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The Water-Economy Nexus and Sustainable Transition of the Pearl River Delta, China (1999–2015)

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Abstract: As the world's largest urban area in both size and population, the rapid development of the Pearl River Delta (PRD) during past three decades has been accompanied by worsening water problems. This paper examines the water-economy nexus of the PRD from the perspectives of both water use and water quality between 1999 and 2015, with a Logarithmic Mean Divisia Index decomposition model as well as an Environmental Kuznets Curve model, in order to assess the sustainable transition of the area. The results show that in this period, while the water dependency of economic development went down by a significant extent, the efficiency gains did not prevail over problems caused by economic scale expansion. However, at the city level, the 2008 financial crisis stimulated an economic transformation of the main economies from being scale-dominated to being efficiency-dominated. From 2009 to 2015, the sewage decreases driven by water dependency of Guangzhou, Shenzhen, and Dongguan outweighed the sewage increases driven by economic scale. While sewage discharge increased, the river water quality of the PRD kept improving. We found an inverted "U"-shaped relationship between GDP per capita and water quality of the PRD, with GDP per capita = ¥14,228.27 as the inflection point for river water quality. Once dubbed the "factory floor" of the world, the PRD has moved into a less environmentally impactful phase of development, with more expenditure on environmental protection and policy reform. However, given the huge and ever-increasing economic and population scales, ensuring a sufficient and safe water supply through industrial recycling and public education, along with even further pollution abatement, will be particularly important.

Keywords: Pearl River Delta; sustainable urbanization; LMDI; water-economy nexus; water policy

1. Introduction

Water is indispensable for the survival and development of human society, but it is also highly susceptible to overexploitation and pollution by anthropogenic activity. Poor water quality and inadequate sanitation undermine public health, material living standards, and ecological integrity [1]. It is already one of the most pressing environmental problems currently facing the world, with more than two billion people still lacking access to safe drinking water, sanitation, and hygiene [2]. Approximately 80% of all wastewater produced globally is discharged into the environment without any treatment [3]. Therefore, addressing the challenge in the sustainable use of water resources is a prominent one for sustainable development [4]: In 2015, "clean water and sanitation" was identified as one of the United Nation's Sustainable Development Goals, which are meant to serve as a global rubric for development in the 21st Century.

As the world's largest economy (in purchasing power parity terms; it is the second largest in market exchange rate terms) and most populous country, China's per-capita freshwater resources only stand at 2100 m^3, which is roughly 28% of the international average. This makes China one of the most water scarce countries in the world [5]. What is worse, due to rapid and intensive urbanization and industrialization, this scarce and declining stock has become severely polluted. By 2015, in eight out of 31 provinces, more than half of the water in major rivers was grade IV or below according to China's national environmental quality standards for surface water—meaning it is not even suitable for human contact, much less consumption. In seven provinces, the water quality of more than 20% of rivers was below grade V—meaning it is unsuitable for any purpose [6]. Therefore, ensuring safe and clean water resources is undoubtedly one of the biggest challenges for China's sustainable development, which means striking a greater balance between its rapid socioeconomic development and environmental protection.

The Pearl River Delta (PRD) is arguably the most representative geographic locus of China's rapid urbanization and economic takeoff since the implementation of the "Reform and Opening Up" policy in 1978 [7]. As shown in Figure 1, the PRD is located in central-south Guangdong province and consists of nine prefecture-level cities, including Guangzhou, Shenzhen, Foshan, Zhuhai, Dongguan, Zhongshan, Huizhou, Jiangmen, and Zhaoqing. The PRD covers 5.47 km^2 of land area, which is only about 0.40% of China's total, but contains 4.30% of the country's population and produces 9.10% of the country's GDP [8]. According to the World Bank, the PRD has overtaken Tokyo as the world's largest urban area in both size and population [9]. From 1999 to 2015, the GDP of the PRD increased from ¥679.43 billion in 1999 to ¥6226.86 billion in 2015, with an annual growth rate of 14.96%. Shenzhen was the fastest growing city, followed by Zhongshan and Donguan. The GDP of the three cities respectively increased by 11.19-, 9.13-, and 8.40-times over this period. As of 2015, in economic structure, "Industry" was the dominant sector, contributing 40.92% of the PRD's GDP, followed by "Other services" (20.04%) and "Retail, hotels, and catering" (13.46%).

Figure 1. The study area.

Accompanying the rapid pace of urbanization has been a concomitant growth in water consumption and sewage discharge, which have had a significant negative impact on surface water quality throughout the region [10–12]. The PRD has a dense river network with an area of 9750 km^2. The western and northern parts of the delta cover 8370 km^2 and have nearly 100 major waterways, with a river network density of 0.81 km/km^2. The eastern river delta covers 1380 km^2 and has five major waterways, with a density of 0.88 km/km^2 [13]. In recent years, the PRD's water demand has increased at an average annual rate of 1.43% [14]. According to the "Guangdong Water Resource Bulletin 2016", in 2016, the PRD area used 22.34 billion tons of water, in which industry consumed 8.41 billion tons, accounting for 37.65%, followed by agriculture (31.86%) and domestic use (18.64%) [15]. For the sewage discharge into rivers, the PRD took up 59.24% of Guangdong's total, reaching 6.23 billion tons [15]. From 1999 to 2005, the sewage discharge of the PRD increased by nearly 1.50-times. The sewage growth rates of Huizhou and Zhongshan were the highest among the nine cities, both increasing over 3-fold compared to their levels in 1999. The net sewage increase of Shenzhen was the largest, reaching 1349.98 megatons, followed by Dongguan (761.01 megatons) and Guangzhou (612.20 megatons). In Guangdong province, the drinking water sources with the poorest quality or that have exhibited the most significant trends in deterioration are concentrated in the PRD [16]. Furthermore, 49.50% of river water functional zones and 47% of river length were deemed substandard by local authorities [15]. In September 2016, the Ministry of Environmental Protection and the Guangdong provincial government signed a Ministry-Province collaboration agreement to build the PRD National Green Development Demonstration Zone. In the meanwhile, Guangdong province established a PRD Regional Water Pollution Prevention and Control Collaborative Group, which aims to establish a unified and efficient coordination mechanism to promote the implementation of water pollution control policies [17].

