Decoupling mechanism of heavy metal water pollutant discharge in the Yellow River Basin

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Abstract. The decoupling of economic growth and heavy metal water pollution discharge in the Yellow River Basin is conducive to the coordinated promotion of large-scale governance. Although there are abundant researches on the decoupling elasticity of resource and environment consumption and its driving effect, there are few microscopic analyses on the driving effect. In view of this, Tapio and LMDI model for the Yellow River basin in 2011-2017 economic growth and heavy metal water pollutants decoupling state and driving effect, explain the decoupling mechanism of heavy metal discharge in the Yellow River basin. The results show that: (1) Although there is a strong decoupling state at the basin level (except 2014-2015), the decoupling situation in the upstream region is still very unstable. (2) The sewage discharge intensity effect is the dominant effect driving the discharge decoupling of heavy metal water pollutants in the basin; The income effect of industrialization is the dominant effect of restraining the decoupling of heavy metal water pollutant discharge.

Keywords: Decoupling; Heavy metal; Yellow River Basin.

1. Introduction

As the mother river of the Chinese nation, the Yellow River plays a prominent role in China's economic and social development and ecological security. Ecological protection and high-quality development of the Yellow River basin is a major national strategy. General Secretary Xi Jinping set forth the requirements for ecological protection of the Yellow River Basin and pointed out the path for high-quality development of the Yellow River Basin under the principle of "joint efforts to promote large-scale protection and coordinated efforts to promote large-scale governance". Since the 12th Five-Year Plan period, significant progress has been made in environmental governance of the Yellow River basin. The total amount of major pollutants in the middle and upper reaches of the basin has been significantly reduced, such as COD and NH3-N emissions, which have been reduced by 14.5% and 11.4% respectively, and water quality has been significantly improved. However, as an important source of water carrying the development of China's important energy and chemical bases, industrial pollution, especially the "five toxic" water pollutants of heavy metals such as cadmium, nickel and mercury has not been effectively controlled. For example, the arsenic, cadmium and mercury pollutants in Shuangqiao, Henan Province exceeded the standard in 2014, the mercury pollution in Sanhekou Bridge, Shaanxi Province exceeded the standard in 2016 and the mercury pollution in Potou, Henan Province...
exceeded the standard for many years. Heavy metal water pollution has a serious impact on the high-quality development of the Yellow River basin. Therefore, how to promote high-quality development while reducing heavy metal emissions, and jointly promote the large-scale governance of the Yellow River Basin, is worth in-depth thinking and research.

In physics, decoupling is used to analyze the strength of the interaction between no less than two physical quantities. In the field of resources and environment, decoupling theory measures the relationship between environmental change and economic development by the rate of change of growth. The relevant research results of domestic and foreign scholars are as follows: (1) The relationship between economic growth and water pollution discharge in different regions. Pan An’è et al. [1] adopted the decoupling evaluation model for the coordinated development of water resources, environment and economy, and learned that the utilization of water resources and economic growth in Hubei Province had declined from the high-quality coordination state before 2005 to the primary coordination state. Ma Hailiang et al. [2] made use of the eight states in the Tapio decoupling model to make a concrete analysis of the mutual relationship and the degree of action between the two, and concluded that the decoupling state in China presented a distribution situation of "weak south and strong north". (2) The relationship between economic growth and water pollution emissions in different industries. Nguyen, Aveso et al. [3] established a model to evaluate the relationship between economic activities and water pollution, analyze the correlation between industries, and divide the roles of industries into key industries, pollution drivers and promoters. Liu Hang et al. [4] drew on the Tapio decoupling model to construct an analysis model of the decoupling state between China’s economic growth and different environment-intensive industries, and made provisions on the criteria for the decoupling state and degree. (3) Factor decomposition of different decoupling states. In the study of the model, Wang Xifeng et al. [5] developed the conceptual model of steam engine and deduced the three sub-effects inside the decoupling effect, and developed the regional decoupling effect model by improving the structural decomposition analysis model based on input and output. On the basis of the Tapio decoupling model, Li Ning et al. [6] decomposed the elastic coefficient of decoupling into structural effect, technical effect and scale effect, and analyzed the decoupling relationship between water environmental pressure and economic growth. Yang Mengjie [7] adopted LMDI decomposition model to analyze the influence of technology, industry, economy and population factors on the change of regional blue water footprint and gray water footprint quantitatively in Shanghai from 1998 to 2016.

