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Challenges for Water Security and Sustainable Socio-Economic Development: A Case Study of Industrial, Domestic Water Use and Pollution Management in Shandong, China

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Abstract: Comprehensive analysis of water use and pollution management plays an important role in regional water security and sustainable socio-economic development. This study applies the environmental Kuznets curve (EKC), Gini index and elasticity coefficient methods to conduct an investigation of industrial and domestic water use and pollution management in Shandong. The results show that industrial water pollution generally displayed a coordinated relationship with socio-economic development, while an uncoordinated relationship occurred between domestic water pollution and socio-economic development. Meanwhile, the Gini index between domestic water use and population in 2017 (0.101) was superior to that of 2003 (0.165), and the Gini index of industrial water use and second industry output in 2017 (0.273) was better than that of 2003 (0.292), indicating that the allocation and equity of domestic and industrial water use in Shandong kept to a good development trend. Additionally, the industrial effect is better than the domestic effect in terms of the control of wastewater emissions and the governance of typical pollutants in wastewater. Accordingly, domestic water pollution has gradually become one of the major sources of water pollution, and the allocation of industrial and domestic water use has room to improve further in Shandong. Conjunctive use of the aforementioned three methods provides an approach to investigate the integrated management of water use and water pollution control from multiple angles.

Keywords: water pollution; water use; socio-economic development; environmental Kuznets curve; Gini index; elasticity coefficient

1. Introduction

The safety of water resources and the ecological environment in the Asian region is facing severe challenges with the rapid socio-economic development [1,2]. There are two main reasons behind this phenomenon. The first is that a large amount of pollutants has been discharged into rivers and lakes, causing the deterioration of regional water quality [3,4]. The other point is that regional water use had increased with economic development and population growth, which results in water resources waste and huge water supply pressure [5,6]. Shandong province, located in north-central China, has a large population and is one of the regions with serious water shortages in China. The domestic and industrial water use in Shandong has increased rapidly in recent years, but the efficiency of water resources utilization is not high. In addition, water pollution in Shandong is also relatively serious. The eutrophication of rivers and lakes, which is mainly caused by the discharge of industrial and domestic wastewater, is more prominent. At present, the discharge of industrial wastewater in Shandong is ranked third, and the discharge of domestic wastewater is also ranked third in China.

However, the number of wastewater treatment facilities in Shandong is ranked 16th in China, far below the ranking of industrial and domestic wastewater emissions. It can be seen that Shandong belongs to a region with serious water pollution in China. Existing research shows that if this trend continues, industrial, domestic water pollution will restrict the water security and sustainable socio-economic development of Shandong in the future. Accordingly, the investigation of industrial, domestic water use and pollution management is becoming increasingly important for promoting water security and sustainable socio-economic development in Shandong.

Over the past few decades, the relationship between environment and economy has concerned relevant researchers, to strengthen pollution emissions control and management [7–9]. Some researchers have pointed out that the environmental pollution increased faster than economic growth during the early stages of economic development, and then decreased at higher economic development levels [10,11]. This is the famous environmental Kuznets curve (EKC), with an inverted-U-shaped nexus between indicators. The EKC hypothesis was first applied to examine the nexus between environment pollution and economic development in the United States [12]. Later, many empirical studies about environmental pollution–economic development nexus have been carried out using EKC. Results showed that an inverted-U-shaped relationship has occurred between environment pollution and economic development in most developed countries [13–16]. Lee et al. [17] revisited a water pollution EKC, they found that the existence of an inverted-U-shaped relationship between biological oxygen demand (BOD) emissions and GDP per capita in Europe and America. Fodha and Zaghdoud [18] found an inverted-U-shaped relationship between SO_2 emissions and GDP per capita using time series data.

In China, similar studies have revealed the existence of a relationship between environmental pollution and economic development [19,20]. Gao et al. [21] established the EKC model to study the relationship between industrial wastewater, SO_2 emissions and GDP per capita in Jiangsu, China. Peng et al. [22] used EKC to study the trend of environmental indicators such as industrial wastewater and industrial COD emissions in Shanghai, plotted against economic development. Liu et al. [23] analyzed the relationship between industrial chemical oxygen demand (COD), NH_3-N, wastewater emissions and per capita GDP in Zaozhuang, Shandong based on the EKC hypothesis. Zhang and Wang [24] used the EKC model to study the relationship between water pollution (industrial and domestic wastewater discharge) and economic development in Shandong.

Overall, most studies using local pollutants as indicators of environmental degradation have found empirical support for the existence of EKC relationships between income and environment [25]. The results of the EKC study are highly dependent on the type of contaminant selected, and EKC might work only for some specific air and water pollutants [26]. Regional pollutants are more suitable for EKC analysis than global pollutants; they are easy to spatially separate and can be controlled at relatively low cost to economic growth [25]. People need better environmental quality, such as clean water and air, when incomes grow. To meet people's life needs, the government will take some measures, such as strengthening environmental laws and investing clean technologies. Therefore, as incomes increase, local specific pollutant emissions begin to decrease.

The pressures of regional water use and supply will be intensified with rapid socio-economic development [27]. Meanwhile, the inefficient utilization and irrational allocation of water resources may generate a series of adverse effects on the regional water security and sustainable socio-economic development [28]. Accordingly, systematic analysis and quantitative study of the water use and pollution control becomes particularly important for regional sustainable water management.

However, a few researchers who have qualitatively analyzed the link between water use and economic development lacked quantitative research [29–32]. In economics, the Lorenz curve is used to investigate the degree of inequality in wealth distribution, which is measured quantitatively using the Gini index [33]. This theory has been widely used in various fields. Liu et al. [34] used the Gini coefficient to evaluate the climate of human settlements. Liu et al. [35] applied the Gini coefficient to study the spatial distribution of grain in China. Delbosc et al. [36] used the Lorenz curve to assess the fairness of public transportation. Sadras et al. [37] used the Lorenz curves and Gini coefficients to analyze the magnitude of grain yield variation at the paddock scale. Groves-Kirkby et al. [38] introduced the Lorenz curve and Gini coefficient to investigate and quantify seasonal variability in environmental radon gas concentration. Jacobson et al. [39] pointed out that the Lorenz method, which is widely employed by economists to analyze income distribution, is largely unused in energy analysis, so they used this method to analyze the allocation of energy. Later, using the concept of the Gini coefficient and Lorenz curve, some scholars analyzed the allocation and equity of energy consumption in some developing and developed countries [40,41].

The Lorenz curves and Gini coefficients were also introduced gradually into the research on the water resources utilization and socio-economic development nexus [42–45]. Gunasekara et al. [46] examined the relationship between water resource abundance and social development using Lorenz curves, and the results implied that differences existed in the effects of different water resource types on socio-economic development. Hanjra et al. [47] investigated linkages and complementarities between agricultural water and socioeconomic development using the Gini index. Meanwhile, similar research has also been carried out in China. Wu et al. [48] applied the Gini coefficient to study the distribution of water resources and secondary industry output, as well as the distribution of water resources and population in Handan, China. Ma et al. [49] mapped the Lorenz curve of water resources and population, as well as water resources and cultivated land resources, and calculated the Gini coefficient to analyze the degree of spatial matching in water resources. Wei et al. [50] used the Lorenz curve and the Gini coefficient to analyze the allocation between water resources and population, as well as water resources and secondary industry output, respectively.

In summary, the Lorenz curve and Gini index are well suited to investigate the allocation and equity between water resources utilization and socio-economic development, which provides a valuable approach to qualitatively and quantitatively study the relationship between the two. They can be applied not just to income but to any quantity that can be cumulated across a population [36]. They can be applied in a range of disciplines, from studies of biodiversity, the allocation of water use and energy consumption to business modeling and even within transport [51].