However, these massive problems regarding water resources have been overshadowed by the much more positive attention paid to the PRD's rapid economic development. Although private prosperity and public infrastructure have seen impressive improvement, this progress has, as indicated above, come at a significant ecological cost, with potentially calamitous implications for long-term human wellbeing. This study aims to disclose the PRD's water-economy nexus by decomposing the socioeconomic driving factors of the changes in sewage discharge and water quality during 1999–2015. This can help promote the sustainable transition of this economically vital region of 80 million people, by allowing policy-makers to better predict future water use patterns and offer insights to larger questions regarding economic growth and natural resource management [18]. More importantly, a more convergent and sustainable water-economy dynamic, underpinned by effective and far-sighted public policy, is not only necessary for the PRD itself but may also prove instructive for the other rapidly urbanizing regions in China and the rest of the world.

2. Literature Review

Urbanization is characterized by population aggregation, land use and land cover change—especially the expansion of built-up spaces—and intensive, localized economic development, all of which have significant impact on water resources and the broader water environment [12,19–22]. In turn, the degradation of water resources encumbers socioeconomic development, for instance through higher costs of water use and sewage treatment, higher incidence of infectious diseases such as cholera and dysentery, and adverse public opinions arising from water pollution and other unpleasant aspects of a degraded environment. Therefore, the analysis and optimal management of the water-economy nexus has become an urgent global challenge, and one especially acute for a transitional economy like China.

Sustainable management of the water-economy nexus has two interdependent facets: The impact of the economy on water resources and the limits water resources place on the economy. Currently, most research focuses on the first causality—i.e., how and to what extent anthropogenic activities drive the deterioration and depletion of water resources [23,24]. In this respect, a large cluster of studies focuses on the relationship between economic indicators and water indicators using econometric models, with particular emphasis on the existence (or not) of an EKC [25–27]. For example, Yoo (2007) found a unidirectional causality running from regional economic growth to urban water consumption, without any feedback effects, in the Taejeon urban area in Korea from 1973–2001 [24]. Katz (2015) elucidated the relationship between income growth and global freshwater use and found that the existence of EKC is sector specific and highly dependent on the choice of datasets and statistical technique [28]. Zhang, Wang et al. (2017) found an inverted U-shaped curved link and a long-term bidirectional causality between economic growth and COD/NH3-N discharge in China from 1990 to 2014 [29].

A second large cluster of studies quantifies the driving forces of water consumption using index decomposition techniques [30–32], or virtual water use (i.e., water footprint analysis with structural decomposition techniques) [33–38]. For example, Kondo (2005) found that, compared to the 1980s, the volume of indirect water change exerts a stronger influence on Japanese virtual water exports and is greatly affected by subsidiaries. Japanese manufacturers depend on the supply of water from developing countries to enhance their competitive strengths [39]. Cazcarro, Duarte et al. (2013) found that from 1980 to 2007, the growth in Spain's demand would have implied an increase in water consumption almost three times the growth actually observed. However, this demand effect was largely offset by technology and intensity effects, mainly due to changes in agricultural crops [38]. Yang, Liu et al. (2015) decomposed the water footprint of Beijing from 1987 to 2007 and found that the technological effect was the dominant contributor to the decrease of the city's water footprint, while the consumption level was the primary factor responsible for increase [35]. Wang, Huang et al. (2016) decomposed China's water footprint from 1997 to 2007 and found that the sector with the most space for saving water changed from agriculture to the tertiary, or service, industry. Technology and economic structure effects always offset increases in the water footprint, whereas the gross economic scale effect always hindered water conservation [37]. Using a multi-regional input-output model, Distefano and Kelly (2017) found that most countries will experience declining water availability and that the most important driver of future water scarcity will be economic growth, which overwhelmed any realistic savings that can be made from increased technological progress and improvements in the efficiency of water use. Population growth and climate change were also found to be important drivers over the long run [40].

As the basis for human development, sustainable management of water resources is key to socioeconomic development, including poverty reduction [41–43]. For example, Tropp (2005) argued that the economic benefits of improved water resource quantity and quality, particularly sanitation, far outweigh the investment costs, which are considerable but are within the financial reach of most nations [43]. Roberts, Mitchell et al. (2006) argued that incomplete water markets and water resource allocation in Australia gave rise to both technical and allocative inefficiencies [41]. However, the cross-country estimations of Barbier (2004) suggested an inverted-U relationship between economic growth and the rate of water utilization. Nonetheless, for most economies—even water-scarce countries—current fresh water utilization rates have not yet been observed to constrain growth [42].