Although there are abundant researches on the decoupling elasticity of resource and environment consumption and its driving effect, there are few microscopic analyses on the driving effect, and the internal micro-factors have not been fully discussed. Moreover, the decoupling elasticity and driving factors of economic growth and resource consumption are easily influenced by samples. Under this premise, most scholars in the current literature only discuss individual provinces or the whole region of China, and fail to take the distribution of rivers in China as the basis of the research object, and fail to fully discuss the relationship and dynamic evolution among provinces within rivers. Therefore, on the basis of LMDI decoupling decomposition, this study analyzed and summarized the decoupling state between economic growth and heavy metal water pollutant discharge in various provinces of the Yellow River Basin.

2. The research methods

2.1. Decoupling decomposition based on LMDI

The Logarithmic Mean Divisia Index (LMDI) proposed by Ang solved the Index decomposition analysis the inherent salvage value and zero value problem, has the advantages of complete decomposition and result uniqueness, based on this, from the aspect of industrial emissions of heavy metals LMDI decomposition model is established, it links the discharge of heavy metal pollutants in waste water with industrial added value, urban population, total population and other factors, specific decomposition formula is as follows:
In the formula, MP represents heavy metal pollution emissions, MP\(_i\) represents heavy metal emissions of type \(i\), IA represents industrial added value, Pu represents urban population of the region, and P represents total population of the region. WS represents sewage discharge structure, WI represents sewage discharge intensity, WD represents income from industrialization, WU represents urbanization rate, and WP represents population size.

Formula (1) can be further simplified as:

\[
\triangle MP = \triangle WS + \triangle WI + \triangle WD + \triangle WU + \triangle WP
\]  

(2)

In the formula, \(\triangle MP\) represents the change in heavy metal pollution emissions; \(\triangle WS\) represents the changes in heavy metal pollution emission caused by sewage discharge structure; \(\triangle WI\) represents the change of heavy metal pollution emission caused by sewage discharge intensity; \(\triangle WD\) represents the change of heavy metal pollution emissions caused by industrial income; \(\triangle WU\) represents the change of heavy metal pollution emission caused by urbanization rate; \(\triangle WP\) represents the change of heavy metal pollution emissions caused by population size. In Formula (2):

\[
X = \sum_{i=1}^{5} W_i(WP_i^T, WP_i^0) \ln \frac{X_i^T}{X_i^0}
\]  

(3)

In the formula, X stands for \(\triangle MP\), \(\triangle WS\), \(\triangle WI\), \(\triangle WD\), \(\triangle WU\) and \(\triangle WP\) respectively. The weight function is defined as:

\[
W_i(WP_i^T, WP_i^0) = \begin{cases} 
\frac{MP_i^T - MP_i^0}{\ln MP_i^T - \ln MP_i^0}, & (MP_i^T \neq MP_i^0) \\
MP_i^T, & (MP_i^T = MP_i^0)
\end{cases}
\]  

(4)

The "decoupling" of Tapio created by the Elastic Coefficient Method reflects the relative change relationship of resources and environment with economic development by the ratio of growth rate, and breaks the limit of time to avoid the unreasonable fluctuation of decoupling state caused by the accidental choice of base period. Referring to the Tapio model, this paper denoted the decoupling index between the discharge of heavy metals in waste water and the added value of industrial production as the total decoupling index, and its formula is:

\[
e_{(WP, IA)} = \frac{\triangle MP / MP^0}{\triangle IA / IA^0}
\]  

(5)

In the formula, \(\triangle MP = MP^T - MP^0\) represents the changes in heavy metal emissions in period T relative to the base period, and \(MP^0\) represents the heavy metal emission in the base period. \(\triangle IA = IA^T - IA^0\) represents the change of industrial added value in T period relative to that in the base period, and \(IA^0\) represents the industrial added value in the base period. According to OECD [8], 0, 0.8, 1.2 is taken as the critical value, the decoupling index is divided into three state (connection status, decoupling and negative decoupling state), and then subdivided into eight grade (expansion connection, recession connection, weak decoupling, strong decoupling, recession decoupling, weak negative decoupling, strong negative decoupling and expansion negative decoupling) of each grade of concrete analysis is shown in figure 1:
The decoupling index between the heavy metal discharge in waste water and the industrial added value alone cannot reflect the specific influence degree of each factor on the decoupling state. Therefore, combined with LMDI method, the original decoupling index was decomposed into multiple decoupling impact indexes. The formula is as follows:

$$e_{(WP,IA)} = (\Delta WS + \Delta WI + \Delta WD + \Delta WU + \Delta WP) \times \frac{MP^0}{\Delta IA / IA^0}$$

