the southern area. Except for Shizuishan, where the intensity of the gray water footprint decreased by 23.51%, other cities decreased by more than 85%, which is related to the total volume and composition of the regional GWF and the degree of economic development. In the south-central region, the GWF decreased and the GDP increased year by year, resulting in a significant decrease in the gray water footprint intensity in Zhongwei, Wuzhong, and Guyuan. The decrease of the gray water footprint intensity in Shizuishan City and its range is still significantly higher than the average level in Ningxia. This indicates that Shizuishan City still has a large room for the reduction of its GWF (Figure 7).

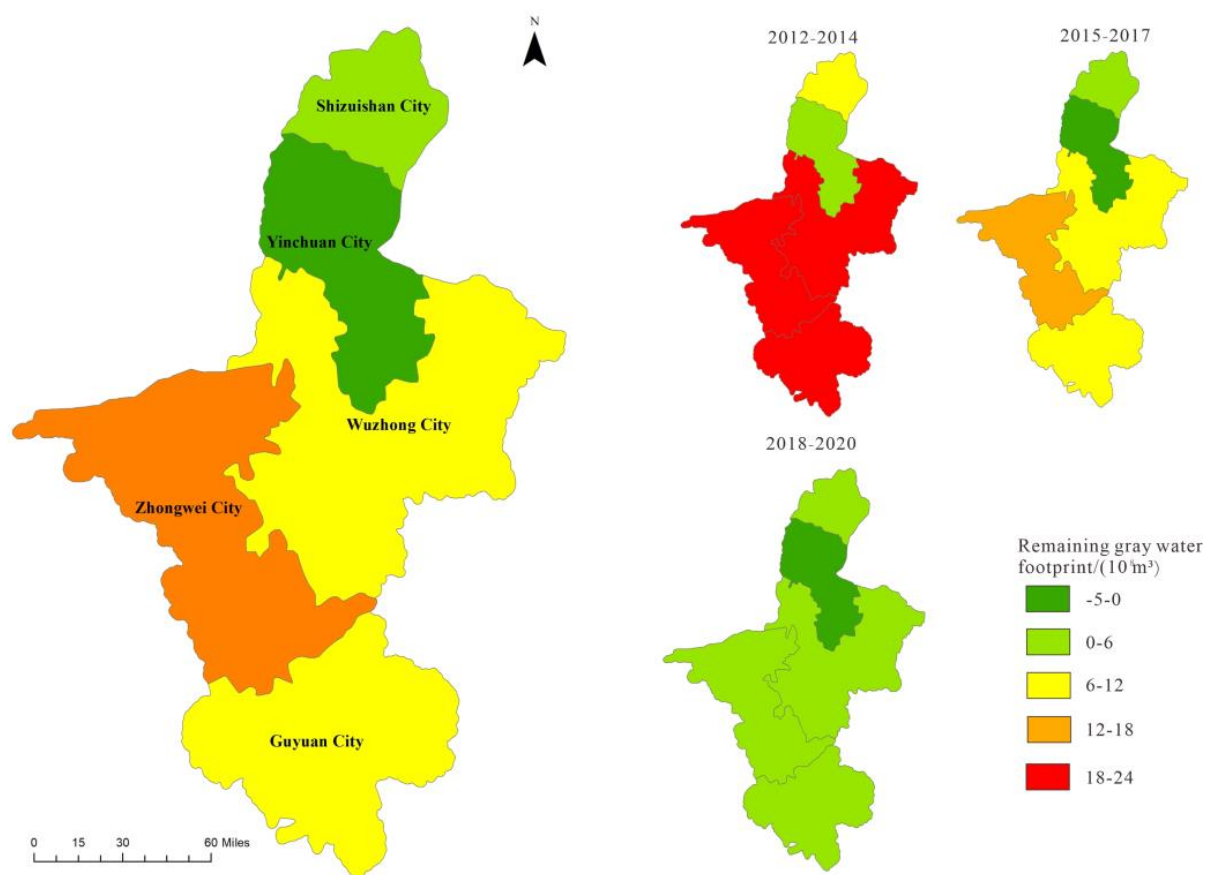


Figure 7. Spatial and temporal variations of the gray water footprint intensity in Ningxia.

