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Decomposition and attribution analysis for assessing the progress in decoupling industrial development from wastewater discharge in China

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ABSTRACT

China's strategy of greening industrial development aims to decouple industrial growth from industrial wastewater discharges (IWDs). This study combines decoupling analysis, decomposition analysis, and attribution analysis to support this goal. First, the decoupling analysis is employed to explore the degree of decoupling between industrial growth and IWDs in China, as well as across 30 provinces, from 2000 to 2015. Next, a decomposition analysis focusing on the change in industrial wastewater discharge intensity (IWDI) is performed to reveal the factors influencing decoupling trends. Then, attribution analysis is used to attribute contributions of these factors to different regions. Our decoupling results indicate an increasing decoupling trend between industrial output and IWDs in China in the past 15 years. Meanwhile, there is a convergence in decoupling degrees among provinces. Decomposition results reveal that water intensity plays a dominant role in promoting decoupling, while the wastewater discharge coefficient negatively impacted decoupling before 2005 but contributed to decoupling later on. Regional attribution results indicate provinces in South China have exerted more efforts in both water saving and wastewater treatment during the study period. Water scarce provinces in North China performed better in terms of water saving, while more developed and water-rich provinces in South China performed better in wastewater treatment. This paper suggests targeted policy methods at province level.

1. Introduction

China has achieved remarkable results in economic development during the last four decades (Feng et al., 2014b; Xing et al., 2018a). In 2010, China overtook Japan and became the second largest contributor to world's gross domestic product (GDP) only next to the United States (Zhu et al., 2017). As a pillar of China's economy, the industrial sector played an important role in this expansion with witnessed sevenfold increase from about 4 trillion yuan in 2000 to nearly 28 trillion yuan in 2015 (2000 constant price, Fig. 1, blue curve). However, the rapid industrialization has resulted in large-scale consumption of natural resources and great environmental pressures (Xing et al., 2018b; Wang et al., 2018b). Water pollution is one of the most severe environmental problems that not only destroys hydrological systems but also exacerbates existing water scarcity issues in China (Feng et al., 2014a). Evidence has been found that the increases in industrial wastewater discharges (IWDs) are the main culprit of much of China's water pollution (Geng et al., 2014). Therefore, IWDs control has become one of the environmental policy foci in the country.

Different from industrial growth (Fig. 1, blue curve), the changing trend of China's IWDs varied in different periods, showing an inverse "U" shape (Fig. 1, orange curve) similar to the Environmental Kuznets Curve hypothesis. In order to coordinate industrial development and IWDs, the Chinese government has launched important water

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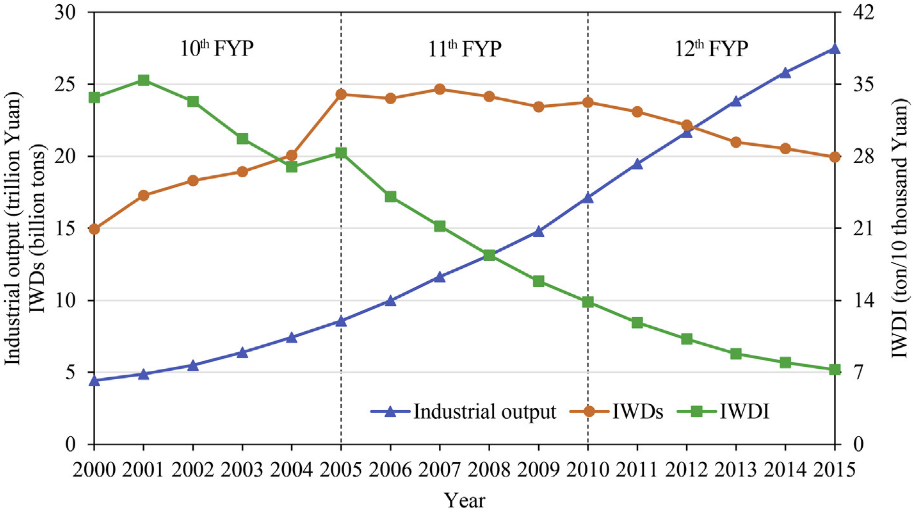

Fig. 1. The trends of industrial output, IWDs and IWDI in China, 2000–2015.[11]

quality control policies, such as the strict water management plan known as the “Three Red Lines” (SCC, 2012) and Water Pollution Control Action Plan named as the “Ten Measures for Water” (SCC, 2015), and introduced a levy system to strengthen wastewater management in Chinese industrial sectors (SCC, 2016a). As regulated by Ministry of Industry and Information Technology of China (MIITC), 2 billion tons of IWDs, 2.5 million tons of chemical oxygen demand and 250 thousand tons of ammonia nitrogen from the industry need to be cut by 2020 on the basis of 2015 (Ministry of Industry and Information Technology of China (MIITC), 2016). The amount of water reaching the quality standards set in water environment function zones was required to reach at least 95% by 2030 (SCC, 2012). To this end, the Chinese government formulated specific treatment schemes for pollution-intensive industrial sectors such as papermaking, coking, nitrogen fertilizer, non-ferrous metals, printing and dyeing to promote the clean transformation (SCC, 2015). Thanks to the long-term efforts made by the Chinese government, the industrial wastewater discharge intensity (IWDI) achieved a significant decline during the study period (Fig. 1, green curve).

China’s green strategy of industrial development aims to decouple industrial development from IWDs and ensure a continual decline in IWDI (Ministry of Industry and Information Technology of China (MIITC), 2016). To support this goal, this study has analyzed the decoupling relationship between China’s industrial growth and IWDs, discussed the factors influencing the decoupling trends, and further attributed the contributions of these factors to different regions. This could help China’s government understand the patterns and causes of the decoupling trends and facilitate targeted mitigation policies at the province level.3

2. Literature review

Since entering the era of Industrial Civilization, the world has been faced with increasing environmental pressures caused by rapid economic growth. In this context, the research on the relationship between economic growth and environmental degradation has received lots of attention. Decoupling analysis, developed by the Organization for Economic Co-operation and Development (OECD), has been a popular technique in this context (OECD, 2002). Literature provides numerous studies on decoupling with a focus on diverse environmental indicators, such as energy usage (Csereklyei and Stern, 2015; Yu et al., 2017; Moreau and Vuille, 2018; Akizu-Gardoki et al., 2018; Zhang et al., 2018), carbon emissions (Grand, 2016; Schandl et al., 2016; Wang et al., 2017b; Wu et al., 2018b; Cohen et al., 2019; Hang et al., 2019) and air pollution (Lu et al., 2015; Åström et al., 2017; Jiao et al., 2017; Madden et al., 2019) to name just a few. Many studies have also focused on the decoupling of economic growth from IWDs in China. For instance, Ma et al. (2017) employed Tapio decoupling model to analyze the relationships between industrial growth and IWDs across 31 provinces of China from 2009 to 2014. They found that most regions except for Guizhou province achieved decoupling. Wang et al. (2018d) applied Tapio decoupling model to investigate the relationship between urban economic output and wastewater discharge in Beijing, Guangzhou, and Shanghai. They found that Guangzhou had the highest degree of decoupling, followed by Shanghai and Beijing. Li et al. (2018) analyzed the decoupling elasticity between economic growth and wastewater discharge in China’s textile industry and its three sub-sectors from 2001 to 2014. The results show an overall decoupling.