Overall, existing research has either investigated water pollution control or study water use allocation, but few studies have considered combining these methods to conduct integrated research. This paper tries to draw on the advantages of different methods to investigate water pollution control and water use allocation in Shandong. The coordination between industrial water pollution and socio-economic development, as well as the coordination between domestic water pollution and socio-economic development, was investigated based on the optimal EKC model. The allocation and equity of industrial water use and secondary industry output, as well as domestic water use and urban population in different years, were evaluated qualitatively and quantitatively according to the Lorenz curve and the Gini index. In addition, the control of wastewater emissions and the governance of typical pollutants (NH_3-N and COD) in wastewater were analyzed quantitatively, relying on the elasticity coefficient method in the context of the Five-Year Plan for Shandong.

Comprehensive analysis of industrial and domestic water use and pollution management will provide theoretical support for the formulation of relevant water environment policies in the future, and further promote water security and sustainable socio-economic development in Shandong. Meanwhile, we hope this study can provide theoretical reference for some regions with similar water resources problems, to optimize water pollution control policies and measures and increase in environmental investment. Additionally, the conjunctive use of the aforementioned three methods provides an approach to investigate the integrated management of water use and water pollution control from multiple angles.

2. Materials and Methods

2.1. Study Area

Shandong is a coastal province of China and is located on the lower reaches of the Yellow River. Shandong covers an area of about 157,200 km^2, with seventeen prefecture-level cities, accounting for 1.6% of the total area of China (Figure 1). The climate in Shandong is a warm temperate monsoon climate and the annual average temperature is 11–14 °C. The average annual precipitation is 106 billion m^3, and only 30% forms runoff. The cubic volume of total water resources in Shandong is 30.58 billion m^3, of which the river runoff is 19.83 billion m^3 and the groundwater is 16.54 billion m^3 (repeated calculation amount is 5.58 billion m^3). Shandong belongs to the basins of the Yellow River, Huaihe River and Haihe River, and therefore there are many rivers and a dense river network in Shandong. At present, there are more than 5000 rivers with a length greater than 5 km, and 1552 rivers with a length greater than 10 km. The average river network density is 0.24 km/km^2.

The resident population of Shandong was 100.472 million (population density of 1452 people/km^2) by the end of 2018. The GDP per capita was RMB ¥76,267, and the GDP is RMB ¥7646.97 billion. The output value of the primary industry, secondary industry and tertiary industry was RMB ¥495.05 billion, RMB ¥3364.17 billion and RMB ¥3787.74 billion, respectively. The industrial structure had been continuously optimized and the economic structure had been gradually developed in Shandong. The states of social economy and water resources in Shandong are shown in Table 1.

Table 1. Social economy and hydrometeorology in Shandong.

<table>
<tr><td rowspan="6">Society and economy (2018)</td><td colspan="2">Population (10^4)</td><td>10,047.2</td></tr>
<tr><td colspan="2">Population density (people/km^2)</td><td>1452</td></tr>
<tr><td colspan="2">Working population (10^4)</td><td>6615.8</td></tr>
<tr><td colspan="2">Per capita disposable income (RMB)</td><td>39,549</td></tr>
<tr><td colspan="2">Per capita consumption expenditure (RMB)</td><td>24,798</td></tr>
<tr><td colspan="2">Consumer price index (%)</td><td>102.5</td></tr>
<tr><td rowspan="13">Hydrometeorology (1956–2018)</td><td colspan="2">Rainfall (mm)</td><td>676.5</td></tr>
<tr><td colspan="2">Evaporation (mm)</td><td>450–600</td></tr>
<tr><td colspan="2">Runoff (10^8 m^3)</td><td>222.9</td></tr>
<tr><td colspan="2">River network density (km/km^2)</td><td>0.24</td></tr>
<tr><td colspan="2">Total river length (km)</td><td>9929.9</td></tr>
<tr><td colspan="2">Utilization rate of water resources (%)</td><td>77.1</td></tr>
<tr><td rowspan="4">Freshwater resources (10^8 m^3)</td><td>Surface water</td><td>198.3</td></tr>
<tr><td>Groundwater</td><td>165.4</td></tr>
<tr><td>Repeated water</td><td>59.8</td></tr>
<tr><td>Total water resources</td><td>305.8</td></tr>
<tr><td rowspan="2">External water resources supply (10^8 m^3)</td><td>Yellow River</td><td>70</td></tr>
<tr><td>Yangtze River</td><td>15</td></tr>
<tr><td colspan="2">Contribution to seawater (10^8 m^3)</td><td>41.4</td></tr>
</table>

Low total water resources, low water resources per capita, and uneven water distribution are the main problems of water resources in Shandong Province. The total water resources in Shandong only account for 1.09% of the total water resources in China. The volume of water resources per capita is 334 m^3, which only accounts for 14.9% of the national water resources per capita (less than 1/6), and 4.0% of the world water resources per capita (1/25), ranking the third from the bottom of all of the provinces of China [52]. This is far less than the internationally recognized critical value of 100 m^3 that is necessary to maintain the economic and social development of a region. Therefore, Shandong is a severe water shortage area with water resources per capita of less than 500 m^3. In addition, the annual average reduction of water resources in Shandong is 15.06%, while the total water demand is progressively increasing. So, the tension between water supply and demand is increasingly prominent. The total water resources and water demand in Shandong in the past 10 years are shown in Figure 2a. According to the "Water Resources Comprehensive Planning of Shandong Province", the water demand in Shandong will reach 32.740 billion m^3 in 2030. If the control measures are not implemented, the water shortage will be 6.353 billion m^3 by 2030 according to the current water supply capacity.

Additionally, water pollution in Shandong is also relatively serious. The eutrophication of rivers and lakes, which is mainly caused by the discharge of industrial and domestic wastewater, is more prominent. Statistics showed that in 2014 only one zone of the 294 measured water functional zones reached the water quality Grade I according to "surface water environmental quality standards in China", and the water quality of 163 water functional zones exceeded Grade III (standard for drinking-water quality) (Figure 2b).

At present, the discharge of industrial wastewater in Shandong is ranked third (2.083 billion tons), and the discharge of domestic wastewater is also ranked third (2.281 billion tons) in China. Shandong had invested RMB ¥29 billion in wastewater treatment by the end of 2015, and built 301 municipal sewage treatment plants and 5142 sets of wastewater treatment facilities (sewage treatment capacity of 13.1 million (t/day)). However, the number of wastewater treatment facilities in Shandong is ranked 16th in China, far below the ranking of industrial and domestic wastewater emissions. It can be seen that Shandong is a region with serious water pollution. The growth rate of wastewater treatment facilities lags behind the growth rate of industrial and domestic wastewater emissions. At present, the quantity and treatment capacity of wastewater treatment facilities cannot meet the increasingly serious industrial and domestic water pollution. Therefore, optimizing the development and utilization of water resources and strengthening sewage treatment capacity are urgent needs for achieving water security and sustainable economic development in Shandong [53].

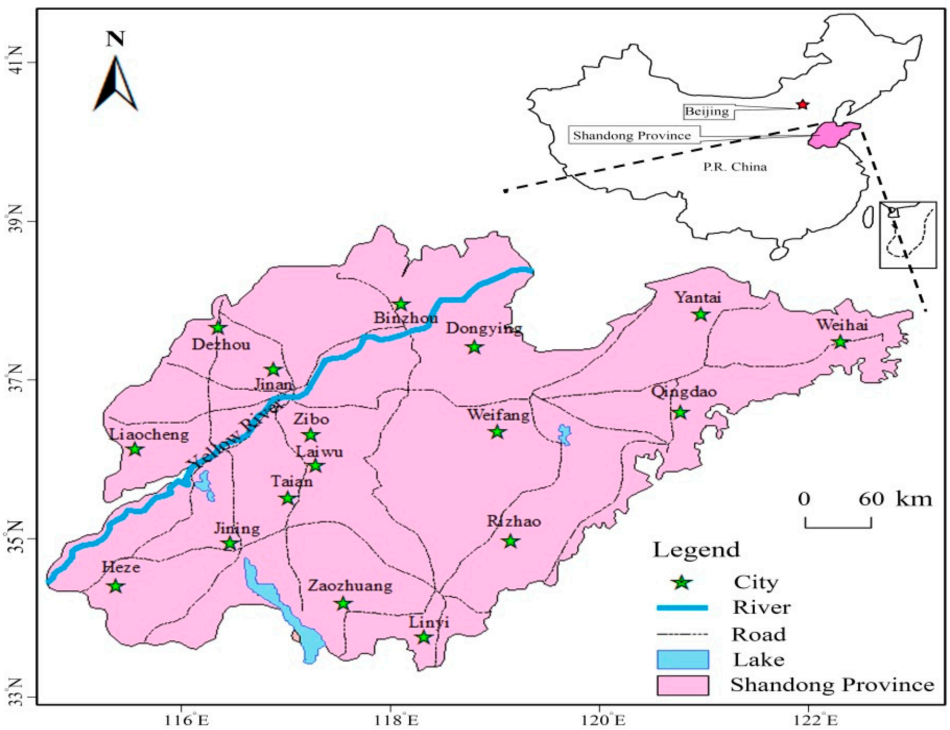

Figure 1. Location of Shandong Province and its seventeen prefecture-level cities.