Due to the important economic status and rapid rate of development of the PRD, a number of studies have analyzed the dynamics of water use in the area. For example, from a historical perspective, Weng (2007) found that water and soil conservancy technology innovations in the PRD reflected local farmers' efforts to cope with various water disasters, and thus suggested that in the course of urbanization and industrialization, the idea of sustainable water use and soil conservancy needs to be more actively and explicitly incorporated into relevant technology design [44]. Both Qin, Su et al. (2014) and Chen, Zhang et al. (2011) tracked surface water quality changes in Shenzhen, the most affluent city in the PRD (in terms of overall GDP), over recent decades and proposed pollution reduction policies [45,46]. Yao, Werners et al. (2015) assessed the sectorial water use in the PRD from 2000 to 2010 [47], while Liu, Peng et al. (2017) provided a general overview of the causes and impacts of water problems in the PRD [13]. In this paper, we assess the impact of urbanization on the PRD's water use and water quality using both index decomposition and Environmental Kuznets Curve estimation. This dual-track approach has not been used in existing studies.

3. Methodology

The overall water quality of the PRD and its nine major cities is first assessed with a water pollution index (WPI). Afterwards, the socioeconomic drivers of the sewage discharge of the PRD is calculated using the LMDI (Logarithmic Mean Divisia Index) decomposition method [48]. Finally, an EKC model is estimated to analyze the relationship and trends between water pollution and economic development of the PRD.

3.1. Water Quality Assessment

The overall water quality of different cities and the whole PRD area is measured using WPI, which is defined as:

$$WPI_t = \frac{1}{n}\sum_{i=1}^{n}\frac{C_{i(t)}}{S_i} \tag{1}$$

where WPI_t is the WPI of a region in year t, n is the number of water quality parameters, $C_{i(t)}$ is the average measured concentration of the parameter i in different monitored sections of a region in year t, and S_i is the maximum permitted concentrations (MPCs) for parameter i. Therefore, the larger is the WPI, the worse is the overall water quality of a region. Generally, if WPI ≤ 1, the overall water quality of a region is regarded relatively good; if WPI > 1, the overall water quality is bad.

During 1999–2015, the number of monitored pollutants and cross-sections in the PRD increased as a result of improvements in environmental protection. In 1999, there were 58 cross-sections that were monitored. In 2015, the number of monitoring sections had increased to 65. Therefore, in order to ensure the consistency of water quality assessment, we first selected the cross-sections and pollutants that have been monitored throughout the analysis period took these pollutants as the water quality parameters for WPI, which are shown in Table 1. This paper uses the grade III standard for rivers in the Environmental Quality Standard for Surface Water in China (GB 3838-2002) as the MPCs for the parameters. Grade III standard is for secondary surface drinking water protection areas, fishery waters, and swimming areas. Those grades below Grade III are generally for waters that do not generally come into direct contact with the human body.

Table 1. Water quality parameters.

Pollutant	MPCs (mg/L)
Dissolved oxygen (DO)	≥ 5
Permanganate Index (COD_{Mn})	≤ 6
5-day biochemical oxygen demand (BOD_5)	≤ 4
Ammonia-nitrogen (NH_3-N)	≤ 1
Arsenic (As)	≤ 0.05
Mercury (Hg)	≤ 0.0001
Cadmium (Cd)	≤ 0.005
Hexavalent chromium (Cr^{6+})	≤ 0.05
Lead (Pb)	≤ 0.05
Cyanide	≤ 0.2
Volatile phenol (V-ArOH)	≤ 0.005
Petroleum	≤ 0.05

3.2. LMDI Decomposition

Let i denote each city in the PRD, then the sewage discharge of the PRD (s) can be decomposed as the following equation:

$$s = \sum s_i = \sum \frac{s_i}{w_i}\cdot\frac{w_i}{g_i}\cdot\frac{g_i}{p_i}\cdot\frac{p_i}{p}\cdot p \tag{2}$$

where s_i is the sewage discharge of city i, w_i is the water supply of city i, g_i is the GDP of city i, p_i is the resident population of city i, and p is the population of the PRD. Therefore, $\frac{s_i}{w_i}$ is the water use efficiency of city i, $\frac{w_i}{g_i}$ is the water dependency of economic development (i.e., water consumption per unit of GDP of city i), $\frac{g_i}{p_i}$ is the economic scale (i.e., GDP per capita of city i), and $\frac{p_i}{p}$ is the proportion of the population of city i in the PRD (i.e., the spatial population structure). Let $A = \frac{s_i}{w_i}$, $X_i = \frac{w_i}{g_i}$, $Y_i = \frac{g_i}{p_i}$, $Z_i = \frac{p_i}{p}$, then the change of the sewage in a certain time period from 0 to T, ΔS, can be expressed as:

$$\Delta S = S^T - S^0 = \Delta S_A + \Delta S_X + \Delta S_Y + \Delta S_Z + \Delta S_P \tag{3}$$

