RESEARCH ARTICLE

Identifying the decoupling pathways of water resource liability and economic growth: a case study of the Yangtze River Economic Belt, China

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Abstract

Identifying the high-quality economic growth pathways under the requirements of water conservation and water pollution reduction is pivotal to realize regional sustainable development. Combined with the theory of resource and environmental value, sustainable development, and environmental accounting, this paper innovatively introduces water resource liability (WRL) to measure water environmental pressure. This study takes the Yangtze River Economic Belt (YREB) as the research area and firstly conducts a spatial–temporal analysis of the WRL change in this region from 2013 to 2018. Then, the Tapio decoupling model is used to analyze the decoupling states and the decoupling stabilities between WRL and economic growth in the 11 provincial areas and 3 sub-regions of the YREB. Finally, the main internal factors affecting the decoupling states are identified from the perspective of decoupling decomposition. The main results show that: (1) The WRL of the YREB increases from 173.36 billion CNY in 2013 to 201.62 billion CNY in 2018, with an increase of 16.3%, showing an upward trend of fluctuation. The WRL of the lower reaches of the YREB is generally higher than those of the upper and middle reaches of the YREB from both the provincial and sub-regional levels. Chongqing has the lowest WRL with an average value of 7.03 billion CNY, while Shanghai has the highest with the average of 28.74 billion CNY. (2) The decoupling state between WRL and economic growth in the YREB is generally stable. The decoupling state of the downstream is better than that of the upper and middle reaches, and the decoupling stability index is 0.59, which is the most stable. (3) The internal influencing factors between WRL and economic development in the YREB include structural effect, technological effect, and silence effect, among which technological effect with the worst decoupling stability is the main driving factor. The findings of this study are crucial for policy makers to formulate targeted policies to decouple WRL from economic growth and to realize sustainable development in the YREB.

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Introduction

Water resource is an important resource necessity for life existence, human production, and daily life and is a significant guarantee for the sustainable development of social economy. Due to the limited amount and the spatial–temporal uneven distribution, about 400 million people are facing varying degrees of water shortages for at least 1 month of a year in the world (Mekonnen and Hoekstra 2016). As a result, there are a series of water resource conflicts inevitably, including transboundary water resource conflicts (Degefu et al. 2018; Yuan et al. 2021). Economic development is closely related to available freshwater resources. Although economic growth can provide the funds needed for water conservation and water environment protection, an unsustainable economic growth model is bound to aggravate water pollution and speed up the consumption of freshwater resources. As it is difficult to make a great breakthrough in water-saving technology and sewage treatment technology in the short term, rapid economic development will make the water crisis increasingly serious (Kong et al. 2021). It is urgent to find a feasible path to alleviate the available water resource and water environment pressure to improve the regional water environmental carrying capacity while developing economy. This asynchronously changing relationship between economic growth and water consumption or water pollution is defined as "decoupling," which is the focus of the Sustainable Development Goals 12 (SDG12). Therefore, to explore the influence mechanism of decoupling is quite necessary.

At present, the existing water resources related decoupling mainly adopt two main models put forward by OECD (2002) and Tapio (2005), respectively. In comparison, the Tapio decoupling model can present more kinds of decoupling states by introducing elastic coefficient. Furthermore, since successfully overcoming the influence of base period selection on the decoupling results, it is more widely accepted and applied. Additionally, in order to quantify the actual consumption of water resources more accurately, Hoekstra (2002) put forward the concept of water footprint based on virtual water (Allan 1998) and ecological footprint (Wackernagel and Rees 1997), which took physical water and virtual water into comprehensive consideration. It consists of blue water footprint, green water footprint, and gray water footprint. The gray water footprint represents the total amount of freshwater resources needed to dilute the concentration of main pollutants in sewage to the standard concentration, which realizes the measurement of water pollution by

water quantity index (Chapagain and Hoekstra 2011). Combined the water footprint method and the Tapio decoupling model, Li et al. (2017a) and Kong et al. (2021) conducted the decoupling analysis in the Central Plains urban agglomeration and the YREB region. Li et al. (2017b) and Li and Wang (2019) studied the decoupling state between water pollution and economic growth in the textile industry. Zhang and Yang (2014) analyzed the decoupling relationships of agricultural water consumption and environmental impact from crop production. In terms of decoupling decomposition, Kong et al. (2019) analyzed the main influencing factors of water footprint decoupling combined with the Tapio decoupling model and the LMDI model. Wang and Wang (2020) used the same methods to explore the water consumption decoupling performance at the national and provincial levels, and six driving factors are decomposed. Gao and Lu (2021) took the Yellow River as the research area to explore the decoupling relationship between water resource utilization and economic growth and the changing trend of decoupling driving factors. Liu et al. (2021) studied the decoupling relationship between sewage environmental damage and economic development in 31 provincial areas in China and found that the strict formulation and implementation of China's environmental policies and the green upgrading of industrial structure were the main influencing factors.

Although previous scholars have made more gratifying achievements in the field of water resource decoupling and have extended relevant methods to study the decoupling relationship between economic development with carbon emissions (Li et al. 2021; Song et al. 2021), other natural resources (Guo et al. 2021), and resources and environment (Luo et al. 2021), these studies fail to consider decoupling decomposition from internal components and quantify the decoupling stabilities simultaneously. This is not conducive to identifying viable paths to decoupling. In addition, although water footprint can measure the actual water consumption and water pollution more accurately, it does not reflect its value attribute. To consider three attributes of water quantity, water quality, and water value simultaneously, Chinese scholars put forward the formulation of water resource balance sheet based on exploring the formulation of natural resource balance sheet proposed at *the third Plenary Session of the 18th Communist Party of China Central Committee* (Hu and Shi 2015; Chai et al. 2016). Since Shen et al. (2005) admitting the existence of WRL in water resource accounting elements, Gan et al. (2014) discussed the specific elements and preparation process of water resource balance sheet. In this study, WRL refers to the current obligations undertaken by

accounting subjects to make up for these losses, which are expected to result in the outflow of economic benefits and destruction of water ecological environment caused by the past behavior of equity subjects. Thus, it is of more theoretical and practical significance to study the decoupling relationship between WRL and economic growth and explore the main influencing factors of decoupling as well as its decoupling stability. The YREB region, economically developed and densely populated, is facing the dual challenges of water pollution control and high-quality economic growth. Hence, the Chinese government has specially promulgated the *Yangtze River Protection Law* to improve the water environmental carrying capacity in this region as well as to realize the regional sustainable development of water resources and economy (Liu et al. 2019; Lin et al. 2020; Xu and Liang 2020; Huang et al. 2021a).