3.2. Concentrations of Contaminants in River and Groundwater

The concentrations of $\text{NH}_3\text{-N}$, $\text{NO}_3\text{-N}$, and COD in river and groundwater samples are showed in Figure 8. A lower section of the upper reaches of the Yellow River enters from Nanchangtan, Zhongwei City, Ningxia Hui Autonomous Region, and exits to Mahuanggou, Shizuishan City, with a total length of 397 km. Along the riverbanks, 66% of the region's population, 43% of the arable land, 80% of the industries, and 90% of the regional GDP are gathered, making this the core of economic production in Ningxia. The Yellow River, as a cross-border river, carries a large amount of irrigation return water, industrial and domestic wastewater which plays an important role in absorbing pollutant discharge from the arid environment. As shown in Figure 8, in the upstream of the Ningxia section, $\text{NH}_3\text{-N}$ and COD showed exceedance in some time periods, especially in August, with a worse state; while in the downstream, the water quality became better overall, with lower $\text{NH}_3\text{-N}$ concentration compared to the national standard [21]. The $\text{NH}_3\text{-N}$ content reflected the agricultural gray water footprint, which could be analyzed indirectly to the changes of $\text{NH}_3\text{-N}$ pollution in the Ningxia region. The change of the agricultural gray water footprint decreased in Yinchuan City > Wuzhong City > Zhongwei City > Shizuishan City > Guyuan City in the Ningxia region in 2013. The Yellow River enters the Ningxia region from Zhongwei City, flows through Wuzhong City and Yinchuan City, and flows out of the Ningxia region from Shizuishan City. It can be seen that a high level of $\text{NH}_3\text{-N}$ created an agricultural gray footprint in the Yellow River in Zhongwei, and the downstream of the Yellow River absorbed little agricultural surface pollution and led to a low agricultural gray water footprint in Shizuishan. The COD concentration in this part was also lower than the national standard in all other months except for July when it exceeded the standard for Class III water [21]. The COD content reflected the industrial and domestic gray water footprint, which could be analyzed indirectly to the changes in COD pollution in the

Ningxia region. The industrial and domestic gray water footprints showed a decreased trend from Wuzhong City > Zhongwei City > Guyuan City > Yinchuan City > Shizuishan City in 2013. It can be seen that higher COD concentration in the Yellow River resulted in higher industrial and domestic wastewater discharges, while the high COD concentration upstream of the Yellow River led to high wastewater discharge in Zhongwei City. And the COD concentration downstream of the Yellow River was low, which led to a low wastewater discharge in Shizuishan City. During the wet season (June–September), $\text{NH}_3\text{-N}$ showed a significant decreasing trend, while the content increased significantly in the dry season. It can be seen from the GWF of Zhongwei City and Shizuishan City in 2013 that the overall GWF of Zhongwei City was higher than that of Shizuishan City, which was consistent with the river water quality.