Each of the five terms in Equation (3) represents a driver's contribution to change in sewage discharge while keeping the other drivers constant. The terms, respectively representing water use efficiency, water dependency of economic growth, economic scale, spatial population structure, and population size, are calculated as:

$$\Delta S_A = \sum_i k_i \times \ln \frac{A_i^T}{A_i^0} \tag{4}$$

$$\Delta S_X = \sum_i k_i \times \ln \frac{X_i^T}{X_i^0} \tag{5}$$

$$\Delta S_Y = \sum_i k_i \times \ln \frac{Y_i^T}{Y_i^0} \tag{6}$$

$$\Delta S_Z = \sum_i k_i \times \ln \frac{Z_i^T}{Z_i^0} \tag{7}$$

$$\Delta S_P = \sum_i k_i \times \ln \frac{P^T}{P^0} \tag{8}$$

$$k_i = \left(S_i^T - S_i^0\right) / \left(\ln S_i^T - \ln S_i^0\right) \tag{9}$$

When measuring the impact of each driver for each city, we use the following equation, considering the fact that the proportion of a city's population in the PRD and the total population of the PRD cannot necessarily explain the impact of population scale on a city's sewage change.

$$s_i = \frac{s_i}{w_i} \cdot \frac{w_i}{g_i} \cdot \frac{g_i}{p_i} \cdot p_i \tag{10}$$

3.3. EKC Estimation

In line with Katz (2015) [28], we use a traditional form of the EKC model to analyze the correlation between economic development and water pollution in the PRD. After the data passed the heteroscedasticity test and Breusch-Godfrey test for autocorrelation, we estimate both quadratic and cubic equations with an OLS regression model:

$$lnWPI_t = \alpha_0 + \alpha_1 lnGPC_t + \alpha_2 lnGPC_t{}^2 + \varepsilon_t \tag{11}$$

$$lnWPI_t = \alpha_0 + \alpha_1 lnGPC_t + \alpha_2 lnGPC_t{}^2 + \alpha_3 lnGPC_t{}^3 + \varepsilon_t \tag{12}$$

In Equations (11) and (12), WPI_t and GPC_t are respectively the water pollution index and GDP per capita of the PRD in the year t; ε_t is an error term and α is the coefficient to be estimated. In Equation (11), if $\alpha_1 > 0$ and $\alpha_2 < 0$, there is an inverted "U" relationship between GPC and WPI. In Equation (12), if $\alpha_1 < 0$, $\alpha_2 > 0$ and $\alpha_3 < 0$, there is a "N"-shaped relationship between GPC and WPI; if $\alpha_1 > 0$, $\alpha_2 < 0$ and $\alpha_3 > 0$, there is an inverted "N"-shaped relationship.

3.4. Data Sources

River water quality monitoring data for different cross-sections from 1999 to 2015 were gathered from the Guangdong Provincial Environmental Monitoring Station. The sources of other data are listed in Table 2.

Table 2. The main data sources.

Data	Source
Sewage discharge of city i (s_i)	Annual statistical yearbooks of the nine cities from 2000 to 2016 Annual "China Statistical Yearbook on Environment" from 2005 to 2016
Water supply of city i (w_i)	Annual statistical yearbooks of the nine cities from 2000 to 2016; Annual "Guangdong Water Resources Bulletin" from 2004 to 2015 Annual "Guangdong Statistical Yearbook" from 2000 to 2016
GDP of city i (g_i)	Annual statistical yearbooks of the nine cities from 2000 to 2016 Annual "China Statistical Yearbook for Regional Economy" from 2000 to 2014 Annual "Guangdong Statistical Yearbook" from 2000 to 2016
Sectoral GDP of city i	Annual statistical yearbooks of the nine cities from 2000 to 2016
Resident population of the PRD and city i (p_i)	Annual statistical yearbooks of the nine cities from 2000 to 2016 Annual "Guangdong Statistical Yearbook" from 2000 to 2016 Annual "China Statistical Yearbook for Regional Economy" from 2000 to 2014 "Urban Agglomeration in the Pearl River Delta Yearbook 2016"
Annual sewage treatment rate	Annual "China City Statistical Yearbook" from 2000 to 2016 Annual "China Urban Construction Yearbook" from 2006 to 2015 Annual "Guangdong Statistical Yearbook" from 2000 to 2016 Annual "Yangtze River Delta & Pearl River Delta and Hong Kong & Macao SAR & Tai Wan Statistical Yearbook" from 2003 to 2009

4. Results

4.1. Water Quality in the PRD

As shown in Figure 2, the overall WPI of the PRD from 1999 to 2015 decreased by 65.29%. The WPI of all the nine cities decreased to different degrees. The decreasing rate for Dongguan, Huizhou, and Shenzhen were the largest, reaching over 70%. Nevertheless, at present, the river quality of Shenzhen and Dongguan are still the poorest among the nine cities.

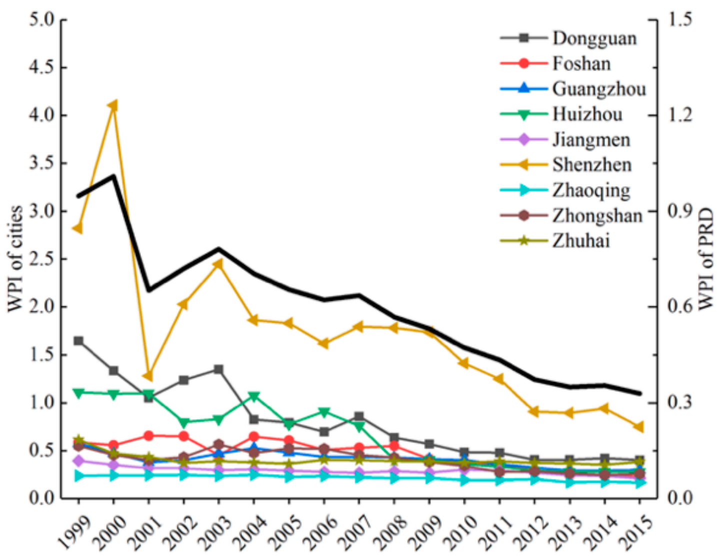

Figure 2. The water pollution index (WPI) of the Pearl River Delta (PRD) (1999–2015).