Decoupling analysis can describe the dynamic relationship between economy and environment, while decomposition analysis can effectively identify socioeconomic factors driving environmental pressures (Hang et al., 2019). In the literature, index decomposition analysis (IDA) and structural decomposition analysis (SDA) are the two widely accepted decomposition methods (Feng et al., 2012). Compared with SDA, IDA has many desirable properties like theoretical foundation, adaptability and ease of use (Mohmmed et al., 2019). In particular, the Logarithmic Mean Divisia Index (LMDI) is a preferred IDA decomposition approach due to its strength in handling zero values (Ang et al., 2015). There is a growing body of literature applying LMDI to energy and emissions issues (Ma and Stern, 2008; Mousavi et al., 2017; Zhang et al., 2016a; Wang et al., 2018a; Dong et al., 2018; Guan et al., 2018; Farajzadeh and Nematollahi, 2018). In terms of IWDs, Geng et al. (2014) employed LMDI method to identify the driving factors of IWDs in China from 1995 to 2010. The results indicated that economic factors were the main driving forces for increasing IWDs, while technology improvement considerably offset the increases. Zhang and Wu (2015) used the LMDI method to analyze the driving factors of the IWDs in China from 1998 to 2012. They found that technology progress inhibited the increase in IWDs, while industrial economic growth and population scale were contributors to IWDs. Chen et al. (2019) applied the LMDI to examine the driving factors of IWDs in Yangtze River Economic Zone from 2002 to 2015. They found that population and economy development effects increased the IWDs, while the technical improvement showed an improvement.

It can be seen that existing studies have either investigated the decoupling relationship between economic development and IWDs, or identified factors influencing the change in IWDs. To the best knowledge of the authors, few scholars have paid attention to the driving forces behind the decoupling trends. In fact, the combined decoupling and decomposition analysis has been widely applied to energy and emissions issues (Diakoulaki and Mandaraka, 2007; Wang et al., 2016, 2020; Zhang et al., 2018; Hang et al., 2019; Zhang et al., 2019b; Wang and Su, 2020). For example, Hang et al., 2019 employed the combined decoupling and decomposition method to explore the decoupling relationship between manufacturing growth and carbon emissions and analyze the factors influencing changes in decoupling status. The results indicated that the potential energy intensity was the dominant factor in promoting the decoupling process, while the output scale effect was the main inhibitory factor.

In addition, the observation of decline in the ratio of environmental pressures to economic output can be interpreted as signaling the decoupling trends between economy and environment (Bithas and Kalimeris, 2018). Thus, Wang et al., 2016 performed a decomposition analysis on the change in carbon intensity to reveal the influencing factors behind the decoupling trends in Taiwan's industry from 2007 to 2013. They found that energy intensity effect played the dominant role in promoting decoupling, and both energy structure effect and industrial structure effect negatively impacted decoupling. Similarly, Zhang et al. (2019b) have investigated factors influencing the decoupling process between industrial development and carbon emissions in Xinjiang, China from 2000 to 2014 by decomposing the change in carbon intensity. They found that energy intensity was a driver for decoupling, whereas industrial structure and energy structure were the barriers to decoupling. Following this example, we performed a decomposition analysis on the change in IWDI to reveal the influencing factors behind the decoupling trends between industrial growth and IWDs.

An extension of IDA method, attribution analysis, proposed by Choi and Ang (2012), can be used to attribute the contributions of different driving factors to individual components like sub-sectors or sub-regions. The method combined with LMDI models has been widely applied in energy and emissions studies. For example, Liu et al. (2015) applied the combined method to explore the driving factors of carbon intensity changes in China's industrial sector and attribute the contribution of each factor to various sub-sectors. Wang et al. (2016) analyzed the driving forces of industrial carbon intensity changes in Taiwan and attributed the contribution of each factor to various sub-sectors. Wang et al. (2017a) performed a similar analysis in changes of carbon intensity in China's energy-intensive industries during 1996–2014. Wang et al. (2018c) applied the integrated model combing decomposition methods and attribution analysis to study changes of China's industrial carbon intensity from 2006 to 2014. Zhang et al. (2019a) identified the influencing factors of energy intensity change in Shanxi, China from 2001 to 2015 and attributed the contribution of each factor to 38 detailed sectors. Following this example, we further attributed the contribution of the factors influencing the change in national IWDI to 30 provincial regions. This could help deepen the understanding of the reasons behind the decoupling trends between industrial growth and IWDs from various regions and assist China's government to formulate targeted wastewater mitigation measures at province level.

There are some research gaps in the literature. First, existing studies have either investigated the decoupling relationship between economic development and IWDs, or identified factors influencing the change in IWDs. However, few studies paid attention to the driving forces behind the decoupling trends, and fewer explored the contributions of various regions to these factors. Second, the decomposition and attribution analysis focusing on the IWDI is relatively less well understood compared to other indicators. To this end, this study performs a systematical investigation on the relationship between industrial development and IWDs among provinces in China from 2000 to 2015 covering the 10th, 11th and 12th Five-Year-Plan periods. More specifically, the decoupling analysis was first employed to explore the decoupling relationship between industrial development and IWDs. Next, the decomposition analysis focusing on the change in IWDI was performed to reveal the factors influencing the decoupling trends. Then, the attribution analysis was used to attribute the contributions of these factors to different regions.

3. Methods and materials

3.1. Decoupling index

The decoupling degree between economy and environment depends on the relative size of their growth rates. When the economy grows faster than environmental impacts, there is a decoupling relationship. Otherwise, a negative decoupling relationship will be observed. According to Wang et al. (2018d) and Zhang et al. (2019b), a decoupling index between IWDs and industrial output can be constructed in Eq. (1).

$$di=\frac{\Delta B\%}{\Delta Y\%}-1=\frac{\Delta B_{\tau,t}/B_\tau}{\Delta Y_{\tau,t}/Y_\tau}-1 \tag{1}$$

where di denotes the decoupling index between IWDs and industrial output; B and Y respectively denote IWDs and industrial output; $\Delta B_{\tau,t}$ and $\Delta Y_{\tau,t}$ respectively denote the changes in IWDs and industrial output between time τ and t; $\Delta B\%$ and $\Delta Y\%$ denote the corresponding percentage changes over the period $[\tau, t]$.

Eq. (1) was employed to estimate the IWDs change ($\Delta B\%$), industrial output change ($\Delta Y\%$) and decoupling index (di) in China from 2000 to 2015. According to these estimates, we can judge the decoupling status between IWDs and industrial output in a certain period. The detailed classification standards on the decoupling relationships are expressed in Table S1.