Thus, based on innovatively introducing the water resource liability method, this study firstly conducts a spatial–temporal analysis of WRL in the YREB from 2013 to 2018. Then, the Tapio decoupling model is used to analyze the decoupling states and their stabilities between WRL and economic growth among the 11 provincial areas and 3 sub-regions of the YREB. Finally, this paper identifies the main internal factors affecting the decoupling situation in the YREB from the perspective of decoupling decomposition. The rest of the study is organized as follows. The second section presents the research methods and data description applied in the research. The third section describes the research results of decoupling analysis and actor decomposition analysis.

The fourth section discusses the above important findings and compares them with previous studies. The conclusions and policy implications are shown in the fifth section.

Material and method

Study area

The Yangtze River Economic Belt (YREB) is the largest relatively complete economic belt connected by the Yangtze River in China and the most important east–west axis in China's land development. It spans three major regions of the east, middle, and west of China and goes across an overall area of about 2.05 million square kilometers, accounting for 21.4% total area of China (Fig. 1). From 2013 to 2018, with an average of 1.31 trillion tons of water resources, accounting for 45.56% of China's average, the YREB achieved an average of 21.55 trillion CNY of GDP, accounting for 51.86% of the national average. The average water consumption in the YREB was 262.68 billion tons, accounting for 43.2% of the Chinese average from 2013 to 2018. Meanwhile, the YREB discharged 33.98 billion tons of wastewater from 2013 to 2018, accounting for 46.68% of the national average. At present, the YREB is facing the contradiction between "joint protection" and "high-quality economic development." It is crucial and difficult about how to achieve economic growth while reducing the water consumption,

Fig. 1 Diagram of the Yangtze River Economic Belt
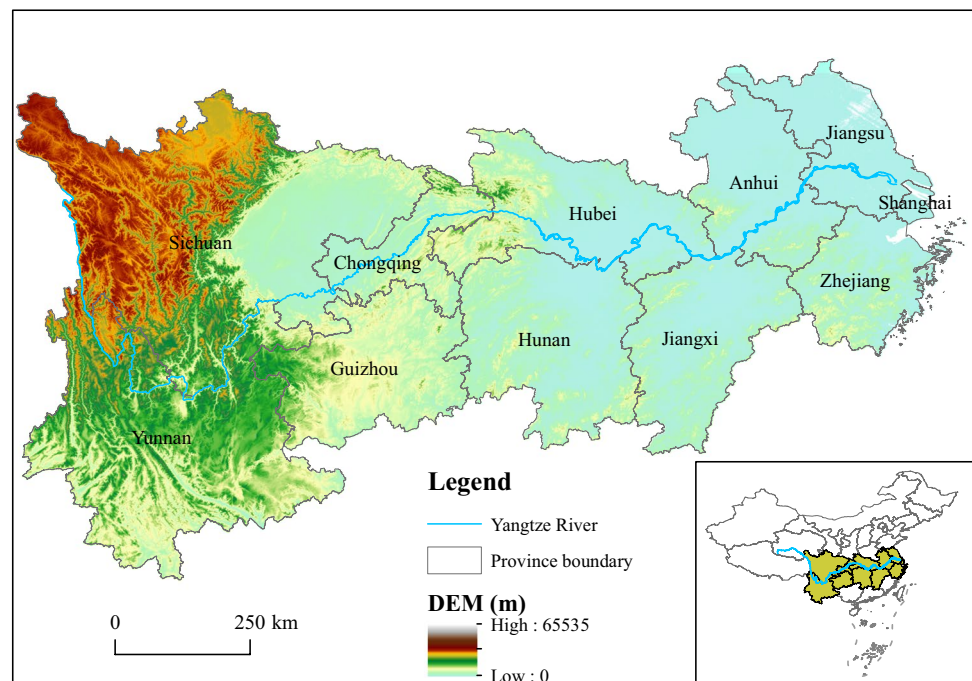
lessening water pollution, and improving the water use efficiency in the YREB.

Methodology

Water resource liability method

Water resource balance sheet is an important tool used for accounting and capital management of water resources (Gan et al. 2014). It is mainly composed of water resource asset, water resource liability (WRL), and water purification resource asset. WRL refers to the current obligation undertaken by the accounting subject to make up for the loss caused by the past behavior of the equity subject, which is expected to lead to the outflow of economic benefits as well as the pollution and destruction of water ecological environment. WRL is a concept which considers the theory of resource and environmental value (Yu et al. 1995; Zhang et al. 2006), sustainable development theory (Niu 2012), and the theory of environmental accounting (Zhou and Tao 2012) simultaneously. Therefore, this paper uses WRL as an indicator to measure water environmental pressure.

Referring to the classification of WRL by Zhu and Xue (2018), Wang et al. (2019a), and Shi and Wang (2021), this study divides WRL into three parts: sewage treatment costs (C_{ST}), investment costs of water resource protection and water pollution control facilities (C_{FI}), and water loss costs (C_{WL}). This paper uses replacement cost method (Li 2019) to calculate WRL, and the specific calculation steps are as follows:

$$WRL = C_{ST} + C_{FI} + C_{WL} \tag{1}$$

The sewage treatment cost C_{ST} is calculated as follows (2):

$$C_{ST} = C_{ST-COD} + C_{ST-AN} \tag{2}$$

where C_{ST-COD} refers to the treatment cost of COD in discharged sewage. $C_{ST\text{-}AN}$ indicates the treatment cost of ammonia nitrogen in discharged sewage:

$$C_{ST-COD} = (Q_{DE-COD} + Q_{IE-COD} + Q_{AE-COD} + Q_{CTE-COD}) \cdot C_{UG-COD} \tag{3}$$

where Q_{DE-COD}, Q_{IE-COD}, Q_{AE-COD}, and $Q_{CTE-COD}$, respectively, represent the COD emissions of domestic, industrial, agricultural, and centralized treatment facilities. C_{UG-COD} manifests the unit treatment cost of COD emission:

$$C_{ST-AN} = (Q_{DE-AN} + Q_{IE-AN} + Q_{AE-AN} + Q_{CTE-AN}) \cdot C_{UG-AN} \tag{4}$$

where Q_{DE-AN}, Q_{IE-AN}, Q_{AE-AN}, and Q_{CTE-AN}, respectively, indicate the ammonia nitrogen emissions of domestic, industrial, agricultural, and centralized treatment facilities.

C_{UG-AN} denotes the unit treatment cost of ammonia nitrogen emission.

