Postprint: Driving Factors of Water Resources Utilization and Decoupling Effect in the Yellow River Basin

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Date: 2025-02-27T00:00:00+00:00

Abstract

Achieving sustainable utilization of water resources is an important component of ecological protection and high-quality development in the Yellow River Basin. This study employs the water footprint method to measure the actual water resource consumption of 56 prefecture-level cities in the Yellow River Basin from 2000 to 2020, utilizes the logarithmic mean Divisia index method to reveal the main influencing factors of water use changes, and constructs a decoupling effort index model based on the DPSIR framework to measure the decoupling effect of water resource utilization. The results indicate that: (1) From 2000 to 2020, water resource utilization in the Yellow River Basin exhibited a fluctuating upward trend, with agricultural production water use constituting the main component, accounting for over 90% of the total. (2) Economic development effect and population scale effect exert positive driving forces on water resource consumption, whereas water use intensity effect and industrial structure effect exert negative driving forces. (3) The decoupling effect between water resource utilization and economic development is generally favorable, primarily manifesting in two states: weak decoupling and strong decoupling. Specifically, the decoupling status in the middle and lower reaches is superior to that in the upper reaches; the decoupling status of industrial water use and service sector water use is superior to that of agricultural water use. (4) In the process of transformation of water resource utilization decoupling effects, industrial structure effect and water resource endowment effect are crucial factors for achieving regional decoupling, while water use intensity effect and water resource endowment effect are key to achieving sectoral decoupling. The research findings can provide theoretical reference for the green and coordinated development of water resources and economy in the Yellow River Basin.

ARID LAND GEOGRAPHY, Vol. 48, No. 1, January 2025

Study on Driving Factors and Decoupling Effects of Water Resources Utilization in the Yellow River Basin

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Abstract: Achieving sustainable water resources utilization is a critical component of ecological protection and high-quality development in the Yellow River Basin. This study employs the water footprint methodology to quantify actual water consumption across 56 prefecture-level cities in the Yellow River Basin from 2000 to 2020. It reveals the primary influencing factors of water use changes through the logarithmic mean Divisia index (LMDI) method and constructs a decoupling effort index model based on the driver-pressure-state-influence-response (DPSIR) framework to measure the decoupling effect of water resource utilization. The results indicate that: (1) Water resource utilization in the Yellow River Basin exhibited a fluctuating upward trend from 2000 to 2020, with agricultural production water accounting for over 90% of total consumption. (2) The economic development effect and population scale effect serve as positive driving factors, while the water use intensity effect and industrial structure effect act as negative driving factors. (3) The decoupling effect between water resource utilization and economic development is generally favorable, primarily characterized by weak decoupling and strong decoupling states. Regionally, the midstream and downstream regions demonstrate better decoupling performance than the upstream region. By sector, industrial production water and service industry water show superior decoupling compared to agricultural production water. (4) In the transition process of water resource utilization decoupling effects, the industrial structure effect and water resource endowment effect are crucial for achieving regional decoupling, while the water use intensity effect and water resource endowment effect are key to achieving sectoral decoupling. These findings provide a theoretical reference for the coordinated green development of water resources and the economy in the Yellow River Basin.

Keywords: water footprint; DPSIR framework; logarithmic mean Divisia index; decoupling model; Yellow River Basin

The Yellow River Basin, as China' s "Mother River," constitutes a vital ecological barrier and economic zone of national significance for ecological security and socioeconomic development. The ecological protection and high-quality development of the Yellow River Basin represent a major national strategy, alongside the coordinated development of the Beijing-Tianjin-Hebei region, the Yangtze River Economic Belt, the Guangdong-Hong Kong-Macao Greater Bay Area, and the Yangtze River Delta integration. While remarkable achievements have been made in socioeconomic development and ecological governance in recent years, water resource scarcity remains pronounced due to natural geographic conditions and anthropogenic factors. This shortage will intensify further with ongoing urbanization and population expansion. Against this backdrop, scientifically quantifying water resource utilization, investigating its driving factors, and analyzing decoupling effects are essential for transforming water resource development patterns and promoting ecological protection and high-quality development in the Yellow River Basin.