Eq. (1) can be transformed to make a connection between decoupling index and IWDI, as shown in Eq. (2).

$$\begin{aligned} di &= \frac{\Delta B_{\tau,t}/B_\tau}{\Delta Y_{\tau,t}/Y_\tau}-1=\frac{(B_t-B_\tau)/B_\tau}{(Y_t-Y_\tau)/Y_\tau}-1=\frac{(B_t/B_\tau-1)-(Y_t/Y_\tau-1)}{Y_t/Y_\tau-1} \\ &= \frac{B_t/B_\tau-Y_t/Y_\tau}{Y_t/Y_\tau-1}=\frac{1}{1-Y_\tau/Y_t}\times\left(\frac{B_t/Y_t}{B_\tau/Y_\tau}-1\right) \\ &= \frac{1}{1-Y_\tau/Y_t}\times\left(\frac{IWDI_t}{IWDI_\tau}-1\right) \end{aligned} \tag{2}$$

where $(1-Y_\tau/Y_t)$ is larger than 0 as the industrial output presents a monotonically increasing trend in the study period (Fig. 1, blue curve). Therefore, as illustrated in Eq. (2), whether the industrial growth and IWDs can be decoupled or negatively decoupled depends on the change of IWDI. More specifically, decoupling occurs when IWDI decreases, otherwise it is negative decoupling (Wang et al., 2016; Bithas and Kalimeris, 2018; Zhang et al., 2019b).

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[1] In line with the Chinese Five-year plan (FYP), we divide the study period (2000–2015) into three stages, namely, 2000–2005 (10th FYP period), 2005–2010 (11th FYP period), and 2010–2015 (12th FYP period).

3.2. Decomposition analysis

Suppose that the entire economy comprises N regions ($j = 1, 2, \ldots, N$). Following Geng et al. (2014) and Chen et al. (2019), the IWDI (BI) can be typically expressed as follows:

$$BI = \frac{B}{Y} = \sum_{j=1}^{N} \frac{B_j}{W_j} \frac{W_j}{Y_j} \frac{Y_j}{Y} \tag{3}$$

where B denotes total IWDs; Y denotes total industrial output; B_j denotes IWDs of region j; Y_j denotes the industrial output of region j; W_j denotes industrial water consumption of region j.

Suppose that the overall IWDI varies from time $t-1$ to t (i.e. BI^t/BI^{t-1}). Such a change can be expressed in the following multiplicative form as Eq. (4).

$$\begin{aligned} \frac{BI^t}{BI^{t-1}} &= \frac{\sum_{j=1}^{N} \left(B_j^t/W_j^t\right) \cdot \left(W_j^t/Y_j^t\right) \cdot \left(Y_j^t/Y^t\right)}{\sum_{j=1}^{N} \left(B_j^{t-1}/W_j^{t-1}\right) \cdot \left(W_j^{t-1}/Y_j^{t-1}\right) \cdot \left(Y_j^{t-1}/Y^{t-1}\right)} \\ &= \frac{\sum_{j=1}^{N} WDC_j^t \cdot WI_j^t \cdot GS_j^t}{\sum_{j=1}^{N} WDC_j^{t-1} \cdot WI_j^{t-1} \cdot GS_j^{t-1}} \end{aligned} \tag{4}$$

where $WDC_j^t = B_j^t/W_j^t$ and $WDC_j^{t-1} = B_j^{t-1}/W_j^{t-1}$ respectively wastewater discharges coefficient of region j at time t and $t-1$; $WI_j^t = W_j^t/Y_j^t$ and $WI_j^{t-1} = W_j^{t-1}/Y_j^{t-1}$ respectively denote water intensity of region j at time t and $t-1$; $GS_j^t = Y_j^t/Y^t$ and $GS_j^{t-1} = Y_j^{t-1}/Y^{t-1}$ denote the share of industrial GDP output of region j at time t and $t-1$.

Eq. (4) indicates that IWDI change is related to three factors, such as wastewater discharges coefficient (WDC), water intensity (WI) and geographical structure of industrial output (GS). Based on the Sato-Vartia LMDI method proposed by Ang and Choi (1997), the decomposition results of total change in IWDI can be given in Eqs. (5a)–(5e).

$$D_{tot}^{t-1,t} = \frac{BI^t}{BI^{t-1}} = D_{WDC}^{t-1,t} \times D_{WI}^{t-1,t} \times D_{GS}^{t-1,t} \tag{5a}$$

$$D_{WDC}^{t-1,t} = \exp\left(\sum_{j=1}^{N} \omega_j^{S-V} \ln \frac{WDC_j^t}{WDC_j^{t-1}}\right) \tag{5b}$$

$$D_{WI}^{t-1,t} = \exp\left(\sum_{j=1}^{N} \omega_j^{S-V} \ln \frac{WI_j^t}{WI_j^{t-1}}\right) \tag{5c}$$

$$D_{GS}^{t-1,t} = \exp\left(\sum_{j=1}^{N} \omega_j^{S-V} \ln \frac{GS_j^t}{GS_j^{t-1}}\right) \tag{5d}$$

$$\omega_j^{S-V} = \frac{L\left(B_j^{t-1}/B^{t-1}, B_j^t/B^t\right)}{\sum_{j=1}^{N} L\left(B_j^{t-1}/B^{t-1}, B_j^t/B^t\right)} \tag{5e}$$

where $D_{WDC}^{t-1,t}$, $D_{WI}^{t-1,t}$ and $D_{GS}^{t-1,t}$ respectively measure the WDC, WI and GS effects over the period $[t-1, t]$; ω_j^{S-V} denotes the weight of region j and $L(a,b) = (b-a)/(\ln b - \ln a)$ is the logarithmic mean function.

Eqs. (5a)–(5e) describes the single-period decomposition results of IWDI change. In the case of the multi-period decomposition, the accumulative effect $D_{tot}^{0,T}$ from time 0 to T can be calculated by Eq. (6) (Choi and Ang, 2012).

$$\begin{aligned} D_{tot}^{0,T} &= \frac{BI^T}{BI^0} = \prod_{t=1}^{T} \frac{BI^t}{BI^{t-1}} = \prod_{t=1}^{T} \left(D_{WDC}^{t-1,t} \times D_{WI}^{t-1,t} \times D_{GS}^{t-1,t}\right) \\ &= D_{WDC}^{0,T} \times D_{WI}^{0,T} \times D_{GS}^{0,T} \end{aligned} \tag{6}$$

where $D_{WDC}^{0,T}$, $D_{WI}^{0,T}$ and $D_{GS}^{0,T}$ are the corresponding cumulative products of single-period decomposed indexes.

