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Evaluation of synergistic and regulatory effects of carbon-reduction and water-saving in the Yangtze River Delta Urban Agglomeration

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Realizing the synergistic effect of urban carbon-reduction and water-saving (CRWS) is of great significance for improving the urban carbon-water nexus and promoting urban sustainable development. From the perspective of the synergistic impact of intensive water resource utilization on carbon emissions, a theoretical framework is constructed. The relevant data on water resources and carbon emissions of the Yangtze River Delta Urban Agglomeration (YRDUA) from 2014 to 2023 are taken as the research objects for analysis. And a series of fixed effect models are adopted to evaluate the synergistic and regulatory effects of urban CRWS. Results show that the production water supply intensity has a positive impact on carbon emission intensity, while production water-saving intensity and ecological water intensity have negative impacts on carbon emission intensity in the YRDUA. Technical factors negatively regulate the synergy of carbon emission intensity and production water supply intensity. Structural factors negatively regulate the synergy between carbon emission intensity and water resource intensive utilization intensity. Technology, structure and scale factors have more significant effects on the synergistic effect of CRWS in areas with higher urban development level.

Keywords Synergistic and regulatory effects, Carbon-water nexus, Carbon emission intensity, Yangtze River Delta Urban Agglomeration, Carbon-reduction and water-saving

In recent years, the level of urban development has been continuously expanding globally[1]. As the main carbon emitters and water consumers, the improvement of the development level of cities has led to a series of problems such as increased carbon emission, water resource consumption, and worsening water pollution[2]. This has had a negative impact on the synergy and virtuous cycle of carbon emission and water resource utilization[3]. Carbon emission and water resource scarcity have gradually become important bottlenecks for the sustainable development of urban systems, and the two have affect and interact with each other[4–6]. Water resources development, transportation, and sewage treatment will cause carbon dioxide emissions, and the climate change caused by carbon emission will also have a profound impact on the improvement of water resource utilization level[7]. Therefore, it is worth considering about how to realizing synergistic development of low carbon emission and water resource utilization, improve the urban carbon–water nexus and promote the sustainable development of urban economy.

At present, the carbon emission issue characterized by the increasing concentration of carbon dioxide in the atmosphere and the water utilization issue characterized by water resource scarcity are the key research focuses in the current theory of urban carbon–water correlation. In industrialized countries, energy consumption leads to large greenhouse gas emissions. In order to achieve low-carbon development, the promotion and utilization of energy technology are essential, and the consumption of water resources also increases accordingly[8]. Byers et al.[9] and Konadu et al.[10] analyzed the implementation path of low-carbon development in the UK. The results suggested that the UK might face significant water stress in the future to enable high carbon capture and storage (CCS) for thermal power generation. However, in the long run, improving the utilization rate of water resources is the most marginal measure to reduce emissions and balance economic development with environmental

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improvement[11]. Therefore, water-saving can lead to cascading energy saving, thus achieving carbon reduction[12]. For a water plant with a conventional water supply of 10^5 t/d, saving 10% of water is 10^4 t/d, and based on the carbon emission of 0.3 kg per ton of water supply, it is preliminarily estimated that carbon emission can be reduced by more than 1095 t/year. Meanwhile, the sustainable utilization of water resources will have an impact on carbon emission[13]. Relevant studies have shown that carbon footprint exists in the construction of water source projects, water supply, and water pollution treatment[14–17]. Wang et al.[18] found that industrial water consumed the most energy and emitted the most carbon during China's economic and social water cycle. The aforementioned studies indicate that there is a close correlation between water resource utilization and carbon emissions. Therefore, it is necessary to formulate relevant policies to determine and balance the carbon-reduction and water-saving goals on the premise of ensuring the normal operation of the economy and society[19]. Factors such as total energy consumption, industrial structure, technological progress and population size has produced significant regulatory effect on urban carbon emission and water resource utilization[20–22]. In addition, the differences in urban development level also have different impacts on controlling carbon emission and improving the efficiency of water resource intensive utilization[23,24].

In 2001, the Intergovernmental Panel on Climate Change (IPCC) defined synergies as the economic and social benefits brought about by the realization of greenhouse gas emission reduction targets, such as technological innovation and progress, air quality improvement, ecological environment improvement, etc. Relevant studies mainly involve the synergistic effect of low-carbon development and production technology development[25], the synergistic effect between pollution reduction and carbon reduction[26,27], and the synergistic effect of energy, climate and environmental policies[28]. The impact of technological progress on carbon emission has a dual characteristic. On the one hand, the progress of production technology can first be reflected in the reduction of fossil fuel demand, thereby achieving a reduction in carbon emission. On the other hand, technological progress can promote economic growth and lead to more energy consumption and carbon dioxide emissions[29]. Climate and environmental policies can effectively reduce carbon emission and energy consumption, and exhibit regional heterogeneity characteristics[30]. At present, research methods for synergistic effects mainly include cross elasticity analysis of collaborative control[31], regression analysis of synergistic effects[32], general equilibrium model[33], STIRPAT model[34], physiological process model[35]. In recent years, quantitative research on the synergy of carbon–water relationships has been continuously deepened. Jiang et al.[36] took Tianjin in China as the research object and used a system dynamics model to study the feedback mechanism between water resource utilization and urban carbon emissions. The results showed that carbon emissions existed throughout the entire life cycle of water resource supply, allocation, and utilization. Danish[7] analyzed the relationship between water productivity and carbon emissions using the auto-regressive distributed lag method. The results indicated that there was a causal relationship between the two in both the long term and the short term. Zhao et al.[37] constructed a policy evaluation model to analyze the energy-carbon–water correlation in China. The results indicated that the environmental effects brought about by water conservation were significant.

There are rich achievements in the research of the synergistic effects brought about by carbon-reduction goals, but research on the synergistic effects of urban carbon emission based on the perspective of water resource intensive utilization is still lacking. Therefore, this study constructs a theoretical framework for evaluating the synergistic effect of urban carbon-reduction and water-saving (CRWS) based on the synergistic impact of water resource intensive utilization on carbon emission. On this basis, the fixed effect panel model and multiple parallel regulation effect model are introduced to analyze the synergistic effect and explore the regulatory effect of urban CRWS under the development level of heterogeneous cities. Finally, the Yangtze River Delta Urban Agglomeration (YRDUA) is taken as the research object for quantitative analysis. The research hypotheses are as follows: (1) The impacts of production water supply, production water-saving, and ecological water use on carbon emissions are different or even opposite. (2) The moderating effects of technical, structural, and scale factors on the synergistic effect of CRWS in the YRDUA vary significantly. (3) Moderating variables such as technical, structural, and scale factors have a more obvious impact on the synergistic effect of CRWS in areas with a higher level of urban development.

This study contributes to the existing literature in three aspects: (1) Three indexes including production water supply intensity, production water-saving intensity and ecological water intensity are adopted to comprehensively reflect the water resource intensive utilization intensity. (2) The synergistic impact of water resource intensive utilization intensity on carbon emission is analyzed. (3) The regulatory effects model of technology, structure, and scale factors on the synergy of urban CRWS are established. In addition, this study takes heterogeneity of urban development level into account to explore whether the synergistic and regulatory effects of CRWS are different under the heterogeneity of city size and urbanization rate. The research on the synergistic and regulatory effects of urban CRWS is helpful to reveal the effective ways of low carbon emission, water resource intensive utilization and urban carbon neutrality, and improve the urban carbon–water nexus from the small and medium-sized regional scale.

Materials and methods

Analysis framework for the synergistic and regulatory effects of urban carbon-reduction and water-saving

As shown in Fig. 1, the impact of water resource intensive utilization on carbon emission can be decomposed into the synergistic effects of the intensive utilization of production water resources and ecological water resources, as well as the role of regulatory variables such as technology, structure, and scale factors.