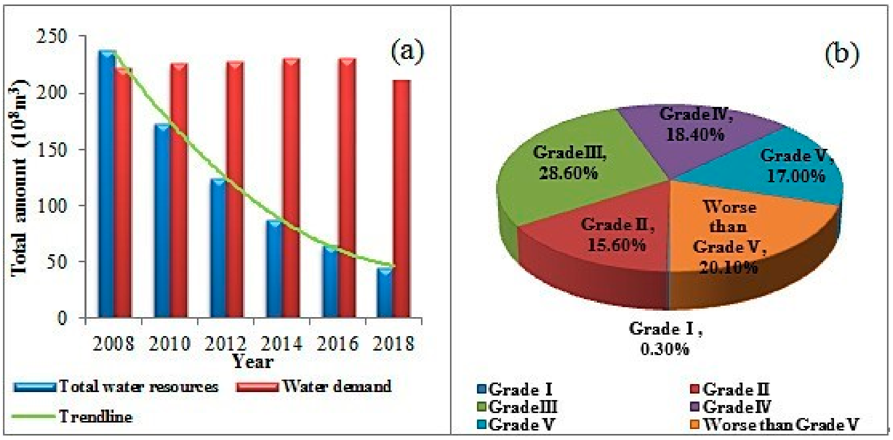

Figure 2. The states of water demand (**a**) and water quality (**b**) in Shandong.

2.2. Construction of Index System

The discharges of industrial, domestic wastewater and COD, as well as NH_3-N, were selected as water pollution indicators, and GDP per capita was used as a socio-economic development indicator. The EKC model was established to analyze the coordination between water pollution and socio-economic development. Furthermore, industrial and domestic water use acted as water use indicators, and the secondary industry output and urban population were selected as social and economic indicators to draw the Lorenz curve (domestic water use–urban population; industrial water use–second industry output) and calculate the Gini coefficient, respectively. Finally, the control of wastewater emissions and the governance of typical pollutants (NH_3-N and COD) in wastewater were analyzed quantitatively using the elasticity coefficient model under the context of the Five-Year Plan for Shandong. All data listed in this paper were from Shandong Water Resources Bulletin (http://www.shandong.gov.cn/col/col2529/index.html) and Shandong Statistical Yearbook (http://www.stats-sd.gov.cn/col/col6279/index.html).

As shown in Figure 3, the GDP per capita in Shandong kept a rising trend in general. Industrial COD and NH_3-N emissions decreased significantly. Industrial wastewater emissions slightly increased, and gradually decreased after 2012. There were slight increases in domestic wastewater, COD and NH_3-N emissions, which reached a turning point in 2012, and then a clear upward trend occurred. Industrial and domestic water use showed an increase in 2017, compared to 2003 (Figure 4). The urban population in 2017 was growing comparing with 2003. Meanwhile, the secondary industry output in 2017 had grown to over two times that of 2003.

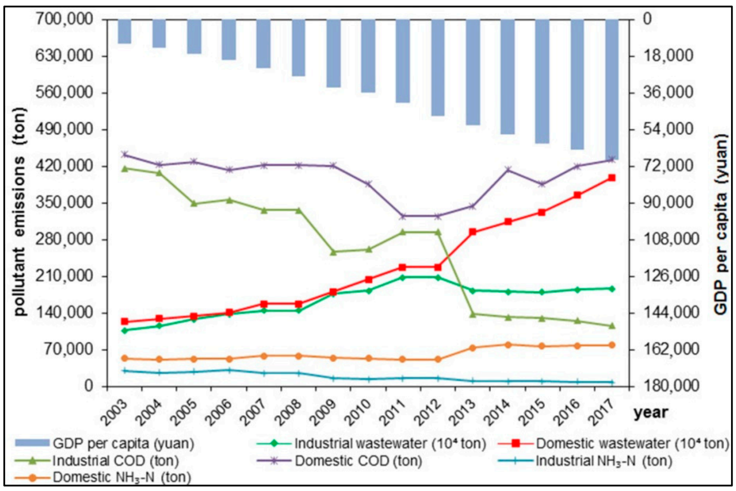

Figure 3. Indicators of water pollution and socio-economic development in Shandong from 2003 to 2017.

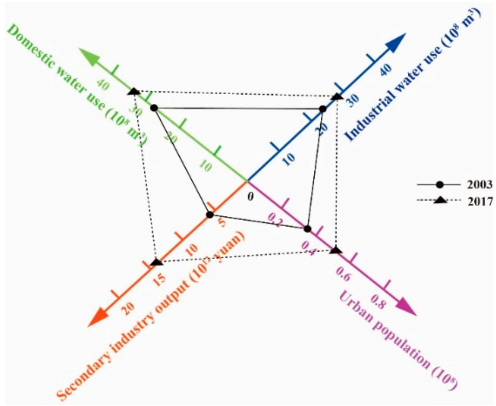

Figure 4. Indicators of water use and socio-economic development in 2003 and 2017.

2.3. Development of EKC Model

The EKC theory was first proposed by Simon Kuznets in 1995, which revealed the coordination between income per capita and environmental quality [54]. In this paper, GDP per capita is taken as an independent variable (X), and industrial, domestic wastewater emissions and typical pollutants in wastewater (COD and NH_3-N) are taken as dependent variables (Y), and the time step to construct the time series EKC model was one year. This paper qualitatively researched the relationship between water pollution and socio-economic development in Shandong from 2003 to 2017 by combining regional environmental and economic policies and related factors. The three basic models are as follows:

Linear model:

$$Y_t = \beta_0 + \beta_1 X_t + \zeta_t \tag{1}$$

Quadratic model:

$$Y_t = \beta_0 + \beta_1 X_t + \beta_2 X_t^2 + \zeta_t \tag{2}$$

Cubic model:

$$Y_t = \beta_0 + \beta_1 X_t + \beta_2 X_t^2 + \beta_3 X_t^3 + \zeta_t \tag{3}$$

where Y_t is pollutant emissions, X_t is GDP per capita. ζ_t is the error term, β_0 is the constant, $\beta_1, \beta_2, \beta_3$ represent the coefficients of independent variable.

(i) Equation (1) reveals an increasing or decreasing linear nexus between indicators.

(ii) Equation (2) indicates that there is an inverted-U-shaped or U-shaped relationship between indicators. An inverted-U-shaped curve exists between indicators when $\beta_1 > 0$, $\beta_2 < 0$. If $\beta_1 < 0$, $\beta_2 > 0$, the relationship between indicators is generally described as a U-shaped. The turning point ($X^* = -\beta_1/2\beta_2$) can be achieved by calculating the derivative of Equation (2).