Water resource research has become an academic hotspot as supply-demand contradictions intensify. Studies on driving factors primarily employ the logarithmic mean Divisia index (LMDI) decomposition method, examining aspects such as economic development level, industrial structure, water use intensity, and population scale. For instance, Liu et al. [?] identify per capita GDP growth as the main cause of total water consumption increase, while water use intensity and industrial structure changes can suppress consumption growth. Qin et al. [?] find that economic development is the decisive factor driving water consumption increase, while industrial structure adjustment can reduce water demand pressure. Sun and Xie [?] conclude that economic development is the primary driver of water consumption, while industrial structure optimization and declining water use intensity inhibit consumption growth. Decoupling analyses focus on agricultural water use [?], industrial water use [?], domestic water use [?], and total water consumption [?], with increasing studies based on water footprint theory [?]. Methodologically, the Tapio decoupling elasticity index method is considered optimal for describing coordinated development between economic growth and water consumption [?].

Existing research covers national [?], provincial [?], urban agglomeration [?], and basin scales [?]. Yellow River Basin studies address acute water supply-demand contradictions [?] and characteristic features of limited water with high sediment load and uncoordinated sediment-water relationships [?], investigating optimal water allocation [?], water ecosystem services [?], and water resource utilization-economic development relationships [?] to inform management decisions.

However, several gaps remain: (1) While many studies apply the Tapio decoupling model, few examine water resource utilization decoupling effects based on the DPSIR framework combined with factor decomposition. (2) Driving factors are incompletely considered, omitting resource attributes such as water resource utilization rates and endowment. (3) Limited attention is paid to prefecture-level cities in the basin. This study addresses these gaps by quantifying actual water utilization across Yellow River Basin cities from 2000-2020 using water footprint methodology, constructing a decoupling effort index model based on the DPSIR framework, and analyzing decoupling effects from regional and sectoral perspectives across different planning periods.

1.1 Study Area Overview

Originating from the northern foothills of the Bayan Har Mountains on the Qinghai-Tibet Plateau, the Yellow River flows through nine provinces/autonomous regions (Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Shandong, and Henan), encompassing 71 counties, cities, and banners [?]. Considering data availability and completeness, this study focuses on 56 prefecture-level cities, excluding regions like Haidong and Haibei with substantial missing data. Using Hohhot in Inner Mongolia and Zhengzhou in Henan as boundaries, the basin is divided into upstream, midstream, and downstream regions.

From 2000-2020, the actual regional GDP of the 56 prefecture-level cities increased from 1.40\$ $\times 10^{12} yuanto11.70 \times 10^{12} yuan, indicatingpositivesocioeconomicdevelopment.Totalwatercon$
m^3, with agricultural production water accounting for the highest proportion, followed by industrial production water and domestic water [?].

[Figure 1: see original paper]

1.2 Data Sources

Data primarily derive from the *China City Statistical Yearbook*, *China Regional Economic Statistical Yearbook*, provincial water resources bulletins, and municipal statistical yearbooks (2001-2021). Missing data were interpolated using interpolation methods. Agricultural water footprint was calculated using the "bottom-up" approach, multiplying agricultural product output by unit virtual water content [?]. Agricultural products were categorized into crops and animal products, with unit virtual water content values referenced from Chapagain and Hoekstra [?] (Table 1).

1.3.1 Water Footprint Calculation Model

Water footprint refers to the total water resources required to produce all goods and services consumed in a region over a certain period [?], comprising internal and external water footprints:

$$WFP = IWFP + EWFP \tag{1}$$

$$IWFP = WFP_{agr} + WFP_{ind} + WFP_{dom} + WFP_{eco} - FW_{export} \tag{2}$$

$$EWFP = FW_{import} - FW_{re-export} \tag{3}$$

where WFP is total water footprint (10^8 m^3), $IWFP$ is internal water footprint, $EWFP$ is external water footprint, WFP_{agr}, WFP_{ind}, WFP_{dom}, and WFP_{eco} represent agricultural, industrial, domestic, and ecological water consumption (10^8 m^3), FW_{export} is virtual water exported to other regions (10^8 m^3), FW_{import} is virtual water imported from other regions (10^8 m^3), and $FW_{re-export}$ is virtual water imported and then re-exported (10^8 m^3).

