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Coupled Spatial–Temporal Evolution and Influencing Factors of Chemical Industry Development and Water Environment in Yangtze River Economic Belt

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Abstract: Revealing the coordinated correlation between chemical industry development and the water environment is essential for promoting high-quality development in the Yangtze River Economic Belt. Based on the data in the Yangtze River Economic Belt from 2011 to 2021, this study explores the spatial–temporal evolution and influencing factors of the coupled coordination between chemical industry development and the water environment by using the global entropy method, a coupling coordination model, and the Tobit model. The results indicate a general upward trend in the comprehensive indices of chemical industry development and water environment systems, albeit with distinct spatial patterns. A mismatch between the two systems is observed in terms of spatial distribution. Regarding the coupling coordination degree, the relationship shows an upward trend, primarily at a mild-to-moderate coupling stage, exhibiting a spatial pattern of "downstream > midstream > upstream". Moreover, a trend of increasing coordination and narrowing disparities between high- and low-level regions can be observed. The model results suggest that environmental regulation, economic development, government capacity, and urbanization play a crucial role in promoting the coupled development of the chemical industry and the water environment. However, openness to external markets may not enhance coupled coordination. These findings may provide policy guidance for the development status of two subsystems in other locations.

Keywords: chemical industry development; water environment; coupling coordination; Yangtze River Economic Belt

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1. Introduction

The chemical industry is a key sector in China's national economy, but it is also a major source of environmental pollution [1,2]. Affected by the "hydrophilic" nature of production and transportation, chemical enterprises are often distributed along the river system, and a large number of chemical enterprises are distributed along the Yangtze River, which has become an important agglomeration area for the development of China's chemical industry. There are more than 400,000 chemical enterprises along the Yangtze River, as well as seven major refineries and large petrochemical bases such as Shanghai, Nanjing, and Yizheng [3]. Among them, 30% of the environmental-risk enterprises are located within 5 km of the drinking water source, which has a profound impact on the water environment and restricts the high-quality development of the Yangtze River Economic Belt to a certain extent [4]. Since the Yangtze River Protection strategy was proposed in 2016, efforts to balance economic growth with environmental protection have gained momentum. The State Council issued guidelines focusing on controlling pollution from chemical industries along the river and strengthening the protection of key water resources. Achieving coordinated development between the chemical industry and the water environment is a crucial step toward high-quality development in the Yangtze River Economic Belt. Without proper coordination, the rapid expansion of the chemical industry could exacerbate water pollution, impeding regional sustainability. This paper aims to fill this gap by examining the coupling relationship between chemical industry development and the water environment and provide valuable insights for policymakers and researchers.

The existing literature focuses on two areas: chemical industry development and water environment. Studies in the first area explore the spatial distribution and environmental impacts of the chemical industry. They show that chemical industries often cluster near water sources [5–9], with factors like economic growth, market demands, and transportation influencing their spatial distribution [10–14]. Additionally, chemical industries are known to cause significant environmental pollution. Dong et al. [15] took the heavy chemical industry in the Yangtze River Economic Belt as their research object and explored the impact of the division of labor in the heavy chemical industry on regional environmental pollution and economic development from the perspective of industrial division of labor. Wang et al. [16] investigated the temporal and spatial changes in the distribution of chemical enterprises in Jiangsu Province and their potential impact on water areas based on enterprise big data and determined that some water areas are greatly affected by the chemical industry. To address these issues, researchers suggest measures like increasing technological investment and strengthening environmental regulations [17–19]. Studies on the water environment primarily investigate water quality assessment, influencing mechanisms, and the interaction between different industries and water resources [20–22]. Research indicates that water quality is influenced by various factors, including economic development and industrial structure [23–26]. Regarding the coupling relationship between economic development and water resources, several studies have measured this interaction at different levels, such as river basins or urban clusters [27,28]. Yu et al. [29] explored the agglomeration of pollutant discharge from industrial enterprises and their spatial coupling characteristics associated with water pollution discharge in the Zhangjiakou area. Zhang et al. [30] investigated the spatial coupling relationship between pollution-intensive industrial agglomeration and water environment pollution and found that the spatial agglomeration of polluting industries is one of the important factors causing water pollution. Huang et al. [31] selected Nanjing as their case study area and carried out spatial coupling based on the spatial pattern of water environment pollution and the current situation of industrial agglomeration to further provide decision-making suggestions for the adjustment of the future development direction of the industry.

A review of the existing literature shows that the existing studies provide some reference for this paper, but there are still the following shortcomings. (1) There is a lack of understanding of the coupling interaction effect between the development of the chemical industry and the water environment. At present, most of the research focuses on the one-way impact of the development of the chemical industry on the water environment, or the coupling and coordination phenomenon between some polluting industries and the water environment, and rarely explores the coupling and interaction between the two. (2) The evaluation of the development of the chemical industry is not systematic enough. Although there is a lot of research on the development of the chemical industry, most studies focus on the spatial layout of the chemical industry and its environmental effects, and there is no consistent discussion on how to scientifically measure the development level of the chemical industry. (3) Attention needs to be focused on the problem of pollution-intensive industrial agglomeration in major national strategic areas; in particular, the research on the environmental effect of chemical industry agglomeration in the Yangtze River Economic Belt, which is the economic support belt of China, needs to be strengthened urgently. Therefore, based on the Yangtze River Economic Belt, a typical chemical industry development area, this paper first constructs a comprehensive evaluation system of the two systems of chemical industry development and the water environment, uses the global entropy method to measure the comprehensive index of the two in 2011~2021, further describes the spatiotemporal evolution characteristics of chemical industry development, the water environment, and coupling coordination, and uses the Tobit model to explore the influencing factors of the coupling coordination degree of the two in order to provide a certain scientific basis for research and government decision-making in related fields. There are two research purposes of this paper. On the one hand, it provides supporting methods for the scientific measurement of the coupling and coordination relationship between chemical industry development and the water environment. On the other hand, it provides a decision-making basis for the promotion of the development of the chemical industry and the water environment in the Yangtze River Economic Belt. The rest of the organized is planned in such a way that Section 2 analyzes the coupling coordination mechanism between chemical industry development and the water environment, Section 3 discusses the research data and methodology, Section 4 presents the results of the analysis, and Section 5 concludes the study and offers policy recommendations.

2. Mechanism of Coupling Coordination between Chemical Industry Development and Water Environment

System theory suggests that systems consist of interconnected subsystems that influence each other, collectively shaping the entire system [32]. Within the high-quality development framework, the development of the chemical industry and the water environment are interlinked subsystems that exhibit a positive coupling relationship, contributing to the high-quality development of the Yangtze River Economic Belt [30,31].

Chemical industry development impacts the water environment in several ways. On the one hand, as a pillar of the national economy, the growth of the chemical industry brings economic benefits that can fund technology and other resources for water environment management, ultimately enhancing water quality. On the other hand, the rapid expansion of the chemical industry can pose potential threats to the water environment. The chemical industry is a known pollutant and uncontrolled growth can lead to increased wastewater discharge, which adds pressure to water environment protection efforts, thereby potentially limiting the sustainable growth of the chemical industry.