In the formula, $tS$ represents the decoupling index of sewage discharge structure, $tI$ represents the decoupling index of sewage discharge intensity, $tD$ represents the decoupling index of industrial income, $tU$ represents the decoupling index of urbanization rate, and $tP$ represents the decoupling index of population scale. If the effect index of decoupling is opposite to that of the total decoupling index, the value of the total decoupling index will be reduced. If the industrial added value is growing, its $\Delta IA > 0$, when $\Delta W > 0$, it is helpful for the total decoupling index to make efforts towards weak decoupling in the first quadrant. When $\Delta W < 0$, it is beneficial for the total decoupling index to make efforts towards the strong decoupling state in the fourth quadrant. If the impact index of decoupling has a positive effect on the total decoupling index, the value of the total decoupling index will increase. If $\Delta W > 0$, the total decoupling index approaches the expansion negative decoupling state in the first quadrant. If $\Delta W < 0$, the total decoupling index has been in a strong decoupling state.

3. Source and analysis of data

3.1. Data source and processing

According to China Statistical Yearbook (2012-2018), the discharge of five heavy metals in the wastewater of the Yellow River provinces during 2011-2017 was obtained. In order to consider the superimposed effects of discharge of multiple pollutants on the water environment, the concept of pollution equivalent number of water pollution was introduced to calculate the comprehensive pollution equivalent number of five heavy metal pollutants and measure their comprehensive effects on the water environment of the basin.

The water pollution standard value takes the 1kg pollutant COD in water as a benchmark pollution equivalent, and then calculates and compares it with COD in accordance with the harmful degree of each water pollutant, the toxicity to organisms and the related costs of treatment. The calculation formula of pollution equivalent number of general water pollution $d$ is as follows:
3.2. Discharge characteristics of heavy metal water pollutants

The heavy metal emissions of each region are shown in Figure 2. It can be seen that the overall trend of heavy metal emissions in various regions is decreasing, and the regional differences showed a narrowing trend. However, heavy metal pollution in Inner Mongolia increased rather than decreased from 2011 to 2015. Especially in 2013 and 2015, the emission growth rate reached 66.74% and 44.65% respectively, until 2016, with a reduction rate of 76.73%, it has recovered to a level similar to that of other provinces. In 2011, Henan had the largest heavy metal emission (988.99t), followed by Gansu (906.31t), and Ningxia had the smallest (31.22t). In 2017, Henan showed a significant reduction in heavy metal emissions (65.40t), Gansu became the region with the largest heavy metal emissions (329.57t), followed by Sichuan (305.82t), and Ningxia still had the lowest heavy metal emissions (29.42t). In terms of the reduction range: Henan has the largest range (93.39%); Shandong followed (81.36%). Among the nine provinces, the least obvious reduction was in Ningxia (5.78%), which maintained a low level of heavy metal pollution all year round.

From the perspective of pollutants, the proportion of various heavy metal pollutants in each province is greatly different, as shown in Figure 3. In the upper reaches of the Yellow River, Qinghai and Inner Mongolia, arsenic accounted for 39.92% and 37.64% of the heavy metal pollutants. The mercury pollution in Sichuan and Ningxia accounted for 30.02% and 39.03% of the heavy metal pollution in the province. Gansu was lead (32.83%); In the middle and lower reaches of the Yellow River, the highest proportion of heavy metal pollution is cadmium, accounting for nearly 40%, and the total amount of cadmium pollution is huge. Among the nine provinces, the proportion of hexavalent chromium pollution is very low except that in Ningxia reaches 26.55%. However, the total amount of heavy metal pollution in Ningxia is always the least, so it can be concluded that the amount of hexavalent chromium pollution in the nine provinces is at a relatively low level.

![Figure 2. Total annual heavy metal emissions in each region](image)

![Figure 3. The proportion of heavy metal pollutants in each region](image)

