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Water resources ecological footprint in the Yellow river Basin: a two-dimensional decoupling analysis and its change trajectory

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Water resource scarcity is a major obstacle to the sustainable development of the Yellow River Basin (YRB). Accurately identifying the decoupling pathways of water resources ecological footprint (WEF) and economic growth is crucial in resolving the dilemma of water resource utilization and economic development in the YRB. To explore the decoupling states of WEF and the economic growth in cities within the YRB, this study proposed a new two-dimensional decoupling model with 24 different decoupling states, based on the Tapio decoupling model and the environmental Kuznets curve (EKC) hypothesis. Using the panel data from 60 cities in the YRB from 2010–2021, this study found that the relationship between WEF and *per capita* GDP followed an N-shape pattern. Decoupling performance shows clear regional differentiation: downstream cities exhibited the best decoupling performance, followed by the midstream cities, while the upstream cities showed the poorest performance. The change trajectory of decoupling states showed a clear tendency toward desirable decoupling: the proportion of cities achieving high-economic-level decoupling states (HE-SD and HE-WD) increased markedly from 18.33% to 43.33%. However, this transition was highly dynamic and non-linear, nearly 95% of cities experienced changes in their decoupling states during the study period. These results highlight the urgency of decoupling water resource utilization from economic growth throughout the YRB. In light of the aforementioned discoveries, this paper proposed corresponding policy recommendations aimed at achieving the ideal decoupling of WEF and economic growth in the Yellow River Basin.

KEYWORDS

tapio decoupling model, water resources ecological footprint (WEF), environmental kuznets curve (EKC), two-dimensional decoupling model, the yellow river basin

1 Introduction

Water resources are crucial for human survival and socioeconomic development (Li and Lu, 2024). As an indispensable natural resource for urban development, it is a rigid constraint on urban development (Wang et al., 2025).The United Nations has identified rational planning and effective management of water resources as a crucial element of Sustainable Development Goal 6. However, due to rapid urbanization under high compression of time and space, cities have expanded in size and economic activity, resulting in a sharp increase in water demand (Qiu and Zhang, 2019; Yang and Qin, 2024). According to China Statistical Yearbook on Environment, urban water supply rose from 50.79 billion m^3 in 2010 to 67.33 billion m^3 in 2021. Meanwhile, urban water consumption has increased even more, from 95.59 billion m^3 to 135.92 billion m^3, creating a significant gap between supply and demand. This has led to almost two-thirds of cities in China experiencing water shortages, and one-sixth of cities suffering from severe water shortages (Zhang, 2023). Furthermore, *per capita* water resources have continued to decrease (Chen and Feng, 2020), highlighting the growing disparity between limited water resources and the rapid growth of water demand. The intensifying contradiction between water supply and demand may lead to issues such as restrictions on industrial development and economic slowdown, and may even trigger public health incidents and social conflicts (Liu, 2025).As a result, the issue of water scarcity has intensified, presenting a significant challenge to regional sustainable development (Huang et al., 2021).

The Yellow River Basin (YRB) stretches across three key economic zones from west to east in China. It serves as an essential ecological security shield and economic belt, but also faces acute water supply and demand issues. The YRB covers an area of 79.5×10^4 km^2, predominantly characterized by arid and semi-arid zones. The total water resources in the YRB are limited and unevenly distributed in both time and space. Economic growth and population concentration have exacerbated the water scarcity issue (Sui, 2025). The total water resources in the basin account for only 2.6% of the national total, and the *per capita* water resources occupancy is a mere 27% compared to the national average. However, the exploitation of water resources has reached up to 86%, far exceeding the ecological warning line of 40% (Sun et al., 2024). This high-intensity development and utilization, coupled with intensified competition for water resources among various industries within the basin, has exacerbated the imbalance between water supply and demand. This has placed the Yellow River water resources system under extreme pressure, not only hindering regional economic development but also posing a threat to the ecological security of the YRB (Bo et al., 2025; Jing and Tian, 2025).The scarcity of water resources has greatly hindered the socioeconomic development and ecological civilization security of not only the YRB but also the country (Hu et al., 2012; Liao et al., 2024; Liu L. et al., 2023).

Water is a vital ecological element and a significant constraint for the high-quality development of the YRB (Lu et al., 2023; Xie et al., 2024). As the urban economy in the YRB continues to rapidly grow, achieving sustainable water resource utilization is crucial for the high-quality development progress of cities. It is important to note that economic development varies greatly from city to city in the YRB (Wang et al., 2023).

However, the compatibility between economic growth and water resource utilization in cities with different levels of economic development was poorly understood. Therefore, this study aims to transcend the limitations by introducing an integrated analytical framework that incorporates the economic development stage into the decoupling model. This enables not only a more accurate distinction of decoupling states in cities at varying development levels but also an analysis of their dynamic trajectory over time. Consequently, our research offers targeted insights that are essential for guiding differentiated policy recommendations and achieving harmonious water-economic development in the YRB.

2 Literature review

The environmental Kuznets curve (EKC) hypothesis is a widely accepted framework for examining the relationships between resource consumption, environmental pollution, and economic growth (Grossman and Krueger, 1995; Song et al., 2020). Its core premise is that environmental degradation intensifies in the early stages of economic development but may eventually diminish as *per capita* GDP exceeds a certain threshold, forming an inverted U-shaped pattern (Grossman and Krueger, 1991; Tenaw and Beyene, 2021).

However, the EKC exhibited varying patterns when examining different pollutants and sample areas, including U-shape, inverted U-shape, N-shape, and inverted N-shape (Fang and Gao, 2023; Gong et al., 2022; Huang et al., 2023; Li et al., 2021; Riti et al., 2017; Zhu, 2014). Economic growth has been a major driving force behind water resource consumption (Qin et al., 2015; Sun and Xie, 2011). Previous literature concluded that the EKC between tertiary industry water consumption and economic growth in China exhibited a linear increase, while the EKC patterns for the total, industrial, and agricultural water consumption all revealed an inverted N-shape (Li Y. et al., 2023). However, in Ningxia from 1980 to 2013 and in the United States from 1960 to 2005, the EKC for industrial water consumption both revealed N-shape patterns (Chen et al., 2021; Katz, 2015).

This heterogeneity in EKC patterns is not anomalous but rather expected, arising from contextual disparities in regional industrial structure, technological advancement, policy enforcement, and the specific water resource indicator examined. However, this indicates that the EKC's enduring value lies not in its predictive precision but in its paradigm-shifting insight: the economic-development-environmental pressure relationship is dynamic and non-linear. However, by focusing predominantly on identifying long-term inflection points, EKC provides little insight into the short-term dynamics and transient decoupling or coupling states between economic growth and resource use.