(iii) Equation (3) shows that an inverted-N-shaped or N-shaped relationship occurs between indicators. The inverted-N-shaped curve exists between indicators when $\beta_1 < 0$, $\beta_2 > 0$, $\beta_3 < 0$, while $\beta_1 > 0$, $\beta_2 < 0$, $\beta_3 > 0$ represents an N-shaped curve. The turning point can be obtained when one and two turning points exist, according to Equations (4) and (5), respectively.

$$X^* = -\beta_2/3\beta_3 \tag{4}$$

$$X^* = \left(-\beta_2 \pm \sqrt{\beta_2^2 - 3 \cdot \beta_1 \cdot \beta_3}\right)/3\beta_3 \tag{5}$$

2.4. The Lorenz Curve and Gini Index

The Lorenz curve was put forward by statistician Lorenz in 1905 to analyze and compare the level of regional wealth fairness, and its curvature degree reflects the degree of inequality in income distribution [55]. As a simple and practical method of analysis, the Lorenz curve has also been studied and applied in the environmental field. Relevant research has shown that industrial water use is closely related to secondary industry output, and domestic water use is closely related to the urban population in Shandong [56,57]. Therefore, to investigate the relationship between water use and socio-economic development, the allocation and equity of domestic water use–urban population, and the industrial water use–secondary industry output in different years were analyzed to in this paper.

The Location Quotient (LQ) is a ratio used to determine the spatial distribution of a phenomenon in the region, and the LQ of water use type in various cities was first calculated.

$$LQ = \frac{A_1}{A_2} / \frac{A_3}{A_4} \tag{6}$$

where LQ is the Location Quotient, A_1 is urban population (or secondary industry output) in a specific city. A_2 is urban population (or secondary industry output) in province. A_3 is domestic water use (or industrial water use) in a specific city. A_4 is domestic water use (or industrial water use) in province.

Secondly, the LQs were sorted from low to high, and the cumulative percentage of each indicator was obtained. Then, the cumulative percentage of domestic water use (X_1) was used as the abscissa, and the cumulative percentage of urban population (Y_1) was taken as the ordinate in a two-dimensional Cartesian coordinate system. Likewise, the cumulative percentage of industrial water use (X_2) was served as the abscissa, the cumulative percentage of secondary industry output was regarded as the ordinate (Y_2). Finally, the Lorenz curve between water use and socio-economic development in Shandong were drawn based on the aforementioned coordinates (Figure 5).

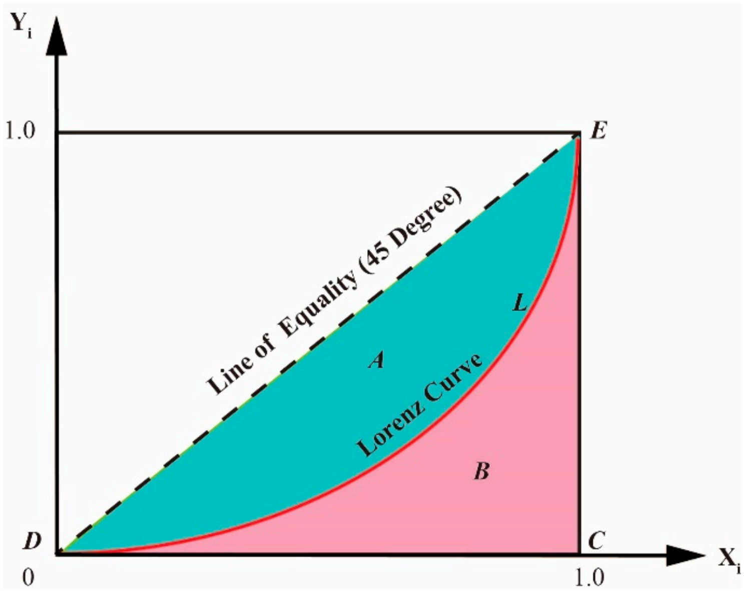

Figure 5. The Lorenz curve.

In economics, the Gini index can realize the purpose of quantifying the Lorenz curve. The value of the Gini index is between 0 and 1, and its evaluation standards are shown in Table 2, according to the regulations of relevant United Nations organizations [58]. The larger the Gini index was, the worse the distribution and equity was; in contrast, the smaller the Gini index was, the better the distribution and equity was. The detailed calculation steps of Gini index were as following:

(i) Calculating the area of the geometric figure.

$$S_B = \int_0^1 F dx \tag{7}$$

where F is the function of Lorentz curve (L) and the integral interval is [0,1].

(ii) Calculating the Gini index.

$$G = S_A/(S_A + S_B) = (S_{\Delta CDE} - S_B)/(S_A + S_B) \tag{8}$$

where G is the Gini index, $S_{\Delta CDE} = S_A + S_B = 0.5$.

(iii) Grading of Gini index.

The Gini index is divided into five subintervals, and each subinterval is set with a group of Gini index grades.

Table 2. Grading of Gini index.

Gini Index	0–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–1.0
Evaluation standards	Highly average	Relatively average	Relatively reasonable	Relatively large disparity	Great disparity

2.5. Elasticity Coefficient Model

In economics, the elasticity coefficient is the ratio of relative change rate between two indicators that are related to each other, which can represent the interdependence between indicators [59]. In this paper, the elasticity coefficient model was applied to analyze the control of wastewater emissions and the governance of COD and NH_3-N in wastewater. The specific formulas were as follows:

$$E_W = \frac{We_i - We_{i-1}}{We_{i-1}} / \frac{Wu_i - Wu_{i-1}}{Wu_{i-1}} \tag{9}$$

where E_W is the elasticity coefficient between industrial (or domestic) wastewater emissions and industrial (or domestic) water use. We_{i-1} and We_i are industrial (or domestic) wastewater emissions of the $(i-1)$th year and the ith year, respectively. Wu_{i-1} and Wu_i are industrial (or domestic) water use of the $(i-1)$th year and the ith year, respectively.

$$E_C = \frac{Ce_i - Ce_{i-1}}{Ce_{i-1}} / \frac{We_i - We_{i-1}}{We_{i-1}} \tag{10}$$

where E_C is the elasticity coefficient between industrial (or domestic) COD emissions and industrial (or domestic) wastewater emissions. Ce_{i-1} and Ce_i are industrial (or domestic) COD emissions of the $(i-1)$th year and the ith year, respectively. We_{i-1} and We_i are industrial (or domestic) wastewater emissions of the $(i-1)$th year and the ith year, respectively.

$$E_N = \frac{Ne_i - Ne_{i-1}}{Ne_{i-1}} / \frac{We_i - We_{i-1}}{We_{i-1}} \tag{11}$$

where E_N is the elasticity coefficient between industrial (or domestic) NH_3-N emissions and industrial (or domestic) wastewater emissions. Ne_{i-1} and Ne_i are industrial (or domestic) NH_3-N emissions of the $(i-1)$th year and the ith year, respectively. We_{i-1} and We_i are industrial (or domestic) wastewater emissions of the $(i-1)$th year and the ith year, respectively.

If $|E| > 1$, high elasticity exists between the evaluation objects. If $|E| = 1$, equivalent elasticity exists between the two evaluate objects. If $|E| < 1$, low elasticity exists between the evaluation objects. $|E| = 0$ represents perfect inelasticity between them, while $|E| \to \infty$ represents perfect elasticity between them.

3. Results

3.1. Relationship of Water Pollution and Socio-Economic Development Based on the Optimal EKC Model

The optimal EKC model would be designed using five goodness-of-fit indexes, such as R-squared (R^2), adjusted R-squared, F statistics, significance and standard error, to draw the EKC of water pollution. Results showed that the regression models have statistical significance. We compared five goodness-of-fit indexes in turn, and concluded that the linear model between industrial COD emissions and GDP per capita was optimal. The quadratic model was ideal in industrial wastewater and NH_3-N, domestic wastewater and NH_3-N emissions, with economic development. The cubic model of domestic COD and GDP per capita was optimal (Tables 3 and 4).

Table 3. Optimal environmental Kuznets curve (EKC) model between industrial pollutants emission and economic growth.