Firstly, the improvement of the production water intensive level brings opportunities for urban low-carbon development. In the process of soc-economic development, human production activities inevitably generate a large amount of carbon dioxide, among which industrial production industries such as cement and steel with high energy consumption are the main carbon emitting industries. Water resources, as a medium or green energy,

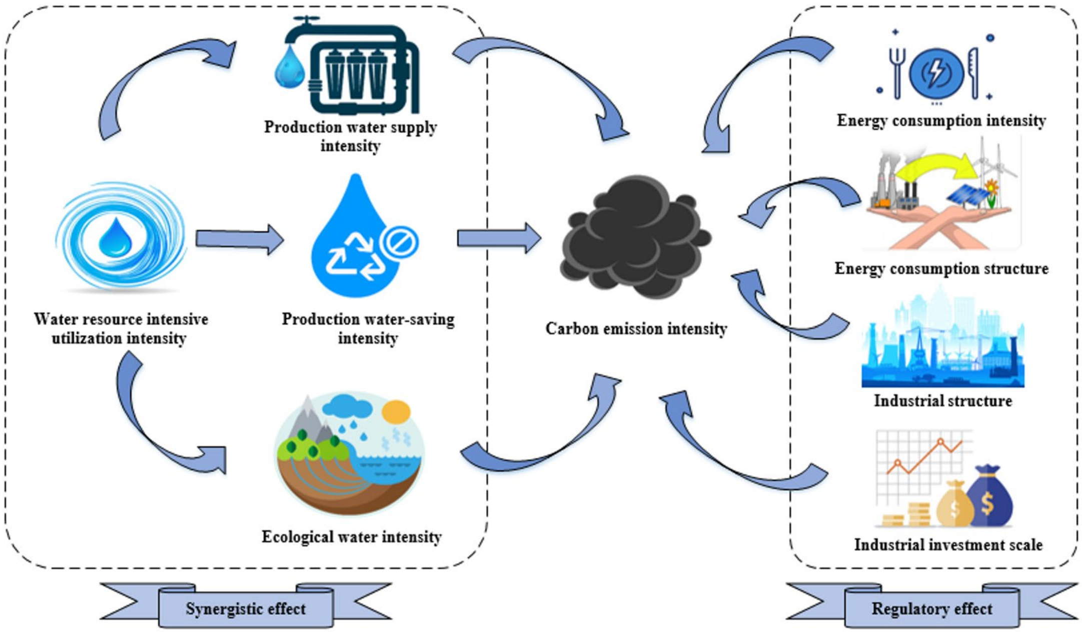

Fig. 1. The synergistic impact mechanism of water resource intensive utilization on carbon emission.

provide important support for reducing carbon sources[38]. On the one hand, the strengthening of production water supply intensity helps to improve the carbon utilization efficiency of carbon-containing resources and reduce carbon emission per unit output[39]. On the other hand, water conservation in production can not only reduce water costs but also decrease the discharge of wastewater, thereby effectively reducing the actual carbon emissions generated during the production process. [40].

Secondly, the improvement of ecological water intensive level is the basis for ensuring the low-carbon development of soc-economy. Plants in ecosystems including woodland, grassland, wetland convert carbon dioxide in the air into organic carbon through photosynthesis, with a carbon sequestration capacity of up to 90%[41]. As a crucial environmental factor, water resources can promote the ecological environment system to give full play to the function of carbon sink. By ensuring that ecological water is not occupied by production water, the utilization intensity of ecological water can be enhanced. It helps to achieve the protection and restoration of natural ecological landscapes such as forests and wetlands, as well as the construction and maintenance of artificial ecological landscapes such as economic forests, green spaces, and parks. While improving residents' living environment and quality of life, urban carbon absorption capacity can be enhanced to reduce atmospheric carbon dioxide concentration[42].

Finally, with the premise of water resource intensive utilization and ecological environment protection, giving full play to the regulatory role of energy-related technologies, structures, and scale factors is an important way to achieve low-carbon development goals. Specifically, strengthening the innovation and promotion of energy utilization technology and reducing energy consumption intensity are conducive to reducing the actual carbon emission generated in the production process[43]. Reducing the consumption of coal in industrial production, appropriately promoting the use of clean energy represented by hydropower, and optimizing the energy structure and industrial structure can promote the formation of a production mode with high output, low consumption and low emission[44]. In addition, relevant studies show that industrial fixed asset investment has a long-term and stable correlation with energy consumption and carbon emission. Therefore, the investment scale of industrial fixed investment is also an important factor affecting low-carbon development[45].

In order to analyze and evaluate the synergistic and regulatory effects of urban CRWS, we proposes a four-stage analysis framework (as shown in Fig. 2). The first stage is to quantitatively analyze the change trend of urban carbon emission intensity and water resource intensive utilization intensity. The second stage is to analyze the synergistic and regulatory effects of urban CRWS. Firstly, production water supply intensity, production water-saving intensity, and ecological water intensity are used to reflect the water resource intensive utilization intensity. A fixed effect model is adopted to analyze the synergistic impact of water resource intensive utilization intensity on carbon emission. Then, a multiple parallel regulation effect model is introduced to analyze the regulation effects of energy-related technology, structure and scale factors on the synergistic effect of urban CRWS. Finally, taking the level of urban development into account, we explore the differences in the synergistic and regulatory effects of CRWS under the heterogeneity of city size and urbanization rate. The third stage is to take the YRDUA as an example to conduct empirical research. The fourth stage is to propose the policy implications of the research.

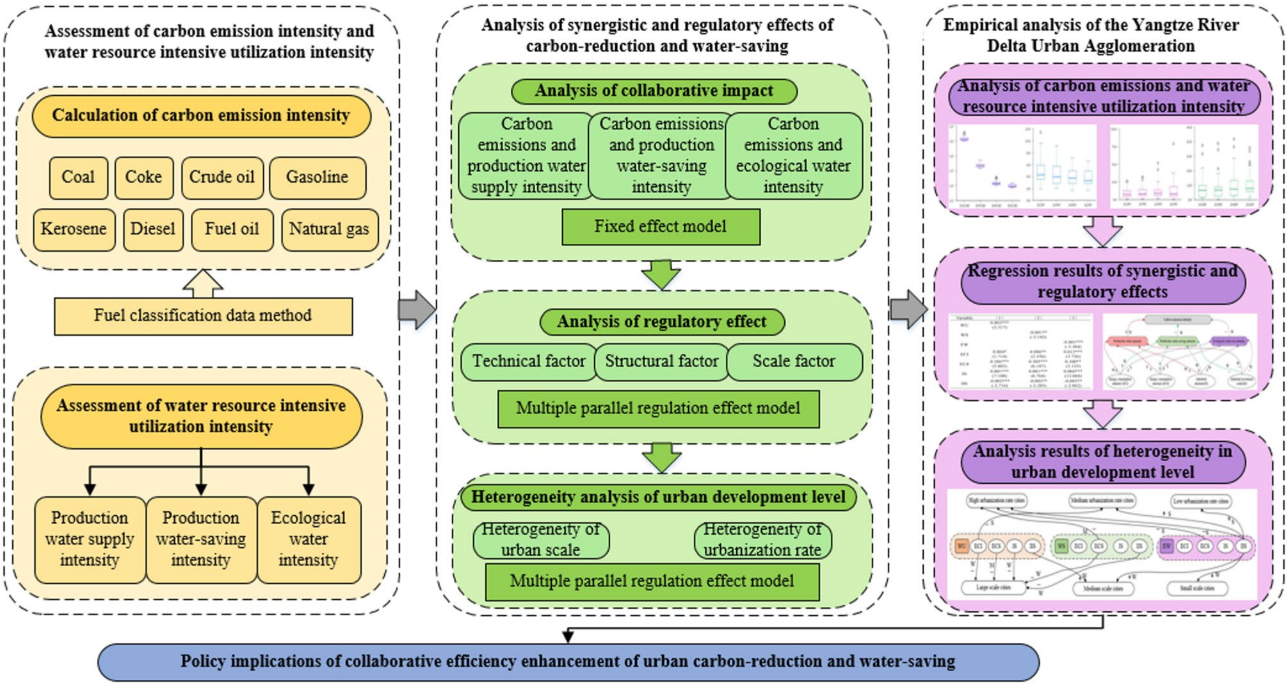

Fig. 2. Urban carbon-reduction and water-saving synergistic effects analysis framework.