Following existing research [?], this study separately calculates ecological water use change effects and net export virtual water change effects, using domestic water consumption as a proxy for service industry water consumption. The change effect of basin water consumption from period 0 to period t is:

$$\Delta W = W_t - W_0 = \Delta W_{agr} + \Delta W_{ind} + \Delta W_{ser} + \Delta W_{eco} + \Delta W_{dev} + \Delta W_{end} + \Delta W_{pop}$$

where ΔW is the total water resource utilization effect; W_t and W_0 are total water consumption in periods t and 0; ΔW_{agr}, ΔW_{ind}, ΔW_{ser}, ΔW_{eco}, ΔW_{dev}, ΔW_{end}, and ΔW_{pop} represent agricultural, industrial, service industry, ecological environment, economic development, water resource endowment, and population scale effects, respectively.

1.3.2 LMDI Factor Decomposition Model

The LMDI factor decomposition model offers complete decomposition without residuals and consistency between additive and multiplicative decomposition, making it a mainstream method for analyzing water use change factors [?]. This study applies the model to decompose Yellow River Basin water consumption:

$$W = \sum_i \frac{W_i}{G_i} \times \frac{G_i}{G} \times \frac{G}{R} \times \frac{R}{P} \times P = \sum_i int_i \times str_i \times dev \times uti \times end \times pop$$

where W is total Yellow River Basin water footprint (10^8 m^3), G_i is value-added of sector i (10^8 yuan), W_i is water footprint of sector i (10^8 m^3), G is total value-added of all sectors (10^8 yuan), R is total water resources (10^8 m^3), P is population (10^4 persons), and int_i, str_i, dev, uti, end, and pop represent water use intensity, industrial structure, economic development, water resource utilization rate, water resource endowment, and population scale, respectively.

The change effect of water resource utilization from period 0 to period t is:

$$\Delta W = W_t - W_0 = \Delta W_{int} + \Delta W_{str} + \Delta W_{dev} + \Delta W_{uti} + \Delta W_{end} + \Delta W_{pop}$$

where ΔW_{int}, ΔW_{str}, ΔW_{dev}, ΔW_{uti}, ΔW_{end}, and ΔW_{pop} represent water use intensity effect, industrial structure effect, economic development effect, water resource utilization rate effect, water resource endowment effect, and population scale effect, respectively. Specific calculations follow Sun et al. [?].

1.3.3 Decoupling Effort Index Model

Drawing on existing research [?], this study constructs a water resource utilization decoupling effort index model by integrating the Tapio decoupling model with the DPSIR framework. The Tapio decoupling model measures the decoupling relationship between water resource utilization and economic growth:

$$e(W,G) = \frac{\Delta W/W}{\Delta G/G}$$

where $\Delta G/G$ is the annual GDP growth rate and $e(W,G)$ is the decoupling elasticity coefficient of economic growth on water resource utilization. The model classifies relationships into three categories—decoupling, negative decoupling, and coupling—further subdivided into eight subcategories including strong decoupling, weak decoupling, expansive negative decoupling, etc. (Figure 2).

[Figure 2: see original paper]

The DPSIR framework—comprising Driver, Pressure, State, Influence, and Response—explains why water resource utilization and economic development change asynchronously. "Driver" represents the primary cause of water scarcity (GDP in this study); "Pressure" is the direct impact of economic drivers on water use (water footprint); "State" reflects water resource conditions under pressure (increasing water footprint); "Influence" represents impacts on economy, society, and ecology (deteriorating decoupling state); and "Response" comprises government efforts and policies for sustainable water use (reducing water use intensity, optimizing industrial structure).

Government "water saving and control" efforts are defined as measures directly or indirectly reducing water consumption, including lowering water use intensity and adjusting industrial structure. The decoupling effort effect formula is:

$$D_t = -\frac{\Delta W_{response}}{\Delta W_{pressure}} = -\frac{\Delta W_{int} + \Delta W_{str} + \Delta W_{uti} + \Delta W_{end}}{\Delta W_{dev} + \Delta W_{pop}}$$

where D_t is total decoupling effect and D_{int}, D_{str}, D_{uti}, D_{end}, and D_{pop} represent decoupling effects of water use intensity, industrial structure, water resource utilization rate, water resource endowment, and population scale, respectively.