Index	Model Type	R^2	Adjusted R^2	F Value	Significance	Standard Error	Optimal Model
Industrial wastewater	Linear	0.650	0.623	24.116	0.000	19,806.600	Quadratic
	Quadratic	0.900	0.883	53.820	0.000	11,031.939	
	Cubic	0.900	0.872	32.895	0.000	11,521.699	
Industrial COD	Linear	0.906	0.899	125.471	0.000	34,402.142	Linear
	Quadratic	0.906	0.891	57.966	0.000	35,791.287	
	Cubic	0.906	0.881	35.429	0.000	37,379.851	
Industrial NH_3-N	Linear	0.882	0.873	97.351	0.000	2999.885	Quadratic
	Quadratic	0.913	0.891	58.086	0.000	2783.535	
	Cubic	0.906	0.889	38.508	0.000	2801.612	

Table 4. Optimal EKC model between domestic pollutants emission and economic growth.

Index	Model Type	R^2	Adjusted R^2	F Value	Significance	Standard Error	Optimal Model
Domestic wastewater	Linear	0.961	0.958	316.873	0.000	19,041.626	Quadratic
	Quadratic	0.991	0.989	636.242	0.000	9649.681	
	Cubic	0.991	0.988	389.605	0.000	10,008.619	
Domestic COD	Linear	0.107	0.038	1.556	0.000	38,074.443	Cubic
	Quadratic	0.514	0.432	6.335	0.000	29,246.372	
	Cubic	0.653	0.558	6.897	0.000	25,803.918	
Domestic NH_3-N	Linear	0.679	0.654	27.484	0.000	6969.480	Quadratic
	Quadratic	0.778	0.741	21.016	0.000	6032.720	
	Cubic	0.780	0.721	13.030	0.001	6265.624	

The EKC of industrial wastewater emissions was an inverted U-shape, showing a declining trend since 2012 (Figure 6a). The turning point occurred at GDP per capita of RMB ¥50,256. A monotonically decreasing linear relationship was found between industrial COD emissions and economic development (Figure 6c). The binding curve of the left of the U-shaped curve occurred in the EKC of industrial NH_3-N emissions (Figure 6e). These meant that industrial pollutants emissions improved gradually with economic development. Accordingly, the nexus between industrial pollution and economic growth in Shandong has gradually tended to coordinated development.

Overall, on the one hand, the optimization and adjustment of the existing industrial structure has been significant in recent years. A proportion of three economic sectors have changed from the "primary industry > secondary industry > tertiary industry" to the "secondary industry > tertiary industry > primary industry". On the other hand, the water quality in the catchment must meet the Environmental Quality Standard for surface water, for China to ensure the water quality security of the South-to-North Water Diversion Project (east route). Shandong has carried out centralized rectification for industrial enterprises with high pollution intensity, and proposed stricter standards of wastewater discharge than national standards. The industrial structure adjustment and other social and economic behaviors at this stage have played a key role in the improvement of water quality, meaning that the coordination between industrial pollutant emissions and socio-economic development in Shandong has gradually been realized.

Domestic wastewater emissions showed an increasing tendency from 2003 to 2017 with economic development (Figure 6b). This was especially true in the years since 2012, when its growth rate was up to 73%, mainly due to rapid urbanization and urban population growth. The EKC of domestic wastewater emissions has still not reached its peak point. The domestic COD emissions showed a downtrend before the turning point, and reached the turning point at GDP per capita of RMB ¥52,168 in 2012 (Figure 6d). Hereafter, with economic development, an increase of 25.6% occurred in COD emissions between 2014 and 2017. The domestic NH_3-N emissions still increased, and had not yet been achieved a coordination relationship with economic growth (Figure 6f). The main reasons for this include the rapid urbanization, the increase in the urban population base, the discharge of untreated domestic wastewater, and the lack of awareness of environmental protection for residents. These large-scale domestic wastewater emissions have posed a potential threat to water quality security in Shandong.

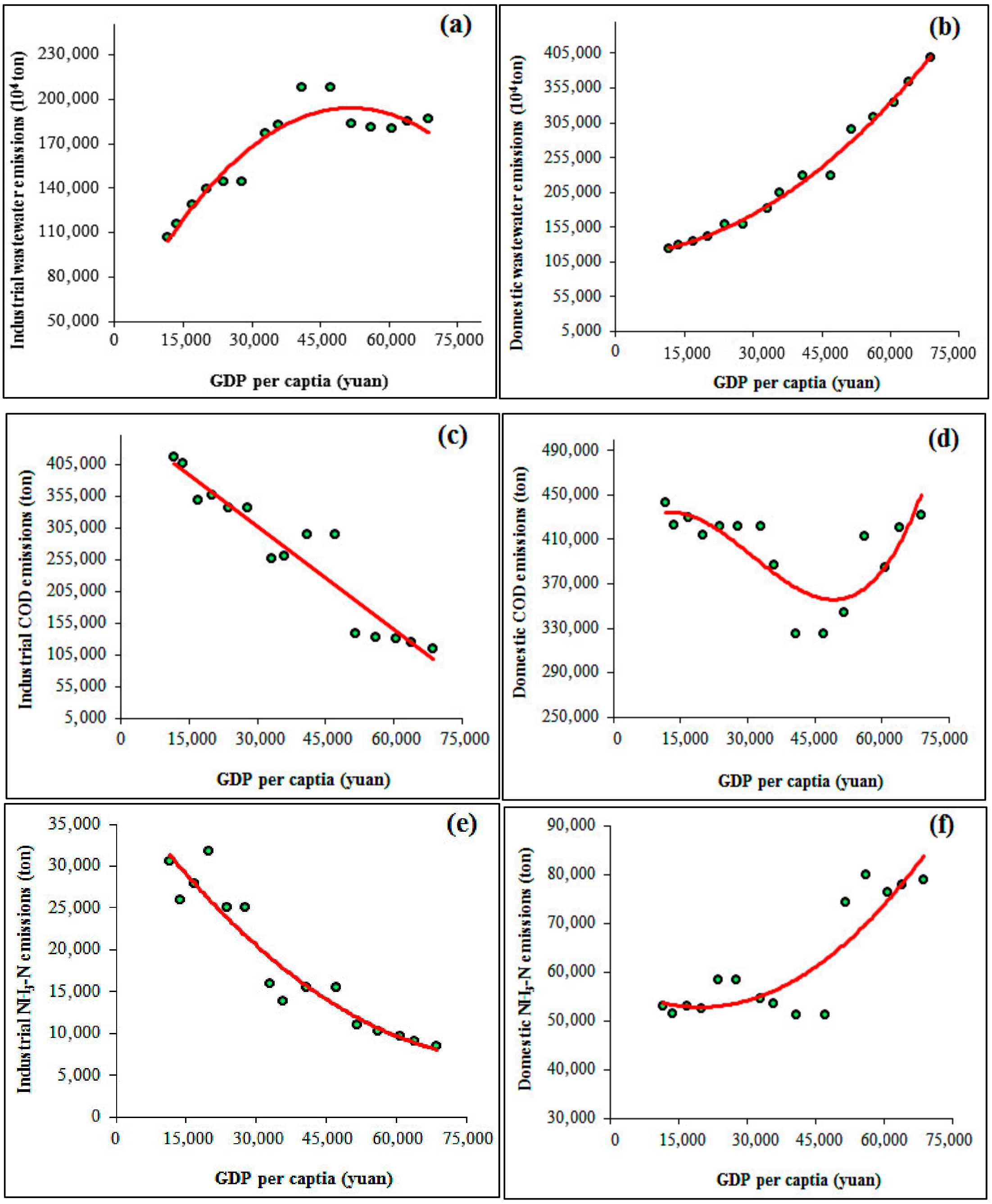

Figure 6. The EKC of industrial pollutant emissions and economic growth (**a**), of domestic wastewater emissions and economic growth (**b**), of industrial COD emissions and economic growth (**c**), of domestic COD emissions and economic growth (**d**), of industrial NH_3-N emissions and economic growth (**e**), of domestic NH_3-N emissions and economic growth (**f**).