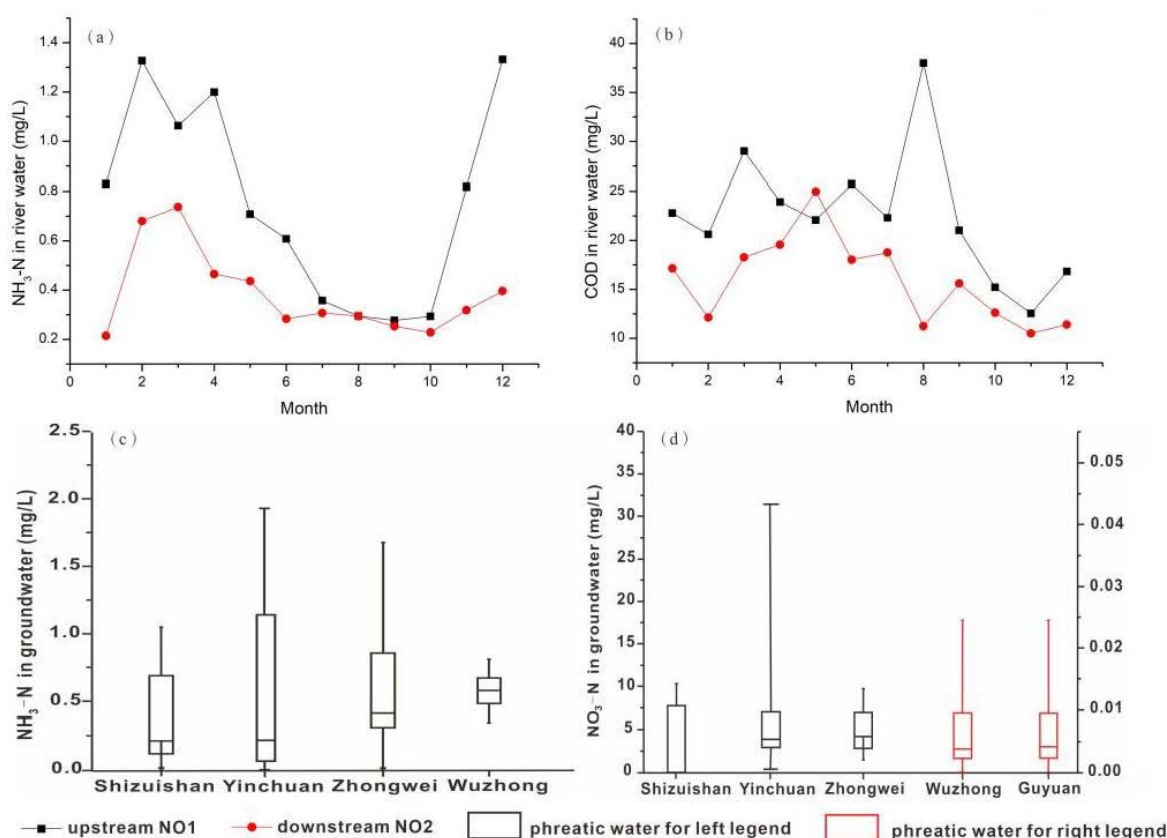


Figure 8. Contaminant content in surface water and groundwater; (a) $\text{NH}_3\text{-N}$ content in rivers; (b) COD content in rivers; (c) $\text{NH}_3\text{-N}$ content in shallow groundwater; and (d) $\text{NO}_3\text{-N}$ content in shallow groundwater.

Unlike river samples, the value of $\text{NO}_3\text{-N}$ and $\text{NH}_3\text{-N}$ in groundwater samples varied greatly in the aquifer (Figure 8c,d). $\text{NO}_3\text{-N}$ concentrations ranged from 0 to 36.2 mg/L in the groundwater. Overall, $\text{NO}_3\text{-N}$ content in the groundwater in Ningxia was relatively low, with the best water quality in Wuzhong and Guyuan cities. The $\text{NH}_3\text{-N}$ concentration in the groundwater ranged from 0 to 2.33 mg/L. The $\text{NH}_3\text{-N}$ in Guyuan was not analyzed because there was no data for Guyuan. The $\text{NH}_3\text{-N}$ content in the groundwater was relatively high in the remaining four cities, among which Yinchuan showed the highest content, which almost exceeded the groundwater quality standard of category III [22]. The $\text{NH}_3\text{-N}$ content reflected the agricultural gray water footprint. The $\text{NH}_3\text{-N}$ concentration gradually decreased from Yinchuan, Zhongwei, Shizhuishan, and Wuzhong, which is shown in Figure 8c; they have the basically same trend with slight differences. The phenomenon may be related to the hysteresis of groundwater flow.