The water environment also impacts chemical industry development. The production and transportation activities of chemical enterprises rely heavily on water resources, providing crucial support for the development of the chemical industry, thus laying a solid physical and ecological foundation. Furthermore, with stricter water environment protection policies, the pressure on the chemical industry to upgrade and transform is expected to foster greener and more sustainable growth, reinforcing the symbiotic relationship between the chemical industry and the water environment, leading to coordinated development.

3. Research Data and Methods

3.1. An Overview of the Research Region

The Yangtze River Economic Belt is a crucial base for petrochemicals, pesticides, coatings, and inorganic chemicals in China. Covering an area of approximately 2.05 million km^2, it represents 21% of China's total land area. The region comprises 11 provinces and cities: Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and Guizhou. It is typically divided into three subregions based on economic development: the upstream region includes Chongqing, Sichuan, Guizhou, and Yunnan; the midstream region comprises Hubei, Hunan, and Jiangxi; and the downstream region includes Shanghai, Jiangsu, Zhejiang, and Anhui (Figure 1). The upstream region is focused on phosphate and natural gas-based chemicals, while the downstream region is known for petrochemicals and fine chemicals. In 2021, the operating income of the chemical industry was CNY 8.8886 trillion in the Yangtze River Economic Belt (it is calculated based on the "*China Industrial Statistical Yearbook 2022*"); the revenue was CNY 1.344 trillion in the upstream region, CNY 1.8725 trillion in the midstream region, and CNY 5.7171 trillion in the downstream region, indicating that the downstream region significantly outperforms the upstream and midstream regions. With the continued advancement of the Yangtze River Protection strategy, significant progress has been made in controlling the chemical plants surrounding the Yangtze River phenomenon, leading to substantial improvements in water quality. Data indicate that in 2021, the proportion of water bodies with good quality in the Yangtze River Economic Belt reached 92.8%, reflecting a positive trend in water environment protection.

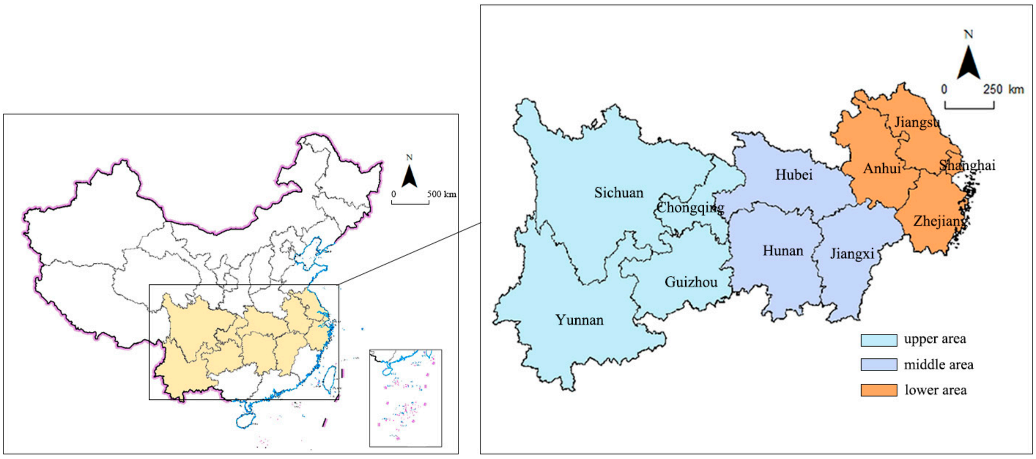

Figure 1. Regional scope of Yangtze River Economic Belt.

3.2. Indicator Selection and Construction

3.2.1. Construction of Evaluation Indicators for Chemical Industry Development and Water Environment

A comprehensive evaluation system was constructed to assess the development of the chemical industry and the water environment following the principles of scientific validity and data availability. The chemical industry development subsystem consists of 9 indicators based on industry scale, industry growth, and industry efficiency. Industry scale encompasses income and employee numbers for large-scale chemical enterprises; growth rate assesses the year-on-year growth of the chemical industry; and industry efficiency examines profitability. The water environment subsystem contains three element levels based on the "pressure–state–response" model, which are water environment pressure, water environment state, and water environment response. Water environment pressure includes factors like industrial pollution, water environment state covers the total volume of water resources and supply, and water environment response involves water resource utilization and management. The detailed indicators are presented in Table 1.

Table 1. Chemical industry development and water environment evaluation index system.

Target	Criterion Layer	Index	Calculation Method
chemical industry development	industry scale	Total assets	The total assets of chemical enterprises above a designated size
		Operating income	The total income of chemical enterprises above a designated size
		Number of employees	The average number of workers employed by chemical enterprises above a designated size
	industry growth	Asset growth rate	(Asset growth/total assets of the previous year) × 100%
		Growth rate of operating income	(Growth in operating income/total operating income in the previous year) × 100%
	industry benefits	Operating income per CNY 100 of assets	(Operating income/total assets) × 100%
		Realized profit per capita	Total profit/average number of workers per year
		Debt-to-asset ratio	(Total liabilities/total assets) × 100%

Table 1. *Cont.*

Target	Criterion Layer	Index	Calculation Method
water environment	water environment pressure	Total industrial water use per unit of industrial output value	(Industrial output value/total industrial water consumption) × 100%
		Total chemical oxygen demand emissions per unit of industrial output	(Industrial output/total chemical oxygen demand emissions) × 100%
		Total nitrogen oxide emissions per unit of industrial output value	(Industrial output/total NOx emissions) × 100%
		Total phosphorus emissions per unit of industrial output value	(Industrial output/total phosphorus emissions) × 100%
	water environment state	Total amount of water resources	The total amount of water resources in the region
		Total amount of water supply	The total amount of water supplied by the region
		Water resources per capita	Total water resources/total population of the region
		Section ratio of class I–III water quality	Section ratio of class I–III water quality
	water environment response	Industrial water reuse	Industrial water reuse
		Industrial water saving per unit of output value	(Industrial output value/total industrial water saving) × 100%
		Wastewater treatment facility capacity	Wastewater treatment facility capacity
		Investment in industrial wastewater treatment accounts for GDP proportion	(Industrial wastewater treatment investment/GDP) × 100%

3.2.2. Selection of Influencing Factors

The coupling coordination degree (D) between chemical industry development and the water environment reflects their two-way characteristic relationship and is influenced by various factors [23,24,26]. This study examines how economic development level, government capacity, environmental regulation, industrial structure, openness to external markets, and technology investment affect the coupling coordination between chemical industry development and the water environment in the Yangtze River Economic Belt by building on existing research (Table 2). (1) Economic development level (ECO): A higher level of economic development brings increased production capacity, funding, and technology investment, which can support chemical industry growth and water environment management as represented by GDP. At the same time, in order to eliminate the influence of heteroskedasticity, GDP is logarithmic. (2) Government capacity (GOV): Local governments, through public fiscal expenditure, provide financial support and infrastructure for the regional chemical industry and water resource development. This support is measured by the ratio of local fiscal expenditure to GDP. (3) Technology investment (TEC): Technology investment provides production and pollution control technologies for the chemical industry and supports water environment protection, promoting the development of both. This investment is represented by the ratio of local science and technology expenditure to total government fiscal expenditure. (4) Environmental regulation (ENV): In the context of the Yangtze River Protection strategy, achieving coordinated economic and environmental development is crucial. According to the Porter Hypothesis, stringent environmental regulations can drive chemical enterprises toward green innovation, enhancing the coupling coordination between chemical industry development and the water environment. This is measured by the ratio of industrial pollution control investment to local fiscal expenditure [33]. (5) Urbanization (URBAN): The development of urbanization has a huge impact on water resource utilization and water consumption [34,35], and the wastewater generated can have negative effects on water quality through a variety of pollutants [36]. It is measured by the ratio of the urban population to the permanent population. (6) Openness to external markets (OPEN): As the "Golden Waterway" of China, the Yangtze River Economic Belt has benefited from international industrial capital inflows, with foreign enterprises contributing knowledge, talent, and technology to the chemical industry. This factor is measured by the ratio of total import and export value to GDP.