3.3. Regional attribution analysis

The attribution analysis is applied to further attribute the changes in driving factors to various regions (Choi and Ang, 2012). The method has a requirement on the weights, the sum of which should equal to unity. This is why we choose the Sato-Vartia LMDI method other than the Montgomery-Vartia to model Eqs. (5a)–(5e) (Choi and Oh, 2014). Regional attribution analysis is given in the following by using the case of the GS effect (i.e. $D_{GS}^{t-1,t}$). The single-period attribution results in the period $[t-1, t]$ can be described in Eq. (7).

$$\begin{aligned} D_{GS}^{t-1,t} - 1 &= \sum_{j=1}^{N} c_{GS,j}^{t-1,t} = \sum_{j=1}^{N} r_{GS,j}^{t-1,t} \left(\frac{GS_j^t}{GS_j^{t-1}} - 1\right) \\ r_{GS,j}^{t-1,t} &= \frac{\dfrac{\omega_j^{S-V}}{L\left(GS_j^{t-1} D_{GS}^{t-1,t}, GS_j^t\right)} GS_j^{t-1}}{\sum_{j=1}^{N} \dfrac{\omega_j^{S-V}}{L\left(GS_j^{t-1} D_{GS}^{t-1,t}, GS_j^t\right)} GS_j^{t-1}} \end{aligned} \tag{7}$$

where $c_{GS,j}^{t-1,t}$ denotes the contribution of region j to the GS effect; $r_{GS,j}^{t-1,t}$ is the weight of region j, indicating its impact on the GS effect. Eq. (7) indicates that the single-period percentage change of the GS effect can be attributed to various regions.

The multi-period attribution results can be derived from Eq. (7) and the formula is described in Eq. (8).

$$D_{GS}^{0,T} - 1 = \sum_{j=1}^{N} c_{GS,j}^{0,T} = \sum_{j=1}^{N} \sum_{t=1}^{T} D_{GS}^{0,t-1} c_{GS,j}^{t-1,t} \tag{8}$$

where the item $c_{GS,j}^{0,T} = \sum_{t=1}^{T} D_{GS}^{0,t-1} c_{GS,j}^{t-1,t}$ refers to the multi-period contribution of region j to the GS effect in period $[0, T]$. Analogs to the foregoing derivations described as Eqs. (7) and (8), we can also obtain the contribution of region j to the WDC and WI effects.

3.4. Date sources

The data for industrial water consumption, industrial output and industrial wastewater discharges of 30 provincial administration regions (denoted as provinces hereafter) in China from 2000 to 2015 were gathered from China Statistical Yearbook on Environment, China Statistical Yearbook and Statistical Yearbooks across 30 provinces between 2001 and 2016. Industrial output is based on 2000 constant prices.

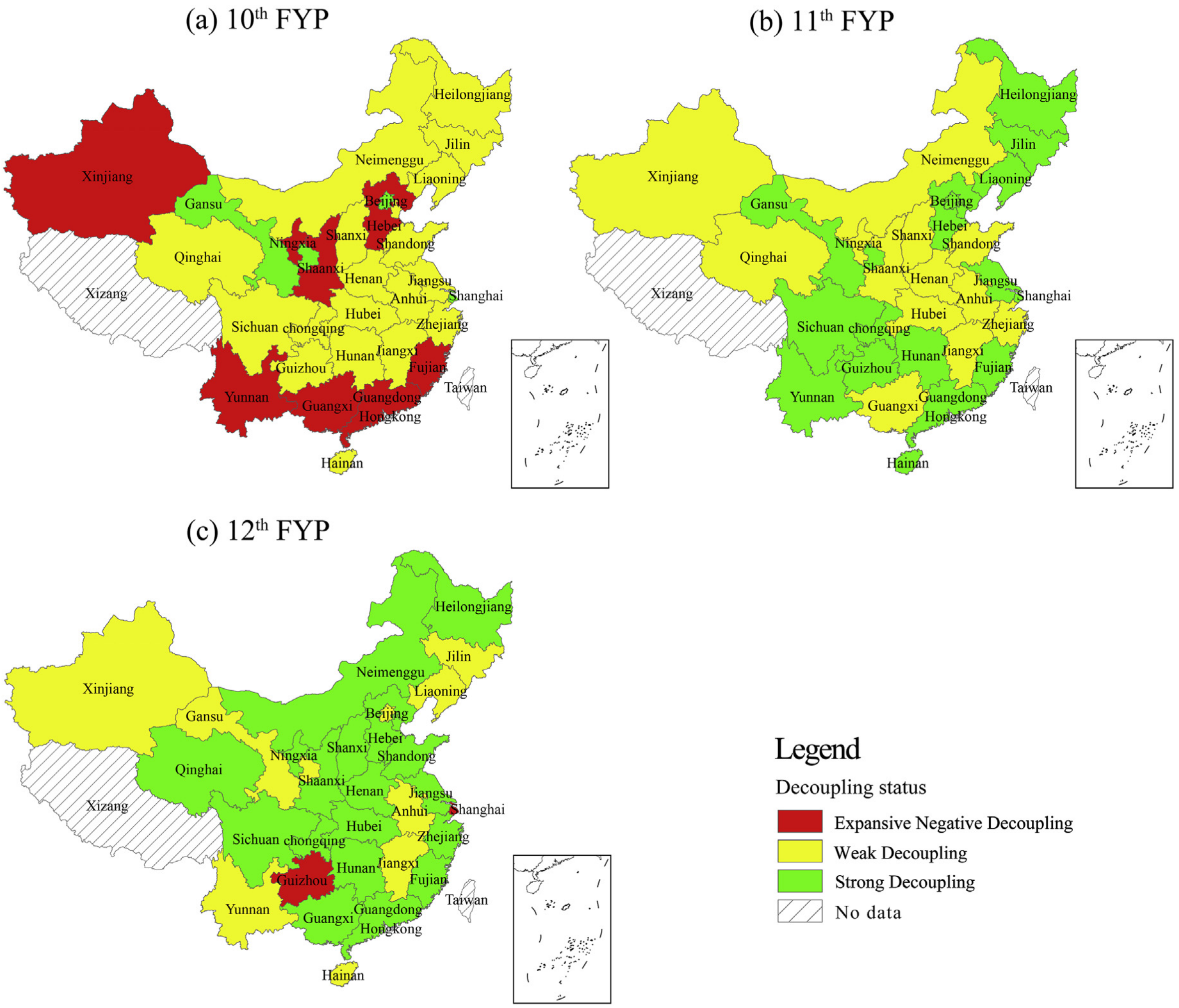

Fig. 2. Decoupling states for the 30 Chinese provinces during three stages.

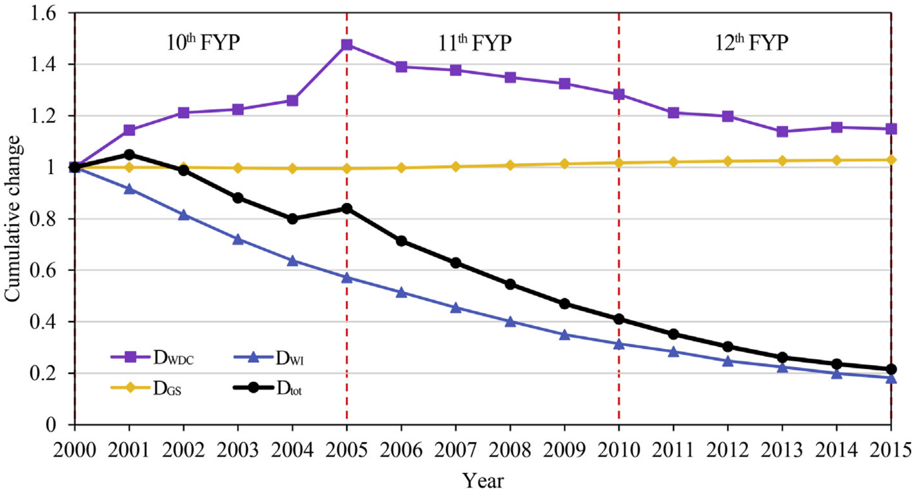

Fig. 3. Cumulative changes in China's IWDI and its decomposition (WDC, WI, GS and tot denote wastewater discharges coefficient, water intensity, geographical structure and total change in IWDI, respectively).