4. Discussion

4.1. Driving Forces of GWF Change

In order to better analyze the changes in socio-economic indicators such as economy, environment, and employment, it is important to assess their potential drivers or determinants. The Logarithmic Mean Divisia Index (LMDI) method proposed by Ang (2005) is adopted for the correlation analysis in this study [29]. According to the LMDI analysis, the contribution of each sector to the change in the total GWF can be clarified. It can be seen that the population scale effect and economic development effect have a promoting effect on the change of the total GWF (in Figure 9), among which the economic development effect has the greatest promoting effect on the GWF, while the technological and industrial structure effect have a suppressing effect, and the technological effect has the greatest abatement, indicating that cleaner production technology and the upgrading of wastewater treatment technology can also be the main direction of environmental management in Ningxia.

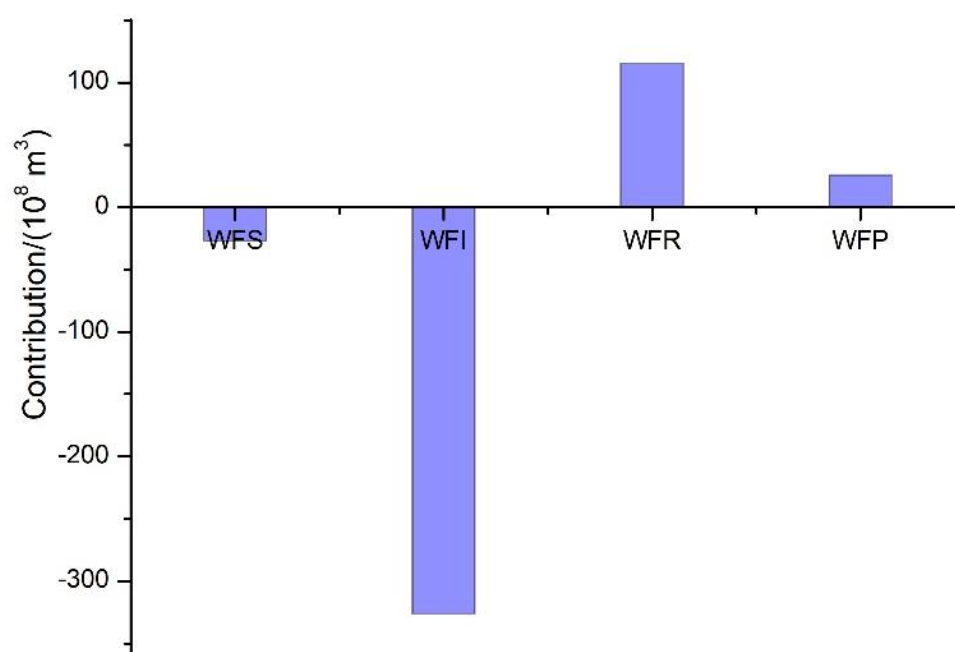


Figure 9. The cumulative contribution of gray water footprint drivers in Ningxia.

Overall, the economic development effect is the main positive driver of the GWF, which is also consistent with the findings of other scholars on the decomposition of GWF drivers [30,33], indicating that economic growth is the main driver of a series of environmental pollution such as carbon emissions, air pollution, and water pollution. The process of economic development urgently needs to take the cost of environmental pollution into account. The contribution of economic factors to the GWF in this study shows a trend of increasing first and decreasing later (Figure 10), indicating that Ningxia's previous extensive development approach at the expense of the environment is gradually transforming into a high-quality development approach oriented to green development and that the efficiency of the GWF of economic development is continuously improving. The positive contribution of the population scale effect is small but shows a trend of increasing year by year, and as the resident population increases or the people's living standards gradually rise, the impact on the change of the GWF will gradually increase. The technological effect, as the factor with the largest cumulative negative contribution, has great potential for emission reduction and can reduce the number of pollutants generated and discharged by means of technical upgrading, improve the sewage treatment system, and further improve the efficiency of the GWF. The technological structural effect of the water footprint plays a limited negative driving role and shows a gradually decreasing trend, indicating that Ningxia has strengthened the adjustment of industrial structure in recent years.