2.1 Water Footprint Composition and Evaluation in the Yellow River Basin

Using water footprint methodology, this study measures the composition and evaluation indicators of water footprints across 56 prefecture-level cities from 2000-2020 (Table 2). Total water footprint shows a fluctuating upward trend, reaching its minimum in 2001 and maximum in 2020. Agricultural production water dominates, consistently accounting for over 90% of the total and correlating strongly with overall water footprint trends. Industrial production water peaked in 2011 before declining. Domestic water increased steadily with urbanization and improving living standards. Ecological environment water showed minor fluctuations before rapid increases, consistent with Li et al. [?]. Net import/export virtual water exhibited fluctuating growth but remained a small proportion (<5%) of total water footprint.

Evaluation indicators reveal slowly growing per capita water footprints, consistent with total water footprint trends. Water scarcity is severe, with water poverty index showing significant variation. Water self-sufficiency rate remains around 95%. Water economic benefit increased from 2.37\$$\times 10^4 yuan/m^3 to 18.60\times$\$10^4 yuan/m^3, indicating annually improving economic returns from water resources.

2.2 Driving Factors of Water Resource Utilization in the Yellow River Basin

The LMDI model decomposes driving factors of water resource utilization changes from 2000-2020. To analyze specific phases, the study period is divided into four planning periods: the 10th Five-Year (2001-2005), 11th Five-Year (2006-2010), 12th Five-Year (2011-2015), and 13th Five-Year (2016-2020) periods (Figure 3).

[Figure 3: see original paper]

Total water use change effect shows a clear declining trend, largest during the 10th Five-Year period, decreasing substantially in the 11th Five-Year period, increasing slightly in the 12th Five-Year period, and continuing to decline in the 13th Five-Year period. Economic development effect is the primary positive driver, increasing water consumption by 194.77\$$\times 10^8 m^3 annually.Industrialstructureeffectisthekeyinhibitingfactor,reducingwaterconsumptionby1$ m^3 annually. Water resource utilization rate shows strong positive driving effects. Water resource endowment exhibits bidirectional driving effects due to insufficient supply and uneven spatial distribution [?]. Ecological water use and net export effects are relatively small.

2.3.1 Overall Decoupling Analysis of Water Resource Utilization

Based on the Tapio model, the decoupling elasticity index between water resource utilization and economic development shows fluctuating decline, with maximum value of 0.85 (weak decoupling) in 2001 and minimum value of -0.21 (strong decoupling) in 2020. This indicates generally favorable decoupling status in the Yellow River Basin, with relatively low or even decreasing water consumption during economic development.

2.3.2 Spatial Distribution Characteristics of Water Resource Utilization Decoupling

Examining spatial heterogeneity, decoupling status is categorized as strong decoupling, weak decoupling, expansive coupling, and expansive negative decoupling based on elasticity indices (Figure 4). At the municipal level, water resource utilization primarily exhibits strong and weak decoupling from 2000-2020, indicating overall favorable decoupling status. In 2001, Xining, Tianshui, and Dingxi showed expansive negative decoupling. By 2020, more cities achieved strong decoupling, though some like Dongying still showed less favorable status. Regionally, decoupling performance follows a downstream > midstream > upstream pattern, reflecting typical unbalanced development characteristics.

[Figure 4: see original paper]

2.3.3 Dynamic Evolution Characteristics of Water Resource Utilization Decoupling by Sector

From the 10th to 13th Five-Year periods, agricultural production water decoupling elasticity indices in the upstream region declined, indicating improving decoupling effects, while industrial production water decoupling fluctuated significantly and service industry water decoupling alternated between positive and negative values (Table 4). The midstream region shows better industrial and agricultural production water decoupling than the upstream region, but service industry water decoupling fluctuates considerably. The downstream region demonstrates superior agricultural production water decoupling compared to industrial and service sectors, though service industry decoupling elasticity indices increased annually, indicating less favorable performance. Overall, agricultural water decoupling in the mid-upstream region and industrial water decoupling in the midstream region improved progressively from the 10th to 13th Five-Year periods. Service industry water decoupling generally outperforms agricultural production water decoupling.