Table 1
Decoupling results between China's industrial output and IWDs from 2000 to 2015.

Stages	Periods	$\Delta Y/Y$	$\Delta B/B$	di	States
10th FYP	2000–2001	0.102	0.157	0.532	END
	2001–2002	0.126	0.060	−0.524	WD
	2002–2003	0.160	0.034	−0.787	WD
	2003–2004	0.167	0.060	−0.643	WD
	2004–2005	0.154	0.212	0.376	END
11th FYP	2005–2006	0.163	−0.012	−1.073	SD
	2006–2007	0.166	0.027	−0.838	WD
	2007–2008	0.129	−0.020	−1.158	SD
	2008–2009	0.127	−0.030	−1.238	SD
	2009–2010	0.160	0.013	−0.917	WD
12th FYP	2010–2011	0.136	−0.028	−1.203	SD
	2011–2012	0.111	−0.040	−1.361	SD
	2012–2013	0.101	−0.053	−1.526	SD
	2013–2014	0.083	−0.021	−1.259	SD
	2014–2015	0.065	−0.028	−1.439	SD

Note: END denotes expansive negative decoupling; WD denotes weak decoupling; SD denotes strong decoupling.

4. Results

4.1. Decoupling analysis

Our results show that two decoupling states of expansive negative decoupling and weak decoupling appeared in the 10th FYP period, two states of weak decoupling and strong decoupling appeared in 11th FYP period, and strong decoupling appeared throughout 12th FYP period. This indicates an increasing decoupling degree between industrial output and IWDs in China over the three time periods. The expansive negative decoupling observed in 2000–2001 and 2004–2005 corresponds to the occurrence of IWDI increase as shown in Fig. 1. It perfectly illustrates the connection between decoupling and IWDI.

Fig. 2 further presents the decoupling of 30 provinces in the three stages (10th FYP, 11th FYP and 12th FYP). As indicated in Fig. 2(a), three decoupling states of expansive negative decoupling, weak decoupling and strong decoupling appeared in the 10th FYP period across 30 provinces. Expansive negative decoupling emerged in 8 provinces and weak decoupling appeared in 19 provinces. Only Beijing, Shanghai and Gansu showed strong decoupling in this time period. The finding that Beijing and Shanghai experienced strong decoupling in the 10th FYP is not surprising, as they were the very few regions in China with advanced technology and equipment (Chen et al., 2016; Wu et al., 2018a), optimized industrial structure (Geng et al., 2014) and preferable environmental policies (Cheng et al., 2018; Chen et al., 2019). However, for the less developed inland province, Gansu, it may be due to that its Zhangye City was selected as the first pilot city for building Water-saving Society in 2002, which helps improve water use efficiency and reduce wastewater discharges of Gansu. The expansive negative decoupling and weak decoupling trends suggest that China's IWDs were closely tied with industrial expansion in this period (Lei et al., 2012; Yang and Li, 2017; Chen et al., 2019). This is related to China's accession to the World Trade Organization (WTO), which resulted in the emergence of a lot of pollution-intensive enterprises and industrial parks. Undoubtedly, the scale expansion in industrial production contributed not only to the boom of industrial economy, but also to the increase of IWDs.

During the 11th FYP period, the decoupling degree was better than that in previous years, as shown in Fig. 2(b). 13 provinces experienced weak decoupling and 17 provinces experienced strong decoupling. Fig. 2(c) shows the strong decoupling trend further expanded to 19 provinces in the 12th FYP period. The finding is not surprising as the water saving and wastewater treatment policies like Water-saving Society Construction, the stringent water management plan of "Three Red Lines" and the Water Pollution Control Action Plan were effectively implemented across all provinces in this period. Notably, our results show that Shanghai had expansive negative decoupling in the 12th FYP period, which seems surprising compared with other provinces. In fact, due to holding the 41st World Expo in 2010, Shanghai largely shut down emission-intensive production activities in this year (The People's Government of Shanghai City, 2011), which undoubtedly reduced IWDs to a lower level than during other years (See Fig. S1 for details). However, with the loosening of environmental regulation after the World Expo, the pollution in Shanghai rebounded after 2010 (Huang et al., 2013). Therefore, it is reasonable that Shanghai showed an expansive negative decoupling state in the 12th FYP period when 2010 is taken as the base year. The decoupling state of Guizhou was found to switch from strong decoupling to expansive negative decoupling in the 12th FYP period (Fig. 3(b) and (c)). The finding is consistent with Zhang et al., 2016b and Ma et al. (2017) and may be due to its strategy of "Industry Strengthens Province" proposed in the outline of the 12th FYP for economic and social development of Guizhou Province (The People's Government of Guizhou Province, 2011). Overall, there is a witnessed convergence in decoupling degrees among provinces during the three periods.

4.2. Decomposition analysis

Fig. 3 shows the decomposition results on the change in national IWDI from 2000 to 2015[2], which could reveal the influencing factors behind the decoupling trends between industrial development and IWDs in China (Table 1). Water intensity effect (D_{WI}) was found to have a trend close to that of IWDI (Fig. 3, blue and black curves), indicating its leading role in decreasing the IWDI. It contributed cumulative reductions of 42.8%, 45.0% and 42.2% in the three FYP periods and a total of 81.8% for the whole study period. Water intensity dropped by 81.1% during the whole study period (See Fig. S2 for detail), thus contributed the most to the rapid decrease in IWDI. This is mainly due to upgrade of the industrial structure, water-saving technological improvement and the effective implementation of water-saving policies (e.g. Water-saving Society Construction) (Geng et al., 2014; Zheng et al., 2018; Zhang et al., 2020). In comparison, the wastewater discharge coefficient effect (D_{WDC}) drove up the IWDI by 14.9% if other factors remained unchanged for the whole study period (Fig. 3, purple curve). Nevertheless, its contribution switched from 47.6% in the 10th FYP period to −13.1% in the 11th FYP period and −10.5% in the 12th FYP period. Geographical structure effect was found with relatively minor impacts on the change in IWDI during the entire study period. This may be due to limited changes in the pattern of China's regional industrial economy.

4.3. Regional attribution analysis

The attribution results for the water intensity effect indicate that its significant downward influence on IWDI over the study period was mainly attributed to Shandong (−9.13%), Jiangsu (−8.39%), Guangdong (−8.29%) and Zhejiang (−7.64%),[3] as shown in Table S3. This implies that provinces in South China have exerted more efforts in water saving by introducing advanced water-saving technologies and by improving the industrial structure (Yao et al., 2019). It is also found that the wastewater discharge coefficient effect

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[2] Detailed decomposition results refer to Table S2.