The decoupling theory was initially proposed by the Organization for Economic Co-operation and Development (OECD) to describe the asynchronous changes between economic growth and environmental stress (OECD, 2002). The Tapio decoupling model, which introduced the elastic coefficient, offers a more detailed breakdown of the decoupling states (Tapio, 2005). This model also addresses the uncertainty that arises from selecting a base period (Cohen et al., 2019; Mikayilov et al., 2018; Sun and Li, 2011). Currently, the Tapio decoupling model is widely utilized to investigate the decoupling relationship between energy consumption, CO_2 emission, resources environment and economic growth (Hu et al., 2023; Zhang Y. et al., 2022; Zhao et al., 2023). Similarly, in water resources research, the Tapio model has been effectively employed to assess the decoupling of water resources utilization and economic development (Jian et al., 2025; Wu et al., 2022; Xu et al., 2022).

In their study of the YRB, Zuo et al. (2021) utilized the Tapio decoupling model to analyze the relationship between water resource utilization and socioeconomic development in five provinces. They concluded that these provinces have not yet achieved ideal decoupling (Zuo et al., 2021). However, some scholars found evidence of a gradual shift from weak to strong decoupling between water footprint and economic growth in the YRB (Li R. et al., 2023; Lu and Zhao, 2020). While these studies provided valuable insights into the relationship between water resources and economic growth in the YRB, they failed to consider the decoupling relationship in cities with varying levels of economic development. In other words, cities with similar decoupling states may differ in their economic development levels. Unfortunately, the Tapio decoupling model alone is unable to identify the impact of economic development on the decoupling states across different cities and time periods.

While the EKC and decoupling analysis are often treated separately, they are conceptually complementary. The EKC provides a long-term, stage-based theoretical perspective but lacks short-term diagnostic power. Conversely, the Tapio model offers a precise, short-term snapshot of the economic-environmental relationship but does not inherently contextualize this state within a broader developmental trajectory. Therefore, simply using either model in isolation presents limitations. To address this, recent studies have begun integrating both frameworks. Xia and Zhong (2016) integrated the two to reclassify the decoupling relationship between pollution emissions and economic development in 271 Chinese cities (Xia and Zhong, 2016). Similarly, Song et al. (2019) developed a two-dimensional decoupling model with 16 different decoupling states to explore the relationship between CO_2 emissions and economic development in China and the United States (Song et al., 2019). Since then, there has been a growing number of studies using two-dimensional decoupling model to analyze the relationship between CO_2 emissions and economic growth in China, Gansu, and the YRB, as well as the relationship between the grey water footprint and economic growth in the Yangtze River Economic Belt (He et al., 2022; Kong et al., 2022; Song et al., 2020; Xin et al., 2021). This integration is crucial because it allows researchers to not only diagnose the current decoupling status but also to interpret that status in relation to a city's level of economic development. Thus, a combined framework provides a more robust, multi-dimensional understanding that can better inform differentiated policy responses across heterogeneous regions.

The water resources ecological footprint (WEF) is a widely used method for assessing human dependence on water resources (Zhu et al., 2019; Zuo et al., 2020). It was developed from the ecological footprint model (Huang et al., 2008; Ouyang et al., 2023; Qin et al., 2023). Although the ecological footprint model includes water area as one of its six categories of bioproductive land areas, it fails to reflect the ecological impact of water resource utilization. To address this issue, the WEF incorporates a water resource land account into the ecological footprint (Huang et al., 2008). This makes the WEF a valuable tool for assessing the ecological services and socio-economic functions of water resources (Čuček et al., 2012; Liu Z. et al., 2023).

In summary, previous studies have examined the relationship between water usage and economic growth in the YRB from various perspectives, including water quantity, water quality, water resources utilization efficiency, and water footprint (Gao and Lu, 2021; Zhang and Zhou, 2023; Zhang h et al., 2022; Zuo et al., 2021). In recent years, some scholars have conducted research on decoupling relationship between the water resources ecological footprint and economic growth (Lai et al., 2024; Zhong et al., 2024). Understanding this relationship is crucial for promoting the sustainable utilization of water resources and the high-quality development of cities in the YRB. Therefore, this study calculated the WEF of 60 cities in the YRB from 2010 to 2021. Then, a new two-dimensional decoupling model, which integrated the EKC and Tapio decoupling model, was developed with the economic development level as a key criterion. This model aimed to comprehensively explore the decoupling relationship and evolutionary trajectory between WEF and economic growth.

3 Methods and data

3.1 Two-dimensional decoupling model

3.1.1 EKC hypothesis

As EKC can take on various forms, this article referred to the previous studies (Katz, 2008; Kong et al., 2022; Zhang et al., 2017) and set the EKC of WEF as a continuous function:

$$\ln WEF_{it} = \alpha_0 + \alpha_1 \ln g_{it} + \alpha_2 (\ln g_{it})^2 + \alpha_3 (\ln g_{it})^3 + \varepsilon_{it} \quad (1)$$

Among them, WEF_{it} and g_{it} refer to the WEF and *per capita* GDP of city i in year t, respectively. α_0 represents the constant term. α_1, α_2, and α_3 indicate the coefficients of the primary, the secondary and the tertiary terms, respectively. ε_{it} denotes random error term. The pattern of the EKC is determined by the values of the coefficients for the respective terms. Specifically, if $\alpha_1 < 0$, $\alpha_2 > 0$, and $\alpha_3 = 0$, the EKC exhibits a U-shaped pattern. If $\alpha_1 > 0$, $\alpha_2 < 0$, and $\alpha_3 = 0$, the EKC presents an inverted U-shape. If $\alpha_1 > 0$, $\alpha_2 < 0$, $\alpha_3 > 0$, the EKC displays an N-shape. If $\alpha_1 < 0$, $\alpha_2 > 0$, $\alpha_3 < 0$, the EKC shows an inverted N-shape.

3.1.2 Two-dimensional decoupling model

In this section, we presented a new two-dimensional decoupling analysis framework by establishing a link between the EKC and the Tapio decoupling theory. To achieve this, we first took a derivative of Equation 1 with respect to g, which yielded Equation 2:

$$\frac{dWEF}{dg} \cdot \frac{1}{WEF} = \left[\alpha_1 + 2\alpha_2 \ln g + 3\alpha_3 (\ln g)^2\right] \cdot \frac{1}{g} \quad (2)$$

Then, Equation 2 can be transformed into Equation 3.

$$\frac{dWEF/WEF}{dg/g} = \alpha_1 + 2\alpha_2 \ln g + 3\alpha_3 (\ln g)^2 \quad (3)$$

According to the relevant literature (Kong et al., 2022; Song et al., 2020), this study assumed that the population growth rate was 0. That was to say $p_t = p_{t-1} = p$. Thus, the well-known Tapio decoupling elasticity index (D) can be expressed as:

$$D = \frac{(WEF + \delta WEF - WEF)/WEF}{(GDP + \delta GDP - GDP)/GDP} = \frac{\delta WEF/WEF}{\delta gp/gp} = \frac{dWEF/WEF}{dg/g} \quad (4)$$