Table 2. Selection of influencing factors.

Influencing Factor	Calculation Method
Economic development (ECO)	Measured in terms of GDP per capita and logarithm
Government capacity (GOV)	The ratio of local fiscal expenditure to GDP
Technology investment (TEC)	The ratio of local science and technology expenditure to government fiscal expenditure
Environmental regulation (ENV)	The proportion of investment in industrial pollution control in local fiscal expenditure
Urbanization (URBAN)	The ratio of the urban population to the resident population
Openness to external markets (OPEN)	Total imports and exports as a percentage of GDP

3.3. Research Methods

3.3.1. Global Entropy Method

In this study, the global entropy method is used to measure the comprehensive index of the two major systems of chemical industry development and the water environment, and the specific calculation steps are as follows [37]:

(1) Construct a global evaluation matrix:

If necessary, use P evaluation indicators x1, x2, . . ., xp, to evaluate the comprehensive level of T year in n regions through the collection of data. A cross-section data table every year $X^t = \left(x_{ij}\right)_{n\times p}$ and a T tension section data table in T year can be observed. Global thinking is introduced to arrange the T section data table in chronological order from top to bottom to form a global evaluation matrix of nT × p, which is recorded as follows:

$$X = (x_1, x_2, \ldots x_T)'_{nT\times p} = x_{ij_{nT\times p}} \tag{1}$$

In the formula, X is the global evaluation matrix; P is the number of evaluation indicators; n is province; T is year; x_{ij} is the value of the j-th index in the i-th evaluation unit.

(2) Standardization of indicators:

$$\text{Positive indicators}: \ z_{ij} = \frac{x_{ij} - \min x_j}{\max x_j - \min x_j} \tag{2}$$

$$\text{Negative indicators}: \ z_{ij} = \frac{\min x_j - x_{ij}}{\max x_j - \min x_j} \tag{3}$$

In the formula, z_{ij} is the normalized index value; x_{ij} is the raw data of the j-th indicator of the i-th province; $\max x_j$ and $\min x_j$ are the maximum and minimum values, respectively. In order to avoid a logarithm of 0 when calculating the entropy of information, 0.0001 is added to all values of both the forward and negative indicators.

(3) Calculate the proportion of the indicator:

$$y_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{nT} x'_{ij}},\ 1 \le i \le nT,\ 1 \le j \le p \tag{4}$$

In the formula, y_{ij} is the proportion of the i-th province in this indicator under the j-th indicator.

(4) Calculate the information entropy:

$$\mathrm{e_j} = -\mathrm{k}\textstyle\sum_{\mathrm{i}=1}^{\mathrm{nT}} \mathrm{f_{ij}}\,\mathrm{ln f_{ij}},\ 1\ \leq \mathrm{i} \leq \mathrm{nT},\ 1\ \leq \mathrm{j} \leq \mathrm{p} \tag{5}$$

Among them, $\mathrm{K} = \frac{1}{\ln \mathrm{nT}}$, where $\mathrm{e_j}$ is the information entropy of the j-th indicator.

(5) Calculate the difference coefficient:

$$\mathrm{g_j} = 1 - \mathrm{e_j} \tag{6}$$

where $\mathrm{g_j}$ is the information utility value of the j-th indicator.

(6) Calculate the weight of each indicator:

$$\mathrm{w_j} = \frac{\mathrm{g_j}}{\sum_{\mathrm{j}=1}^{\mathrm{p}} \mathrm{g_j}} \tag{7}$$

where $\mathrm{w_j}$ is the weight of the j-th indicator.

(7) Calculation of composite index:

$$\mathrm{F_i} = \sum_{\mathrm{j}=1}^{\mathrm{P}} \mathrm{w_j y_{ij}} \tag{8}$$

where $\mathrm{F_i}$ is the composite index.

3.3.2. Coupling Coordination Degree Model

The coupling coordination degree reflects the level of coordination between systems [38]. Compared to the coupling degree, the coupling coordination degree is more effective in evaluating the coordination during the interaction and coupling process [39]. This study uses the coupling coordination degree model to assess the degree of coordination between the chemical industry and the water environment. The formula for calculating the coupling coordination degree is as follows [40]:

$$C = \left\{ \frac{(p \times e)}{\left[\frac{(p+e)}{2}\right]^2} \right\}^k \tag{9}$$

$$T = \alpha p + \beta e \tag{10}$$

$$D = \sqrt{C \cdot T} \tag{11}$$

where C represents the coupling degree between the chemical industry system and the water environment system; p is the comprehensive development index for the chemical industry system; e is the comprehensive development index for the water environment system; k is the coordination coefficient, set to 2; D is the coupling coordination degree, with higher values indicating stronger coupling coordination between the two systems; T is the overall coordination index for both systems. The values for α and β are coefficients set to 0.5.

Research on the classification of coupling coordination types is quite extensive [41,42], with common benchmarks used to categorize the levels of coupling coordination into six stages: severely disordered, moderately disordered, mildly coordinated, preliminarily coordinated, moderately coordinated, and highly coordinated development. The coupling coordination degree can be classified into these stages of 0–0.2, 0.2–0.4, 0.4–0.5, 0.5–0.6, 0.6–0.8, and 0.8–1, respectively.

3.3.3. Relative Development Degree Model

The coupling coordination degree model can effectively evaluate the coupling and coordinated development level of chemical industry development and the water environment, but it cannot evaluate the relative development status of the two [43]. So, the relative development index can be used to reflect the relative development degree between the two systems [41,44]. It is calculated as follows:

$$E = p/e \tag{12}$$

where E is the relative development coefficient; p is the comprehensive development index for the chemical industry system; e is the comprehensive development index for the water environment system. An E value between 0 and 0.8 indicates that the water environment is lagging behind; an E value between 0.8 and 1.2 suggests synchronized development; while an E value greater than or equal to 1.2 indicates that the chemical industry lags behind (Table 3).

Table 3. Period and type of coupling coordination development and water environment.