The cost of facility investment C_{FI} is calculated as follows (5):

$$C_{FI} = C_{OWTF} + C_{IEPCE} + C_{IWLCTF} \tag{5}$$

where C_{OWIF} represents the operation cost of wastewater facilities, C_{IEPCE} denotes the investment in facilities and equipment in the investment in environmental pollution control, and C_{IWLCTF} indicates the investment in facilities and equipment in the investment in comprehensive treatment of water resources.

The cost of water loss C_{WL} is calculated as follows (6):

$$C_{WL} = Q_{WL} \cdot P \tag{6}$$

where Q_{WL} denotes the amount of water lost, which is equal to the amount of wastewater discharge and P represents the unit water price:

$$P = (P_{DWC} \cdot Q_{DWC} + P_{NDWC} \cdot Q_{NDWC})/Q_{TWC} \tag{7}$$

where P_{DWC} and P_{NDWC} represent the price of domestic water and non-domestic water, respectively. Q_{DWC} and Q_{NDWC} refer to domestic water consumption and non-domestic water consumption, respectively.

$$Q_{NDWC} = Q_{AWC} + Q_{IWC} + Q_{EWC} \tag{8}$$

where Q_{AWC} represents agricultural water consumption, Q_{IWC} denotes industrial water consumption, and Q_{EWC} expresses ecological water consumption.

Tapio decoupling index

In 2005, Tapio subdivided the traditional decoupling status into eight types by introducing decoupling elasticity coefficient (as shown in Table 1) (Tapio 2005). The calculation formula of Tapio decoupling elasticity coefficient between WRL and economic growth is as follows (9):

$$E_t = \frac{\frac{WRL_t - WRL_{t_0}}{WRL_{t_0}}}{\frac{GDP_t - GDP_{t_0}}{GDP_{t_0}}} = \frac{\frac{\Delta WRL}{WRL_{t_0}}}{\frac{\Delta GDP}{GDP_{t_0}}} \tag{9}$$

where t and t_0 represent the current period and base period of decoupling index, respectively. E_t denotes the decoupling elasticity coefficient in year t, GDP_t represents the actual GDP in year t, and WRL_t expresses the WRL in year t. GDP_{t_0} indicates the actual GDP of the base period, WRL_{t_0} refers to the WRL of the base period, and ΔGDP and ΔWRL denote the difference of the actual GDP and the WRL between year t and the base period, respectively. Strong decoupling is the most ideal decoupling state, which means that WRL

Table 1 The classification criteria of the Tapio decoupling states (Kong et al. 2021)

Decoupling type	Growth rate of WRL	Growth rate of economy	Elasticity coefficient	Decoupling status
Decoupling	>0	>0	$(0, 0.8]$	Weak decoupling (WD)
	<0	>0	$(-\infty, 0]$	Strong decoupling (SD)
	<0	<0	$(1.2, +\infty)$	Recession decoupling (RD)
Negative decoupling	>0	>0	$(1.2, +\infty)$	Expansion negative decoupling (END)
	>0	<0	$(-\infty, 0]$	Strong negative decoupling (SND)
	<0	<0	$(0, 0.8]$	Weak negative decoupling (WND)
Link	>0	>0	$(0.8, 1.2]$	Extended link (EC)
	<0	<0	$(0.8, 1.2]$	Recession link (RC)

Strong decoupling is the most ideal decoupling state in Table 1, while strong negative decoupling is the worst

decreases with economic growth. Weak decoupling is the second ideal decoupling state, indicating that the growth rate of WRL is less than that of economic growth. In both states, the WRL generated by unit GDP is declining, indicating that the water use efficiency is improving.

Therefore, the Tapio decoupling calculation of WRL and economic growth in this study can be further deduced as follows:

$$E_t = \frac{\frac{WRL_t - WRL_{t_0}}{WRL_{t_0}}}{\frac{GDP_t - GDP_{t_0}}{GDP_{t_0}}} = \frac{\frac{(C_{ST_t} + C_{FI_t} + C_{WL_t}) - (C_{ST_{t_0}} + C_{FI_{t_0}} + C_{WL_{t_0}})}{WRL_{t_0}}}{\frac{GDP_t - GDP_{t_0}}{GDP_{t_0}}} \quad (10)$$

Formula (10) can be further transformed as follows:

$$E_t = \frac{\frac{C_{ST_t} - C_{ST_{t_0}}}{WRL_{t_0}}}{\frac{GDP_t - GDP_{t_0}}{GDP_{t_0}}} + \frac{\frac{C_{FI_t} - C_{FI_{t_0}}}{WRL_{t_0}}}{\frac{GDP_t - GDP_{t_0}}{GDP_{t_0}}} + \frac{\frac{C_{WL_t} - C_{WL_{t_0}}}{WRL_{t_0}}}{\frac{GDP_t - GDP_{t_0}}{GDP_{t_0}}} = E_{ST} + E_{FI} + E_{WL} \quad (11)$$

According to formula (11), the decoupling elasticity index E_t of WRL is equal to the sum of the decoupling elasticity coefficients of E_{ST}, E_{FI}, and E_{WL}, where E_{ST} indicates the structural effect between the decoupling of WRL and economic development, E_{FI} refers to the technological effect, and E_{WL} denotes the silence effect. There is no clear relationship between the above three effects, and the decoupling states of E_{ST}, E_{FI}, and E_{WL} are not necessarily related to the decoupling state of E_t. Structure effect E_{ST}, technology effect E_{FI}, and silence effect E_{WL} are the internal influencing factors of the decoupling state between WRL and economic growth.

Considering that there may be a variety of decoupling states between WRL and economic growth with fluctuations, this study uses the decoupling stability index δ to measure the stability degree of decoupling state at the present stage, and the specific calculation formula is as follows (Han et al. 2021):

$$\delta = \frac{1}{Y - 1} \sum \left| \frac{E_{t+1} - E_t}{E_t} \right| \quad (12)$$

where t denotes the year studied and Y refers to the numbers of the decision-making units. The larger the δ values, the more unstable the decoupling state. If δ is less than 1, the decoupling state is stable; if δ is between 1 and 3, the decoupling state is relatively stable; if δ is greater than 3, the decoupling state is unstable (Qi and Chen 2012; Tu et al. 2014).