[3] The percentages in the brackets denote the shares of provinces in the total reduction rate.

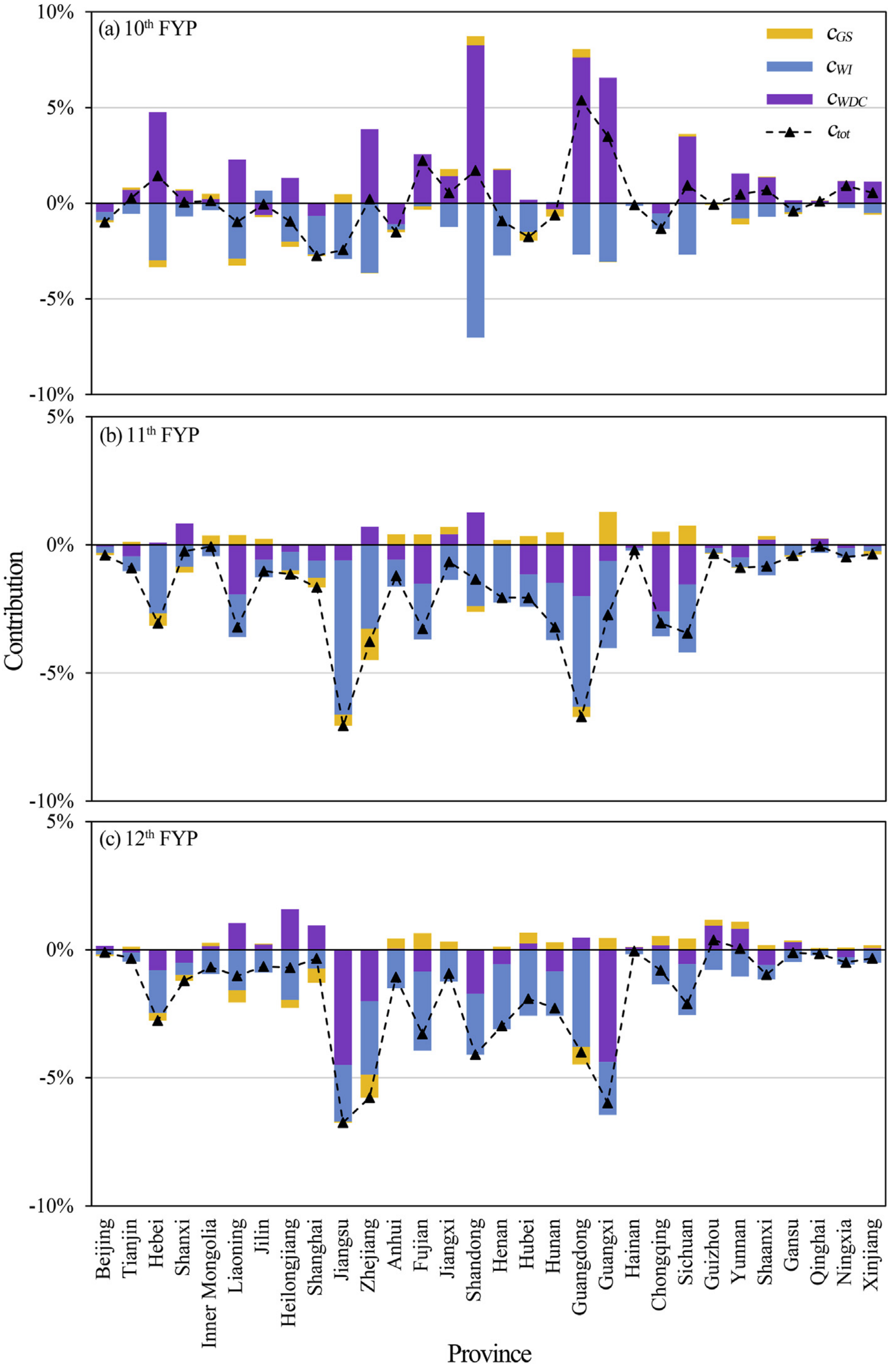

Fig. 4. Multi-period attribution results for the three FYP periods.

switched from a barrier to a driver in decreasing IWDI after 2005, as shown in Table S4. This downward influence on IWDI in Beijing, Jilin, Shanghai, Jiangsu, Anhui, Fujian, Hubei, Hunan and Chongqing implies that Southern provinces have exerted more efforts in wastewater treatment.

Fig. 4 shows the multi-period attribution results for the three FYP periods, which may provide explanation for decoupling trends among provinces in the three periods (Fig. 2). As shown in Fig. 4(a), Hebei, Fujian, Guangdong, Guangxi, Yunnan, Shaanxi, Ningxia and Xinjiang were found to have positive contributions to the increase in IWDI in the 10th FYP period, which may be responsible for their expansive negative decoupling states as shown in Fig. 2(a). All provinces were in weak or strong decoupling states in the 11th FYP period (Fig. 2(b)) may be related to the occurrence of negative contributions in all provinces as indicated in Fig. 4(b). Guizhou was in expansive negative decoupling state in the 12th FYP period (Fig. 2(c)) corresponding to its negative contribution in this period (Fig. 4(c)). By comparing Fig. 4(a) and (c), it can be concluded that the significant enhancement of decoupling trends in the 12th FYP period is mainly because of the downward influence of wastewater discharge coefficient on IWDI in most provinces (Fig. 4, purple bar).

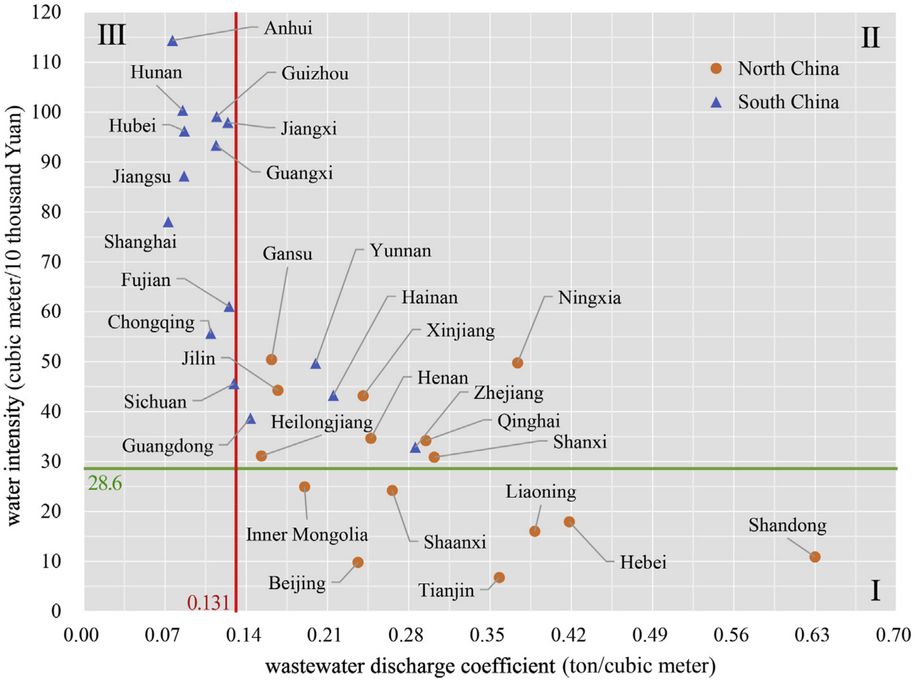

Fig. 5. Performance matrix based on wastewater discharge coefficient and water intensity levels in 2015.[41]