Study area and data sources

The YRDUA is located on the alluvial plain at the mouth of the Yangtze River, with a total area of 211,700 square kilometers and a population of 225 million. The YRDUA consists of Shanghai, 9 cities including Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Zhenjiang, Yancheng and Taizhou in Jiangsu Province, 9 cities including Hangzhou, Ningbo, Wenzhou, Huzhou, Jiaxing, Shaoxing, Jinhua, Zhoushan and Taizhou in Zhejiang Province, and 8 cities including Hefei, Wuhu, Ma'anshan, Tongling, Anqing, Chuzhou, Chizhou and Xuancheng in Anhui Province. With the proposal of the integrated development strategy for the YRDUA in 2018, coupled with the development strategy of the Yangtze River Economic Belt, the YRDUA is facing significant development opportunities. However, due to the rapid population growth and the accelerated urbanization process, the YRDUA still faces huge dual pressures of resource and environment. Therefore, conducting relevant research on the synergistic and regulatory effects of CRWS can provide a basis for improving the utilization level of water resources and enhancing environmental quality in the YRDUA. And it has guiding significance for the management practice of promoting the green and low-carbon development of the YRDUA. In view of this, the study takes 27 cities in the YRDUA as the basic research area.

The panel data involved in this study spans from 2014 to 2023. Statistical data such as GDP and population of each city are acquired from the China Urban Statistical Yearbook, and the statistical data such as carbon emission intensity, production water consumption, production water-saving, and energy consumption are sourced from the China Urban Construction Yearbook. Statistical data such as industrial structure and industrial fixed investment are obtained from the Shanghai Statistical Yearbook, Jiangsu Statistical Yearbook, Zhejiang Statistical Yearbook, and Anhui Statistical Yearbook. For a small portion of missing data, interpolation method is used to fill in.

Variable selection

Carbon emission intensity

The carbon emission intensity represents the amount of CO_2 emitted per unit of output. It can be expressed as Eq. (1):

$$CAR_j = T_j / GDP_j \tag{1}$$

where CAR_j refers to the carbon emission intensity of city j, T_j refers to the total carbon emission of the city j, and GDP_j refers to the gross domestic product of the city j.

We draw on the method of Xu et al.[46], which calculates the carbon emission of different types of energy consumption separately and then accumulates them to obtain the total CO_2 emissions. It can be expressed as follows:

$$T_j = \sum_{i=1}^{8} E_{ji} \times f_i \tag{2}$$

where i represents the types of fossil fuels, namely coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil and natural gas. E_{ji} represents the consumption of energy i by the city j. f_i is the carbon emission coefficient of energy i, mainly derived from the National Greenhouse Gas Inventory Guidelines published by the Intergovernmental Panel on Climate Change (IPCC) in 2006. The carbon emission coefficients of the above five fossil fuels are 0.5714, 0.8550, 0.5857, 0.6185 and 0.4483 respectively.

Water resource intensive utilization intensity

The water resource intensive utilization intensity is a concept that balances the production and ecological benefits of water resources. We adopt the production water supply intensity, production water-saving intensity, and ecological water intensity to describe the water resource intensive utilization intensity. Specifically, the production water supply intensity refers to the amount of water consumed per unit of output. The production water-saving intensity refers to the proportion of water saved per unit of water consumption. Ecological water intensity refers to the per capita water consumption in the ecological environment. They are expressed in Eqs. (3) ~ (5):

$$WU_j = WC_j / GDP_j \tag{3}$$

$$WS_j = PW_j / WC_j \tag{4}$$

$$EW_j = EE_j / POP_j \tag{5}$$

where WU_j, WS_j, and EW_j respectively represent the production water supply intensity, production water-saving intensity, and ecological water intensity of the city j. WC_j, PW_j, and EE_j respectively represent the total amount of production water, production water-saving, and ecological environment water used of the city j. GDP_j and POP_j respectively represent the gross national product and total population of the city j.

Regulatory variables

Energy consumption intensity Energy consumption intensity reflects the progress of regional energy utilization technology. The lower the energy consumption intensity, the stronger the urban energy rational utilization capacity and the higher the energy technology level[47]. We adopt the total amount of energy consumed per unit of output to represent the energy consumption intensity, which can be calculated as follows:

$$ECI_j = EC_j / GDP_j \tag{6}$$

where ECI_j and EC_j represent the energy consumption intensity and total energy consumption of the city j, respectively.

Energy consumption structure Coal consumption is the main source of CO_2 emissions, and could have a significant impact on atmospheric carbon emission. Therefore, we use the proportion of coal consumption in total energy consumption to represent the energy consumption structure, which can be calculated as follows:

$$ECS_j = CC_j / EC_j \tag{7}$$

where ECS_j and CC_j represent the energy consumption structure and total coal consumption of the city j, respectively.

Industrial structure As the main sector of energy consumption, industry has a significant impact on carbon emission intensity[48,49]. We use the industrial output as a proportion of the gross national product to express the industrial structure, which can be calculated as follows:

$$IS_j = IO_j / GDP_j \tag{8}$$

where IS_j and IO_j represent the industrial structure and industrial output of the city j, respectively.

Industrial investment scale The increase in industrial investment scale represents the expansion of industrial production scale, which can exacerbate the expansion effect of carbon emission to some extent[50]. We use the per capita fixed industrial investment to represent the scale of industrial investment, which can be calculated as follows:

$$IIS_j = IIA_j / POP_j \tag{9}$$

where IIS_j and IIA_j represent the industrial investment scale and total industrial fixed assets investment of the city j, respectively.

Synergistic effect analysis model

The synergistic effect of urban CRWS is analyzed from a quantifiable perspective using a panel fixed effect model. Taking into account the characteristics of the carbon–water nexus and combining with the theoretical mechanism analysis mentioned earlier, we divide the regulatory variables related to energy into three categories: technical, structural and scale factors. The energy consumption intensity is adopted to reflect technical factor, energy consumption structure and industrial structure are adopted to reflect structural factors, and industrial investment scale is adopted to reflect scale factors. On this basis, a fixed effect model is constructed to analyze the synergistic effect of water resource intensive utilization on carbon emission. The model can be constructed as follows:

$$CAR_{jt} = \alpha_{01} + \alpha_{11}WU_{jt} + \alpha_{21}ECI_{jt} + \alpha_{31}ECS_{jt} + \alpha_{41}IS_{jt} + \alpha_{51}IIS_{jt} + \lambda_{j1} + \mu_{t1} + \varepsilon_{jt1} \quad (10)$$

$$CAR_{jt} = \alpha_{02} + \alpha_{12}WS_{jt} + \alpha_{22}ECI_{jt} + \alpha_{32}ECS_{jt} + \alpha_{42}IS_{jt} + \alpha_{52}IIS_{jt} + \lambda_{j2} + \mu_{t2} + \varepsilon_{jt2} \quad (11)$$

$$CAR_{jt} = \alpha_{03} + \alpha_{13}EW_{jt} + \alpha_{23}ECI_{jt} + \alpha_{33}ECS_{jt} + \alpha_{43}IS_{jt} + \alpha_{53}IIS_{jt} + \lambda_{j3} + \mu_{t3} + \varepsilon_{jt3} \quad (12)$$

where $\alpha_{0m} \sim \alpha_{5m}$ ($m = 1, 2, 3$) are the parameters to be estimated. λ_j,μ_t and ε_{jt} represent individual fixed effects, time fixed effects and random error terms, respectively.

Multiple parallel regulatory effect model

The regulatory effect means that the direction and degree of the influence of the regulatory variable on the main effect can be different due to individual characteristics or environmental conditions[51,52]. In empirical studies, the regulatory effect is specifically manifested as the strengthening or weakening of the relationship between the explanatory variable and the explained variable by the regulatory variable[53]. In general, the regulatory effect is based on the main effect. By constructing corresponding interaction terms and combining the symbols of the main effect and the regulatory effect, the direction and degree of the influence of the regulatory variables on the main effect are judged and analyzed (as shown in Fig. 3).