Data sources

The calculation in this study is mainly divided into three aspects: WRL, Tapio decoupling index, and decoupling stability index. Considering that some important index data can only be obtained until 2018, this study selects 2013–2018 as the research time span. The data of water consumption, sewage and pollutant discharge, facility investment cost, and other indicators used to calculate WRL are mainly obtained from *China Statistical Yearbook (2014–2019) (National Bureau of Statistics of China* 2014a*-*2019*)*, *China Environmental Statistical Yearbook (2014–2019) (National Bureau of Statistics of China* 2014b*–2019)*, *China Water Resources Bulletin (2014–2019) (National Bureau of Statistics of China* 2013*–2018)*, and the Statistics Yearbook (2014-2019), Water Resources Bulletin (2013-2018), and Environmental Statistics Bulletin (2013–2018) of 11 provincial areas along the YREB. The data for calculating Tapio decoupling index comes from *China Statistical Yearbook (2014–2019)* and the statistical yearbook of provinces (2014–2019). The decoupling stability index is calculated based on the Tapio decoupling index. It is worth noting that (1) the unit treatment costs C_{UG-COD} and C_{UG-AN} in this study refer to the unit cost data calculated by Wang et al. (2009); (2) all the GDP-related indicators involved

in this study are represented by the real GDP converted at constant prices in the year 2000.

Results

Result analysis of WRL

The water resource liabilities (WRLs) of 11 provincial areas and 3 sub-regions of the YREB during 2013–2018 are shown in Table 2.

At the provincial level, the WRLs of 11 provincial areas during 2013–2018 can be divided into four grades from low to high. As shown in Table 2, Chongqing's WRL is in the fourth grade, which is the lowest with the range of (6, 8) billion CNY and shows an overall upward trend with an increase of 30.61% in 2018 compared with 2013. The WRLs of Guizhou and Anhui are in the third grade with the generally range of (8, 10) billion CNY, and Anhui's WRL exceeded 10 billion CNY only in 2018. The WRLs of Yunnan, Hunan, and Jiangxi are the second highest with the range of (10, 20) billion CNY. The WRLs of Jiangsu, Shanghai, Sichuan, Zhejiang, and Hubei are in the first grade with the main range of (20, 30) billion CNY. Shanghai's WRL exceeded 30 billion CNY in 2017 and 2018. As for the sum and mean of WRL, Shanghai's WRL is much higher than those of other provincial regions both on average and in sum with an increase of 35.51% in 2018 compared with 2013. Chongqing has the lowest average and sum of all provincial regions, with an average of 7.03 billion CNY and a sum of 42.18 billion CNY. By comparison, Shanghai's sum is followed by Jiangsu, Sichuan, Zhejiang, and Hubei, all of them have the sum WRL of

more than 100 billion CNY. Except Hubei, the other three provinces have the average WRL of more than 20 billion CNY.

From the perspective of the YREB and its 3 sub-regions, the WRL of downstream is always the highest from 2013 to 2018. The WRL is the lowest from 2013 to 2015 in the upstream, and it is the lowest from 2016 to 2018 in the midstream. Compared with 2013, the WRLs in the upper, middle, and lower reaches increased by 27.75%, 2.96%, and 18.29%, respectively, in 2018, while the WRL in the YREB increased by 16.3%. The WRLs of the YREB and its sub-regions mainly show an upward trend, and the upstream shows the largest increase. The WRL of the middle reaches in the YREB decreased significantly in 2016 and did not exceed the peak value of 54.56 billion CNY in 2015 although it increased in 2017 and 2018. In 2016, the WRL of the middle reaches of the YREB decreased by 22.27%, exceeding the 9.62% increase of the upper reaches and 4.72% increase of the lower reaches, which directly led to the decrease of WRL of the YREB in that year. At a forum on promoting the development of the YREB held in Chongqing on January 5, 2016, Chinese President Xi Jinping called on us "to step up conservation of the Yangtze River and stop its over development." Provincial areas in the middle reaches of the YREB responded positively to this and promptly issued relevant policies on water conservation and water pollution control, which effectively reduced the WRL and led to a decline in the value of WRL in 2016. By comparison, it can be found that the average value of total WRL in the midstream is the lowest, followed by the upstream and the downstream. In terms of the mean value of each province, WRL is higher in the downstream than in the midstream and then higher in the midstream than in the

Table 2 The WRL change of the YREB from 2013 to 2018 (billion CNY)

Area	2013	2014	2015	2016	2017	2018	Mean	Sum
Yunnan	11.02	11.39	10.35	13.02	15.08	15.54	12.73	76.39
Guizhou	8.43	10.05	9.79	9.39	8.87	9.51	9.34	56.05
Sichuan	18.88	21.80	23.30	24.59	27.59	23.74	23.32	139.89
Chongqing	6.11	6.21	6.46	7.71	7.71	7.98	7.03	42.18
Hubei	20.12	21.20	22.82	14.18	15.56	16.12	18.33	110.00
Hunan	14.68	14.43	16.07	12.39	15.48	16.38	14.91	89.44
Jiangxi	15.15	16.04	15.67	15.83	16.65	18.91	16.38	98.25
Anhui	8.83	9.06	9.81	9.06	9.26	11.33	9.56	57.35
Jiangsu	26.00	23.21	24.70	24.60	23.72	23.11	24.22	145.34
Zhejiang	19.63	20.05	20.79	23.64	24.81	25.76	22.45	134.67
Shanghai	24.53	27.16	27.09	28.98	31.46	33.24	28.74	172.46
Upstream	44.44	49.45	49.90	54.70	59.25	56.77	52.42	314.51
Midstream	49.94	51.67	54.56	42.41	47.69	51.42	49.62	297.69
Downstream	78.99	79.48	82.39	86.28	89.25	93.44	84.97	509.83
YREB	173.36	180.60	186.86	183.39	196.19	201.62	187.00	1122.02

Green in Table 2 indicates the fourth grade with the range of (6, 8) billion CNY; yellow is the third grade, and orange is the second grade; red represents the first grade with the range of (20, 30) billion CNY

upstream. The WRL of the downstream is 1.62 times of the upstream and 1.71 times of the midstream, respectively. This indicates that the GDP growth of downstream provinces has caused greater environmental pressure.

Tapio decoupling analysis

According to Formula (10), this study calculates the Tapio decoupling elastic coefficient (DEC) in 11 provincial areas of the YREB during 2014–2018; see Table S1 in the Appendix. The decoupling status of WRL and economic development is shown in Table 3. The decoupling stability index (DSI) of the YREB is shown in Table 4, and the decoupling states of the YREB and 3 sub-regions are shown in Table S2 in the Appendix.