D Value	**Period**	**Basic Type**	
		Relative Coefficient of Development	**Type of Coupling Coordination**
$0.8 < D \leq 1$	High-level coupling coordination	$0 < E \leq 0.8$ $0.8 < E < 1.2$ $E \geq 1.2$	High-level coupling coordination–water development lagging High-level coupling coordination–synchronized development High-level coupling coordination–chemical industry lagging
$0.6 < D \leq 0.8$	Moderate coupling coordination	$0 < E \leq 0.8$ $0.8 < E < 1.2$ $E \geq 1.2$	Moderate coupling coordination–water development lagging Moderate coupling coordination–synchronized development Moderate coupling coordination–chemical industry lagging
$0.5 < D \leq 0.6$	Preliminary coupling coordination	$0 < E \leq 0.8$ $0.8 < E < 1.2$ $E \geq 1.2$	Preliminary coupling coordination–water development lagging Preliminary coupling coordination–synchronized development Preliminary coupling coordination–chemical industry lagging
$0.4 < D \leq 0.5$	Mild coupling coordination	$0 < E \leq 0.8$ $0.8 < E < 1.2$ $E \geq 1.2$	Mild coupling coordination–water development lagging Mild coupling coordination–synchronized development Mild coupling coordination–chemical industry lagging
$0.2 < D \leq 0.4$	Moderate imbalance and decline	$0 < E \leq 0.8$ $0.8 < E < 1.2$ $E \geq 1.2$	Moderate imbalance and decline–water development lagging Moderate imbalance and decline–synchronized development Moderate imbalance and decline–chemical industry lagging
$0 < D \leq 0.2$	Severe imbalance and decline	$0 < E \leq 0.8$ $0.8 < E < 1.2$ $E \geq 1.2$	Severe imbalance and decline–water development lagging Severe imbalance and decline–synchronized development Severe imbalance and decline–chemical industry lagging

3.3.4. Kernel Density Estimation

Kernel density estimation is a non-parametric method that can describe the distribution location, shape, and extent of the coupling coordination degree solely based on sample data, offering robust results [45]. This study uses kernel density estimation to depict the dynamic evolution characteristics of the coupling coordination degree between chemical industry development and the water environment, with the following calculation formula:

$$\mathrm{f(x)} = \frac{1}{\mathrm{nh}}\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{k}\left(\frac{\mathrm{x} - \mathrm{x_i}}{\mathrm{h}}\right) \tag{13}$$

where f(x) represents the density function; n is the number of cities; Xi is the coupling coordination degree for each province and city in the Yangtze River Economic Belt; x is the mean coupling coordination degree; h is the bandwidth; and k( ) is the kernel function.

3.3.5. Tobit Model

The coupling coordination degree between chemical industry development and the water environment in the Yangtze River Economic Belt falls between 0 and 1, suggesting a censored dependent variable, making the Tobit model an appropriate choice for analysis [46,47]. This study uses the Tobit model to empirically examine the factors affecting the coupling coordination degree in the Yangtze River Economic Belt. The formula is as follows:

$$\mathrm{Y_{it}} = \begin{cases} \mathrm{y^{*}_{it}} = \beta_0 + \sum\limits_{t=1}^{n} \beta_t \mathrm{x_{it}} + \varepsilon_{it} \\ 0,\ \mathrm{y^{*}_{it}} \le 0 \end{cases} \tag{14}$$

where $\mathrm{Y_{it}}$ is the dependent variable; $\mathrm{x_{it}}$ represents the independent variable; β_0 is the constant term;β_t is the vector of corresponding coefficients; i = 1, 2, . . . , 11, which denotes the 11 provinces and cities in the Yangtze River Economic Belt that are the focus of this study; t = 1, 2, . . . , n, and n indicates the number of independent variables; and ε_{it} is the random error term.

3.4. Data Sources and Processing

Following the industry classification methods outlined in the *China Chemical Industry Yearbook* and the *China Industrial Statistics Yearbook*, the chemical industry is defined as comprising five sub-sectors within the manufacturing industry: petroleum, coal, and other fuel processing; chemical raw material and chemical product manufacturing; pharmaceutical manufacturing; chemical fiber manufacturing; and rubber and plastic products. The data in this study come from various sources, including the *China Industrial Statistics Yearbook, China Statistical Yearbook*, and *China Environmental Statistics Yearbook* from 2012 to 2022, and statistical yearbooks and ecological environment bulletins from Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Guizhou, and Yunnan. In addition, in order to eliminate the influence of price factors on the calculation and regression results, this paper uses 2000 as the base period for all economic indexes. The underlying data are deflated using the GDP deflator. For missing statistical data, the mean interpolation method was used to fill in the gaps, with the following calculation formula:

$$\overline{y} = \frac{\sum_{i=1}^{n} B_i y_i}{n_i} \tag{15}$$

where $\overline{y}$ is the mean; B_i is a descriptive symbol indicating whether or not to answer, where B_i = 1 is "yes" and B_i = 0 is "no"; $\mathrm{n_i}$ is a single number.

Additionally, Table 4 provides the descriptive statistics for the coupling coordination degree and its influencing factors.

Table 4. Descriptive statistics.

Variable	Mean	Std. Dev	Min	Max	Obs
D	0.507	0.010	0.328	0.741	121
ECO	8.523	0.535	7.410	9.589	121
GOV	0.299	0.268	0.121	1.208	121
TEC	0.026	0.015	0.008	0.059	121
ENV	0.006	0.006	0.0001	0.034	121
URBAN	0.586	0.133	0.350	0.896	121
OPEN	0.320	0.315	0.029	1.398	121

4. Results and Analysis

4.1. Analysis of Chemical Industry Development

Figure 2 shows the comprehensive evaluation indices for chemical industry development from 2011 to 2021 in the Yangtze River Economic Belt, calculating the annual means for the entire belt and for the upstream, midstream, and downstream areas (Figure 2).

Overall, the comprehensive evaluation index of chemical industry development showed a fluctuating upward trend, increasing from 0.2330 in 2011 to 0.3277 in 2021. Regionally, the trends in each subregion aligned with the overall Yangtze River Economic Belt. The downstream region consistently led the trend throughout the observation period, followed by the midstream and upstream regions, which remained below the belt's average level. The downstream region's economic growth and higher consumption rates contributed to its strong chemical industry development, whereas the midstream and upstream regions focus on phosphate and natural gas-based chemicals, with lower added value compared to the downstream petroleum and fine chemicals, which explains their lower indices. In particular, the average value of the upstream area is significantly lower than that of the midstream and downstream areas, which is due to the fact that the upstream area is in the Yangtze River Economic Belt zone of loose environmental regulation, and in the process of gradient transfer of the chemical industry, the chemical enterprises it encompasses are more inefficient and more polluting and the economic development of the region is relatively backward as a whole, so the comprehensive development level of the chemical industry is significantly low.