The water resource intensive utilization intensity indicators (*i.e.* WU_{jt}, WS_{jt}, and EW_{jt}) are adopted as the main effect to carbon emission intensity (CAR_{jt}), and ECI_{jt}, ECS_{jt}, IS_{jt}, and IIS_{jt} are adopted as regulatory variables. By introducing the interaction terms between the four regulatory variables mentioned above and the intensity variable of water resource intensive utilization, a multiple parallel regulatory effect model is constructed as follows:

$$CAR_{jt} = \alpha_{01} + \alpha_{11}WU_{jt} + \alpha_{21}ECI_{jt} + \alpha_{31}ECS_{jt} + \alpha_{41}IS_{jt} + \alpha_{51}IIS_{jt} + \beta_{11}WU_{jt} \times ECI_{jt} + \beta_{21}WU_{jt} \times ECS_{jt} + \beta_{31}WU_{ji} \times IS_{jt} + \beta_{41}WU_{jt} \times IIS_{jt} + \lambda_{j1} + \mu_{t1} + \varepsilon_{jt1} \quad (13)$$

$$CAR_{jt} = \alpha_{02} + \alpha_{12}WS_{jt} + \alpha_{22}ECI_{jt} + \alpha_{32}ECS_{jt} + \alpha_{42}IS_{jt} + \alpha_{52}IIS_{jt} + \beta_{12}WS_{jt} \times ECI_{jt} + \beta_{22}WS_{jt} \times ECS_{jt} + \beta_{32}WS_{ji} \times IS_{jt} + \beta_{42}WS_{jt} \times IIS_{jt} + \lambda_{j2} + \mu_{t2} + \varepsilon_{jt2} \quad (14)$$

$$CAR_{jt} = \alpha_{03} + \alpha_{13}EW_{jt} + \alpha_{23}ECI_{jt} + \alpha_{33}ECS_{jt} + \alpha_{43}IS_{jt} + \alpha_{53}IIS_{jt} + \beta_{13}EW_{jt} \times ECI_{jt} + \beta_{23}EW_{jt} \times ECS_{jt} + \beta_{33}EW_{ji} \times IS_{jt} + \beta_{43}EW_{jt} \times IIS_{jt} + \lambda_{j3} + \mu_{t3} + \varepsilon_{jt3} \quad (15)$$

where $\alpha_{0m} \sim \alpha_{5m}$ ($m = 1, 2, 3$), $\beta_{1n} \sim \beta_{4n}$ ($n = 1, 2, 3$) are the parameters to be estimated. λ_j,μ_t and ε_{jt} represent individual fixed effects, time fixed effects and random error terms, respectively.

In order to further analyze whether the regulatory effects of energy-related technology, structure and scale factors as regulatory variables would be different due to different levels of urban development, we group the study regions according to urban development scale and urbanization level. The synergistic and regulatory effects of CRWS based on the heterogeneity of urban development levels are studied. Specifically, the scale of urban development is defined according to the range of the permanent population of the city. The level of urbanization is defined based on the size of the urbanization rate. The groups are shown in (Tables 1, 2).

Results

Trends of carbon emission and water resource intensive utilization intensity

The trends of carbon emission intensity and water resource intensive utilization intensity in 27 cities of the YRDUA from 2014 to 2023 are shown in Fig. 4. The averages of carbon emission intensity and production water supply intensity show decreasing trend year by year. Specifically, the average of carbon emission intensity decreased from 0.229 tons/10^4 yuan in 2014 to 0.149 tons/10^4 yuan in 2023 (Fig. 4a). The average of production water supply intensity decreased from 4826 $m^3/10^4$ yuan in 2014 to 3708 $m^3/10^4$ yuan in 2023 (Fig. 4b). The average of production water-saving intensity increased year by year, from 9.528% in 2014 to 12.925% in 2023

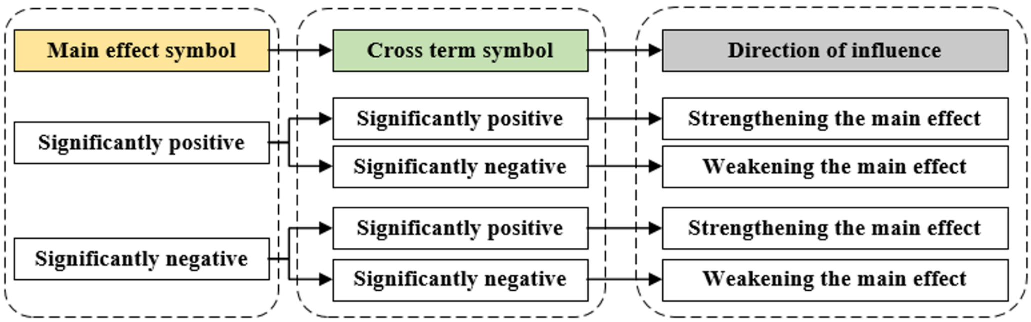

Fig. 3. Schematic diagram of the regulatory effect.

Urban development scale	Urban permanent population(10^4 people)	City
Large scale cities	Population greater than 1 million	Shanghai, Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Yancheng, Hangzhou, Ningbo, Wenzhou, Shaoxing, Taizhou (Zhejiang), Hefei, Wuhu
Medium scale cities	Population between 500 thousand and 1 million	Zhenjiang, Taizhou (Jiangsu), Jiaxing, Jinhua, Zhoushan, Maanshan, Anqing, Chuzhou
Small scale cities	Population less than 500 thousand	Huzhou, Tongling, Chizhou, Xuancheng

Table 1. Classification of urban development scale.

Urbanization levels	Urbanization rate(%)	City
High urbanization rate cities	Urbanization rate above 80%	Shanghai, Nanjing, Wuxi, Suzhou, Hangzhou, Hefei
Medium urbanization rate cities	Urbanization rate between 70 and 80%	Changzhou, Nantong, Yangzhou, Zhenjiang, Ningbo, Wenzhou, Jiaxing, Shaoxing, Zhoushan, Wuhu, Maanshan
Low urbanization rate cities	Urbanization rate below 70%	Yancheng, Taizhou (Jiangsu), Huzhou, Jinhua, Taizhou (Zhejiang), Tongling, Anqing, Chuzhou, Chizhou, Xuancheng

Table 2. Classification of urbanization levels.