As shown in Table 3, there are four kinds of decoupling states in the YREB, which are strong decoupling (SD), weak

Table 3 The decoupling types of WRL and economic growth of 11 provincial areas in the YREB

Provincial area	2014	2015	2016	2017	2018
Yunnan					
Guizhou					
Sichuan					
Chongqing					
Hubei					
Hunan					
Jiangxi					
Anhui					
Jiangsu					
Zhejiang					
Shanghai					

Green in Table 3 represents strong decoupling which is the most ideal decoupling state; light green indicates weak decoupling which is relatively the ideal decoupling state; yellow refers to extended connections; red indicates expansion negative decoupling which is the worst decoupling state among these four types

decoupling (WD), expansion link (EC), and expansion negative decoupling (END). Specifically, Jiangsu has the largest number of SD with four times, followed by Guizhou with three times. WD occurred most frequently in Chongqing and Zhejiang, both of which were four times. Yunnan, Sichuan, Hunan, and Shanghai showed the most END with twice. EC appeared less frequently and only appeared twice in Anhui and Shanghai during 2014–2018. SD occurred most frequently in the YREB in 2016, while END occurred most frequently in 2017.

From the provincial level, Jiangsu has the most ideal decoupling state in the YREB, followed by Guizhou, while Shanghai is the worst. There were only two types of decoupling states in Jiangsu from 2014 to 2018, including four SD and one WD, while Jiangsu's DSI was 1.09, indicating general stability. In this study, water resource liability intensity (WRLI) (Sun et al. 2013) is used as an indicator of water resource utilization efficiency, which is obtained through dividing total WRL by GDP. The higher the WRLI is, the higher the WRL per unit GDP is. Jiangsu's WRLI is gradually decreasing, and it indicates that Jiangsu can realize economic growth while causing less water environment pollution. Guizhou's decoupling status is in the second grade, and there are three types of decoupling, which are three SD, one WD, and one END. The DSI of Guizhou is 0.46, indicating a stable decoupling state. The decoupling states between WRL and economic growth from 2014 to 2018 in Shanghai were the worst, with three types of decoupling, including one SD, two EC, and two END as Shanghai's DSI was 2.73, representing that the overall decoupling state was relatively unstable. It shows that although Shanghai has a large economic volume, its WRL and WRLI are also high. In terms of the changing trend of the decoupling status of provincial areas from 2014 to 2018, the decoupling status of Jiangxi and Anhui showed an increasingly worse trend. Jiangxi and Anhui's decoupling state was WD in 2014; however, it became END and EC in 2018. Guizhou and Sichuan showed

Table 4 The decoupling stability index in the YREB

Provincial area	Decoupling stability index	Stability ranking	Sub-region	Decoupling stability index	Stability ranking
Yunnan	0.86	4	**Upstream**	1.23	3
Guizhou	0.46	3			
Sichuan	0.40	1			
Chongqing	10.89	11			
Hubei	0.88	6	**Midstream**	0.79	2
Hunan	1.46	8			
Jiangxi	0.87	5			
Anhui	1.53	9	**Downstream**	0.59	1
Jiangsu	1.09	7			
Zhejiang	0.44	2			
Shanghai	2.73	10			

an increasingly better change trend from END in 2014 to WD and SD, respectively, in 2018. Yunnan, Chongqing, Hubei, Hunan, and Zhejiang are showing a change trend from ideal to not ideal and then to ideal. Jiangsu's decoupling has always been desired, while Shanghai's decoupling state has been worse with the emergence of more END.

From the sub-regional level, the decoupling state of WRL and economic development in the downstream region is the best and the most stable, while the decoupling state in the upstream is worst and unstable. The details can be seen in Table S2 in the Appendix.

Analysis on the influence mechanism of WRL decoupling

Since the Tapio DEC of WRL is equal to the sum of the DECs of the three components, to explore the influence mechanism of the decoupling index between WRL and economic growth of the YREB, this study decompresses WRL according to its components and makes comparative analysis. According to Formula (11), structural effect E_{ST}, technological effect E_{FI}, and silencing effect E_{WL} are calculated and shown in Table 5. According to formulas (11) and (12), the decoupling stabilities of the three decoupling effects of the 11 provinces and 3 sub-regions of the YREB are calculated, as can be seen in Table S3 in the Appendix.

As shown in Table 5, the structural effect E_{ST} shows that the 11 provincial areas of the YREB have achieved good decoupling states from 2014 to 2018, and 85.45% of them are SD states. The DECs of the 11 provincial areas show little difference, and the decoupling states are stable, indicating

that all provincial areas of the YREB have paid great attention to sewage treatment. The discharge of COD and ammonia nitrogen in wastewater decreased year by year. From the perspective of sub-regional decoupling, the YREB and its sub-regions have performed well. Among them, the number of SD occurred in the YREB accounted for 80% from 2014 to 2018, and the number of SD occurred in each sub-region accounted for 86.67%. The decoupling state of the structure effect is relatively stable in the upper and lower reaches while relatively terrible in the middle reaches. This shows that the cost of wastewater treatment is decreasing yearly, and the structural effect has little influence on the decoupling between WRL and economic development.

The decoupling status of technological effect E_{FI} during 2014–2018 can be seen in Table 5. The state of technological effect decoupling varies among provincial areas, among which Jiangxi is in a better state and stable, with DSI being 0.99. The decoupling states of Hubei and Jiangsu are ideal, while their decoupling stabilities are terrible. The possible reason is that the two provinces have paid more attention to the investment of water resource protection and water pollution treatment facilities in recent years, which leads to the great change and fluctuation of DEC between WRL and economic development. The decoupling states of Chongqing, Guizhou, Yunnan, and Jiangxi are stable, with DSI less than 1. From the perspective of sub-regions, the decoupling states of three reaches of the YREB are stable. However, the decoupling state of the upstream is poor, and the decoupling stability is the worst among the three sub-regions. The reason may be that the overall economic development of the upstream is inadequate and there is less investment in

Table 5 The influence mechanism of decoupling status of the YREB from 2014 to 2018

Area	2014			2015			2016			2017			2018		
	E_{ST}	E_{FI}	E_{WL}	E_{ST}	E_{FI}	E_{WL}	E_{ST}	E_{FI}	E_{WL}	E_{ST}	E_{FI}	E_{WL}	E_{ST}	E_{FI}	E_{WL}
Yunnan															
Guizhou															
Sichuan															
Chongqing															
Hubei															
Hunan															
Jiangxi															
Anhui															
Jiangsu															
Zhejiang															
Shanghai															
Upstream															
Midstream															
Downstream															
YREB															

Green in Table 5 represents strong decoupling which is the most ideal decoupling state; light green indicates weak decoupling which is relatively the ideal decoupling state; yellow refers to extended connections; red indicates expansion negative decoupling which is the worst decoupling state among these four types

sewage treatment facilities and equipment, which fails to meet the requirements of WRL management.