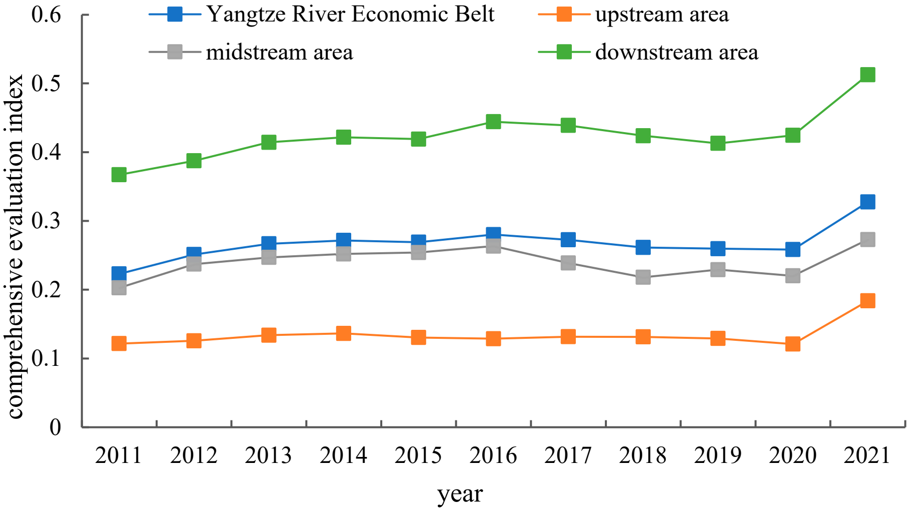

Figure 2. Temporal evolution of the comprehensive evaluation level of chemical industry development in the Yangtze River Economic Belt from 2011 to 2021.

By selecting the years 2011 and 2021 as key time points, the comprehensive evaluation indices of chemical industry development were categorized into five levels (Figure 3). In general, the Yangtze River Economic Belt exhibited a growth trend, with an "east-high, west-low" spatial pattern, indicating that the eastern region's chemical industry development was significantly ahead of other regions. Additionally, the spatial structure remained relatively stable from 2011 to 2021. Notable exceptions can be observed in the upstream and midstream regions, with Hubei's chemical industry advancing from the third to the second level, driven by the province's 14th Five-Year Plan for High-Quality Manufacturing that emphasized the modernization of the chemical and energy industries. Conversely, Hunan's chemical industry fell from the second to the third level, likely due to the province's 2020 implementation of the Relocation and Reconstruction Plan for Chemical Enterprises Along the River that caused many chemical enterprises to relocate away from the river, reducing Hunan's chemical industry status.

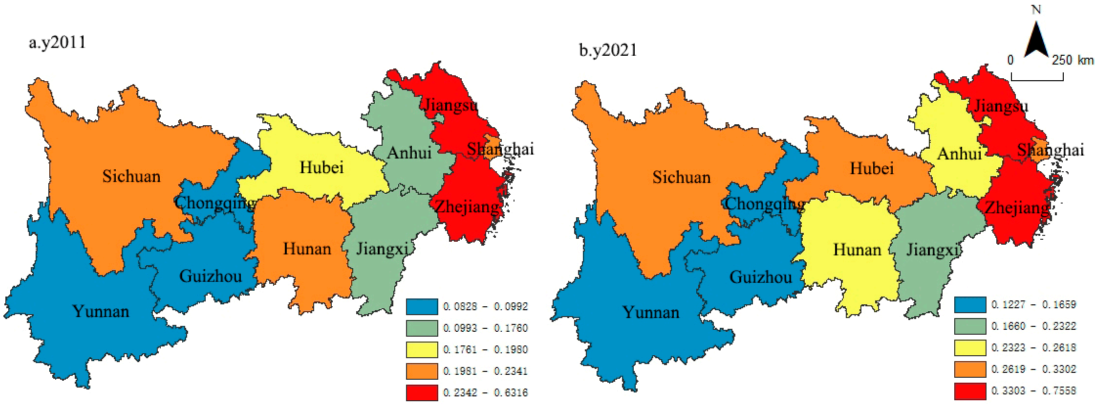

Figure 3. Spatial evolution of the comprehensive evaluation level of chemical industry development in the Yangtze River Economic Belt from 2011 to 2021.

4.2. Analysis of the Water Environment

The comprehensive evaluation index for the water environment from 2011 to 2021 was calculated, with annual means for the overall region and the upstream, midstream, and downstream areas (Figure 4). Overall, the water environment index showed a slow upward trend, with a peak in 2016 at 0.3162, suggesting that the Yangtze River Protection strategy had a significant impact on reducing industrial pollution and improving water quality. Regionally, due to the abundant wetland resources in the middle reaches of the Yangtze River, strong hydrological regulation and control capabilities, and numerous restoration engineering cases [48], the comprehensive evaluation index of the water environment is always higher than the overall level of the water environment in the Yangtze River Economic Belt and shows an obvious "M"-shaped fluctuation trend, which is affected by the "Yangtze River Protection" strategy. In 2016, the highest value was 0.4023, while the upstream and downstream areas generally showed characteristics of a low comprehensive level of the water environment, which was due to the fact that the total phosphorus discharge concentration in the Yangtze River basin was generally characterized by a high concentration in the upstream and downstream reaches and a low concentration in the middle reaches [49]. Among them, the upstream area was only higher than the global average in 2012 because the "Yangtze River Basin Comprehensive Utilization Plan" (2012–2030) released in 2012 planned a number of hydropower stations in the upstream main stream and main tributaries, which adjusted the water ecological service function of the upstream area in the short term. The downstream areas have a high degree of urbanization, high population density, dense areas such as nature reserves and drinking water source protection areas, and prominent sudden environmental risks [50], and their comprehensive water environment scores are always lower than the average level of the Yangtze River Economic Belt. It can be seen that in the process of water environment management in the Yangtze River Economic Belt, attention should be paid to the protection and governance of water resources in the upstream and downstream areas.

Using 2011 and 2021 as key time points, the comprehensive evaluation index of the water environment was divided into five levels (Figure 5). Generally, the indices across provinces and cities showed an upward trend, with a "west-high, east-low" spatial distribution, indicating a spatial mismatch with the chemical industry development pattern. Notable changes occurred between 2011 and 2021, with stable patterns observed in Hubei, Anhui, and Shanghai, and these cities maintained their respective third, fourth, and lowest levels. Among the upstream areas, Sichuan, Yunnan, and Chongqing's water environment indices declined, while Guizhou rose from the lowest to the third level, likely due to precise strategies aimed at improving the quality of the Wujiang River's water. In the midstream region, Hunan's water environment advanced from the fourth level in 2011 to the highest level in 2021, indicating that the chemical industry relocation initiative had a positive impact on water protection. Conversely, the status of Jiangxi dropped from the highest to the second level. In the downstream region, both Jiangsu and Zhejiang's water environment indices fell, suggesting that these eastern provinces focused more on the economic benefits of chemical industry development than on water protection.

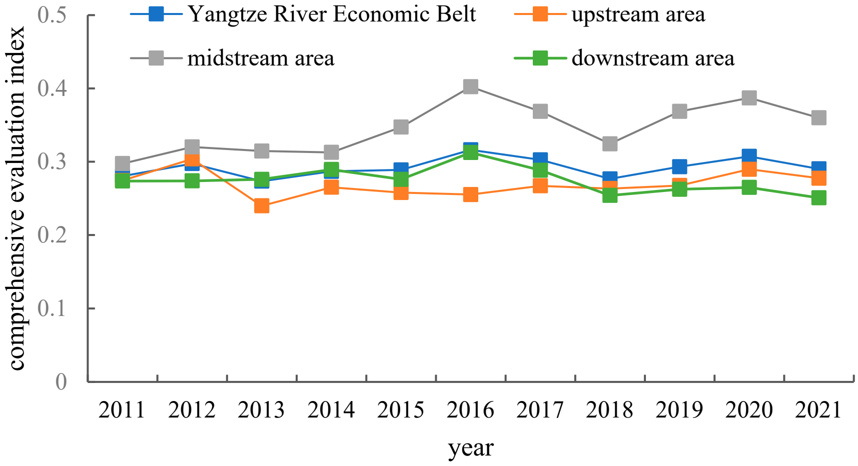

Figure 4. Temporal evolution of the comprehensive evaluation level of the water environment in the Yangtze River Economic Belt from 2011 to 2021.