Combining Equation 3 and Equation 4, the Tapio decoupling index also can be written as:

$$D = \alpha_1 + 2\alpha_2 \ln g + 3\alpha_3 (\ln g)^2 \quad (5)$$

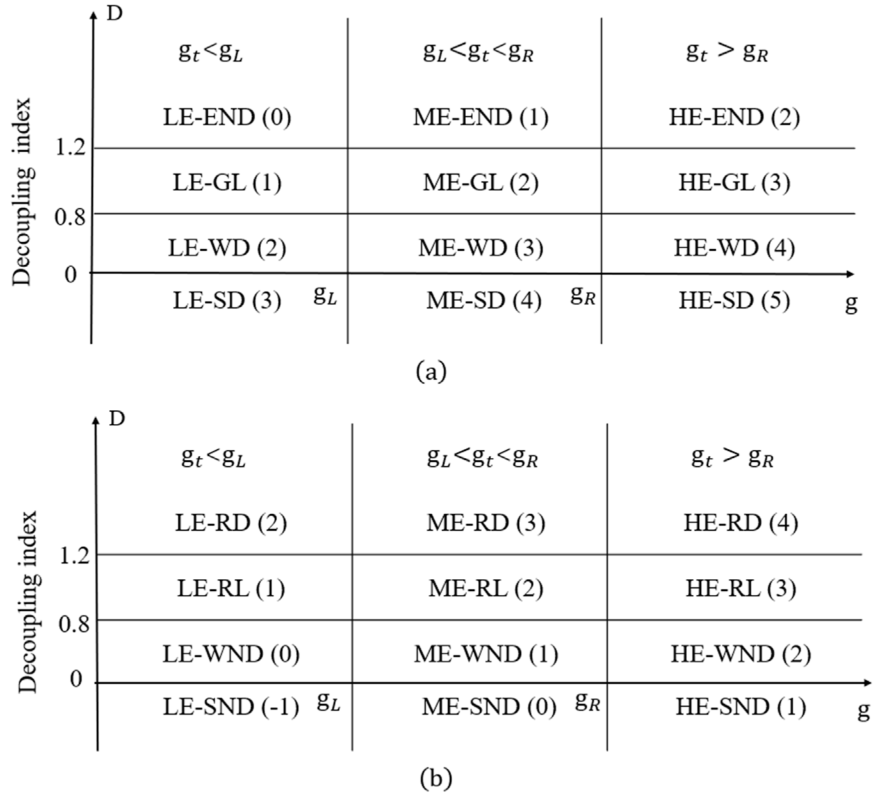

FIGURE 1
Two-dimensional decoupling classification and decoupling scores. **(a)** $\Delta g > 0$. **(b)** $\Delta g < 0$.

The inflection points of the EKC are equal to the extreme values of Equation 1. Thus, let $D = 0$, the threshold values g can be obtained as follows.

$$g_R = e^{\frac{-2\alpha_2 + \sqrt{4\alpha_2^2 - 12\alpha_1\alpha_3}}{6\alpha_3}} \tag{6}$$

$$g_L = e^{\frac{-2\alpha_2 - \sqrt{4\alpha_2^2 - 12\alpha_1\alpha_3}}{6\alpha_3}} \tag{7}$$

This paper used the methodology established by previous studies (Song et al., 2019; Xia and Zhong, 2016) to incorporate the inflection point of the EKC into the decoupling criteria of the Tapio model. As a result, a new two-dimensional decoupling analysis framework is presented in Figure 1. This study employs panel data from 60 prefecture-level cities in the YRB covering the period 2010–2021, conducting regression analysis using Stata software. The results indicated that there was an N-shaped curve that represented the correlation between WEF and the *per capita* GDP of cities in the YRB. Based on this, the framework in this paper includes 24 different decoupling states.

The Tapio decoupling model contains eight decoupling states: strong decoupling (SD), weak decoupling (WD), recessive decoupling (RD), expansive negative decoupling (END), strong negative decoupling (SND), weak negative decoupling (WND), recession link (RL), and growth link (GL). As shown in Fiure 1, the two critical points (g_L and g_R) divided economic development into three stages: low level (LE), medium level (ME), and high level (HE). According to the Tapio decoupling model, 0, 0.8 and 1.2 are used to determine the decoupling state divisions. Figure 1a displays the decoupling divisions when there is a positive change in *per capita* GDP. Otherwise, Figure 1b shows the decoupling classification in the case of a negative change.

According to previous research (Kong et al., 2022; Song et al., 2020), each decoupling state shown in Figure 1 was assigned a numerical score. This resulted in seven different scores for all 24 types of decoupling states. The most ideal decoupling state, HE-SD, was given a score of 5. ME-SD was given a score of four and LE-SD was given a score of 3. Similarly, HE-WD, HE-GL, and HE-END were given scores of 4, 3, and 2, respectively. The scores for ME-WD, LE-WD, ME-GL, LE-GL, ME-END, and LE-END were 3, 2, 2, 1, 1, and 0, respectively. If $\Delta g < 0$, HE-RD is considered the best decoupling state, it was given a score of 4, with the scores for other decoupling states listed in the parentheses.

3.2 Water resources ecological footprint

WEF is a measure used to convert the water resources usage into a standardized unit of bioproductive land area, enabling easy comparison across various regions (Huang et al., 2008). Previous literature (Huang et al., 2008; Zhang et al., 2024) outlined the following formula for calculating the WEF.