4.4. *Water saving vs. wastewater treatment*

Fig. 5 compares the performance of 30 provinces in terms of wastewater discharge coefficient and water intensity in 2015. The distribution pattern in this figure shows significant regional characteristics that provinces in North China centered at the lower right part with a lower water intensity and a higher wastewater discharge coefficient (Fig. 5, orange point), while provinces in South China centered at the higher left part with a lower wastewater discharge coefficient and a higher water intensity (Fig. 5, blue point). Water intensity and wastewater discharge coefficient indicate water saving and wastewater treatment levels, respectively. We used two lines (red line stands for the average wastewater discharge coefficient level in South China and green line stands for the average water intensity level in North China) to classify the 30 provinces into three categories, as shown in Fig. 5. In addition, Fig. 6 indicates the attribution results of wastewater discharge coefficient and water intensity effects between 2006 and 2015. This figure is also divided into three areas corresponding to the classification of 30 provinces in Fig. 5.

As shown in Fig. 5, provinces such as Beijing, Tianjin, Shandong, Liaoning, Hebei, Shaanxi and Inner Mongolia in Area I are referred to as “water-saving provinces”, since their water saving level is better than the average, but wastewater treatment levels need to be improved. However, the contributions to water intensity effect varied largely among them (Fig. 6, Area I, blue bar). Beijing and Tianjin contributed less but still took the top in the water intensity level, as they had done a good job in water savings before 2000 (Zhang and Brown, 2005). Shandong, Liaoning and Hebei contributed largely to the water intensity effect reflecting their ranking in water savings (Wu and Tan, 2012; Li et al., 2016a, Li et al., 2019b). Nevertheless, they also made a significant contribution to the wastewater discharge coefficient effect in increasing the IWDI, which may result in their backward positions in terms of wastewater treatment levels (Fig. 5).

In Area II, provinces such as Shanxi, Heilongjiang, Qinghai, Henan, Xinjiang, Jilin, Ningxia, Gansu, Zhejiang, Hainan, Yunnan and Guangdong are referred to as “balanced provinces”, as these regions have a balanced value in wastewater discharge coefficient and water intensity (Fig. 5). Except for Henan and Heilongjiang, most of the northern provinces in this area contributed little to the water intensity effect (Fig. 6, Area II, blue bar), primarily leading to their backward positions in the water intensity level within North China as shown in Fig. 5 (Zhang et al., 2020). Southern provinces in this area like Zhejiang, Yunnan and Guangdong contributed significantly to the wastewater discharge coefficient effect in increasing the IWDI (Fig. 6, Area II, purple bar), which is consistent with findings in Chen et al. (2016). It may explain why they were lagging behind in the wastewater discharge coefficient level as shown in Fig. 5. Nevertheless, Zhejiang and Guangdong contributed largely to the water intensity effect (Fig. 6, Area II, blue bar), and that is why they have a better water intensity level than other southern provinces (Fig. 5).

Finally, provinces such as Shanghai, Anhui, Hunan, Jiangsu, Hubei, Chongqing, Guangxi, Sichuan, Fujian, Jiangxi and Guizhou in Area III are referred to as “wastewater-treatment provinces”, as wastewater treatment level is better than the average, but water saving level needs to be improved (Fig. 5). Most of provinces in this area contributed significantly to the water intensity effect (Fig. 6, Area III, blue bar), but provinces like Anhui, Guizhou and Hunan which were lagging behind in the water intensity level (Fig. 5) had relatively minor contributions (Zhang et al., 2020). Additionally, provinces such as Jiangsu, Chongqing, Hunan and Anhui made the largest contributions to the wastewater discharge coefficient effect in decreasing the IWDI (Fig. 6, Area III, purple bar), which may be responsible for their leading positions in the wastewater discharge coefficient level (Fig. 5). The finding that Shanghai contributed less but also took the top in the wastewater discharge coefficient level is because its performance in industrial wastewater treatment before 2000 (Bithas and Kalimeris, 2018).

5. Discussions and policy implications

The decoupling, decomposition and attribution analyses are

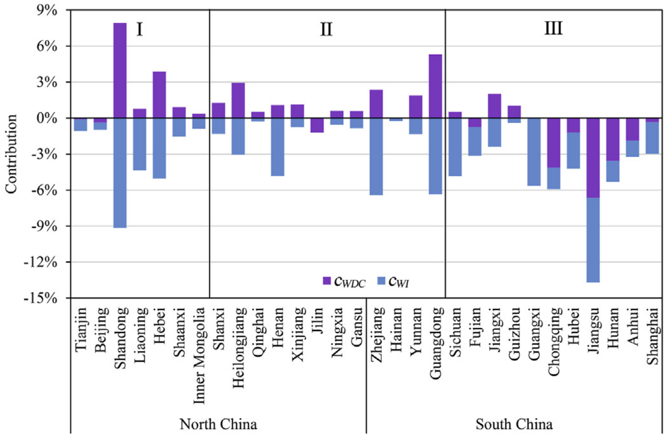

Fig. 6. Attribution results of wastewater discharge coefficient and water intensity effects in 2000–2015.[51]

interconnected in this study. The decomposition results of the change in national IWDI could reveal the influencing factors (Fig. 3) behind the decoupling trends between China's industrial output and IWDs (Table 1), while the multi-period regional attribution results (Fig. 4) could provide explanations for the decoupling trends among provinces in the three FYP periods (Fig. 2). We found that the effect of wastewater discharge coefficient played an important role in decoupling industrial growth from IWDs at both national and provincial levels. Since China's accession into the WTO, a large amount of pollution-intensive enterprises and industrial parks have sprung up. However, wastewater-treatment technology and environmental regulation could not keep up with the pace of the booming industrial economy, thereby leading to the coupling of industrial growth and IWDs (Lei et al., 2012; Yang and Li, 2017; Chen et al., 2019). To this end, the Chinese government strengthened the control of chemical oxygen demand and ammonia nitrogen emissions from pollution-intensive industries in the 11th FYP for national environmental protection (SCC, 2007). In addition, the stringent water management plan of "Three Red Lines" and Water Pollution Control Action Plan were launched in the 12th FYP period to force enterprises to eliminate backward production capacities (Lyu et al., 2016) and introduce advanced wastewater treatment technologies (e.g. membrane technology) (Zheng et al., 2015). Consequently, the effective implementation of environmental policies led to a decline in chemical oxygen demand (COD) emissions by −12.5% and −12.9% in the 11th and 12th FYP periods, respectively (SCC, 2011, 2016b).