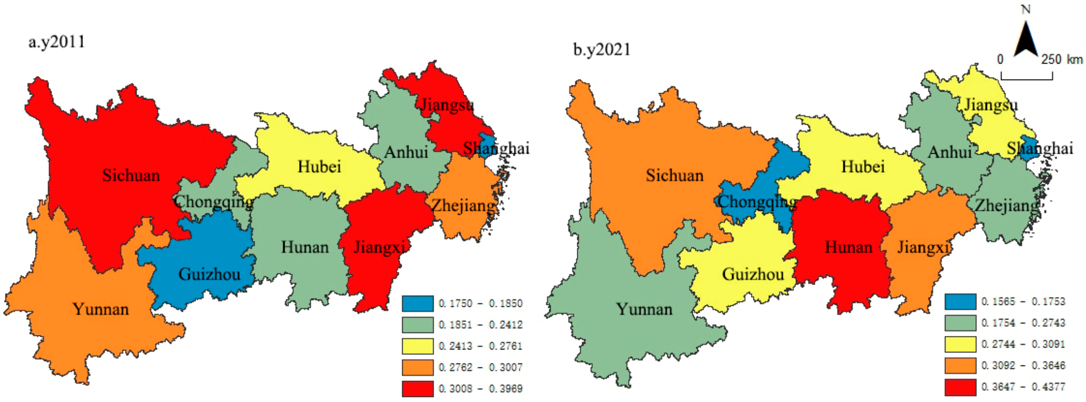

Figure 5. Spatial evolution of the level of comprehensive water environment assessment in the Yangtze River Economic Belt from 2011 to 2021.

4.3. Analysis of the Coupling Coordination Degree

4.3.1. Spatiotemporal Evolution Pattern

Figure 6 depicts the temporal evolution characteristics of the coupling coordination degree between chemical industry development and the water environment in the Yangtze River Economic Belt during 2011–2021. The coupling coordination degree displays a gradual upward trend, with an increase from 0.4868 to 0.5352, indicating a progression from mild to preliminary coupling coordination. Regionally, the pattern "downstream > midstream > upstream" persisted throughout the study period, with the downstream and midstream regions maintaining a higher coordination degree than the belt's overall level. The downstream region experienced stages of preliminary and moderate coordination, with the highest coordination degree of 0.6104 in 2016, reflecting its rapid response to the Yangtze River Protection strategy as the most economically developed and open region. The midstream region, primarily in the stages of mild and preliminary coordination, also peaked in 2016 at 0.5705, indicating the beneficial effects of the Yangtze River Protection policy in improving the coordination between chemical industry development and the water environment. The upstream region remained in mild coordination throughout the study period, with its lower coordination degree attributed to its relatively lower economic development and limited resources and technology for chemical industry and water environment advancement.

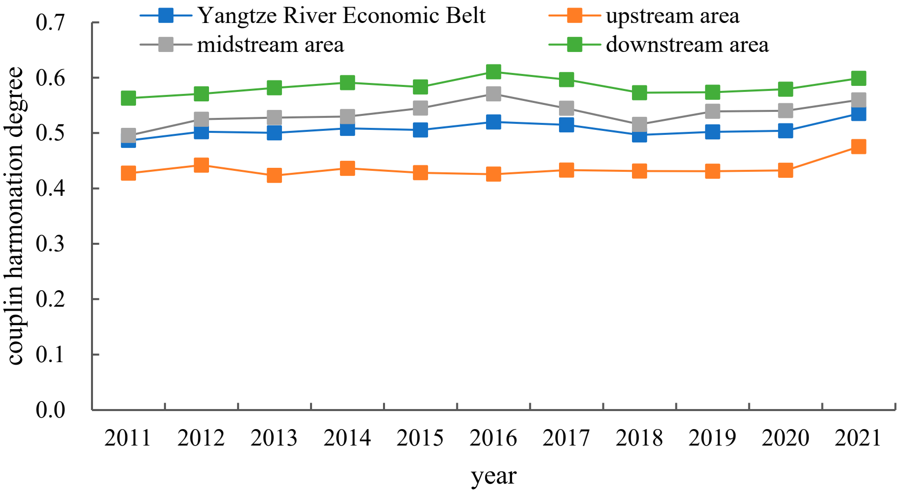

Figure 6. Coupling and coordination of chemical industry development and water environment in Yangtze River Economic Belt from 2011 to 2021.

An examination of the spatial and temporal differences in coupling coordination stages during the study period (Figure 7a) highlights the pattern of higher levels in Jiangsu and Zhejiang, and lower levels in Chongqing, Sichuan, and Yunnan. Jiangsu and Zhejiang maintained moderate coordination throughout the study period, with mean coordination degrees of 0.7000 and 0.6267, respectively. In contrast, Jiangxi and Sichuan remained in the preliminary coordination stage, with mean values of 0.5370 and 0.5438. Regions like Hunan, Chongqing, and Guizhou exhibited progressive improvements in their coordination degrees. However, notable decreases in coupling coordination were observed in Shanghai, Anhui, and Hubei, suggesting that these regions might have focused excessively on chemical industry development or water environment governance at the expense of maintaining a balanced approach.

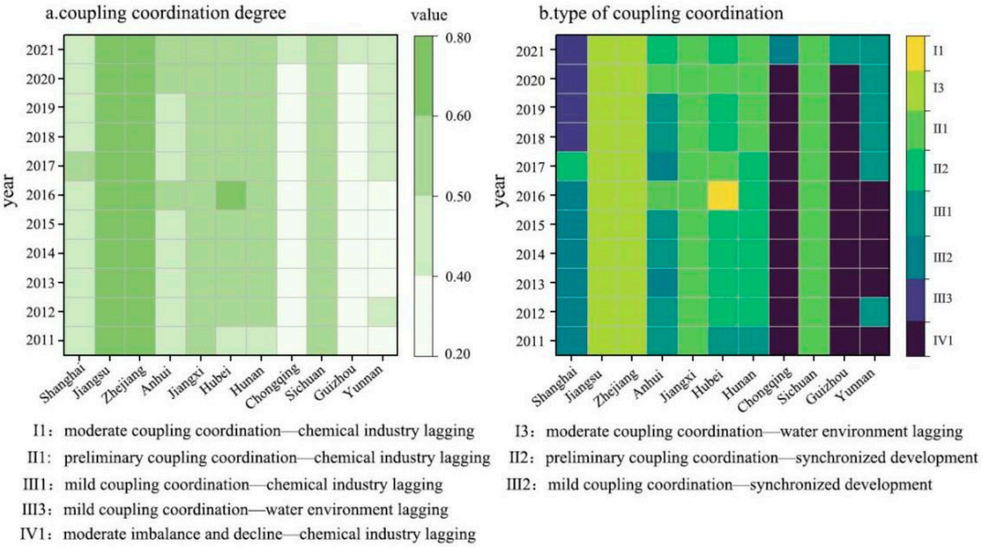

Figure 7. Coupling and coordination stages and types of chemical industry development and water environment in the Yangtze River Economic Belt from 2011–2021.