4.2. The Socioeconomic Drivers of Sewage Discharge

As shown in Figure 3, economic scale was the largest driver of sewage discharge in the PRD from 1999 to 2015, leading to 8307.88 megatons of sewage increase. In this period, the GDP per capita of the PRD increased from ¥16,859.99 to ¥106,002.02, with an average annual growth rate of 12.30%, which was 37.12% higher than the national average and thus made the region one of the fastest-growing economies in the world. The second largest driver was population size, which led to an increase of 1701.73 megatons of sewage discharge. The largest decreasing factor for sewage discharge was the water dependency of economic growth, improvements in which contributed a reduction of 6528.55 megatons of sewage. From 1999 to 2015, the water consumption per unit of GDP of the PRD decreased from 5.45 kg/yuan to 1.30 kg/yuan, falling 76.15%. However, the great improvement in production efficiency was offset by the greater expansion of economic scale and population. Being at the forefront of China's economic opening and reform, the PRD has always been one of the most attractive destinations for internal Chinese migration because of the abundance of employment opportunities. Excluding the large floating population, which was a factor in the urbanization of the PRD but for which accurate data is difficult to obtain, the permanent population in the PRD increased by 45.77% from 1999 to 2015. The change of water use efficiency reduced the total sewage discharge until 2007, after which water use efficiency led to an increase of the sewage discharge. Water recycling to reduce sewage discharge did not seem to be a major consideration for the water users in the PRD. The impact of spatial population structure on sewage discharge was slight and negligible.

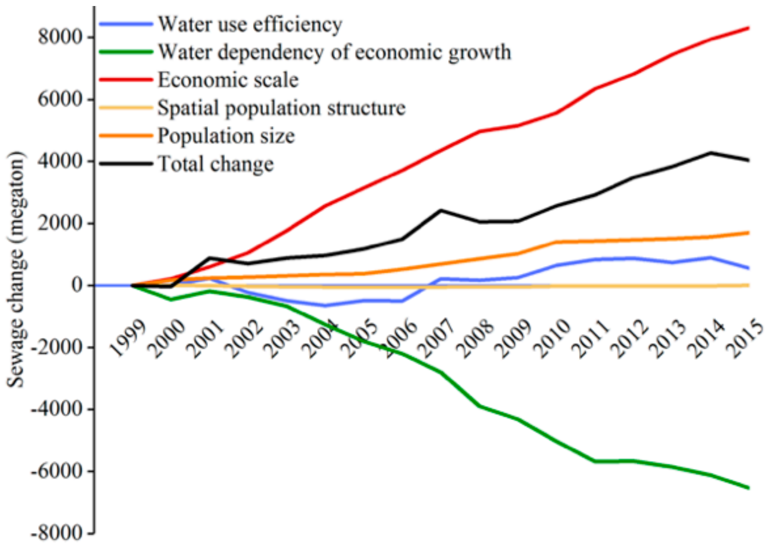

Figure 3. The socioeconomic drivers of sewage discharge in the PRD (1999–2015).

As shown in Figure 4, the expansion of economic scale drove the increase of all the nine cities' sewage discharge. The sewage increase of Guangzhou was the largest, reaching 2238.78 megatons and accounting for 26.95% of the total sewage change driven by the growth of economic scale. Shenzhen was the second largest (1613.31 megatons, 19.42%), followed by Dongguan (1565.53, 18.84%) and Foshan (946.52, 11.39%). The GDP per capita of the four cities respectively increased by 5.20-, 5.78-, 5.45-, and 5.01-times. Apart from these four cities, the sewage changes of the other five cities driven by economic scale accounted for only 23.40% of that of the PRD in total. It is noteworthy that in 2009, the sewage discharge of Dongguan decreased and the sewage increase of Shenzhen slowed down. In 2010, the sewage discharge of Guangzhou also decreased. The most plausible reason was the financial crisis of 2008, which led to a slowdown in foreign trade, especially manufactured exports, which have been central to the economies of these three cities. After the brief decrease, the sewage discharge of the three cities returned to a monotonically increasing trend. In particular, the speed of sewage growth of Shenzhen even outstripped the period before 2008. To a large extent, the shock of the financial crisis actually helped the economic transformation of Shenzhen. Today, policymakers are actively trying to move the city from an economic model that relies of industrial imitation and large-scale manufacturing to one based on innovation, high-end technology, and more value-ended production. Shenzhen has been one the most successful role models in this type of economic restructuring and upgrading in China, which has important implications for environmentally-friendly, low-pollution development [49].