Table 5 also represents the decoupling status of silence effect E_{WL} in the 11 provinces of the YREB. The decoupling stabilities of Sichuan and Anhui are the best, with DSI less than 1, and the decoupling states are ideal. The decoupling stabilities of Yunnan, Zhejiang, Jiangsu, and Jiangxi are negative, with DSI greater than 3. The decoupling stabilities of

other provincial areas are general, the DSI is in the interval of (1, 3). From the perspective of sub-regions, the decoupling states and the decoupling stabilities of upstream and downstream are good, with DSI values of 0.23 and 0.67, respectively. The decoupling state in the middle reaches is not good with twice of EC, and the decoupling state is unstable with DSI being 6.51.
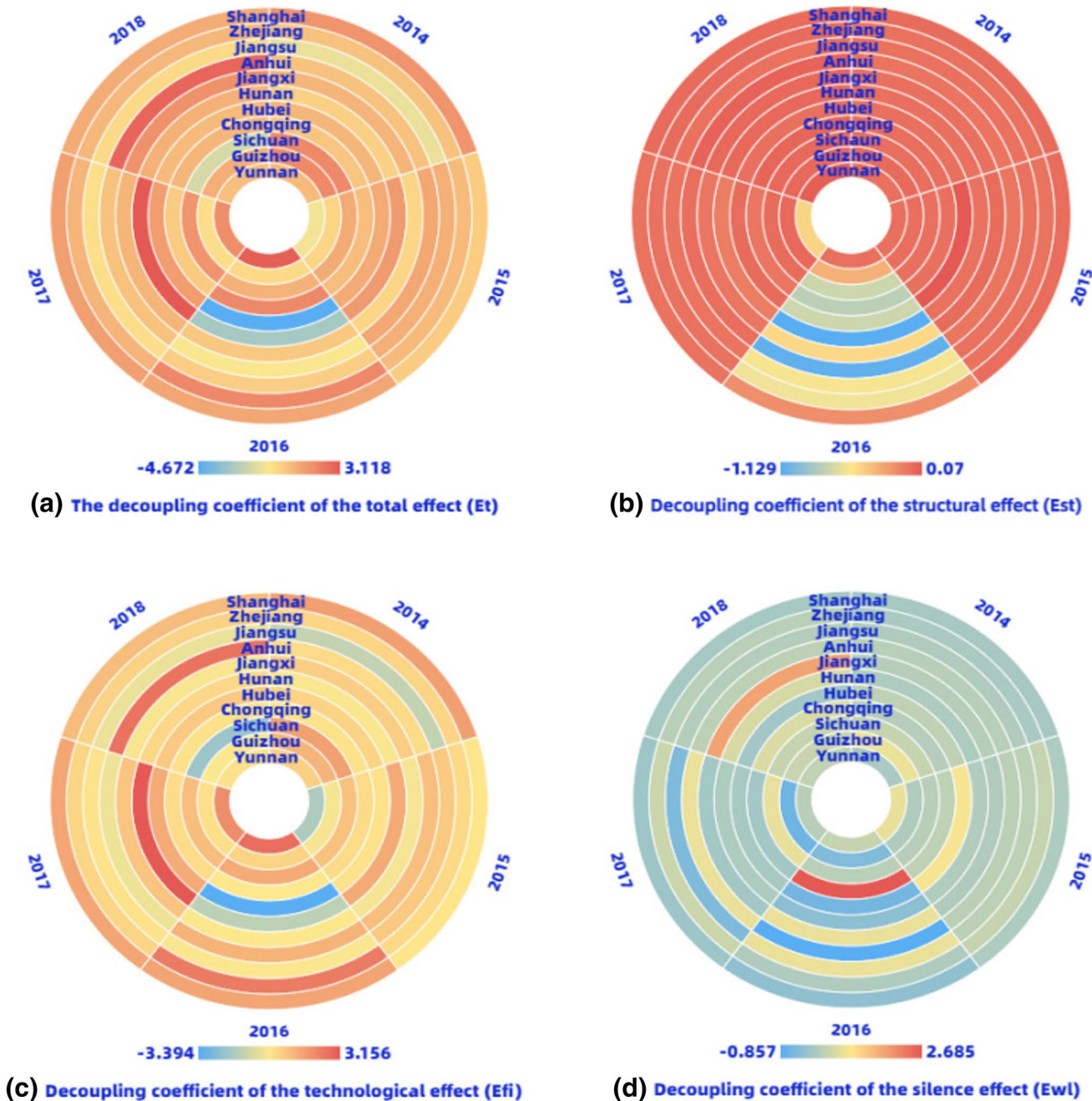

Fig. 2 The comparison between the total effect and the structural effect, the technological effect. and the silence effect. Note: **a** represents the DEC of Tapio decoupling for the total effect (E_t); **b** indicates the DEC of structural effects (E_{ST}); **c** refers to the DEC of technical effects (E_{FI}); **d** shows the DEC of silencing effect (E_{WL})

Figure 2 shows the comparison of E_T, E_{ST}, E_{FI}, and E_{WL} in 11 provinces of the YREB from 2014 to 2018 and indicates that the total decoupling effect E_T is greatly affected by the technical effect E_{FI} with the same change trend. The reason may be that once there is investment in equipment and facilities for water resource pollution control, the technical level can be rapidly improved, leading to the greater reduction of WRL. In addition, the investment in water pollution control equipment can be used to purchase fixed assets such as sewage treatment facilities, which is also an increase in actual GDP. Therefore, compared with the structural effect and silencing effect, the technical effect has greater influence on the decoupling state between WRL and economic development.