Regarding the type of coupling coordination, significant and diverse changes could be observed across the provinces and cities of the Yangtze River Economic Belt from 2011 to 2021 (Figure 7b). The three main types identified were chemical industry lagging, water environment lagging, and synchronized development, accounting for 57.9%, 21.5%, and 20.7%, respectively. Spatially, the pattern showed that "chemical industry lagging" types were concentrated in the upper and middle reaches of the river, while "water environment lagging" types were more common in the lower reaches. At the provincial and municipal level, Jiangsu and Zhejiang consistently fell under the "moderate coupling coordination–water environment lagging" type, while Jiangxi and Sichuan remained in the "mild coupling coordination–chemical industry lagging" type. Meanwhile, Chongqing and Guizhou transitioned from "moderate imbalance and decline–chemical industry lagging" to "mild coupling coordination–synchronized development". However, Hubei experienced several transitions from "mild coupling coordination–synchronized development" to "preliminary coupling coordination–synchronized development" and later to "moderate coupling coordination–chemical industry lagging". Similarly, Anhui, Shanghai, and Hunan showed various types over time, indicating that the coupling interaction between chemical industry development and the water environment in these regions is unstable and requires special attention.

4.3.2. Dynamic Evolution Characteristics

Using kernel density estimation, this study analyzed the dynamic evolution characteristics of the coupling coordination degree between chemical industry development and the water environment in the Yangtze River Economic Belt from 2011 to 2021 (Figure 8). With the Epanechnikov kernel function, three cross-sectional points—2011, 2016, and 2021—were selected to assess the dynamic evolution of coupling coordination through variations in distribution position, peak count, and distribution shape. The results indicate a general rightward shift in the density curve, signifying an upward trend in coupling coordination across the Yangtze River Economic Belt's region. An examination of the peak height and distribution shape shows a decline in peak height followed by an increase, with the peak width expanding initially and then contracting, indicating a growing disparity in absolute coordination levels. In 2011, the coordination degree clustered around 0.45, mainly in Shanghai and Anhui. In 2016, the range was between 0.50 and 0.56, with a focus on Anhui, Jiangxi, Hunan, and Sichuan; by 2021, the concentration was at 0.52, primarily in the midstream areas of Anhui, Jiangxi, and Hubei. The changes in distribution pattern also suggest a decreasing gap between high-level coordination provinces like Jiangsu and Zhejiang and the overall average level in the Yangtze River Economic Belt, pointing to a more balanced trend in coupling coordination.

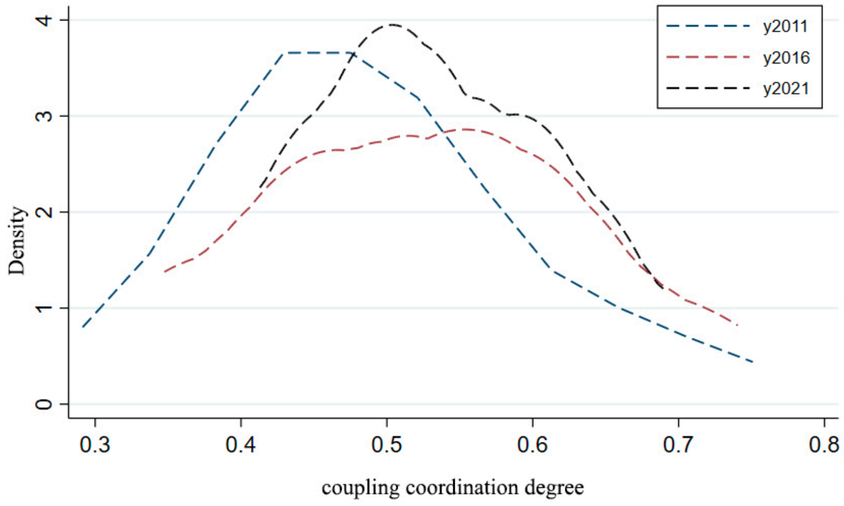

Figure 8. Kernel density estimation of coupling coordination degree between chemical industry development and water environment in Yangtze River Economic Belt from 2011 to 2021.

4.4. Analysis of Influencing Factors on the Coupling Coordination Degree

Before estimating the regression of the influencing factors of the coupling coordination degree of the two systems, a collinearity test is required (Table 5). As can be seen from Table 4, the VIF value of each variable is less than 10, and its mean value is 3.74, indicating that there is no collinearity and a regression estimation can be made. The regression analysis of the influencing factors on coupling coordination between chemical industry development and the water environment in the Yangtze River Economic Belt is shown in Table 6. Overall, economic development (ECO), urbanization (URBAN), government capacity (GOV), and environmental regulation (ENV) have significant positive effects, while openness (OPEN) exhibits noticeable negative impacts. Technology investment (TEC) has limited explanatory power. Specifically, the regression coefficient for local economic development (ECO) is 0.108 and is significant at the 1% level, indicating that improved economic development promotes coupling coordination between chemical industry development and the water environment in the Yangtze River Economic Belt. The coefficient for urbanization (URBAN) is 0.504, also significant at the 1% level, indicating that urbanization positively affects the coupled development of the chemical industry and the water environment. The reason may be that urbanization reflects the continuous expansion of the urban economy, and relevant studies have pointed out that the rapid agglomeration of the population is conducive to the rational use of water resources, and the scale effect brought by urbanization can promote the coupling coordination of the two systems to a certain extent. Government capacity (GOV) has a regression coefficient of 0.159, which is significant at the 1% level, implying that government capacity may significantly promote the improvement in coupling coordination between the chemical industry and the water environment. The impact of technology investment (TEC) on coupling coordination is not statistically significant, suggesting that technology investment has yet to play a significant role in fostering coupling coordination between the chemical industry and the water environment. This lack could be because the chemical industry, as a pollution-intensive sector, sees much of the government's technology investment directed toward high-end industries, reducing the positive impact of technology on coupling coordination. The regression coefficient for environmental regulation (ENV) is the largest at 4.860 and is significant at the 1% level, indicating that environmental regulation is a powerful driver of coupling coordination, with increasingly stringent policies promoting coordinated development. Hence, increasing the strength of environmental regulation is critical for achieving coupling coordination in the Yangtze River Economic Belt. The regression coefficient for openness (OPEN) is −0.156 and is significant at the 1% level, suggesting that openness to foreign markets may negatively impact coupling coordination between the chemical industry and the water environment. This possible effect could be because, in a typical pollution-intensive industry like the chemical industry, the "pollution haven" hypothesis indicates that foreign investment might bring high-energy-consumption and high-emission industries into the host country, causing irreversible environmental damage and inhibiting coupling coordination [51].