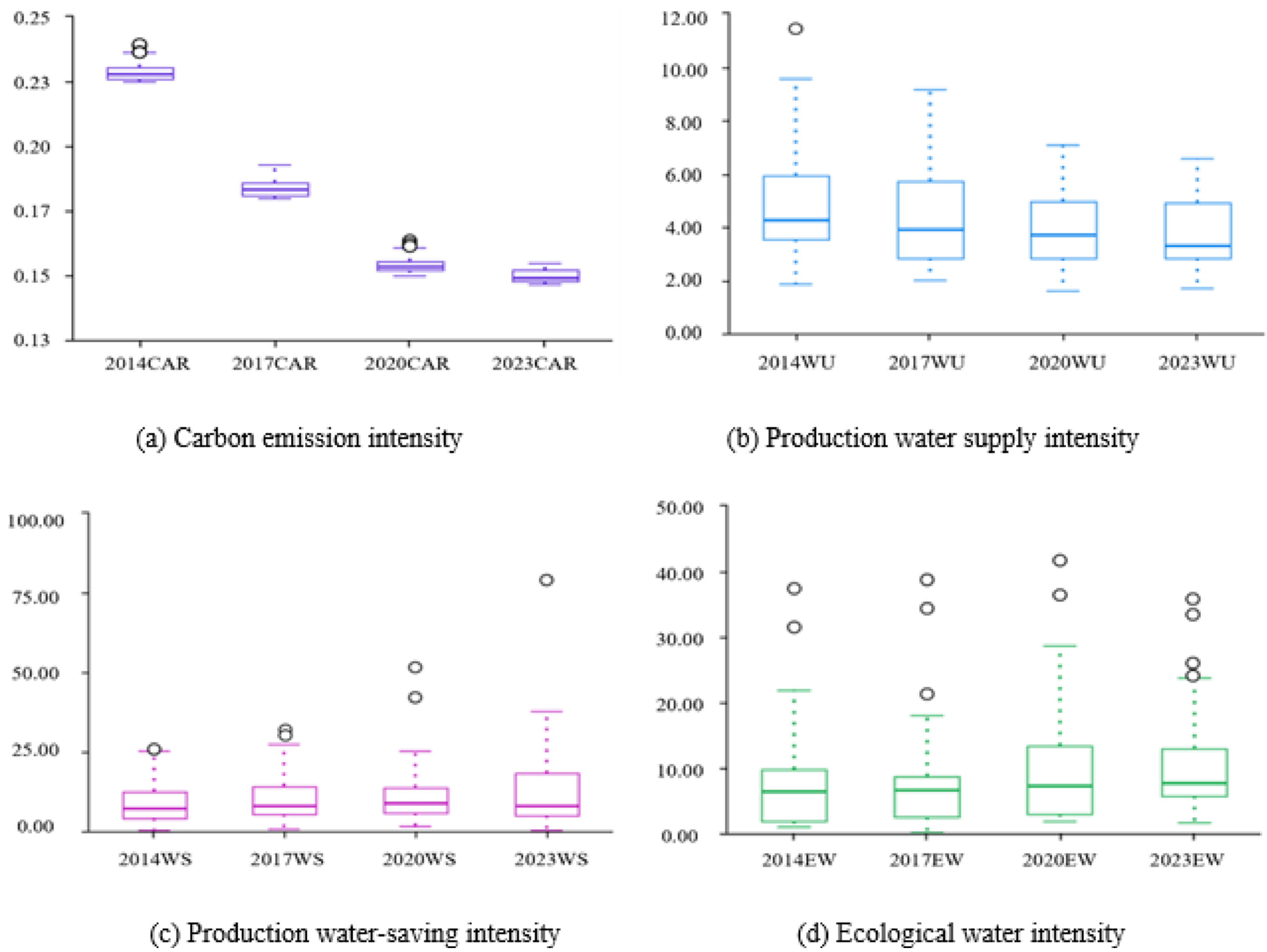

Fig. 4. Evolution trends of the intensity of carbon emission and water resource intensive utilization in the YRDUA.

(Fig. 4c). The average of ecological water intensity showed a fluctuating upward trend, decreasing from 8.451m^3/person in 2014 to 8.356m^3/person, and gradually increasing to 10.961m^3/person in 2023 (Fig. 4d). Overall, during the study period, the carbon emission per unit output of the YRDUA continued to decrease, while the level of water resource intensive utilization improved.

The trends of carbon emission intensity and water resource intensive utilization intensity in Shanghai, Jiangsu, Zhejiang, and Anhui are shown in Fig. 5. During the study period, the carbon emission intensity in Shanghai, Jiangsu, Zhejiang and Anhui showed a fluctuating downward trend (Fig. 5a). However, in 2018, carbon emissions in various provinces showed an upward trend, mainly attributed to the stable growth of coal consumption and the continuous increase in the use of oil and natural gas. The production water supply intensity in Shanghai showed a significant downward trend and was significantly higher than that of other three provinces (Fig. 5b). The production water-saving intensity in Shanghai and Jiangsu has been continuously improving, while that in Zhejiang and Anhui has not changed much (Fig. 5c). Except for Shanghai, the ecological water intensity in Jiangsu, Zhejiang and Anhui decreased before 2016 and gradually increased after that. It might be because in the early years, in order to expand production, production water has encroached upon ecological water. However, with the development of the economy and the deterioration of the ecological environment, the government has realized the importance of ecological protection and thus gradually increased ecological water consumption (Fig. 5d).

The synergistic effect of CRWS in the YRDUA

Before the synergistic effect analysis, the appropriate model form is selected and analyzed by F-test and Hausman test. The results show that F-value is 4.193 and χ^2 is 123.779, both of which pass the significance test at 1% level. Therefore, the fixed effect model (FE model) should be selected as the most appropriate model. Based on Eqs. (10) ~ (12), the regression results of the synergy effect of CRWS in 27 cities of the YRDUA are obtained, as shown in Table 3.

As can be seen from models (1) to (3) in Table 3, the production water supply intensity has a positive impact on carbon emission intensity. With the increase of production water supply intensity, the carbon emission intensity also increase, and both have the same change trend. However, the production water-saving intensity has a negative impact on carbon emission intensity, indicating that the increase of production water-saving intensity weakens the increase of carbon emission to a certain extent. The ecological water intensity has a significant negative impact on carbon emission intensity, indicating that the increase in ecological water consumption contributes to the reduction of carbon emission. The adjusted R^2values in Table 3 range from 0.367 to 0.417, indicating a relatively low goodness-of-fit of the model. This may be because the model only considers the impacts of the level of intensive water resource utilization and moderating factors on carbon emissions, without taking into account the impact of the interaction between them on carbon emissions. In addition, the

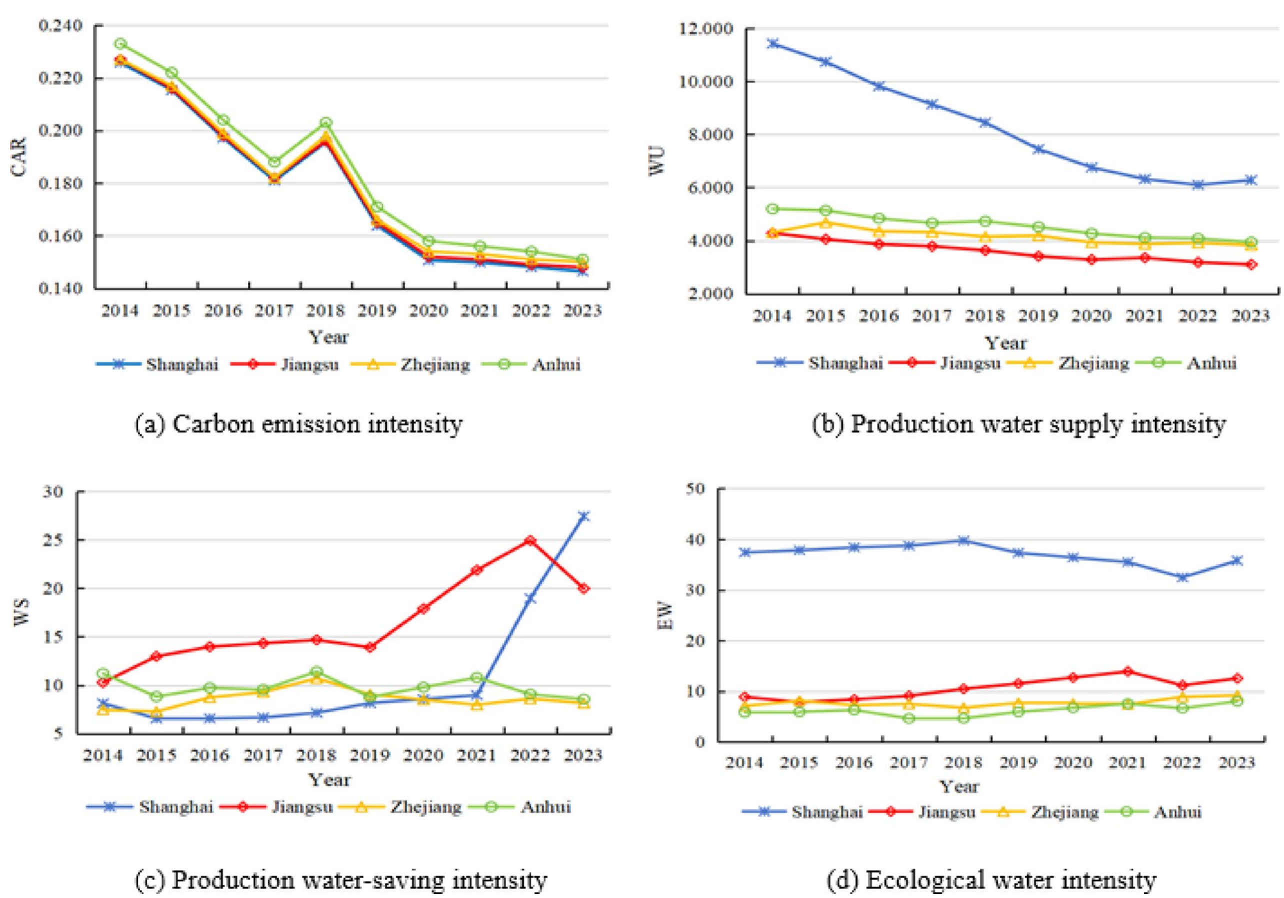

Fig. 5. Trends of carbon emission intensity and water resource intensive utilization intensity at the provincial level.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
WU	0.003*** (3.317)			0.002** (2.189)			
WS		-0.001** (-2.142)			-0.001** (-2.059)		-0.003** (-2.380)
EW			-0.001*** (-3.384)			-0.001*** (-5.238)	
ECI	0.004* (1.714)	0.006** (2.256)	0.012*** (3.726)	0.004** (2.437)	0.003* (1.676)	0.005* (1.644)	0.006** (2.523)
ECS	0.286*** (5.803)	0.305*** (6.187)	0.100** (2.125)	0.290*** (5.737)	0.291*** (5.769)	0.305*** (6.000)	0.280*** (5.645)
IS	0.001*** (7.108)	0.001*** (6.764)	0.004*** (12.064)	0.002*** (6.564)	0.002*** (6.780)	0.001*** (5.807)	0.001*** (6.909)
IIS	-0.002*** (-2.716)	-0.002** (-2.285)	-0.003** (-2.062)	-0.002*** (-2.688)	-0.002** (2.473)	-0.002** (-2.080)	-0.002** (-2.573)
Constant	-0.119*** (-3.276)	-0.119*** (-3.220)	-0.087*** (-2.603)	-0.122*** (-3.273)	-0.116*** (-3.093)	-0.124*** (-3.309)	-0.100*** (-2.687)
Adjust R^2	0.417	0.381	0.367	0.318	0.317	0.307	0.312
F test	27.068***	25.205***	24.012***	25.241***	25.079***	23.914***	24.535***