Discussion

The water resource liability of the YREB

Overall, the WRL of the YREB is high and shows a steady increase trend, and the provincial WRL can be divided into four grades from low to high: (6, 8), (8, 10), (10, 20), and (20, 30) billion CNY. Whether it is comparing with the sub-regional or provincial level, the WRLs of the downstream areas are generally higher than that of the upper and middle reaches. The calculation method of WRL in this study is similar to that of Yang et al. (2017), Qiu et al. (2019), and Zheng and Song (2021). However, Yang et al. (2017) only considered water quantity and water quality, and Qiu et al. (2019) only took the water volume into account when calculating WRL. That is why their calculation results are smaller than that of this study. Zheng and Song (2021) calculated the WRL in Hubei and it was slightly larger than the result in this paper, possibly because they took COD, ammonia nitrogen, and total phosphorus as pollutant sources, while this paper only considered COD and ammonia nitrogen emissions because of data accessibility. Specially, Zhu et al. (2019) measured the WRL of Sichuan in 2016 by using the energy conversion method which was higher than that in this study. In addition, Tang et al. (2020) calculated the WRL of the Yangtze River Basin, which was also slightly larger than that of this research. This may be because the region studied by Tang et al. (2020) is the Yangtze River Basin, which includes 19 provincial areas, while the research area in this paper is the YREB including 11 provincial areas. Besides, Tang et al. (2020) calculated the Yangtze River Basin as a whole, whereas, in this paper, the WRL of the YREB is calculated based on individual provincial areas. By comparison, the WRL value of this study is more credible since we calculated the water resource liabilities of 11 provinces and 3 sub-regions in the YREB from 2014 to 2018 considering water quantity, water quality, and water value.

At the provincial level, the increase rates of WRL in Yunnan, Guizhou, Sichuan, Hubei, Jiangsu, and Shanghai in 2018 are smaller than that in 2014, while Jiangxi and Anhui have a larger increase rate in 2018 compared with 2014 and Chongqing, Hunan, and Zhejiang have little change rate. This shows that *the Environmental Protection Law of the People's Republic of China (2015)*, *the Action Plan for Controlling the Total and Intensity of Water Resources Consumption during the 13th Five-Year Plan period (2016)*, and *the Water Pollution Prevention and Control Law of the People's Republic of China (2017)* promulgated by the Chinese government in recent years in order to purify the water environment have alleviated the pressure on the water environment. The lowest value of Hubei's WRL appeared in 2016 and the highest value in 2015. In 2016, Hubei issued policies to protect water resources due to the "Yangtze River Protection," leading to the WRL decline in 2016. Jiangsu's WRL showed a trend of fluctuation and decline with the highest in 2013 and the lowest in 2018. This shows that Jiangsu has realized the importance of water resource protection earlier, which may be due to the good economic development of Jiangsu, with its GDP ranking among the top in the YREB and even China. Economic improvement brings technological upgrading and conceptual change. As early as 2003, Jiangsu promulgated and implemented *the Jiangsu Water Resources Management Regulations* to better protect, save, utilize, and manage water resources.

From the perspective of sub-regions, the WRL of downstream is higher than that of the upper and middle reaches, which is closely related to the economic development of each sub-region. Since *China's reform and opening-up*, economic development in the lower reaches of the YREB has put more pressure on the water environment. Compared with the upstream and middle reaches, the downstream has caused more pollutions and damages to the water environment, so it needs to undertake more obligations to control water pollution and repair the water environment. However, the upstream and midstream provinces are mostly involved in China's "Western Development" and "Rise of Central China" strategy. Compared with the eastern coastal provinces, their economic development is more backward, resulting in less water environment burden. But the YREB has a high WRL. Although the "Opinions on the Implementation of the Strictest Water Resources Management System" in January 2012 clearly put forward the main objectives of "three red lines" for the control of water resource development and utilization, the control of water use efficiency, and the limitation of water pollution in water functional areas, the actual implementation consequence is not ideal. There is no unified water resource management system between the upper, middle, and lower reaches of the YREB.

Decoupling of WRL and economic development

In this paper, it is concluded that the WRL can indeed be used as an effective indicator to measure water environmental pressure. The decoupling relationship between WRL and economic growth obtained by this research is in accordance with the result of employing water consumption of a certain industry (Huang et al. 2021b), water resource utilization (Wu et al. 2021), water footprint (Zhang et al. 2021a, b), and wastewater discharge (Zhang et al. 2021c) as an indicator reflecting water environmental pressure to explore the decoupling state between it and economic development.

There is no clear relationship between WRL and economic development decoupling state and economic development level, and higher economic level does not mean better decoupling state. Take Shanghai and Guizhou for example. In recent years, Shanghai's GDP ranks 6th among 11 provinces in the YREB, while Guizhou ranks 11th. In numerical terms, Shanghai's GDP is more than twice that of Guizhou. However, it can be seen from Table 3 that the decoupling state between WRL and economic development in Shanghai is worse, with END for twice, and WRLI is the highest in the YREB. Although the economic development of Guizhou is not as good as that of Shanghai, it pays more attention to water resource protection, and the decoupling state is better, with three SD. This indicates that although the economic development of Shanghai is better than that of Guizhou, the decoupling relationship between WRL and economic development does not form a direct causal relationship with the economy.

On the other hand, there are many cases in this study that the same provincial area has the same decoupling state in different years or different provincial areas have the same decoupling states in the same year. In addition, neither of these two cases can distinguish the same decoupling states under different economic levels or WRL levels, which is difficult to give specific suggestions to policy makers. For example, Jiangsu and Guizhou showed SD in 2016 and 2017. Table 6 shows the comparison of actual GDP and WRL of the two provinces in 2016 and 2017. Jiangsu and Guizhou

Table 6 The comparison of Jiangsu and Guizhou in 2016 and 2017

Year	Province	Actual GDP (billion CNY)	WRL (billion CNY)	Decoupling state
2016	Jiangsu	5024.60	24.60	SD
	Guizhou	581.24	9.39	SD
2017	Jiangsu	5386.37	23.72	SD
	Guizhou	640.53	8.87	SD

The GDP data comes from the statistical yearbooks of Jiangsu and Guizhou, WRL are sorted and calculated by the author, and actual GDP is calculated based on the year 2000

are both in the SD state. However, in comparison, Jiangsu's WRL was 2.62 times and 2.67 times of that in Guizhou in 2016 and 2017, respectively. Meanwhile Jiangsu's GDP was 8.64 times and 8.41 times of that in Guizhou in 2016 and 2017, respectively. Because Jiangsu is in the case that both WRL and GDP are multiples of Guizhou, the final decoupling states of these two provinces can remain consistent. However, the two provinces should have different policy emphases. Guizhou has lower WRL and lower GDP development level, so it can give priority to economic development. Jiangsu's economic development has reached a desired state, but WRL is high, so Jiangsu is expected to pay more attention to pollution control and reduce WRL. This shows that although there is the same state of decoupling, the actual situation of provincial areas cannot be generalized, and the policy focus is also different. Therefore, in order to judge the decoupling state of the two years, it may be necessary to introduce other indexes; for example, the secondary decoupling coefficient and the decoupling stability index (DSI) are taken as auxiliary judgment. In addition, the promulgation of policies by the government will affect the WRL in each year, which will also have an impact on the decoupling state between provincial WRL and economic development.