Comparatively speaking, the relationship between industrial pollutants emissions and economic growth has tended gradually to coordinated development. However, domestic pollutants emissions showed an upward trend with economic growth, and coordinated development had not occurred yet under current conditions. Domestic water pollution has progressively become one of the potential risk sources for water security in Shandong. Domestic wastewater emission will seriously threaten the water security of Shandong and restrict the sustainable development of the social economy in the future. Accordingly, some control and management measures should be carried out, for example, increasing governance for domestic pollutants, investing more funds to build municipal sewage treatment plants, optimizing wastewater treatment equipment and enhancing the utilization of reclaimed water. To achieve coordinated development between the regional water environment and the social economy, the change of growth patterns and socio-economic behaviors, such as institutional design, policy formulation and implementation, are particularly important.

3.2. Allocation and Equity of Water Use Based on the Lorenz Curve and Gini Index

Socio-economic development plays a certain role in regional water resource planning and management, and unreasonable development and utilization of water resources in a region will generate a negative impact on water security and sustainable socio-economic development. This paper plotted the Lorenz curve (Figure 7) based on Tables 5–8, and the Gini index was then calculated to analyze the allocation and equity of industrial water use and secondary industry output, as well as domestic water use and the urban population in Shandong (Table 9).

The Gini index of domestic water use–urban population in 2017 (0.101) was less than that of 2003 (0.165), indicating that the allocation between domestic water use and the urban population belonged to the highly average grade (Table 2). The interannual variation of Gini index was −0.064 (Table 9), meaning that the allocation of domestic water use was more equitable in 2017 compared to 2003 (Figure 7a). The amount of domestic water use was roughly in proportion to the size of the urban population in most cities (Tables 5 and 6). However, the size of the urban population was slightly larger than the amount of domestic water use in Jinan, Rizhao, Weihai, Qingdao, Weifang and Yantai, indicating that the allocation and equity of domestic water use was relatively low in these cities. The main reasons for the above results are: (1) Rizhao, Weihai, Qingdao, Weifang and Yantai are coastal cities, and Jinan is the capital of Shandong and the center of political culture. These cities have relatively developed economies, which attract a large number of people to settle down, resulting in a large urban population; (2) Coastal cities are often threatened by seawater intrusion, and these natural geographical factors may result in the relatively small amount of freshwater resources. Therefore, the allocation and equity of domestic water use and populations in these cities are relatively poor.

Accordingly, optimizing water resources allocation is necessary. Shandong should control the growth rate of the urban population and strengthen residents' awareness of water saving to ease pressure on the urban water supply. In addition, some water diversion projects should be given appropriate supports, especially the South–North Water Diversion Project (eastern route) that has achieved success in terms of increasing the urban water supply. In 2013, "Longmen Reservoir", "Zhuangli Reservoir," and other water conservancy projects were established to alleviate the pressure on the urban water supply. Meanwhile, the measures of seawater desalination should be increased on the existing basis for coastal cities (Rizhao, Weihai, Qingdao, Weifang and Yantai) [60]. Overall, the allocation and equity between domestic water use and the urban population are still relatively poor in some cities of Shandong. To realize rational allocation of domestic water use and urban population in all cities, Shandong should increase the supportability of the water supply and control the urban population growth rate in Jinan, Rizhao, Weihai, Qingdao, Weifang and Yantai.

Table 5. Calculation of domestic water use Gini index based urban population of Shandong in 2003.

Region	Proportion of Domestic Water Use (%)	Proportion of Urban Population (%)	LQ	Cumulative Proportion of Domestic Water Use (%)	Cumulative Proportion of Population (%)
Laiwu	2.6	1.4	0.542	2.6	1.4
Jining	11.0	7.3	0.656	13.6	8.7
Linyi	8.6	6.0	0.701	22.2	14.7
Dongying	3.0	2.2	0.728	25.2	16.8
Zaozhuang	4.7	3.5	0.754	29.9	20.4
Heze	6.4	5.1	0.796	36.3	25.5
Taian	5.0	4.5	0.909	41.2	30.0
Binzhou	3.2	3.0	0.912	44.5	32.9
Dezhou	4.9	4.5	0.931	49.4	37.5
Zibo	5.5	5.2	0.947	54.9	42.7
Liaocheng	6.1	5.9	0.962	61.0	48.6
Jinan	10.7	12.2	1.139	71.7	60.8
Rizhao	2.3	2.8	1.261	74.0	63.6
Weihai	2.7	3.4	1.267	76.7	67.1
Qingdao	10.2	13.3	1.294	86.9	80.3
Weifang	7.5	11.3	1.501	94.4	91.6
Yantai	5.6	8.4	1.508	100.0	100.0

Table 6. Calculation of domestic water use Gini index based urban population of Shandong in 2017.

Region	Proportion of Domestic Water Use (%)	Proportion of Urban Population (%)	LQ	Cumulative Proportion of Domestic Water Use (%)	Cumulative Proportion of Population (%)
Dongying	3.7	2.5	0.677	3.7	2.5
Laiwu	2.0	1.4	0.692	5.7	3.9
Linyi	9.5	7.4	0.782	16.9	12.6
Zaozhuang	4.6	3.7	0.787	21.5	16.3
Taian	6.4	5.7	0.885	28.0	22.0
Heze	7.4	6.7	0.915	35.3	28.7
Zibo	5.2	5.0	0.967	38.2	31.5
Dezhou	4.2	4.1	0.999	49.7	43.0
Binzhou	3.7	3.7	1.007	53.4	46.8
Jining	7.6	7.7	1.011	61.1	54.5
Liaocheng	4.7	4.8	1.037	65.7	59.3
Jinan	11.1	11.5	1.037	75.2	69.1
Rizhao	2.9	3.2	1.093	80.3	74.7
Weifang	7.7	9.2	1.199	88.0	83.9
Weihai	2.6	3.2	1.227	90.6	87.1
Qingdao	11.5	14.3	1.242	94.8	92.4
Yantai	5.2	7.6	1.477	100.0	100.0

The Gini index between industrial water use and secondary industry output in 2017 (0.273) was less than that of 2003 (0.292). The interannual variation of the Gini index was −0.019 (Table 9), indicating that relatively better allocation existed between industrial water use and secondary industry output in 2017, compared with 2003 (Figure 7b). Meanwhile, this also implied that a certain proportion of water use can create the corresponding proportion of regional output value. However, irrational allocation still existed in Rizhao, Weihai, Qingdao, Weifang and Yantai. The main reasons are that the economics are relatively good, the production technology of industrial enterprises is advanced, and the utilization rate of reclaimed water is relatively high in these coastal cities. Consequently, it is urgent that we optimize water resources allocation, promote industrial structural upgrades, improve technologies of water recycling and enhance the efficiency of reclaimed water use.

Table 7. Calculation of industrial water use Gini index based secondary industry output of Shandong in 2003.

Region	Proportion of Industrial Water Use (%)	Proportion of Secondary Industry Output (%)	LQ	Cumulative Proportion of Industrial Water Use (%)	Cumulative Proportion of Secondary Industry Output (%)
Laiwu	3.7	1.4	0.373	3.7	1.4
Jining	9.2	3.8	0.413	13.0	5.2
Jinan	9.7	4.0	0.415	22.7	9.2
Binzhou	3.3	2.0	0.622	26.2	11.4
Heze	5.5	3.5	0.637	31.7	14.9
Zaozhuang	4.4	3.4	0.773	36.0	18.3
Linyi	7.2	5.6	0.783	43.3	23.9
Liaocheng	6.4	5.4	0.840	49.7	29.4
Dezhou	2.7	2.6	0.977	59.2	38.7
Zibo	9.1	9.5	1.040	68.3	48.1
Taian	4.5	4.7	1.040	72.8	52.8
Dongying	6.1	8.4	1.375	78.9	61.2
Rizhao	3.5	5.0	1.447	82.3	66.0
Qingdao	8.3	12.5	1.501	90.6	78.5
Weihai	2.4	4.8	1.965	93.0	83.3
Weifang	9.5	18.8	1.986	95.7	88.6
Yantai	4.3	11.4	2.638	100.0	100.0

Table 8. Calculation of industrial water use Gini index based secondary industry output of Shandong in 2017.