Table 3. Regression results of synergistic effect of CRWS in the YRDUA. The value in parenthesis refers to t-value. ***, ** and ** indicate significant differences at the 10%, 5%, and 1% levels, respectively. The same below.

Variable	Coefficient	Variable	Coefficient	Variable	Coefficient
*WU*ECI*	-0.003** (-2.289)	*WS*ECI*	-0.001 (-0.040)	*EW*ECI*	-0.001 (-1.479)
*WU*ECS*	-0.072*** (-3.175)	*WS*ECS*	-0.009* (1.642)	*EW*ECS*	-0.007** (-2.155)
*WU*IS*	-0.001 (-0.423)	*WS*IS*	0.001 (0.238)	*EW*IS*	0.001 (0.874)
*WU*IIS*	0.001 (0.479)	*WS*IIS*	-0.001 (-1.087)	*EW*IIS*	0.001 (1.235)

Table 4. Regression results of CRWS regulatory effect in the YRDUA.

heterogeneity in urban development levels can also lead to differences in the impact of the level of intensive water resource utilization.

In addition, except for the industrial fixed asset investment, the regression coefficients of energy consumption intensity, energy consumption structure and industrial structure are significantly positive. It indicates that, with the increase of energy consumption, coal consumption and industrial output, carbon emission of the YRDUA also increase.

To further verify the reliability of the conclusion, this paper adopts two methods for robustness test: changing the sample size and replacing the core independent variables. First of all, the Shanghai area holds a special political and economic status in China, and there may be particularities in water resource utilization and carbon emission control. Therefore, Shanghai is excluded and the relevant data of the remaining 26 cities are used for regression analysis again. Second, the industrial water-saving intensity is used to replace the production water-saving intensity for regression analysis. The results of the robustness test are shown in models (4) to (7) in Table 3. It can be known that whether special samples are excluded or core explanatory variables are replaced, the synergy effect exists. Meanwhile, the coefficients and significance levels of other variables have not changed significantly, further indicating that the regression results are robust.

The regulation effect of CRWS in the YRDUA

Collinearity diagnosis is conducted on four moderating variables: energy consumption intensity, energy consumption structure, industrial structure, and industrial investment scale. Pairwise comparison of the above four variables revealed that the maximum correlation coefficient is 0.2498 (i.e., the correlation coefficient between industrial structure and industrial investment scale). Therefore, it can be considered that there is almost no collinearity among the moderating variables. On this basis, multiple parallel regulatory model is introduced to explore the regulatory effects of technical factors, structural factors and scale factors on the synergistic effect of CRWS in the YRDUA, and the results are shown in Table 4. From the perspective of technology, the increase in energy consumption has a negative effect on the synergy between carbon emission and production water supply intensity. The energy consumption intensity does not have a significant regulatory effect on the synergy dominated by production water-saving intensity and ecological water intensity. From the perspective of structure, compared with the adjustment of industrial structure, the optimization of energy consumption structure has a more significant regulatory effect on the synergy dominated by production water supply intensity and production water-saving intensity in the YRDUA. From the perspective of scale, the industrial investment scale has no significant regulatory effect on the synergistic effect of CRWS in the YRDUA.

The synergistic and regulatory effects of CRWS in the YRDUA based on the heterogeneity of urban development level

Analysis based on the heterogeneity of urban scale

According to the urban resident population, 27 cities in the YRDUA are divided into large scale cities, medium scale cities and small scale cities. The synergistic effect and the regulatory effects of technology, structure and scale factors of CRWS are analyzed respectively, and the results are shown in Table 5.

From models (1) to (3) in Table 5, it can be seen that the production water supply intensity and production water-saving intensity of large scale cities have a significant positive impact on the carbon emission intensity. In addition to the scale of industrial investment, energy consumption intensity, energy consumption structure and industrial structure have a negative regulatory effect on the synergy dominated by production water supply intensity in large cities. The energy consumption structure and industrial investment scale have negative regulating effects on the synergy of carbon emission and production water-saving intensity in large cities.

From models (4) to (6) in Table 5, it can be seen that production water supply intensity and ecological water intensity of medium scale cities have significant positive and negative impacts on carbon emission intensity, respectively. With the increasing of production water consumption and decreasing of ecological water consumption, carbon emission of medium-sized cities increases significantly. In terms of the regulatory effect of technology, structure and scale factors on the synergistic effect of CRWS, industrial structure has a positive regulatory effect on the synergy of carbon emission and production water supply intensity of medium scale

Variable	Large scale cities			Medium scale cities			Small scale cities		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
WU	0.069*** (3.363)			0.130** (2.178)			0.095* (1.642)		
WS		0.015** (2.236)			0.001 (0.171)			0.013 (0.726)	
EW			-0.001 (-0.203)			-0.025* (-1.628)			-0.050 (-1.090)
ECI	0.042*** (4.919)	0.002 (0.380)	0.006 (1.083)	0.023 (1.033)	0.017* (1.724)	0.008 (0.673)	0.020 (0.552)	-0.010 (-0.514)	0.004 (0.222)
ECS	0.288** (2.220)	0.480*** (4.247)	0.176* (1.765)	0.390 (1.436)	0.283* (1.942)	0.067 (0.386)	0.254 (0.653)	0.191 (0.710)	-0.290 (-0.915)
IS	0.005*** (3.948)	0.001*** (2.618)	0.003*** (5.053)	0.004** (2.360)	0.003*** (2.772)	0.002* (1.841)	0.005* (1.764)	0.003 (1.195)	0.007*** (3.161)
IIS	-0.004 (-0.763)	0.001 (0.546)	-0.004 (-1.699)	-0.003 (-0.429)	-0.006 (-1.385)	-0.016*** (-3.461)	-0.054*** (-2.794)	-0.054*** (-3.307)	-0.047*** (-3.074)
*WU*ECI*	-0.005*** (-3.445)			-0.005 (-0.791)			-0.005 (-0.520)		
*WU*ECS*	-0.064** (-2.594)			-0.093 (-1.183)			-0.083 (-0.918)		
*WU*IS*	-0.001** (-2.262)			-0.001 (-0.950)			-0.001 (-0.755)		
*WU*IIS*	0.001 (1.008)			0.003* (1.844)			0.007** (2.165)		
*WS*ECI*		0.001 (1.398)			-0.001 (-0.319)			0.001 (0.275)	
*WS*ECS*		-0.023** (-2.385)			-0.010 (-1.101)			-0.016 (-0.744)	
*WS*IS*		0.001 (1.094)			0.001* (1.772)			-0.001 (-0.384)	
*WS*IIS*		-0.001* (-1.665)			0.001 (0.650)			0.002*** (2.816)	
*EW*ECI*			-0.001 (-0.447)			0.001 (0.433)			0.001 (0.051)
*EW*ECS*			0.006 (1.057)			0.002 (0.089)			0.081 (1.193)
*EW*IS*			-0.001*** (-2.790)			0.001 (1.410)			-0.001* (-1.835)
*EW*IIS*			0.001 (1.015)			0.002*** (3.026)			0.004** (2.762)
Constant	-0.224* (-1.654)	-0.252*** (-3.037)	-0.106 (-1.483)	-0.427** (-2.150)	-0.162 (-1.534)	0.090 (0.695)	-0.262 (-0.798)	0.004 (0.020)	0.198 (0.851)
Adjust R^2	0.723	0.441	0.442	0.624	0.521	0.565	0.707	0.674	0.596
F test	10.930***	9.142***	8.803***	11.605***	7.606***	9.076***	7.229***	6.204***	4.421***

Table 5. Analysis of regulatory effect of CRWS in the YRDUA based on urban scale heterogeneity.

cities. The industrial investment scale also has a positive regulatory effect on the synergy of carbon emission and ecological water intensity in medium scale cities.