2.4 Decoupling Efforts of Water Resource Utilization in the Yellow River Basin

2.4.1 Regional Heterogeneity Analysis of Water Resource Utilization Decoupling Efforts

Regional heterogeneity is examined across upstream, midstream, downstream, and the entire basin (Table 5). Basin-wide decoupling effort indicators increased continuously, with decoupling effects improving over time. Upstream decoupling effects show fluctuating growth but remain inefficient. Midstream decoupling effort indicators first declined then increased, exhibiting dynamic evolution from "no decoupling effect → weak decoupling effect → strong decoupling effect." Downstream regions showed no decoupling effect only during the 13th Five-Year period.

Industrial structure effect contributes most to water resource utilization decoupling, followed by water resource endowment effect. Water use intensity effect shows stronger pulling effects on upstream regions. Water resource utilization rate effect only emerged during the 13th Five-Year period. Population scale effect inhibits decoupling but with relatively small impact. Therefore, future efforts should prioritize industrial structure optimization, water resource allocation improvement, and water use intensity reduction to foster water-saving industries and society.

2.4.2 Sectoral Heterogeneity Analysis of Water Resource Utilization Decoupling Efforts

Given varying decoupling status across sectors, policy effectiveness is analyzed by sector (Table 6). Agricultural production water decoupling effort indicators increased progressively from the 10th to 13th Five-Year periods, achieving strong decoupling during the 12th-13th Five-Year periods. Industrial production water decoupling effects remained weak overall, indicating insufficient government "water saving and control" efforts to offset economic growth-induced consumption increases. Service industry water decoupling effects were less favorable, with effort indicators first increasing then decreasing. Water use intensity effect contributed most to decoupling, while water resource endowment effect showed both positive and negative driving effects. Industrial structure effect only influenced agricultural production water decoupling, and population scale effect contributed minimally. Water resource utilization rate effect only emerged during the 13th Five-Year period.

3 Discussion

This study examines water resource utilization-economic development decoupling effects in water-scarce Yellow River Basin prefecture-level cities from the 10th to 13th Five-Year periods, providing more objective, comprehensive, and detailed analysis than existing studies [?]. Results show fluctuating upward water footprint trends with agricultural production water as the main component, consistent with Pan and Chen [?] and Li et al. [?]. Weak decoupling status aligns with Gao and Lu [?]. Hu and Guo [?] analyzed Qinghai Province' s decoupling status, providing valuable reference for this study region.

Current decoupling research inadequately considers natural factors like water resource utilization rates and endowment [?]. This study finds that water resource endowment effects influence both water use changes and decoupling effects, with varying impacts across regions. Water resource utilization rate effects only emerged during the 13th Five-Year period. Different factors significantly affect various regions and sectors. Water use intensity and industrial structure effects notably inhibit water consumption, corroborating existing research [?].

4 Conclusions

This study reaches the following conclusions: (1) From 2000-2020, the Yellow River Basin' s total water footprint showed fluctuating upward trends, with agricultural production water as the main component (>90% annually), followed by industrial and service water. Ecological environment water and import/export virtual water each accounted for \$ \$5%. (2) From the 10th to 13th Five-Year periods, total water use change effects showed fluctuating decline characteristics. Economic development and population scale effects positively drove water consumption, while water use intensity, industrial structure, and other factors negatively drove consumption, with economic development as the decisive factor for increased water use. (3) Water resource utilization-economic development decoupling effects are generally favorable, primarily showing weak and strong decoupling. Regionally, midstream and downstream decoupling performance exceeds upstream performance. By sector, industrial and service water decoupling outperforms agricultural water decoupling. (4) Government "water saving and control" efforts significantly influence decoupling effects. At the regional level, industrial structure and water resource endowment effects are crucial for decoupling. At the sectoral level, water use intensity effect is key to achieving decoupling. Population scale and water resource utilization rate effects require further strengthening for regional and sectoral decoupling.

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