$$WEF = N \times wef = \gamma_w \times \left(\frac{W}{P_w}\right) \tag{8}$$

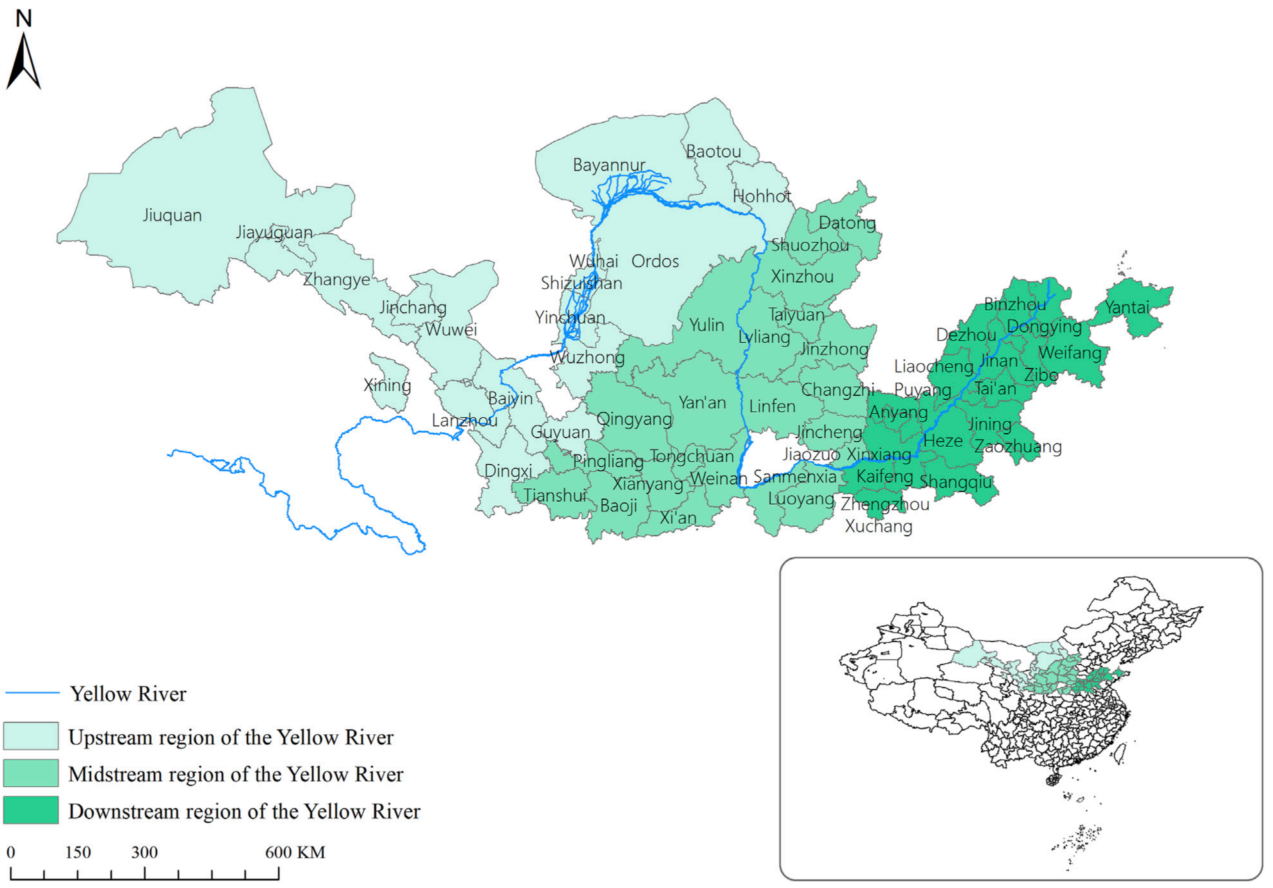

FIGURE 2
Schematic diagram of the research region.

Among them, WEF denotes the water resources ecological footprint (hm^2), N represents the regional population, wef denotes the *per capita* water resources ecological footprint ($hm^2/capita$). In Equation 8, W stands for the total water consumption consumed by a region (m^3), γ_w is the global equilibrium factor of water resources, P_w is the global average production capacity of water resources ($m^3 \cdot hm^{-2}$). Among them, γ_w is 5.19 and P_w is 3,140 $m^3 \cdot hm^{-2}$.

3.3 Study area and data sources

The Yellow River, China's second longest river, is also a representative example of a resource-based water-deficient river. Using the Outline for Ecological Protection and High-quality Development of the Yellow River Basin as a guide, this study encompassed 60 cities in eight provinces, as depicted in Figure 2. These cities were carefully selected based on three criteria: the integrity of administrative area units, the relevance of regional functions to the Yellow River, and the availability of data. The research focused on 18 upstream, 22 midstream, and 20 downstream cities. It is important to note that cities in Sichuan Province were not included in this study, as the Yellow River only runs through five counties (Aba, Hongyuan, Ruoergai, Songpan, and Shiqu) in that province.

The data on GDP, population and water consumption of each city from 2010 to 2021 were extracted from the China City Statistical Yearbook, the Statistical Yearbook of the eight provinces and the Water Resources Bulletin of each city. At the same time, the GDP was adjusted to the real terms using 2010 as the base year.

4 Results and discussion

4.1 Per capita GDP and water resources ecological footprint in the YRB

From 2010 to 2021, the *per capita* GDP in the YRB experienced a significant increase, rising from 34,031 yuan to 72,843 yuan, as depicted in Figure 3. Meanwhile, the WEF decreased from 114.43 million hm^2 to 112.65 million hm^2, indicating a fluctuating downward trend that aligned with previous findings (Gan et al., 2024a).

Since 2013, there has been a sharp decline in the WEF. This decline could be attributed to the 18th National Congress of the Communist Party of China in 2012. Following the congress, China implemented the ideas of "giving priority to water conservation, seeking spatial equilibrium, implementing systematic governance, and achieving government-market synergy" in its water governance actions. As a result, the WEF fluctuated slightly between 2014 and

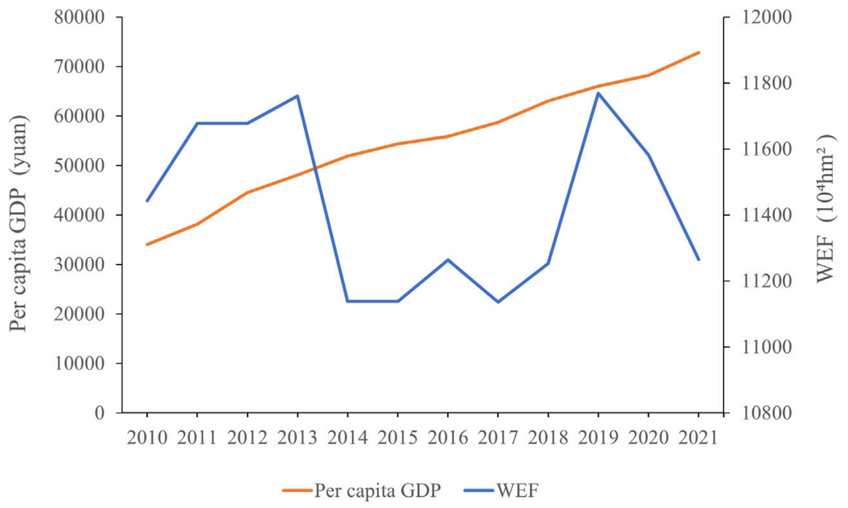

FIGURE 3
The *per capita* GDP and WEF in the YRB from 2010 to 2021.