Table 5. Collinearity test results.

Variable	VIF
ECO	2.31
URBAN	6.98
GOV	2.39
TEC	3.39
ENV	1.65
OPEN	5.71
Mean	3.74

Table 6. Tobit regression results.

Variable	Regression Coefficients	Standard Error	z-Statistic	p-Value
ECO	0.108 ***	0.018	5.960	0.000
URBAN	0.504 ***	0.126	4.000	0.000
GOV	0.159 ***	0.037	4.354	0.000
TEC	−0.319	0.768	−0.415	0.678
ENV	4.860 ***	1.287	3.776	0.000
OPEN	−0.156 ***	0.048	−3.238	0.001
Constant	−0.725	0.160	−4.544	0.000

Note: *** indicate significance at the 1% level.

5. Conclusions and Policy Recommendations

5.1. Conclusions

This study constructs a comprehensive evaluation indicator system for both the chemical industry development system and the water environment system based on an analysis of the coupling mechanism between chemical industry development and the water environment. It employs the global entropy method to calculate the weights and comprehensive indices, constructing a coupling coordination model to analyze the relationship between chemical industry development and the water environment from 2011 to 2021 in the Yangtze River Economic Belt. The use of this method allows for a clear understanding of spatiotemporal evolution patterns and influencing factors. The following conclusions can be drawn:

(1) From 2011 to 2021, the overall level of chemical industry development in the Yangtze River Economic Belt consistently improved, exhibiting a relatively stable spatial distribution pattern with a noticeable “east-high, west-low” trend. The comprehensive water environment index showed a slow upward trend with relative stability, presenting a spatial pattern of “west-high, east-low”, which significantly differs from the spatial pattern of chemical industry development.

(2) The coupling coordination degree between chemical industry development and the water environment showed a relatively small variation with a general upward trend, maintaining a state of mild-to-preliminary coordination. The spatial pattern indicated a “downstream > midstream > upstream” pattern. At the provincial level, Jiangsu and Zhejiang are high-level coupling coordination regions, while Chongqing, Yunnan, and Guizhou are low-level regions. The dynamic analysis suggests that coupling coordination will continue to increase, with the gap between high-level regions and the overall level in the Yangtze River Economic Belt narrowing.

(3) The Tobit model regression analysis of influencing factors indicates that coupling coordination between chemical industry development and the water environment in the Yangtze River Economic Belt is influenced by multiple factors. Specifically, economic development, government capacity, urbanization, and environmental regulation have significant positive effects, while openness has significant negative impacts, with technology investment having a limited effect.

5.2. Policy Recommendations

The Yangtze River Economic Belt is a major strategic region and economic support belt in China, and the coordination between the chemical industry and the water environment is directly related to the realization of high-quality development in the region. Based on the research findings for the spatiotemporal differentiation characteristics and influencing factors of the coupling coordination degree between chemical industry development and the water environment in the Yangtze River Economic Belt from 2011 to 2021, this paper puts forward the following policy recommendations:

(1) The Yangtze River Economic Belt spans across different regions of China with varying natural conditions and resource endowments, leading to heterogeneity in the development of the chemical industry and the water environment. The chemical industry

shows an “east-high, west-low” spatial distribution pattern, consistent with Chen et al. [52]. Meanwhile, the water environment demonstrates a “west-high, east-low” pattern, aligned with the findings of Yang et al. [53]. Considering the chemical industry’s development trends, the downstream region significantly outperforms the midstream and upstream regions, possibly because downstream areas focus on high-added-value industries like petrochemicals and fine chemicals. The overall water environment trend follows a pattern of “midstream > upstream > downstream”, likely due to tighter water environment management strategies in the midstream region. Differentiated development strategies should be adopted to address the significant spatial mismatch between chemical industry development and the water environment. The downstream region in the Yangtze River Economic Belt should focus on improving water environment quality through governance and protection efforts. The midstream and upstream regions need to prioritize chemical industry development and promote industry upgrades and transformations to increase value chain integration.

(2) Studies indicate that while coupling coordination between chemical industry development and the water environment has shown an upward trend in recent years, it still remains at a mild-to-preliminary stage of coordination, suggesting the existence of significant room for improvement in achieving coordinated development. Additionally, specific strategies should be proposed given the differences in coupling coordination stages and types across regions. For example, high-level coordination regions like Jiangsu and Zhejiang should address their water environment lags, continue to implement strict environmental regulation policies, and increase funding for water environment protection while promoting green upgrades in chemical industry structures. Regions like Shanghai, Hubei, Hunan, and Anhui, with varying coordination types, should monitor changes in their coupling coordination stages and regularly assess chemical industry development and water environment status, employing various measures to stabilize coordination types. These measures could include strengthening environmental regulations in the chemical industry and formulating appropriate water environment protection policies. In Jiangxi and Sichuan, which consistently show “mild coordination with chemical industry development lagging”, the focus should be on increasing technology and capital investment in chemical industry development, continually driving industry transformation and upgrading for high-quality growth. For regions like Chongqing and Guizhou, which have transitioned from “moderate disorder with chemical industry lagging” to “mild coordination with synchronized development”, reliance on past chemical industry and water environment development strategies should continue to achieve sustained synchronized development.

(3) The effects of factors like economic development, urbanization, environmental regulation, government capacity, and openness must be considered thoroughly to improve coupling coordination between chemical industry development and the water environment in the Yangtze River Economic Belt. The regression coefficient for environmental regulation is the highest, indicating that stringent environmental regulation has the strongest effect on coupling coordination, consistent with Zou et al. [54]. Therefore, reasonable increases in environmental regulation intensity are key to achieving coordinated chemical industry development and water environment protection in the Yangtze River Economic Belt. On the one hand, it is necessary to strictly enforce the environmental control policies of the chemical industry in the Yangtze River Economic Belt and strengthen the policy of eliminating backward production capacity in the chemical industry. On the other hand, relevant water resource protection policies should be formulated and implemented to strictly protect the ecological environment of water resources. Additionally, it is necessary to give full play to the scale effect brought about by urbanization and improve the overall water resource utilization efficiency of the Yangtze River Economic Belt. We should give full play to the government’s role in regulation and control, appropriately increase local investment in the chemical industry and water environment governance, and promote the coordinated development of the two; pay attention to the negative effects of opening up to the outside world, strictly regulate the access system of relevant foreign-funded chemical enterprises,

and realize the transformation of the chemical industry from "quantity" to "quality"; finally, pay attention to the insignificant role of scientific and technological investment, increase scientific and technological investment in technological innovation and water environment management in the chemical industry, and promote innovation with science and technology.

Due to the difficulty of obtaining data on the development of the chemical industry and the water environment, this study took 11 provinces and cities in the Yangtze River Economic Belt as the research object to explore the coupling coordination level of the development of the chemical industry and the water environment. It is surely necessary to further optimize the index system in the future and include more perspectives and compare different areas, so as to more systematically explore the internal mechanisms and influencing factors of chemical industry development and the water environment. In particular, the river flow has an important impact on chemical industry development and the water environment, and it is necessary to include the flow direction of water in the influencing factors of coupling coordination in order to better explore the synergistic interaction.

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