Influencing factors and stability analysis of the decoupling state of the YREB

This study analyzes the internal factors influencing the decoupling relationship between WRL and economic development. Based on the decomposition of Tapio decoupling elasticity by Li and Sun (2016), this study divides the influencing factors of WRL decoupling from economic growth into structural effect, technological effect, and silence effect. It is found that technological effect is the main internal factor for the decoupling state of WRL and economic development in the YREB. The conclusions of this paper on the driving factors of decoupling are consistent with those of Zhang et al. 2021a), which also studied the influencing factors of decoupling in the YREB. More importantly, this paper has drawn the similar conclusions to the research exploring the factors influencing decoupling between water environmental pressure and economic development on the Yellow Sea and Bohai Sea (Qiu et al. 2018), Beijing (Wang et al. (2019b)), Jiangsu (Sun et al. 2020), and southwest China (Pan et al. 2021), which all consider technological effect as the main driving factor.

The technological effect mainly studies the investment of water resource protection and water pollution control facilities in the YREB. Investment in the current year can pay off in the current period, effectively reducing WRL. As for the structural effect and silence effect, there may be two main reasons for why they have less influence on the overall decoupling state than the technological effect: (1) the

research period of this study is from 2014 to 2018, and the structural effect is mainly reflected in the treatment of wastewater, reducing the concentration of COD and ammonia nitrogen in sewage. However, wastewater treatment mainly relies on the self-purification capacity of water, whose recovery degree is very limited in such a short period. The influence of structural effect needs a long time to show up. (2) The silence effect is mainly reflected in water loss from 2014 to 2018. Although each province has a part of water loss every year, the amount of water loss is limited compared with the water use of each province. Besides, water loss will change with different natural conditions and is uncontrollable, so it has little influence on the decoupling relationship between WRL and economic development.

By comparison, this study combined the driving factors with the decoupling stability analysis; thus, the analysis results can provide more enlightenment (Han et al. 2021). The decoupling state in the YREB is relatively stable although the decoupling states between WRL and economic development in some provinces are not so ideal. Among the internal factors, the technological effect decoupling state fluctuates the most, while the structural effect and silencing effect are more stable. The DSI of the YREB is between 0.5 and 3.0, among which the decoupling stability of Sichuan is the most ideal. The decoupling stabilities of Chongqing and Shanghai are terrible. This shows that the YREB has attached great importance to water environment protection in recent years, and the effect of governance is gradually accumulating. However, some provinces may not have enough implementation efforts, and water resource protection needs to be further emphasized and promoted in the future.

Limitations and recommendations

Although this study innovatively takes WRL as an indicator to measure the environmental pressure brought by economic development and analyzes the decoupling state, decoupling stability, and internal decoupling decomposition effect of WRL and economic growth, there are still two deficiencies expected to be further improved in the future research:

(1) For the sake of data acquisition, this study only considers COD and ammonia nitrogen emissions as the two most important pollutants when calculating "sewage treatment cost." In order to make the calculation result more accurate, we will try to collect more complete pollutant data such as total phosphorus and total nitrogen in future studies and incorporate them into the calculation.

(2) The same decoupling state occurs in different provinces in the same year or in different years in the same province for many times in this study. As the Tapio decoupling elasticity coefficient measures the ratio of

percentages, the same decoupling states obtained by the above classification based on the range of elasticity index are different, such as different economic levels or environmental pressure levels. In the future, two-dimensional decoupling analysis is needed to achieve more accurate decoupling state segmentation.

Conclusions and implications

To crack the profound contradiction between economic growth and the water resource crisis is helpful for realizing regional SDGs. To this end, based on innovatively introducing the WRL method, this study takes the YREB as the research area and combines with the decoupling states and decoupling decomposition with decoupling stability to identify the feasible pathways of realizing regional sustainable development of water resources and economic growth simultaneously. This study has not only enriched the decoupling theory and method, but also provided a new idea for the evaluation and path of regional sustainable development. The main conclusions are as follows:

(1) The WRL in the YREB is relatively high in general and presents an upward trend of fluctuation. The WRL in the downstream of the YREB is generally higher than those in the upstream and midstream both at the sub-regional and provincial levels. Among them, the investment cost in facilities for water resource protection and water pollution control accounts for the largest proportion in WRL.

(2) Overall, the decoupling state between WRL and economic development in the YREB is stable, and there is no obvious causal relationship between WRL decoupling and economic development level in the YREB. A high level of economic development does not mean a good decoupling state. At the sub-regional level, the decoupling state and decoupling stability between WRL and economic growth in the downstream of the YREB are the best. Compared with other provincial areas, Jiangsu and Guizhou have the most ideal decoupling states, while Shanghai has the worst decoupling state. Meanwhile, the decoupling stability is the best in Sichuan and the worst in Chongqing.

(3) The decoupling decomposition effects between WRL and economic development in the YREB include structural effect, technological effect, and silence effect. Technological effect is the main driving factor leading to the decoupling between WRL and economic development, but its decoupling stability is the worst. Both structure effect and silence effect have good decoupling stabilities.

In short, the decoupling results of WRL and economic development above are very important for the high-quality economic development of the YREB, which is conducive to the formulation of targeted economic development policies for each provincial area. Based on the above conclusions, this study puts forward the following three suggestions:

(1) In terms of the WRL in the YREB, the investment cost of facilities accounts for the largest proportion. The upstream provinces need to steadily increase investment in water resource protection and water pollution control facilities and improve their own economic development at the same time. On the premise of maintaining the current level of economic development, the downstream provinces should control the investment expenditure on facilities and equipment and improve the efficiency of investment utilization. The YREB should formulate a unified system of joint prevention and control of water resources, further promote the "river chief system," and strengthen the monitoring of water quantity and quality at provincial demarcation points to reduce WRL.

(2) In order to achieve better decoupling status and improve decoupling stability of the YREB, all the provinces in the YREB should pay attention to the WRL management. The provinces with high economic level should reduce WRL by improving the investment efficiency and controlling investment expenditure, while the provinces with low economic level should improve their economic strength on the premise of protecting water resource environment.

(3) The YREB should adhere to sustainable water resource management. The competent departments at all levels should reduce the cost of water pollution control by strengthening the current pollution control of water resources, reducing the investment cost of water resources facilities and equipment by enhancing the utilization efficiency of water resources facilities, and reducing the cost of water loss by strengthening the efforts of water conservation.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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