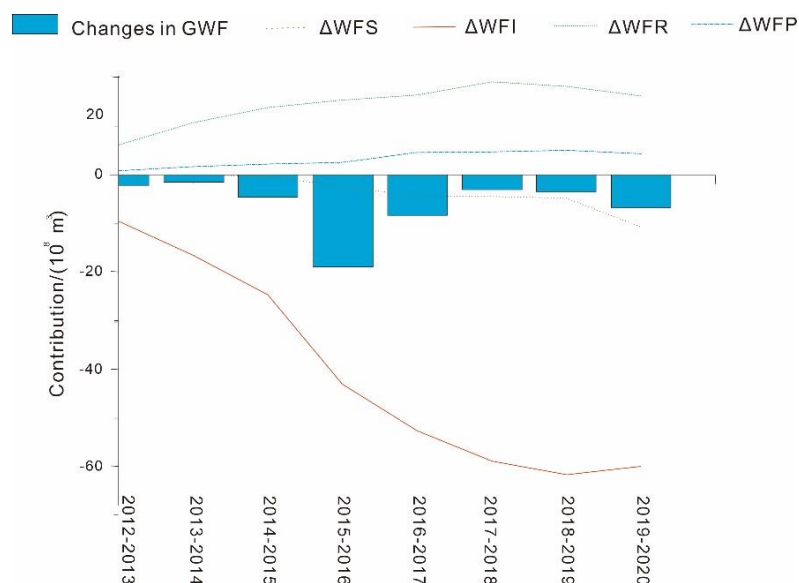


Figure 10. Analysis of drivers of change in the gray water footprint in Ningxia.

The decomposition analysis of the GWF drivers for each city in Ningxia is shown in Figure 11. The economic development effect is the major positive driver of GWF change in each city with one exception: the economic factor of Yinchuan presents negative inhibiting effects, so greenness should guide the direction of high-quality economic growth in this city. The population scale effect is the major negative driver of GWF change in each city, with Yinchuan being an exception again. The population factor in Yinchuan serves as a positive driver, indicating that Yinchuan should pay attention to the positive driving force of the population factor and strengthen the urban domestic sewage management effort. The technological effect is the most important negative driver, and the industrial structural factor is the secondary negative driver in each city, among which the negative contribution of the technological effect is higher in Wuzhong and Zhongwei, but the two factors in Shizuishan both serve as positive drivers. Wuzhong has the largest negative change in the GWF, indicating that the city has achieved significant strategic adjustment during this period, taking into account the reduction of industrial pollutants and ecological agriculture along with economic development. Shizuishan City is the only region with positive changes in the GWF during the study period, and water environmental sustainability is still decreasing.