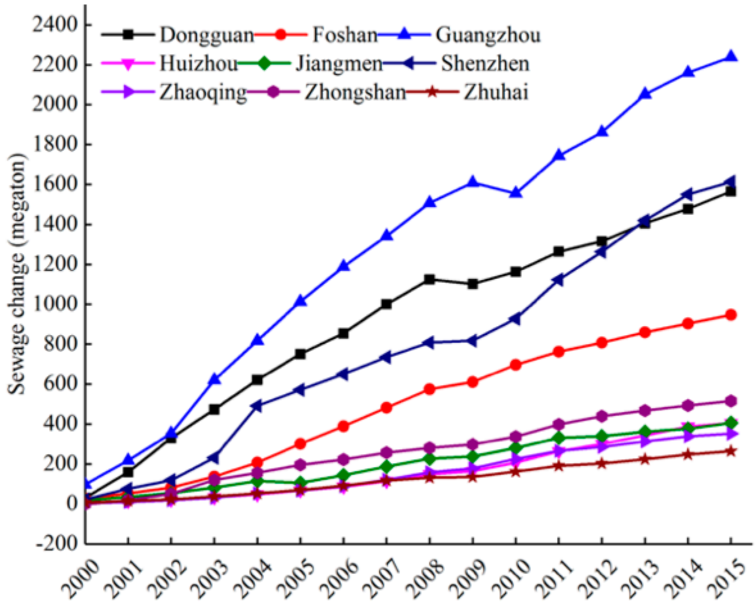

Figure 4. The accumulative contributions of each city's economic scale to changes in sewage discharge (2000–2015).

Figure 5 shows the impact of the water dependency of the economy on the sewage discharge of the cities. The decrease in water dependency drove decreases in sewage discharge in all nine cities. Among them, the most significantly affected were Guangzhou, Shenzhen, and Dongguan, demonstrating that while economic scale expanded rapidly, the water dependency of the economy actually declined. Because of these gains in economic efficiency, Guangzhou saw a reduction of 1992.17 megatons of sewage from 1999 to 2015. Shenzhen saw reductions of 1619.69 megatons and Dongguan 1238.05 megatons. In aggregate, the sewage decreases of the three cities accounted for 74.29% of the total sewage decrease of the PRD. More importantly, after the financial crisis of 2008—i.e., from 2009 to 2015—the sewage decreases driven by improved water dependency of the three cities and Zhaoqing outweighed the sewage increase driven by growing economic scale. This phenomenon further supports the hypothesis that the 2008 financial crisis stimulated the transformation of theses main urban economies from being scale-driven to being efficiency-driven.

In terms of the impact of population scale, as shown in Figure 6, overall, the change of population scale led to an increase in sewage discharge for all the cities. The sewage increase of Shenzhen was the largest, followed by Guangzhou, Dongguan, and Foshan. The sewage increases driven by population growth of the four cities were respectively 477.41, 443.18, 268.33 and 210.00 megatons, accounting for 81.97% of the total change in sewage discharge of the PRD. In this period, the permanent populations of Shenzhen, Guangzhou, Dongguan, and Foshan respectively increased by 5,053,100 (increasing rate: 79.88%), 3,994,600 (42.02%), 2,594,300 (45.84%), and 2,387,200 (47.33%). The sewage changes for Guangzhou fluctuated more compared with the other cities, and Shenzhen was more stable in a monotonically increasing trend. After 2010, the rates of sewage increase of the cities were slower than the period before 2010. The main reason was that immigration started to slow down. However, after 2014, the sewage discharge of Shenzhen and Guangzhou again increased to a higher rate.

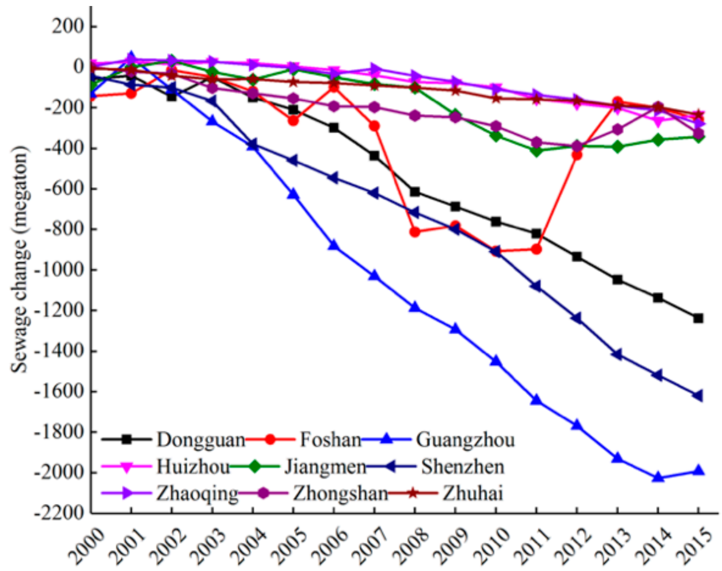

Figure 5. The accumulative contributions of each city's water dependency to changes in sewage discharge (2000–2015).