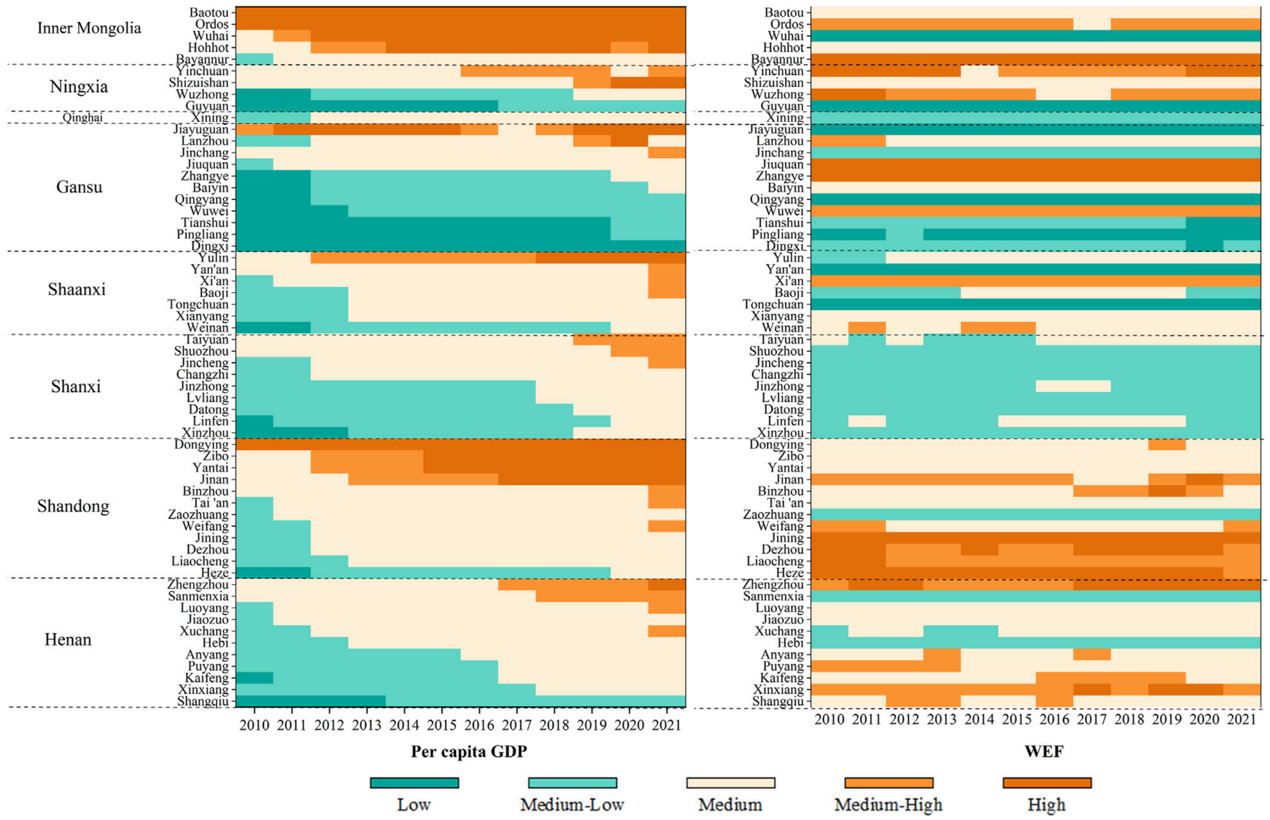

FIGURE 4
The prefectural *per capita* GDP and WEF in the YRB.

2017. However, from 2017 to 2019, it entered another period of rapid escalation. Since 2019, the WEF once again experienced a rapid decline period. This can be attributed to the promotion of ecological conservation and high-quality development in the YRB as a principal national strategy.

Furthermore, this study employed the mean–standard deviation method to divide the WEF and *per capita* GDP into five distinct grades: low, medium-low, medium, medium-high, and high grade. The heat maps of *per capita* GDP and WEF in the YRB were illustrated in Fiure four to visually represent the distribution of these grades.

Figure 4 showed a decrease in the number of cities with low and medium-low *per capita* GDP grades over time, while there was an increase in the number of cities with medium-high and high grades. Throughout the study period, approximately 45% of cities maintained a medium grade. In terms of spatial distribution, cities with high *per capita* GDP were primarily located in Inner Mongolia and Shandong, while cities with low *per capita* GDP were mainly concentrated in Gansu. It is noteworthy that there was a considerable disparity in *per capita* GDP among cities in the YRB. For example, Dingxi had the lowest average annual *per capita* GDP, which was only 6% of the highest annual average *per capita* GDP in Ordos.

In terms of WEF, there was no significant change in the number of cities at low and medium-low grades during the period. However, there was a gradual decrease in the number of cities with medium-high and high grades. On the other hand, the proportion of cities with medium grade increased from 28% to 35%. The majority of cities with high WEF were located in Shandong, which can be attributed to its strong economic development. This finding was consistent with previous literature (Gan et al., 2024a). In contrast, cities with low WEF were primarily located in Shanxi and Qinghai. Notably, Bayannur had the highest annual average WEF in the YRB, reaching 8.117 million hm^2. This can be attributed to the presence of the Hetao Irrigation District, the largest gravity irrigation district in Asia. Additionally, Bayannur is known for being the largest dairy production area and the only four-season sheep farm among prefectural cities in China. In summary, there was a significant variation in WEF among cities in the YRB, with Tongchuan having the lowest annual average WEF, which was only 2% of the highest city, Bayannur.

Overall, there was a significant imbalance in the *per capita* GDP and WEF among cities in the YRB. More specifically, Figure 4 showed that four cities (Bayannur, Jiuquan, Zhangye, and Jining) had a *per capita* GDP below the medium grade while maintaining a high grade for WEF. However, Wuhai had a *per capita* GDP above the medium grade but consistently received a low grade for WEF. Additionally, the *per capita* GDP of Wuwei fluctuated between low and medium-low grades, but its WEF consistently remained at a high grade. This suggested that cities with varying levels of economic development may exhibit the same Tapio decoupling correlation between *per capita* GDP and WEF. To further understand this decoupling, a two-dimensional decoupling model was used to examine the relationship between economic growth and WEF in cities at different stages of economic growth in the YRB.

4.2 Two-dimensional decoupling analysis of cities in the YRB

4.2.1 EKC estimation for the WEF

According to the EKC set in Equation 1, a panel regression analysis was conducted using data from 60 cities in the YRB from 2010 to 2021. Figure 5 showed the fitted curve of lnWEF on lng.

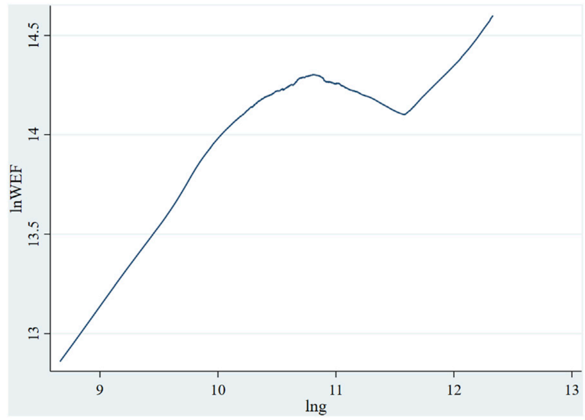

FIGURE 5
The fitted curve of lnWEF on lng

As illustrated in Figure 5, there was an N-shaped curve that represented the correlation between WEF and the *per capita* GDP of cities in the YRB. The regression coefficient for the primary term ($\ln g$) was 9.811, which was significant at the 10% level. The secondary and tertiary terms had coefficients of −0.99 and 0.033, respectively, both of which were significant at the 5% level. According to Equations 5–7, the two inflection points of the EKC occurred at *per capita* GDP levels of 8,518.5 yuan and 56,954 yuan, respectively.