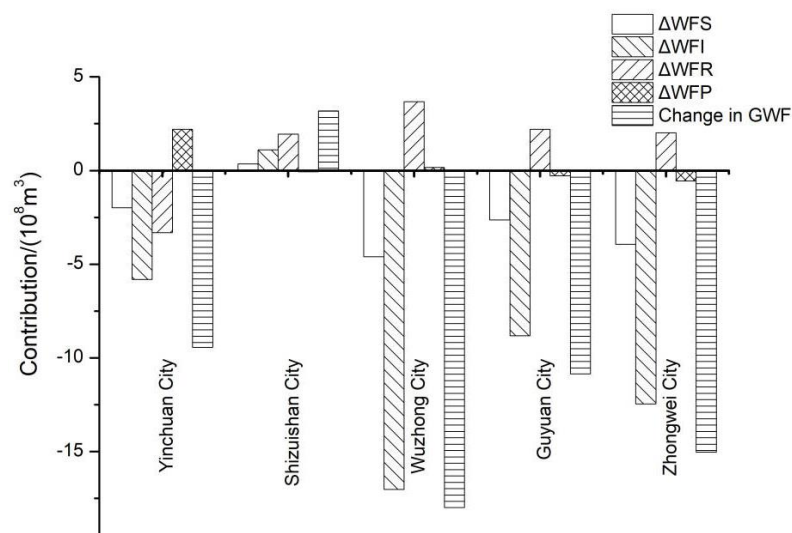


Figure 11. Decomposition of gray water footprint drivers by cities in Ningxia, 2012–2020.

4.2. Effect of the Pollutant Load on Water

The National Bureau of Statistics of China (2019) defines water resources as “the run-off of surface water from rainfall and the recharge of groundwater within a given area, including transit water” [34], and, according to Equation 6, the water pollution level in Ningxia is obtained as being between 2.27 and 7.69. This indicates that the waste assimilation capacity is not sufficient to carry the pollutant load of the region. In fact, the Yellow River as a transboundary river crossing Ningxia has a significant complementary effect on local water resources and receives a large amount of irrigation return water, industrial and domestic wastewater on its way through. Therefore, the water pollution level of 0.49–1.30 can better reflect the actual situation if the water resources of the Yellow River ($59.45 \times 10^8 \text{ m}^3/\text{a}$ on average per year) are taken into account, as shown in Table 3.

Table 3. Results of water pollution levels in Ningxia taking the Yellow River into account; units: GWF: 10^8 m^3 , water resource: 10^8 m^3 .

Year	Total GWF	Total Water Resource	Water Resource (Yellow River)	Original WPL	Modified WPL
2012	79.21	10.81	60.89	7.33	1.30
2013	76.89	11.27	63.30	6.83	1.21
2014	75.25	10.07	61.61	7.48	1.22
2015	70.44	9.16	62.03	7.69	1.14
2016	51.34	9.59	56.09	5.36	0.92
2017	35.13	10.77	56.67	3.26	0.62
2018	33.26	14.67	55.87	2.27	0.60
2019	29.06	12.58	59.74	2.31	0.49
2020	29.09	11.04	58.84	2.64	0.49

The results of the evaluation of the GWF and water pollution levels show that the water pollution level in the Ningxia region is gradually decreasing, but there is still a risk of pollution. According to the analytical results of Mekonnen and Hoekstra (2015), the total nitrogen load in the agricultural sector of the Yellow River accounts for 95%, and the domestic sector accounts for 5%, resulting in a water pollution level of 8.3, which is basically consistent with the results obtained in a paper in 2015, which verifies the validity and accuracy of the analysis and calculation in this study [7].

Results of the actual water quality data in the Ningxia region showed that surface water $\text{NH}_3\text{-H}$ and COD exceeded the standard in some regions. $\text{NO}_3\text{-N}$ and $\text{NH}_3\text{-N}$ were detectable in the groundwater throughout Ningxia, especially with a relatively high content of $\text{NH}_3\text{-N}$. Due to irrigation infiltration and river and canal infiltration to recharge the groundwater, $\text{NO}_3\text{-N}$ and $\text{NH}_3\text{-N}$ in shallow groundwater are likely to lead to pollution through the exchange between surface water and groundwater. The nitrogen fertilizer applied during agricultural irrigation is also likely to cause $\text{NH}_3\text{-N}$ pollution in groundwater, especially in the Yinchuan area, where $\text{NH}_3\text{-N}$ in the groundwater has exceeded Class III water standards [22]. And, the nitrate in groundwater may be attributed to the nitrification. Element N is detected in the whole area in groundwater samples, with even a trend of exceeding the standard, which may lead to the continuous downward migration of groundwater pollution with groundwater transport.