Region	Proportion of Industrial Water Use (%)	Proportion of Secondary Industry Output (%)	LQ	Cumulative Proportion of Industrial Water Use (%)	Cumulative Proportion of Secondary Industry Output (%)
Laiwu	3.2	1.2	0.364	3.2	1.2
Dongying	6.7	2.8	0.418	7.6	3.0
Jinan	8.5	3.6	0.425	16.1	6.6
Zibo	8.4	3.8	0.459	24.5	10.5
Zaozhuang	3.8	2.5	0.649	28.3	12.9
Liaocheng	7.7	6.2	0.810	36.0	19.2
Taian	5.7	4.6	0.817	41.7	23.8
Heze	4.8	4.6	0.952	46.5	28.4
Binzhou	3.5	3.3	0.953	55.7	37.2
Linyi	7.4	7.2	0.967	63.1	44.3
Jining	8.4	8.2	0.984	71.5	52.6
Dezhou	5.0	6.3	1.273	76.4	58.9
Rizhao	4.4	6.4	1.455	83.1	68.6
Weifang	9.2	13.6	1.479	86.6	73.7
Qingdao	7.1	11.2	1.586	93.6	84.9
Weihai	2.4	4.7	1.910	96.1	89.6
Yantai	3.9	10.4	2.659	100.0	100.0

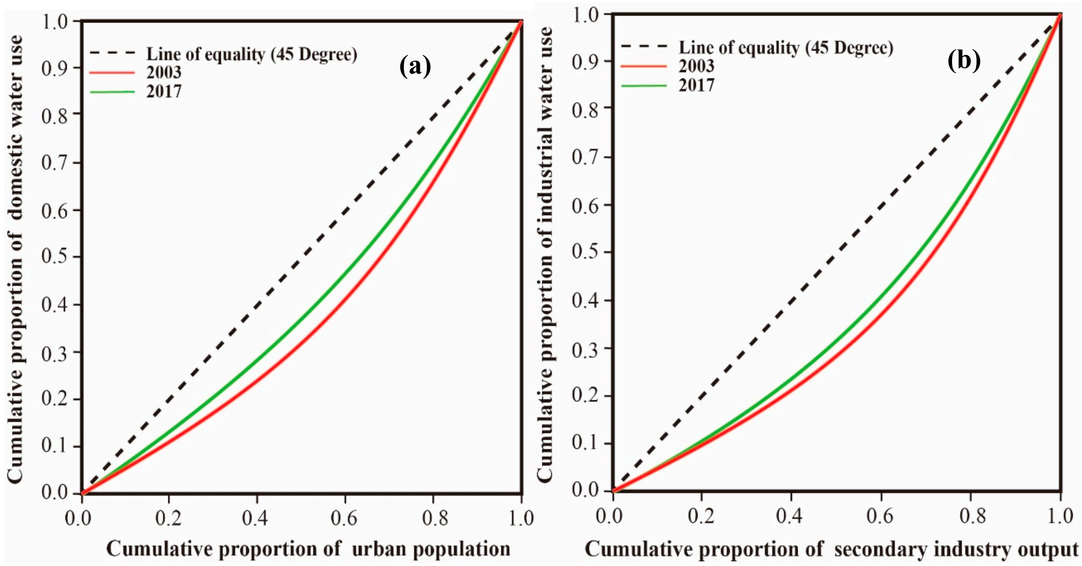

Figure 7. Lorenz Curve of domestic water use–urban population (**a**) and of industrial water use–secondary industry output (**b**) in Shandong in 2003 and 2017.

Table 9. Gini index of industrial and domestic water use in Shandong in 2003 and 2017.

Year	Domestic Water Use	Evaluation Result	Interannual Variation	Industrial Water Use	Evaluation Result	Interannual Variation
2003	0.165	Highly average	−0.064	0.292	Relatively average	−0.019
2017	0.101	Highly average		0.273	Relatively average	

As an area which experiences water shortages, Shandong has devoted itself to optimizing allocation of water use and improving water use efficiency in recent years [61,62]. Overall, the allocation and equity of domestic and industrial water use had improved in 2017, compared to 2003. It can be concluded that a certain amount of water use can achieve a proportional socio-economic benefit in Shandong, meaning that the allocation between them is relatively good. However, irrational allocation of socio-economic development and water resources utilization still exists in some cities. Therefore, regional GDP created by industrial water use in Shandong has room for further improvement. Meanwhile, the irrational allocation of domestic water use will be improved gradually by strengthening water resource planning and management.

3.3. Control of Pollution Emissions Based on the Elasticity Coefficient Model

The control of wastewater emissions and the governance of typical pollutants (NH_3-N and COD) in wastewater play an important role in achieving water safety and sustainable socio-economic development. In this paper, the elasticity coefficient method was applied to analyze the dynamic changes in water use and pollution emissions in Shandong. The industrial E_W from 2013 to 2017 was less than 1 (standard line), indicating that the growth rate of industrial wastewater emissions was lower than that of industrial water use as a whole (Figure 8). In addition, the industrial E_W decreased significantly between 2016 and 2017. This resulted from the combined policy of the Five-Year Plan for national economic and social development in Shandong, which was because the supervision of industrial wastewater emissions was intensified in the beginning of the 13th Five-Year Plan, and the growth rate of industrial wastewater emissions had shown a significant downward trend.

A downward trend occurred in domestic E_W in 2017, compared to 2013. However, domestic E_W was greater than 1, indicating that the growth rate of domestic wastewater emissions still was greater than the growth rate of domestic water use under the current conditions, and the domestic E_W was greater than industrial E_W in each year. In general, the growth rate of industrial wastewater emissions had been controlled well. Although the discharge of domestic wastewater had improved as a whole, the growth rate was still higher than the growth rate of water use. So, the control of domestic wastewater emissions needs to be further improved.

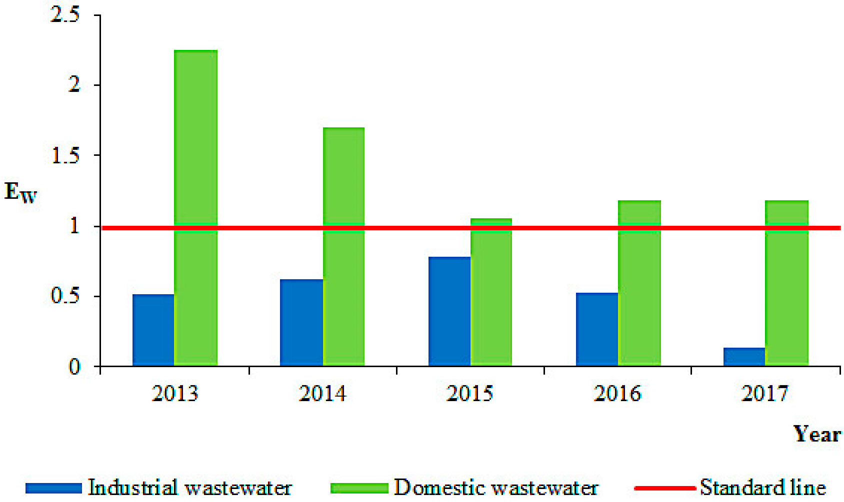

Figure 8. The elasticity coefficients between industrial (or domestic) wastewater emissions and water use.

Although the industrial E_C were all greater than 1 between 2013 and 2015, a significant downward trend occurred from 2013 to 2017 (Figure 9). This showed that the growth rate of industrial COD emissions decreased significantly. Meanwhile, the negative value in industrial E_C at the beginning of the 13th Five-Year Plan (2016 and 2017) indicated that a significant treatment effect occurred in industrial COD. Although the fluctuation trend existed in domestic E_C, the elasticity coefficients were all less than 1 between 2015 and 2017, which indicated that a good governance effect occurred in domestic COD over the past three years.