The rapid expansion of economic activity triggered a corresponding surge in WEF. As *per capita* GDP passed the first inflection point, the technique effect and structure effect became prominent. Specifically, the technological progress and upgrading industrial structure prompted a reduction in water consumption in both production and daily life, resulting in a decrease in WEF. However, as output continued to rise, the inhibitory effects of technological progress and industrial structure upgrading on water resources utilization were outweighed by the pulling effect induced by scale expansion (Li R. et al., 2023; Lu and Guo, 2008), leading to a rebound in WEF.

4.2.2 Two-dimensional decoupling score in the YRB

The economic level in the YRB was divided into three stages based on the two inflection points of the EKC. Then, according to Figure 1, the two-dimensional decoupling states and decoupling scores of 60 cities in the YRB during the following three periods: 2010–2014, 2014–2018 and 2018–2021, were obtained respectively (as shown in Supplementary Table SA1).

Referring to the previous studies (Haberl et al., 2020; Huang, 2024; Kong et al., 2022), this study categorized the total decoupling score of cities into three intervals: (1–5), (6–10), and (11–15). These intervals corresponded to the three levels of sustainable water resource utilization: low, medium, and high. The number of cities in each level of sustainable water resource utilization was shown in Figure 6.

Figure 6 highlighted the two-dimensional decoupling performance of downstream cities was the best, followed by those in the midstream. However, the performance of upstream cities was the worst. Specifically, there were more cities in the upstream and midstream with total decoupling scores between 6 and 10 compared to those in the downstream. The number of cities with total decoupling scores between 11 and 15, showed a

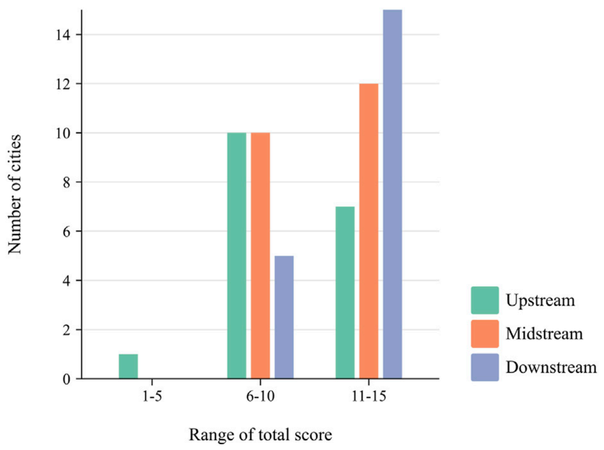

FIGURE 6
Number of cities in the three levels of sustainable water resources utilization.

descending order: downstream, midstream, and upstream. As shown in Figure 6, out of the 60 cities in the YRB, 34 cities had a high level of sustainable water resource utilization, while 25 cities were at a medium level. Only Bayannur, located upstream, had a low level of sustainable water resource utilization. These disparities may stem from the distinct water resource endowments, industrial structures, and policy orientations across regions, as well as the resources and capabilities of individual economic entities (Chen et al., 2025; Grossman and Krueger, 1995; Ma and Appolloni, 2025). Downstream regions have achieved dual efficiency in water resource utilization and economic development through their more advanced industrial structure and robust capabilities in policy implementation and technology application. Midstream regions face dual challenges of path dependence on heavy industry and water scarcity, remaining reliant on traditional resource-based economic growth models. Upstream regions, constrained by "ecological priority" policies, experience limited economic development space and sluggish growth (Gao, 2025; Ren and Wang, 2025; Zhang et al., 2025).

Existing literature, which primarily focused on the Tapio decoupling model, concluded that the performance of decoupling between water resources utilization and economic development in the YRB was positive, with a prevalence of both weak and strong decoupling (Yang et al., 2025). However, in this paper, we provided a more comprehensive and precise analysis of this relationship.

Table 1 displayed the two-dimensional decoupling states of typical cities in the YRB. Zibo achieved the highest two-dimensional decoupling score in the YRB. Its *per capita* GDP surpassed the second inflection point in 2010–2014, indicating a significant increase in economic development. The decoupling state was dominated by HE-SD, indicating that it successfully achieved the dual goals of economic development and absolute decoupling. Zibo has actively promoted the intensive and conservation-oriented use of water resources, resulting in notable improvements in the conservation and intensive capacity of water resources each year (Gan et al., 2024b). In 2021, Zibo began to implement integrated water resources management for a moistened Zibo, with the aim of promoting the synchronized advancement of economic progress and the conservation of water resources.

On the contrary, Bayannur got the lowest decoupling score and its decoupling state was dominated by ME-END, indicating that its economic growth was highly dependent on water resource consumption. In other words, Bayannur was a city that experienced extensive economic growth.

As illustrated in Table 1, all cities except for Dingxi had a *per capita* GDP that exceeded the first threshold. However, in 2014, Dingxi's *per capita* GDP reached 9,935.15 yuan, surpassing the first inflection point of the EKC. It continued to gradually rise, reaching 17,058.03 yuan in 2021. Despite this growth, Dingxi, located at the intersection of the Loess Plateau and Qinling Mountains, faced challenges due to its limited water resources and an unsustainable water consumption structure, with agriculture accounting for 69.2% of the total water usage. From 2010 to 2014, Dingxi's decoupling state between the WEF and economic growth was classified as LE-SD, indicating that its economic growth was lagging behind its decoupling state. Since 2014, Dingxi's *per capita* GDP has crossed the first inflection point of the EKC, and its decoupling state has shifted from ME-SD to ME-WD.

TABLE 1 Two-dimensional decoupling scores of typical cities in the YRB.