The water pollution level in the Ningxia region was 6.83 in 2013, which is a high-risk area. Results of actual water quality data also supported that conclusion. Combined with the analysis results of the two methods, it can be seen that the water quality in the Ningxia region is poor. According to the GWF in 2013, in the Ningxia region, the industrial sector was its main contributor. Thus, the regulation of effluent discharges in the industrial sector should be strengthened, and the development of green industries is necessary. By city, Wuzhong was the main contributor to the GWF of Ningxia. Effluent discharges of Wuzhong should be strictly limited and a centralized sewage treatment is necessary. From the aspect of surface water quality, the monitoring of surface water in Shizuishan and the management of surface water outfalls should be strengthened. From the aspect of

surface water quality, groundwater management and monitoring should be strengthened in Yinchuan, and the management of outfalls and supervision of agricultural surface sources should be strengthened.

4.3. Implications in Water Management

It has been shown that combining the GWF with the hydrological cycle and actual water quality data can provide a more comprehensive picture of the current status of regional water pollution and the carrying capacity of its water resources. Although the total GWF showed a decreasing trend during 2012–2020 in Ningxia region, the pressure from the agricultural and domestic sectors had created a bottleneck effect in water resource management. Ningxia is in an arid and semi-arid environment with limited water resources and a strong evaporation climate, and the transiting Yellow River has a large impact on the water cycle in the region. All these factors are affecting the availability of water resources in Ningxia [35–38]. And with economic development, people's living standards will continue to improve, and so will the role of human activities in the GWF. Therefore, there is a need to increase the collection and treatment capacity of wastewater. In addition, during the current large-scale urban land expansion, the importance of the previous urban fringe areas in the evaluation of the GWF is increasing. Meanwhile, more detailed and thorough pollutant discharge data and deep groundwater quality data are also important parameters to improve the accuracy of GWF evaluation.

The results of the driving force analysis suggest that the main factors affecting the GWF of the Ningxia region are economic development and technology effects, with the economic effect being the major positive driving factor and the technological effect being the major negative inhibiting one. Therefore, we should continue to improve the technology effect in the future and advance the technical conditions of energy-saving and emission-reducing production technologies and pollutant treatment technologies in all aspects, including agriculture, industry, and living, to improve the regional GWF. In the planning of economic development and industrial adjustment, the green economy, water-saving industry, and high-tech industry should also be gradually strengthened to achieve coordinated development of the economy and environment.

5. Conclusions

By calculating the GWF of Ningxia, it can be seen that the GWF of Ningxia changed in the range of $29.09\text{--}80.20 \times 10^8 \text{ m}^3/\text{a}$ and showed a significant decreasing trend (2012–2020). The agricultural gray water footprint was in a steady state and accounted for 36.92% of the GWF. The industrial gray water footprint showed a clear downward trend. The domestic gray water footprint changed the most. It also had a gradually increasing impact on the GWF, which accounted for up to 40.58% of the GWF. By decomposing the driving forces of the GWF, the result shows that the economic development effect is the largest positive driver and the technology effect is the largest negative driver. Therefore, economic growth was putting more pressure on the sustainable use of water resources. Thus, reducing the intensity of the GWF while scaling up the effects of technology effect is currently the biggest challenge in the region's development.

Combing the GWF with actual water quality data, the quality of river and groundwater is basically consistent with the local GWF, which could more comprehensively reflect the current status of local water pollution. The water pollution level in the region is located between 0.49 and 1.30, which is almost at the limit stage. At the same time, agricultural surface pollution should be given more attention. This study combined the actual water quality data into the GWF evaluation, which made the GWF evaluation more feasible. Moreover, this method can be applied to other regions to guarantee the sustainable use of water resources. However, this method is still uncertain and only provides a qualitative–quantitative description of the regional water pollution level. For further detailed research, a hydrological model covering the amount of water pollution can be constructed.

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