4. Analysis on decoupling state and driving effect of heavy metal water pollution discharge

According to formula (5), the decoupling of heavy metal pollution emissions in various regions from 2011 to 2017 is shown in Table 1. From the overall level of all regions, the elasticity index of decoupling...
in 2011-2012 was -1.6, showing strong decoupling. From 2012 to 2014, the elasticity index of decoupling increased to -0.2, which still maintained a strong decoupling state, but there was a bad omen. From 2014 to 2015, the elasticity index of decoupling increased to 4.0, showing expansion negative decoupling, indicating that the Yellow River Basin region did not implement environmental protection policies while developing industry in this year, resulting in a sharp decline from strong decoupling to expansion negative decoupling. From 2015 to 2016, relevant departments of the State Council will further intensify efforts to urge provinces lagging behind to accelerate the implementation of the Comprehensive Prevention and Control of Heavy Metal Pollution "Twelfth Five-Year Plan" (hereinafter referred to as the "Plan"). The elasticity index of decoupling in regions along the Yellow River has been reduced to -8.7, restoring the state of strong decoupling. In 2016, the Ministry of Environmental Protection, together with relevant departments of the State Council, conduct a comprehensive assessment of the implementation of the Plan, and carry out a limited approval of environmental impact assessment for areas that fail to meet the targets of the Plan. From 2016 to 2017, the elasticity index of decoupling of all regions along the Yellow River remained -3.6, still in a state of strong decoupling. From the perspective of each region, from 2011 to 2012, except for Inner Mongolia, which was in a weak decoupling state, all other regions were in a strong decoupling state, and decoupling status of all regions was relatively good in this year. From 2012 to 2013, Shandong showed weak decoupling, Gansu showed expansion connection, Qinghai and Inner Mongolia showed expansion negative decoupling. From 2013 to 2014, the decoupling state of Inner Mongolia is still not ideal, and the extent of expansion negative decoupling is enhanced. Shaanxi showed weak decoupling, and the other regions are strong decoupling. From 2014 to 2015, the situation in all regions generally deteriorated. The decoupling index in Sichuan suddenly changed to 23.2, indicating a serious deterioration of the decoupling situation. Sichuan, Gansu and Inner Mongolia were also in the state of expansion negative decoupling, Shaanxi was in the state of expansion connection, and Shanxi was in the strong negative decoupling situation with the decline of industrial added value and the increase of heavy metal pollution. From 2015 to 2016, Ningxia showed expansion negative decoupling, while other regions improved and showed strong decoupling. From 2016 to 2017, the decoupling situation in some regions rebounded again. Qinghai, Sichuan, Ningxia and Shanxi showed expansion negative decoupling. In Gansu, the industrial added value decreased, and the decoupling state was recession decoupling. Shandong showed weak decoupling, and other regions maintained strong decoupling. It can be seen that the decoupling situation in the upper and middle reaches is very unstable and fluctuates greatly. The regulation of heavy metal pollution in these two regions needs to be further strengthened to maintain the common development between industry and environment and avoid the situation of developing industry at the expense of environment in some years. The decoupling situation of the two downstream regions, Henan and Shandong, is relatively stable and good, with strong decoupling in most years, and only Henan has experienced two weak decoupling.

| region         | 2011-2012 | 2012-2013 | 2013-2014 | 2014-2015 | 2015-2016 | 2016-2017 |
|----------------|-----------|-----------|-----------|-----------|-----------|-----------|
|                | 2012-2013 | 2013-2014 | 2014-2015 | 2015-2016 | 2016-2017 |
| Qinghai        | -2.9      | Strong    | 1.9       | Expansion negative | -1.1 | Strong | -1.1 | Strong | -5.3 | Strong | 3.7 |
| Sichuan        | -0.5      | Strong    | -4.1      | Strong | -0.9 | Strong | 23.2 | Expansion negative | -9.8 | Strong | 18.2 |
| Gansu          | -0.5      | Strong    | 0.8       | Expansion connection | -5.5 | Strong | 4.6 | Expansion negative | -3.1 | Strong | 51.4 |
| Ningxia        | -0.9      | Strong    | -2.6      | Strong | -9.6 | Strong | -1.7 | Strong | 12.2 | Expansion negative | 14.9 |
| Inner Mongolia | 0.6       | Weak      | 2.1       | Expansion negative | 21.5 | Expansion negative | 5.6 | Expansion negative | -11.1 | Strong | -29.8 |
| Shaanxi        | -2.6      | Strong    | -0.9      | Strong | 0.1 | Weak | 1.1 | Expansion connection | -4.0 | Strong | -2.5 |
| Shanxi         | -0.8      | Strong    | -1.3      | Strong | -8.5 | Strong | -5.3 | Strong negative | -53.0 | Strong | 27.8 |
| Henan          | -3.8      | Strong    | -1.8      | Strong | -3.8 | Strong | -5.5 | Negative | -4.3 | Strong | -8.0 |
| Shandong       | -2.1      | Strong    | 0.7       | Weak | -1.1 | Strong | -0.8 | Strong | -11.6 | Strong | 0.6 |
| River basin    | -1.6      | Strong    | -0.2      | Strong | -0.2 | Strong | 4.0 | Expansion negative | -8.7 | Strong | -3.6 |