From models (7) to (9) in Table 5, it can be seen that with the increase of water consumption in production, the carbon emission of small scale cities also increases. In terms of the regulatory effect of technology, structure and scale factors, only the scale factor (industrial investment scale) has a positive regulatory effect on the synergy of carbon emission and production water supply intensity.

Analysis based on the heterogeneity of urbanization level

According to the urbanization rate, 27 cities in the YRDUA are divided into cities with high urbanization rate, medium urbanization rate and low urbanization rate. The synergistic effect of urban CRWS and the regulatory effect of technology, structure and scale factors are analyzed respectively, and the results are shown in (Table 6).

From models (1) to (3) in Table 6, it can be seen that the production water-saving intensity and ecological water consumption intensity of cities with high urbanization rate have a significant positive impact on carbon emission intensity. It indicates that the increase of production water-saving amount and ecological water consumption have a positive impact on the increase of carbon emission of cities with high urbanization rate. In terms of the regulatory effects of technology, structure and scale factors, energy consumption structure weakens the synergistic effect of production water-saving intensity in cities with high urbanization rate. Energy consumption intensity and industrial investment scale have a negative regulatory effect on the synergy of carbon emission and ecological water intensity in cities with high urbanization rate.

From models (4) to (6) in Table 6, it can be seen that the increase of production water consumption and the decrease of ecological water consumption have positive impacts on the increase of carbon emission in cities with

Variable	High urbanization rate cities			Medium urbanization rate cities			Low urbanization rate cities		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
WU	0.029 (1.096)			0.052* (1.624)			0.091* (1.891)		
WS		0.058** (2.446)			-0.002 (-0.281)			0.004 (0.516)	
EW			0.007* (1.630)			-0.028** (-2.000)			-0.019 (-0.550)
ECI	0.033** (2.425)	0.003 (0.337)	0.010 (0.812)	0.047*** (2.967)	0.014* (1.883)	0.010 (1.003)	0.020 (1.090)	0.014 (1.407)	0.006 (0.609)
ECS	0.284 (1.493)	0.776*** (2.798)	0.154 (0.972)	0.119 (0.532)	0.155 (1.118)	-0.166 (-1.010)	0.257 (1.152)	0.182 (1.234)	-0.034 (-0.183)
IS	-0.002 (-0.791)	0.002 (1.737)	0.004*** (2.800)	0.006*** (3.122)	0.003*** (3.463)	0.004*** (3.601)	0.005*** (2.904)	0.004*** (4.296)	0.005*** (4.225)
IIS	-0.002 (-0.258)	0.002 (0.201)	0.011** (2.509)	-0.004 (-0.912)	0.001 (0.144)	-0.008** (-2.197)	-0.021** (-2.532)	-0.015** (-2.290)	-0.028*** (-4.526)
*WU*ECI*	-0.003* (-1.661)			-0.007* (-1.871)			-0.004 (-0.772)		
*WU*ECS*	-0.067** (-2.161)			-0.030 (-0.593)			-0.066 (-1.066)		
*WU*IS*	0.001*** (2.778)			0.001 (-0.803)			-0.001 (-0.881)		
*WU*IIS*	0.001 (0.671)			0.001 (1.165)			0.003* (1.713)		
*WS*ECI*		0.000 (0.121)			0.001 (0.781)			-0.001 (-0.443)	
*WS*ECS*		-0.075** (-2.016)			-0.008 (-0.761)			-0.005 (-0.613)	
*WS*IS*		-0.001 (-0.221)			0.001** (2.448)			-0.001 (-0.030)	
*WS*IIS*		-0.001 (-0.110)			-0.001 (-0.493)			0.001 (0.542)	
*EW*ECI*			-0.001 (-0.568)			0.001 (0.744)			0.001 (0.447)
*EW*ECS*			-0.011* (-1.619)			0.023 (1.084)			0.031 (0.590)
*EW*IS*			0.001 (1.587)			0.001 (0.588)			-0.001* (-1.685)
*EW*IIS*			-0.001** (-2.309)			0.001** (2.588)			0.003*** (3.195)
Constant	-0.098 (-0.614)	-0.492** (-2.581)	-0.145 (-1.251)	-0.284* (-1.707)	-0.122 (-1.309)	0.127 (1.169)	-0.290* (-1.713)	-0.113 (-0.963)	0.052 (0.412)
Adjust R^2	0.827	0.485	0.744	0.713	0.638	0.691	0.595	0.496	0.542
F test	23.938***	35.345***	14.517***	24.829***	17.619***	22.378***	13.203***	8.872***	10.645***

Table 6. Analysis of regulating effect of CRWS in the YRDUA based on urbanization level heterogeneity.

medium urbanization rate. In terms of the regulatory effects of technology, structure and scale factors, energy consumption intensity has a negative regulatory effect on the synergy of production water supply intensity in cities with medium urbanization rate. The industrial investment scale has a strong effect on the synergy of carbon emission and ecological water intensity in cities with medium urbanization rate.

From models (7) to (9) in Table 6, it can be seen that the increase of water consumption in production has a positive impact on the increase of carbon emission in cities with low urbanization rate. In terms of the regulatory effects of technology, structure and scale factors, only the scale of industrial investment has a positive regulatory effect on the synergy of carbon emission and production water supply intensity.

Discussion

Analysis of carbon emission and water resource intensive utilization

In recent years, the diversification of energy structure and non-fossil energy types in the production process has contributed to the continuous reduction of carbon emission intensity in the YRDUA[54]. However, the pressure of carbon emission reduction in the YRDUA is still great, and the energy structure and industrial structure need to be further optimized and adjusted to meet the national emission reduction targets[55]. The water resource intensive utilization in the YRDUA has been improved, which is partly attributed to the strictest water resource management system implemented in China. The reduction of supply has promoted the innovation of production technology and water-saving technology, and effectively reduced the demand for production water and increased the production water-saving amount[56]. In addition, some areas are indeed in the state of "no water available", and a large number of virtual water imports have led to changes in China's water consumption pattern, which has inhibited the growth of production water demand (Wang and Ge, 2020[57]). Therefore, the water resource management policies adopted must effectively improve the level of water resource intensive utilization from multiple aspects such as improving the water utilization efficiency and increasing the amount of water-saving in production. For example, innovations in water recycling and sewage treatment technologies can not only improve the efficiency and effectiveness of production water use, promote water conservation in production, but also ensure the amount of ecological water use. Guaranteeing the construction of green facilities such as urban green spaces, parks, and artificial forests through the ecological supply of water resources is conducive to enhancing the carbon sequestration capacity of the region.

The synergistic impact of water resource intensive utilization on carbon emission intensity

The synergistic effect of intensive water utilization intensity on carbon emission intensity in the YRDUA is significant (Fig. 6). Specifically, the production water supply intensity, production water-saving intensity and ecological water intensity are significant at the levels of 10%, 5% and 1% respectively. The regression coefficient of production water supply intensity is 0.003, indicating that it has the same changing trend as carbon emissions. The regression coefficients of production water-saving intensity and ecological water intensity are both -0.001, indicating that their changing trends are opposite to that of carbon emission intensity.This means that appropriate reduction of production water consumption, improvement of production water-saving level, and protection of ecological water consumption can improve the level of water resource intensive utilization and help reduce carbon emission[58].