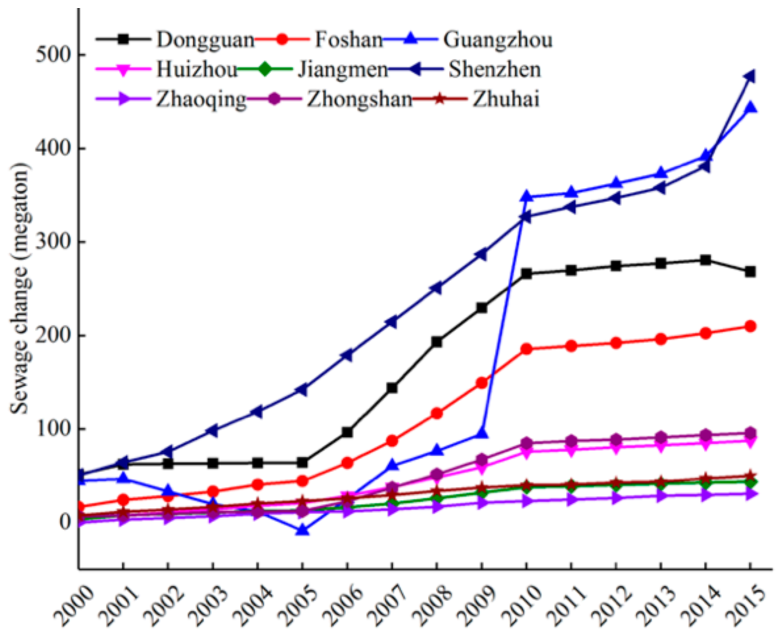

Figure 6. The accumulative contribution of each city's population scale to changes in sewage discharge (2000–2015).

For the impact of spatial population structure, it can be seen from Figure 7 that except for Shenzhen and Huizhou, all the other cities' sewage discharge decreased because of the reduced population proportion in the region. The sewage discharge of Shenzhen and Huizhou respectively increased by 165.88 and 1.69 megatons, with their respective population proportions in the PRD increasing by 0.037 and 0.004. Evidently, as China's first special economic zone after the implementation of the epochal opening and reform policies a generation ago, Shenzhen remains one of the most attractive cities for migrants in the PRD.

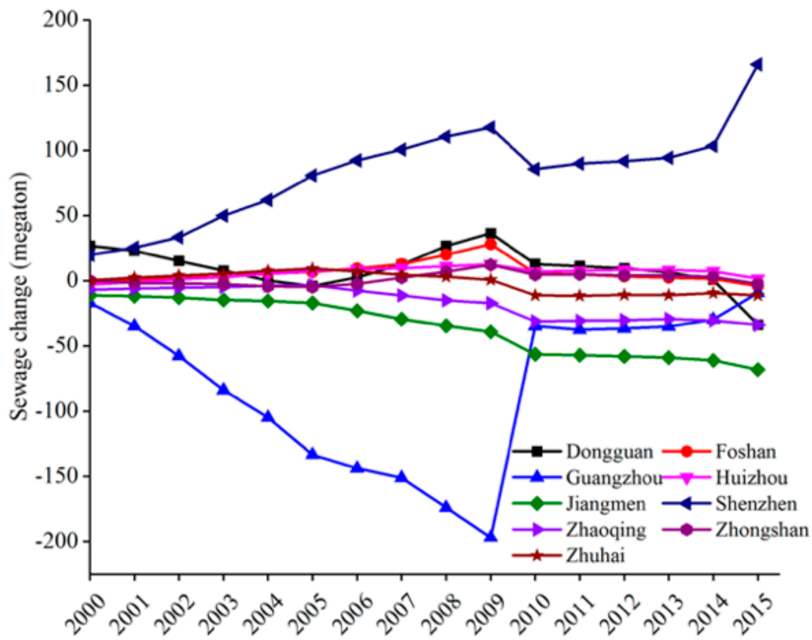

Figure 7. The accumulative contribution of spatial population structure to sewage change (2000–2015).

4.3. The EKC of the Relationship Between Water Quality and Economic Development

The result of the EKC estimation is shown in Table 3. The significance levels of the coefficients in the quadratic model are significantly higher than those in the cubic model. Thus, the quadratic model likely better explains the variation of the dependent variable, and thus more accurately depicts the relationship between water quality and economic development in the PRD. It is specified in the following equation:

$$lnWPI_t = 4.533lnGPC_t - 0.237lnGPC_t{}^2 - 21.794. \quad (13)$$

In Equation (13), when $lnGPC < 9.56$ i.e., $GPC < 14228.47$, $lnWPI$ increases as $lnGPC$ increases; when $lnGPC > 9.563$, i.e., $GPC > 14{,}228.47$, $lnWPI$ decreases as $lnGPC$ increases. In other words, there is an inverted "U"-shaped relationship between the GDP per capita and water quality of the PRD; and GDP per capita = ¥14,228.27 appears to be the inflection point. At the starting point of our research period, the GDP per capita of the PRD already exceeded ¥14,228.27 and kept on increasing, so the WPI showed a decreasing trend from 1999 to 2015.

Table 3. The results of OLS regression.

Cubic Model	Dependent Variable	$lnWPI$	$n = 17$	Quadratic Model	Dependent Variable	$lnWPI$	$n = 17$
Independent Variable	**Coefficient**	**Std. Error**	**Prob.**	**Independent variable**	**Coefficient**	**Std. Error**	**Prob.**
C	314.507	164.351	0.077 *	C	−21.794	8.841	0.027 **
$lnGPC$	−90.316	46.402	0.073 *	$lnGPC$	4.533	1.618	0.014 **
$(lnGPC)^2$	8.663	4.359	0.068 *	$(lnGPC)^2$	−0.237	0.073	0.006 ***
$(lnGPC)^3$	−0.277	0.136	0.0623 *				
Model summary				Model summary			
R^2		0.935		R^2		0.922	
Adjusted R^2		0.920		Adjusted R^2		0.911	
Prob (F-statistic)		0.000		Prob (F-statistic)		0.000	
Prob (Wald F-statistic)		0.000		Prob (Wald F-statistic)		0.000	

Note: The symbols *, **, *** represent statistical significance at the 10%, 5%, and 1% levels respectively.