**Table 1. Decoupling of years by region**

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The text above discusses the decoupling of industrial added value and heavy metal pollution in various regions along the Yellow River, with specific emphasis on the period from 2011 to 2017. It highlights the varying decoupling states across different regions, with a particular focus on the changes in elasticity indices and the implications for environmental protection policies. The table summarises the decoupling status for each region in the specified years, providing a clear overview of the decoupling trends.
(Explanation: The industrial added value of Shanxi Province during 2014-2015 and Gansu Province during 2016-2017 was negative)

On the analysis of the Yellow River basin, the regional industrial added value of production and the heavy metal pollution emissions, on the basis of decoupling state, in order to further explore the decoupling, using LMDI model, according to the formula (1) - (6), the total decoupling index subdivided into sewage discharge structure decoupling index, sewage discharge intensity decoupling index, industrial income decoupling index, urbanization decoupling index and population size decoupling index. (See figure 4 and 5.)

According to Figure 4 and 5, from 2011 to 2017, the sewage discharge structure of the upper reaches of the Yellow River showed a negative to positive effect on the total decoupling index, which was not conducive to the strong decoupling of the total decoupling index. In Inner Mongolia, the decoupling index of sewage discharge structure changed from 0.004 to -2.224, and the decoupling index of sewage discharge structure had a greater influence on the strong decoupling of the total index.

From 2011 to 2017, the decoupling index of pollutant discharge intensity in all regions of the upper reaches of the Yellow River is still not ideal. The change from negative to positive effect is not conducive to the trend of decoupling of the total decoupling index. In addition, the decoupling index of sewage discharge intensity in Gansu reached 49.771 in 2017, which had a huge impact on the total decoupling index. Inner Mongolia, Shaanxi, Henan and Shandong performed well in terms of sewage discharge intensity.

From 2011 to 2017, industrialization income decoupling index, urbanization decoupling index and population size decoupling index in all regions of the Yellow River had little change on the whole, which had a positive effect on the total decoupling index all year round, and was not conducive to the trend of decoupling of the total decoupling index.

By comparing the five decoupling indexes, it can be seen that from 2011 to 2017, except for Inner Mongolia, Shaanxi and Henan, the decoupling index of sewage discharge intensity shows a good trend, while the other regions show a change from negative to positive effect on the total decoupling index. The situation is not optimistic. The decoupling index of sewage discharge intensity in Gansu, Ningxia
and Shanxi all reached a large value, which had a great adverse effect on the total decoupling index. Except Inner Mongolia, the industrial income decoupling index in other regions has a positive effect on the total decoupling index, and the change is small. Except for Gansu, urbanization decoupling index and population size decoupling index in other regions have positive effects on the total decoupling index, and the effects are small and relatively stable.

5. Conclusion and discussion
The Tapio and LMDI models were used to obtain the decoupling state and driving effect of economic growth and heavy metal water pollutant discharge in the Yellow River Basin from 2011 to 2017. The specific conclusions and policy recommendations are as follows.

(1) From the perspective of the total decoupling index at the Yellow River Basin level, in the observation period, except for the expansion negative decoupling in 2014-2015, all other periods showed strong decoupling. After the sharp decline from strong decoupling to expansion negative decoupling, the relevant departments of the State Council further implemented the Plan. In the next year, the regions along the Yellow River resumed the state of strong decoupling, and the national regulation of industrial pollution played a vital role. Horizontally, the decoupling situation in the upper and middle reaches is very unstable and fluctuates greatly. The supervision of heavy metal pollution in these two regions needs to be further strengthened to maintain the common development between industry and environment and avoid the situation of developing industry at the expense of environment in some years. The decoupling situation of the two downstream regions, Henan and Shandong, is relatively stable and good, with strong decoupling in most years.

(2) The sewage discharge intensity effect is the dominant effect driving the decoupling of heavy metal water pollutants in the river basin. Enterprises should correct the discharge of heavy metal pollution from the following two aspects: First, the most fundamental is to reform the production process. Do not use or use less toxic heavy metals; Secondly, the use of reasonable technological process, scientific management and operation, reduce the amount of heavy metal and waste water loss, as far as possible to reduce the amount of waste water discharge. The income effect of industrialization is the dominant effect of restraining the decoupling of heavy metal water pollutant discharge. We should put an end to the serious absence of environmental regulation by local governments under the impulse of "GDP first". From the perspective of industrial optimization and upgrading, experience shows that the formation of environmental coercion mechanism can effectively promote the transformation and upgrading of the heavy metal industry.

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