Cities	Two-dimensional decoupling states			Decoupling score			Total score
	2010–2014	2014–2018	2018–2021				
Zibo	HE-WD	HE-SD	HE-SD	4	5	5	14
Yantai	HE-SD	HE-WD	HE-WD	5	4	4	13
Dingxi	LE-SD	ME-SD	ME-WD	3	4	3	10
Zhengzhou	HE-WD	HE-WD	HE-WD	4	4	4	12
Zhangye	ME-SD	ME-SD	ME-SD	4	4	4	12
Xinzhou	ME-WD	ME-WD	ME-WD	3	3	3	9
Ordos	HE-SD	HE-WND	HE-SND	5	2	1	8
Wuhai	HE-WD	HE-WND	HE-SND	4	2	1	7
Bayannur	ME-WD	ME-END	ME-END	3	1	1	5

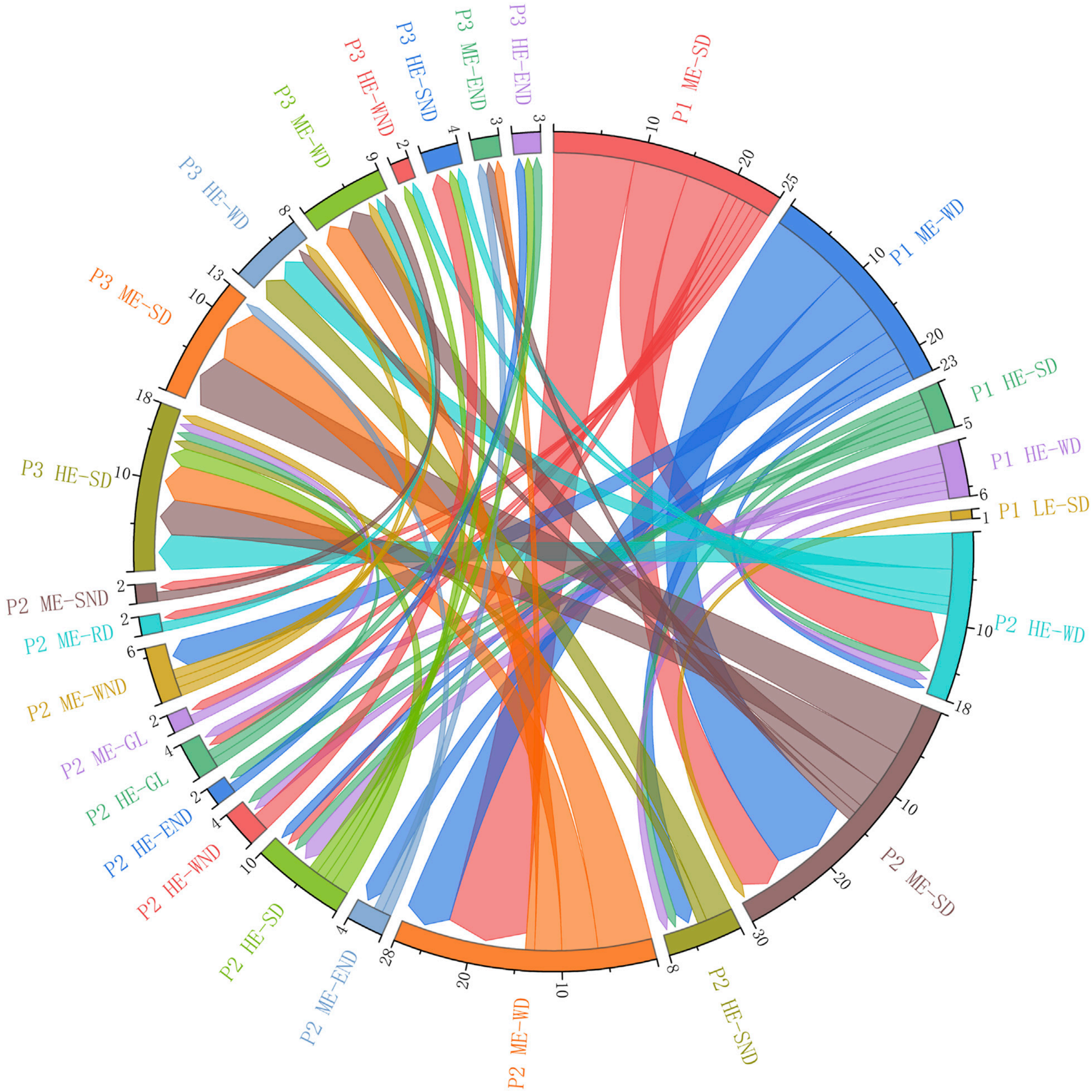

FIGURE 7
Trajectories of the two-dimensional decoupling states in the YRB.

It is worth noting that the two-dimensional decoupling state of Yantai deteriorated from HE-SD to HE-WD. In the first period, Ordos and Wuhai had two-dimensional decoupling states of HE-SD and HE-WD, respectively. However, in the second period, both cities changed to HE-WND, and in the third period, they became HE-SND. This indicated that these two cities were experiencing unsustainable urban development. The economic growth in both Ordos and Wuhai shifted from positive to negative, while the WEF in the two cities changed from decreasing to increasing. Previous literature also revealed that the water resource constraint effect in Wuhai was higher than the overall level of the YRB (Chen et al., 2024). Additionally, the two-dimensional decoupling state in Zhengzhou, Zhangye, and Xinzhou remained at HE-WD, ME-SD, and ME-WD, respectively.

4.2.3 Trajectory characteristics of the decoupling states in the YRB

This paper presented a transformation diagram that analyzed the trajectory of the two-dimensional decoupling states for 60 cities in the YRB during the three distinct periods: 2010–2014 (P1), 2014–2018 (P2), and 2018–2021 (P3). The diagram was shown in Figure 7.

Figure 7 showed that during period P1, there were five types of two-dimensional decoupling among cities: LE-SD, ME-SD, ME-WD, HE-SD, and HE-WD. Among these, ME-SD and ME-WD accounted for 80%, while HE-SD and HE-WD accounted for

18.33%. In period P2, there were 13 different two-dimensional decoupling states in the YRB. ME-SD and ME-WD accounted for 48.33%, while HE-SD and HE-WD accounted for 23.33%. During this period, Qingyang's decoupling state performed the worst, which was classified as ME-SND, indicating negative economic growth but a significant increase in WEF.

In period P3, there were a total of eight two-dimensional decoupling states observed in the YRB. Among these, HE-SD, ME-SD, HE-WD, and ME-WD accounted for 80% of the total. Specifically, HE-SD and HE-WD accounted for 43.33% of the total. It is worth noting that the proportion of HE-SD and HE-WD increased gradually over time. In period P3, 18 cities, including Zibo, Taiyuan, and Baotou, achieved the most desirable two-dimensional decoupling state (HE-SD). This means that these cities successfully achieved absolute decoupling between economic growth and WEF. On the other hand, Wuhai, Ordos, Jinan, and Yinchuan had the poorest decoupling state (HE-SND). Despite the *per capita* GDP in these four cities passing the second inflection point, their economic growth was negative while the WEF continued to increase.

In summary, the cities in the YRB showed a tendency towards decoupling. Previous studies found that the water resources carrying capacity and high-quality development in the YRB have gradually improved from the dysregulated recession and barely coordinated development stage to the primary coordinated development stage, which was similar to the conclusion of this study (Xie et al., 2024). However, the two-dimensional decoupling states of cities in the YRB were unstable. Except for Zhengzhou, Zhangye, and Xinzhou, the decoupling state of the other cities has changed. Specifically, the five cities with HE-SD in the P1 period all showed varying degrees of deterioration in the following two periods. In addition, three of the six cities with HE-WD in the P1 period experienced a deterioration in the subsequent two periods. Over time, 58.33% of the cities in the YRB exceeded the second inflection point. Among them, 25.71% have still not reached the HE-SD and HE-WD states. Therefore, the coordination of decoupling and economic development in the YRB needed to be further improved.