Technology and structural factors have improved the carbon emission intensity of the YRDUA to a certain extent, indicating that while technological progress has brought about the improvement of production

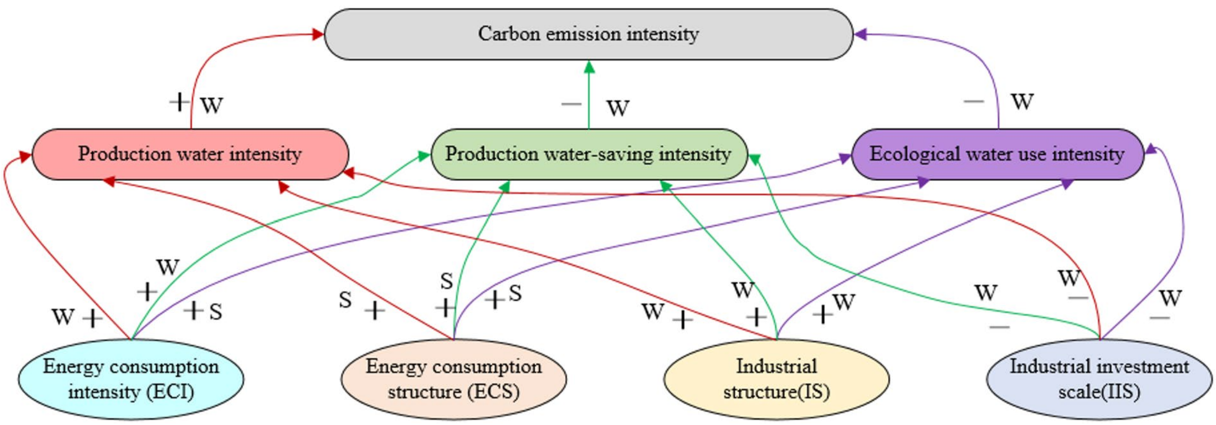

Fig. 6. Analysis of synergistic effect of CRWS in the YRDUA. The red arrow refers to the influence of the regulatory variables with the main effect of production water supply intensity. The green arrow refers to the impact of the regulatory variables with the main effect of water-saving intensity in production. The purple arrow refers to the impact of the regulatory variables with the main effect of ecological water intensity. + refers to the positive influence, W, M and S represent the degree of weak, medium and strong influence, and the scope of corresponding regression coefficients are (0.00, 0.05), [0.05, 0.10) and [0.10, ∞).—refers to the negative influence, W, M and S represent the degree of weak, medium and strong influence, respectively, and scope of the corresponding regression coefficients are (-0.05, 0.00), (-0.10, -0.05], (-∞, -0.10].The same below.

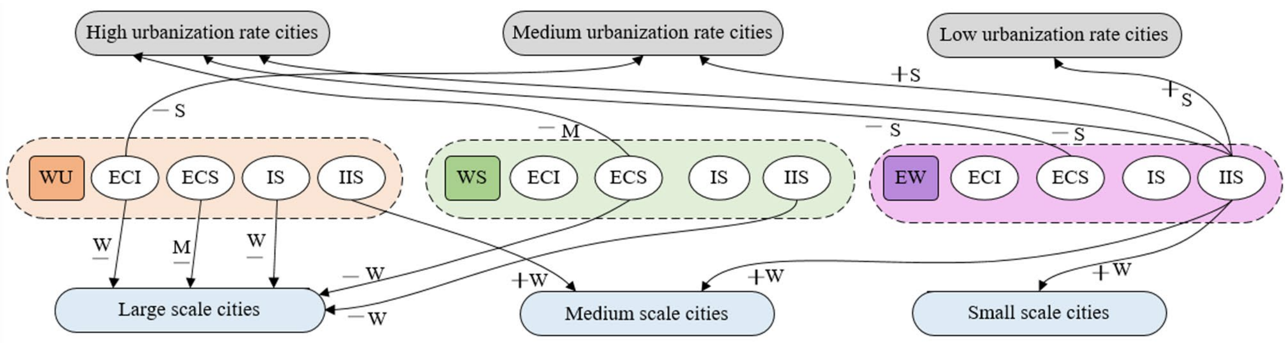

Fig. 7. Analysis of regulatory effect of CRWS in the YRDUA.

efficiency, its rebound effect on carbon emission reduction and water-saving has gradually emerged, resulting in the decrease of the synergy of CRWS[59]. On the one hand, technological progress can effectively improve the efficiency of water resource utilization, reduce carbon emissions per unit of water used, and achieve water conservation. On the other hand, technological progress will lead to the further expansion of production scale, the production water consumption and its carbon emissions will also increase accordingly, thereby generating a rebound effect. The foundation of energy structure and industrial structure is relatively weak, and the secondary industry characterized by high-pollution and high-emission still occupies a dominant position. It not only intensifies the contradiction between production water and ecological water, but also weakens the synergistic effect of CRWS[60]. However, if only a single carbon emission reduction target is set, it would cause excessive emission reduction burden on the traditional industries that support economic development, and weaken the power of urban economic development. Therefore, the adoption of total water resource management measures from the perspectives of water resource intensive utilization, combined with the appropriate adjustment and improvement of energy structure and industrial structure, can help to promote the synergistic effect of CRWS.

Heterogeneity analysis and policy implications of CRWS regulatory effects

Compared with areas with lower urban development level, regulatory variables such as technology, structure and scale factors have more obvious influences on the synergistic effect of CRWS in areas with higher urban development level (Fig. 7). For cities with large scale and high urbanization level, energy consumption intensity, energy consumption structure, industrial structure and industrial investment scale all negatively regulate the synergistic effect of CRWS. This is because in cities with a higher level of development, highly developed industrial production has an increasing demand for water resources and high-emission fuels such as coal, which leads to more severe problems of water resource consumption and carbon emission[61]. In addition, policies and measures dominated by command-based environmental regulations make industrial production more inclined to adopt end-treatment methods to reduce water utilization and carbon emission, rather than innovation and promotion of production technology[62]. The status quo of high energy and water consumption industries has not been fundamentally improved, resulting in the inability to achieve synergies of CRWS. The scale of industrial investment has a strong regulatory effect on the synergy of CRWS in cities with low development level. Compared with large cities, small cities have relatively sparse population and abundant energy resources. With the rapid expansion of industrial investment scale, water resource and carbon emission are concentrated in a small number of industries with high water consumption and energy consumption, which is more conducive to the concentration and consistency of management objectives, thus promoting the synergy of CRWS[63]. Therefore, according to the difference of urban development level, management measures based on the regulatory effect of technology, structure and scale factors should be adopted to promote the synergistic effect of urban CRWS.

We acknowledge that there are some limitations to the data used in the current research. For example, data on production water-saving for certain years are unavailable (the proportion of missing data does not exceed 5%). The interpolation method has been used to predict the missing data, which may lead to uncertainties in subsequent analyses. In addition, the research scale is only limited to small and medium-sized cities, and further refinement is needed, especially in the study of synergy effect of CRWS at the industry and enterprise levels in different regions, which needs to be further strengthened. This is of great significance for supplementing relevant policies to improve and balance the regional carbon–water relationship. Therefore, the above limitations can be addressed by improving research data at a more detailed level through field research and government consultation in the future.

Conclusions

This study designs an analytical framework to evaluate the synergistic and regulatory effects of urban CRWS, and applies it to the study of the YRDUA. The fixed effect analysis model is used to evaluate the synergistic effect of CRWS. The regulatory effects of technology, structure and scale factors on the synergy of CRWS are analyzed by adopting multiple parallel regulation model. Based on the heterogeneity of urban development level, the differences of synergistic and regulatory effects of CRWS are analyzed. The results indicate that the urban carbon emission intensity shows a downward trend, while the water resource intensive utilization intensity shows an upward trend in the YRDUA. Production water supply intensity has a positive impact on carbon emission intensity, production water-saving intensity and ecological water intensity have a negative impact on carbon emission intensity. Technical and structural factors negatively regulate the synergy of carbon emission intensity and production water supply intensity. Structural factors negatively regulate the synergy of carbon emission intensity and production water-saving intensity, and the synergy of carbon emission intensity and ecological water intensity. Compared with areas with lower urban development level, regulatory variables such as technology, structure and scale factors have more obvious impacts on the synergistic effect of CRWS in areas with higher urban development level. Therefore, the government should formulate targeted policies to achieve synergies of CRWS and promote sustainable economic development.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Qian Wang: Conceptualization, Methodology, Formal analysis, Investigation, Software, Validation, Writing—original draft, Writing—review & editing, Supervision. Shouqiang Xu: Data curation, Resources, Investigation, Visualization. Zuqin Ding: Investigation, Visualization. All authors reviewed the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

Additional information
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