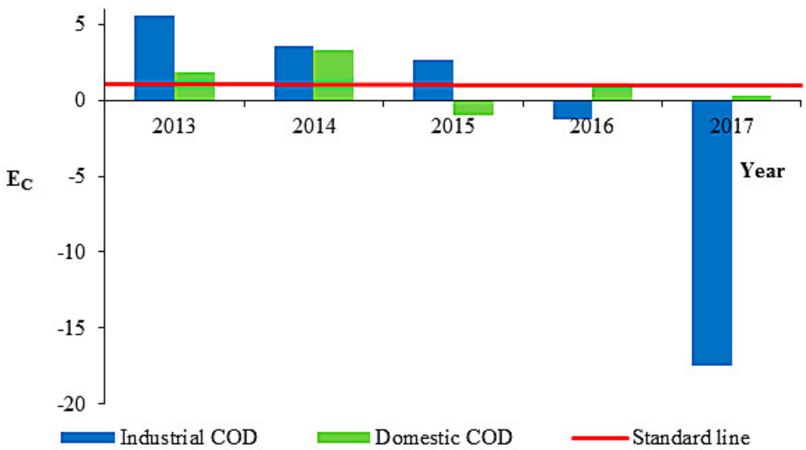

Figure 9. The elasticity coefficients between industrial (or domestic) COD emissions and wastewater emissions.

The domestic E_N values were all less than 1 between 2013 and 2017 (Figure 10), except for in 2014. The growth rate of domestic NH_3-N emissions was less than that of domestic wastewater emissions, indicating that there was a good governance effect. The industrial E_N in 2013–2015 were all greater than 1 and showed a growth trend, meaning that the growth rate of industrial NH_3-N emissions in wastewater had not been treated well. However, negative growth occurred in industrial NH_3-N emissions since 2016. Overall, the governance of domestic NH_3-N achieved better results in the past five years, and a significant improvement appeared in the governance of industrial NH_3-N at the beginning of the 13th Five-Year Plan.

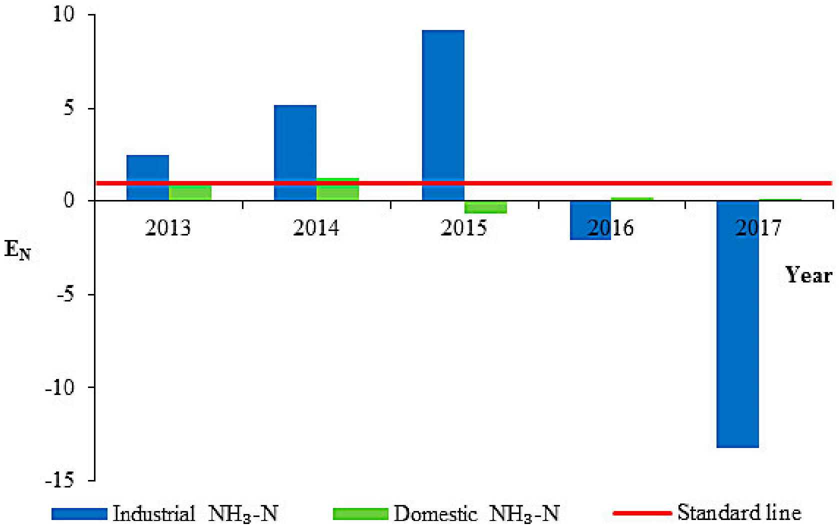

Figure 10. The elasticity coefficients between industrial (or domestic) NH_3-N emissions and wastewater emissions.

4. Discussion

To promote water security and sustainable socio-economic development, industrial, domestic water use and pollution management were investigated in this paper. The research results reveal the states of water pollution control and management, and provide theoretical support for formulating relevant environmental policies and implementing social and economic activities in Shandong. Meanwhile, we hope this study can provide a theoretical reference for some regions with similar water resources problems, to optimize water pollution control policies and measures and increase environmental investment. However, some deficiencies still exist in this study. Possible future research deriving from this paper includes the following: (i) Classic EKC models were adopted to draw the two dimensional EKC between water pollution and socio-economic development and analyze the relationship between them in this paper. However, pollution is not only a function of income. Besides income, environmental policies, technological progress, industrialization process, residents' environmental awareness, and other factors all affect environmental change. The aforementioned factors have not been considered in EKC modeling in this paper. In future research, we will draw on existing research to improve the EKC model, and consider more relevant factors to increase the independent variable in EKC modeling. (ii) Existing research in Shandong has shown that industrial water use is most closely related to secondary industry output, and domestic water use is most closely related to population. Realistically, there are many socio-economic indicators related to water use, these indicators can be investigated and selected in the future by mathematical and statistical methods (principal component analysis and grey relational analysis, etc.). (iii) Existing research shows that industrial and domestic water use and pollution in Shandong have threatened the regional water security and sustainable socio-economic development to a certain extent. In view of the current situation of water use and pollution in Shandong, the research scope of this paper included industrial and domestic water use and pollution, not considering agricultural water. This part will be further researched in the future according to detailed investigation results on agricultural water.

5. Conclusions

To effectively conduct the integrated planning and management of regional water resources and the social economy, in this paper the optimal EKC models were established based on comparison in the five goodness-of-fit indexes to analyze the water pollution–socio-economic development nexus.

The Lorenz curve and the Gini index were applied to quantitatively study the allocation and equity of water use and socio-economic development. Additionally, the control of wastewater emissions and the governance of COD and NH_3-N in wastewater were investigated based on the elasticity coefficient model in the context of the Five-Year Plan for Shandong. Accordingly, specific suggestions were proposed according to the current situation between water use and pollutant emissions in Shandong. The conjunctive use of the aforementioned three methods can be valuable for investigating industrial and domestic water use and pollution management from multiple angles.

The EKC of industrial water pollution (wastewater, COD, NH_3-N emissions) in the period 2003–2017 showed an inverted-U-shaped, a linear decrease and a binding curve on the left side of the U-shaped curve, respectively. Overall, a coordinated relationship between industrial water pollution and socio-economic development has basically been realized in Shandong. The EKC of domestic water pollution (wastewater, COD, NH_3-N emissions) from 2003 to 2017 showed an increasing tendency, a U-shaped curve and a binding curve of the right side of U-shaped curve, respectively. Collectively, the coordinated relationship between domestic water pollution and socio-economic development still has not been achieved. Meanwhile, we found that the type of EKC differed across the type of water pollutant. At present, domestic water pollution in Shandong has become more serious, compared to industrial water pollution. On the one hand, Shandong should pay attention to the treatment of domestic pollutants in the future. On the other hand, Shandong should draw on similar research experiences and lessons from other countries or regions to implement some control and management measures, such as increasing governance for domestic pollutants, investing more funds to build municipal sewage treatment plants, and optimizing wastewater treatment equipment.

The comparison of the Gini indexes in 2003 and 2017 indicated that there was relatively good allocation of water use and socio-economic development in Shandong in 2017. However, some coastal cities (Rizhao, Weihai, Qingdao, Weifang and Yanta) still displayed relatively irrational allocation in industrial and domestic water use. Accordingly, in terms of domestic water use, the supportability of water supply can be increased and the urban population growth rate should be controlled in Jinan, Rizhao, Weihai, Qingdao, Weifang and Yantai. In terms of industrial water use, non-coastal cities of Shandong can draw on experiences in industrial development of coastal cities to improve the production technology and the rate of reclaimed water utilization for industrial enterprises.

The condition of pollution emissions control from 2013 to 2017 was analyzed quantitatively using the elasticity coefficient theory. Relatively good control occurred in industrial wastewater emissions. Although the growth rate of domestic wastewater emissions had decreased, it was still greater than the growth rate of domestic water use. The governance of COD and NH_3-N in wastewater has achieved relatively good results over the past few years. In general, the management of domestic wastewater emissions control in Shandong needs to be further improved.

In summary, Shandong should draw on relevant experiences and lessons to change growth patterns and socio-economic behaviors, including institutional design, formulation and implementation of environmental policy, and strengthening of public environmental awareness. These play an important role in achieving water security and sustainable development of the social economy in Shandong.

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