5 Discussion

5.1 Relationship between water resource ecological footprint and economic growth

This study constructed a novel two-dimensional decoupling framework for targeted analysis of the relationship between the water resource ecological footprint (WEF) and economic growth in the Yellow River Basin. While extensive research either concentrated on EKC to examine nonlinear links between single indicators and GDP or adopted the conventional Tapio model with 8 decoupling types for single-dimensional analysis(Gao and Lu, 2021; Ji and Sun, 2024; Li R. et al., 2023; Xia et al., 2022), this study proposed a two-dimensional framework based on N-shaped EKC to conduct a more precise classification of decoupling states (24 states), which can capture complex dynamics, such as recoupling that occurs at higher development stages.

The study found that the decoupling state between WEF and economic growth in the YRB has improved, and the decoupling performance in the lower reaches of the YRB is better than that in the middle and upper reaches, which is consistent with previous studies (Li R. et al., 2023; Yang et al., 2025). Moreover, by analysing data at the prefecture-level city scale, this study found there was an N-shaped curve relationship in YRB, which suggested that water resource pressure may re-emerge after exceeding a certain economic threshold, meaning that environmental governance needs to be continuously strengthened along with economic development rather than relaxed.

5.2 Limitations and future recommendations

Due to the limitation of data availability, the analysis was conducted up to 2021. The absence of the latest data after 2021 limited the ability to capture the latest decoupling states under the new water resource governance policies. Although this study provided a detailed analysis at the basin level, the conclusions were based on the specific background of the Yellow River Basin. Caution should be exercised when extending the conclusions to other river basins with different economic structures, hydrological conditions and policy environments.

Promising research directions may include the following aspects, such as collecting updated data, examining the inequality of decoupling processes in different regions, identifying the key factors driving the state transitions and evaluating the effectiveness of specific regional policies aimed at achieving strong decoupling. These efforts will help formulate more tailored and effective water resource management strategies in the YRB.

6 Conclusion and recommendations

6.1 Conclusion

Water resources are essential for the YRB and play a crucial role in supporting its high-quality economic development. To maintain a balance between economic growth and the preservation of water resources, it is imperative to achieve a decoupling between WEF and economic growth. To address this issue, this study utilized a combination of the EKC and Tapio models to construct a new two-dimensional decoupling model with 24 different states. This model was then used to analyze the two-dimensional decoupling states of WEF and *per capita* GDP in the YRB, as well as their trajectories. The main findings were outlined below:

1. Between 2010 and 2021, the *per capita* GDP of cities in the YRB exhibited a significant growth trend, indicating promising economic development for the region. However, there were notable differences in spatial distribution. Inner Mongolia and Shandong were high-value agglomerations, while Gansu was characterized as a low-value agglomeration region. In the meantime, the WEF in the YRB displayed a fluctuating trend. In terms of spatial distribution, Shandong was the region with a high-value cluster, while Shanxi was the region with a low-value cluster. Overall, the *per capita* GDP and WEF in the YRB revealed a clear imbalance in both spatial and temporal distribution.
2. The relationship between WEF and *per capita* GDP in cities in the YRB followed an N-shaped curve, with inflection points at 8,518.5 yuan and 56,954 yuan, indicating that environmental

pressure re-emerges after certain economic thresholds. Decoupling performance varied spatially: the downstream cities showed the best decoupling performance, followed by the midstream cities, while the upstream cities performed the poorest. Among the cities, Zibo stood out as the top performer in two-dimensional decoupling, successfully balancing economic development with sustainable water resource usage. On the other hand, Bayannur, whose economic growth was highly dependent on water resource consumption, scored the lowest.

3. The two-dimensional decoupling states of cities in the YRB were found to be unstable, with only three cities (Zhengzhou, Zhangye, and Xinzhou) maintaining their decoupling states. The remaining 57 cities experienced shifts in their decoupling states. Although the proportion of the two ideal decoupling states, HE-SD and HE-WD, increased from 18.33% to 43.33%. one-quarter of the cities whose GDP crossed the second inflection point still failed to achieve sustainable decoupling. In addition, the decoupling state is prone to change, especially the ideal decoupling state is difficult to maintain. Therefore, decoupling WEF from economic growth remains an urgent issue in the YRB.

6.2 Recommendations

Reducing the dependence of economic growth on WEF is a pressing concern that we must address in the sustainable development of the Yellow River Basin. Based on the above research findings, the following policy recommendations were proposed:

1. Water conservation is a promising solution to address the water scarcity in the YRB. It is crucial to reinforce the strict limitations on water resources in the region. Urban development and production must avoid exploiting water resources in a harmful manner. In particular, water-intensive industries and projects should be phased out. When determining urban water consumption indicators, emphasis should be placed on achieving a balance between water usage and economic development. Thus, establishing an information-sharing platform for the YRB will aid in coordinating inter-regional water use conflicts and improving the allocation of water resources within the basin, ultimately reducing disparities in the WEF.
2. Cities with a *per capita* GDP surpassing the second inflection point (56,954 yuan) are more likely to rely on water resources for their economic development. Therefore, when improving the eco-sustainable usage of water resources in cities in the YRB, economic development must be taken into account. This means that cities should not prioritize economic growth at the expense of over-consuming water resources, nor should they overlook the disparity between decoupling and economic development. In particular, for the upstream cities and midstream cities, several key measures can help alleviate the contradiction between the WEF and economic growth. These measures include rational city planning, improving industrial water use technology and water resources utilization efficiency, and fostering the construction of water-saving cities.
3. The coordination between economic development and decoupling in the YRB needs to be improved. Currently, 41.67% of the cities in the YRB are facing the challenge of balancing economic growth with sustainable water resource consumption. To address this issue, cities must modify their economic development patterns and accelerate the advancement of water-saving industries. However, the two-dimensional decoupling state of WEF in the YRB was found to be unstable. Cities that have successfully achieved the dual goals of economic development and ideal decoupling should focus on further improving the quality of economic development. This can be achieved by implementing strategies such as fostering the application of water-saving technology and continuously optimizing the economic development mode. In addition, cities like Wuhai, Ordos, Jinan, and Yinchuan, characterized as unsustainable development types, still face the dual task of sustaining economic growth and facilitating decoupling. These cities must prioritize enhancing the marginal benefit of water resources to achieve sustainable usage while maintaining economic growth.

Data availability statement

The raw data supporting the conclusion of this article will be made available by authors, without undue reservation,please contact to the corresponding author if you need the raw data.

Author contributions

XZ: Conceptualization, Methodology, Writing – review and editing. XL: Data curation, Formal Analysis, Writing – review and editing. YX: Validation, Visualization, Writing – original draft.

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1658998/full#supplementary-material

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