It is accepted that resource endowment has a significantly adverse effect on resource utilization efficiency, as the resource curse not only affects regional economic development, but also local resource utilization efficiency (Wolfe et al., 2009; Zhang and Liang, 2010). As shown in Fig. 7, China's water resources are distributed more in the south and less in the north (Zhao et al., 2015; Cai et al., 2019; He et al., 2019). The extremely unbalanced distribution of water resources may be responsible for regional differences in water intensity and wastewater discharge coefficient. To this end, the correlation analysis is employed to explore the impact of water endowment on water intensity and wastewater discharge coefficient. Table 2 indicates that water intensity was found to have a significantly positive correlation with water endowment (Table 2, $p = 0.004 < 0.01$, Pearson's $r = 0.509$), while wastewater discharge coefficient had a significantly negative correlation with water endowment (Table 2, $p = 0.006 < 0.01$, Pearson's $r = -0.489$). It is consistent with findings in previous studies (Li et al., 2008, Li et al., 2019a; Qian and He, 2011; Zheng et al., 2018). The more easily accessible and abundant the water resources are, the lower the water resource utilization efficiency is, the higher the wastewater treatment level is. In comparison, the more difficult and scarce the water resources, the higher is the water resource utilization efficiency, and the lower is the wastewater treatment level.

Based on the findings above, targeted policy methods could be formulated for different categories of provinces. Provinces in "water-saving areas" should give a higher priority to policy measures such as introducing advanced technologies to promote wastewater treatment and recycling, and enforcing more strict wastewater discharge levy system. For example, Shandong would be adviced to introduce cost-effective pollution control technologies to its pollution-intensive industries such as papermaking, food processing, and petrochemicals (Li et al., 2016b). Wastewater treatment technologies like Biological Aerated Filters, Coagulation-Flotation process, Precipitation should be implemented to the petrochemical industry in Liaoning (Li et al., 2011). Inner Mongolia would be adviced to promote wastewater recycling in its coal-dominated power generation system (Xin et al., 2015).

Provinces in "wastewater-treatment areas" would need to improve water use efficiency by introducing advanced water-saving technologies and optimizing the industrial structure. Especially for Anhui, the province with the lowest water resource utilization efficiency, should focus on its high-water-consuming industries such as power generation, ferrous metal and chemicals. Local government would need to improve the preferential compensation system for water-saving enterprises and promote enterprises to actively introduce technologies and processes with low water consumption (Liu and Bai, 2012). Jiangsu could promote recirculating cooling technologies in its power generation to reduce water consumption (Zhou et al., 2019).

Provinces in "balanced areas" are adviced to give attention to both of water saving and wastewater treatment sides. Heilongjiang, Henan, Zhejiang and Guangdong could maintain their current choices of policy methods in water savings, but for the other provinces, policy measures still need to be strengthened to further improve water efficiency.

6. Conclusions

This study employs the combined decoupling, decomposition and attribution analysis to examine the decoupling relationship between industrial growth and IWDs in China, discussed the factors influencing the decoupling trends, and further attributed the contributions of these factors to different regions. Several key findings are provided in the following.

First, there was an increasing trend in decoupling between industrial output and IWDs in China, in which expansive negative decoupling and weak decoupling appeared in 2000–2005, weak decoupling and strong decoupling appeared in 2005–2010, and strong decoupling appeared throughout 2010–2015. Meanwhile, there was a witnessed convergence in decoupling degrees among provinces.

Second, the change in national IWDI was decomposed into three driving forces including wastewater discharge coefficient, water intensity and geographical structure. Of these factors, the water intensity effect was the dominant one leading to IWDI decline, while the wastewater discharge coefficient effect acted as a barrier

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[4] Area I indicates the lower water intensity and dominates in water saving; Area III indicates the lower wastewater discharge coefficient and dominates in wastewater treatment; Area II indicates medium values in both water intensity and wastewater discharge coefficient and occupy a moderate but balanced position in water saving and wastewater treatment.

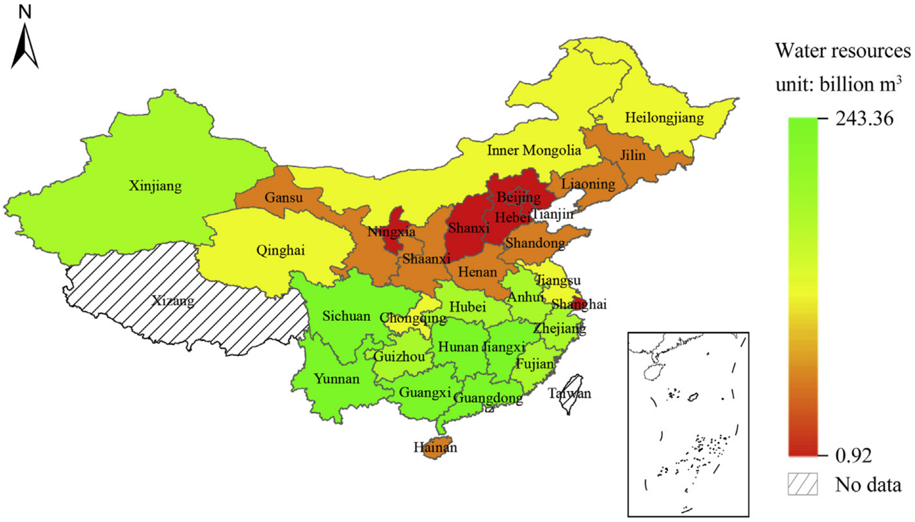

Fig. 7. The distribution of water resources among provinces in China in 2015.

Table 2
Correlation analysis between water endowment and water intensity and wastewater discharge coefficient.

		water intensity	wastewater discharge coefficient
water endowment	Pearson correlation	0.509**	–0.489**
	Sig. (2-tailed)	0.004	0.006
	N	30	30

** Correlation is significant at the 0.01 level (2-tailed).

before 2005 but then tended to drive down the IWDI.

Third, North China performed better in water saving while South China had a better wastewater treatment level. Regional attribution results indicate provinces in South China have exerted more efforts in both of water saving and wastewater treatment during the study period. Provinces were classified into three categories of water-saving area, balanced area and wastewater-treatment area to provide targeted policy suggestions.

In spite of the contributions, this study inevitably has some limits. Industrial structure (internal structure of industrial sector) is certainly an important factor influencing the decoupling trends. However, this factor was not included in our decomposition analysis due to data limitation. Future research should investigate its impacts by including more regional and sectorial characteristics of industrial sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Zhencheng Xing: Conceptualization, Investigation, Writing - original draft. **Jigan Wang:** Writing - review & editing, Supervision, Funding acquisition. **Kuishuang Feng:** Validation, Writing - review & editing, Supervision. **Klaus Hubacek:** Project administration, Writing - review & editing.

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Appendix A. Supplementary data

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[5] Provinces in North China are ranked by increasing order of water intensity, and provinces in South China are ranked by decreasing order of wastewater discharge coefficient.

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