5. Discussion and Conclusions

Since the economic opening and reforms China began to undertake in 1980s, the PRD has been one of the country's most economically dynamic regions and thus has attracted generations of migrants from all over the country. Although the PRD is among the most water abundant regions in China [47], the enormous water demand driven by high speed economic growth and population influxes has made water shortages a challenging issue for the area, especially given the fact that future water use in the PRD is expected to continue increasing significantly. In addition, water pollution further aggravates the water scarcity dilemma of the PRD. Therefore, it is imperative to understand the relationship between water problems and socioeconomic development to affect more sustainable urbanization in the region.

From 1999 to 2015, the sewage discharge of the PRD increased from 2827.33 to 6869.03 megatons, with an average annual growth rate of 6.11%. The most significant driver for the sewage increase was expanding economic scale, i.e., GDP per capita, which grew at an annual rate of 12.30%. Economic growth experienced a slight and brief weakening after the global financial crisis in 2008. But overall, sewage discharge driven by the expansion of economic scale showed a monotonically increasing trend from 1999 to 2015. While the scale-driven sewage discharge continuously went up, the water dependency of economic development in the PRD went down by a very significant extent. From 1999 to 2015, the water consumption per unit of GDP of the PRD decreased at an average annual rate of 8.42%. Nevertheless, the economic efficiency gains did not prevail over the scale expansion. In the meantime, population growth also exacerbated the amount of sewage discharge. From 1999 to 2015, the permanent population of the PRD increased at an average annual rate of 2.40%. Considering the official statistical yearbooks do not tabulate floating population, the actual sewage increase driven by population scale was likely larger than the estimation. Water use efficiency appeared to be an unstable factor affecting the sewage change. Although China issued the "Circular Economy Promotion Law" in 2009, water recycling was not a major concern for the industries and governments in the PRD. The impact of spatial population structure on sewage discharge change was slight, indicating a convergent water use mode among the different cities.

At the city level, overall, economic scale and population scale drove the sewage growth of all nine cities, among which the sewage increases of Guangzhou, Shenzhen, and Dongguan were the largest. The financial crisis in 2008 drove a brief decline of sewage discharge in the three cities, but these resumed monotonically increasing trends in 2009–2010. In particular, the rate of sewage increase associated with the economic scale of Shenzhen even outstripped the period before 2008. The decrease of water dependency drove the sewage decrease of all nine cities. The most significantly affected cities were also Guangzhou, Shenzhen, and Dongguan. More importantly, after the financial crisis in 2008, i.e., from 2009 to 2015, the sewage decreases driven by water dependency of the three cities outweighed the sewage increase driven by economic scale. Therefore, the 2008 financial crisis actually stimulated an economic transformation of the main economies of the PRD from being scale-dominated to being efficiency-dominated. This was particular true for Shenzhen, which has experienced an economic restructuring towards innovation and high value-added industries. Shenzhen was also the most attractive city for migrants in the PRD. From 2009 to 2015, the sewage increase of Shenzhen driven by population growth was the largest among the nine cities.

While sewage discharge largely increased in 1999–2015, the river water quality of the PRD kept improving: The average WPI dropped by 65.29%. We found an inverted "U"-shaped relationship between GDP per capita and water quality of the PRD, with GDP per capita = ¥14,228.27 as the inflection point for river water quality. We argue that this was because, first, in the overall economic structure, the proportion of traditionally water polluting sectors, mainly "Industry", "Construction", "Transport", and "Agriculture", decreased from 66.57% in 1999 to 49.69% in 2015. These were increasingly replaced by service industry sectors, such as "Retails, hotels, and catering", "Finance", and "Real estate", the proportions of which increased from 33.43% to 50.31%. Second, once dubbed the "Factory Floor" of the world, the PRD has increasingly become known as the "Silicon Delta" of

China, through successful industrial transformation from labor-intensive to advanced manufacturing and hi-tech industries [50]. As of 2014, the value added from the modern service industry accounted for 61.80% of the whole service industry in the PRD. The value-add of advanced manufacturing and hi-tech manufacturing respectively accounted for 53.10% and 30.30% of the value-add of the industries above designated size. Research and development expenditure as proportion of GDP reached 2.65% [51]. For leading cities like Shenzhen, the proportion was up to 4% [50], while the technical self-sufficiency rate was over 70% [51]. Technological upgrading and industrial system transformation thus contributed to the decoupling of economic development and environmental pollution. Third, environmental expenditures, regulation, and other aspects of policy reform improved in parallel with rapid economic growth [52,53]. The domestic sewage treatment rate of the PRD increased from 32.96% in 1999 to 93.38% in 2015. The industrial sewage compliance rate of each city kept growing until they reached nearly 100%.

On current trends, rates of water resource utilization and water pollution control, in addition to more secular trends in economic efficiency and structure, are exerting an increasingly positive influence on water quality in the PRD. However, given the huge economic and population scales, which will continue to increase apace for the foreseeable future, ensuring a sufficient and safe water supply is still a daunting challenge. The Guangdong provincial government is now implementing a "West Water to East" project to ensure the water supply of Guangzhou, Shenzhen, and Dongguan. This is so far the largest water project in Guangdong's history. Facing such challenges, water conservation and protection through industrial recycling and public education, along with further pollution abatement, will be integral to the sustainable urbanization of the PRD.

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