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Water Use Efficiency Improvement against a Backdrop of Expanding City Agglomeration in Developing Countries—A Case Study on Industrial and Agricultural Water Use in the Bohai Bay Region of China

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Abstract: Most city agglomerations of developing countries face water shortages and pollution due to population growth and industrial aggregation. To meet such water security challenges, policy makers need to evaluate water use efficiency at the regional or basin level because the prosperity of city agglomerations is indispensable to the sustainable development of the region or basin. To solve the issue, this paper adopts a non-directional distance function within the framework of environmental production technology to measure water use efficiency. Based on the distance between actual water use efficiency and the ideal efficiency, it calculates the potential reduction space of water input and pollutants by slack adjustment. Added to the Malmquist index, it forms a non-radial Malmquist water use performance index, which can be divided into technological change and technical efficiency change, to measure dynamic water use efficiency. Further, water use efficiency change is analyzed from the perspectives of technological improvement and institutional construction. Bohai Bay city agglomeration, a typical water-deficient city agglomeration in China, is taken as a case study, and data on water resource, environment, and economy from 2011 to 2014 have been used. In conclusion, there is much space for water use efficiency improvement on the whole. However, even having considered potential reduction space of water input and pollutant discharge under current environmental production technology, it is still not enough to support the city agglomeration's sustainable development. To relieve current potential water safety hazards, not only technical improvement but also institution innovation for highly efficient water use should be kept accelerating in Bohai Bay region. In terms of urban water management in developing countries, the research conclusion is of theoretical and practical significance.

Keywords: non-radial directional distance function; Malmquist index; dynamic total-factor water use efficiency; water conversation; water pollutant discharge reduction; Bohai Bay region city agglomeration

1. Introduction

City agglomeration in developing countries has not only driven socioeconomic development, but also presented a huge challenge to the environment in the past five decades. Due to an economic catch-up strategy, cities can provide advanced education, more job opportunities, and an improved social security system, which attracts young people from rural locations for generation after generation, thus gradually forming a huge city agglomeration. Examples of city agglomeration are seen in the India River Basin, Saint Paul city in Brazil, the Southern Gulf of Mexico, and Bohai Bay, Yangtze River Delta, and Pearl River Delta in China. Today, these city agglomerations have become industrial, capital, technological, and population centers in their local economies. However, rapid population and industrial expansion, massive resource consumption, and major discharge of pollutants place extreme pressure on the environment, especially water resources.

Water, a necessity for life and production, is also the main carrier of pollutants, so now suffers from great pressure in city agglomerations of developing countries. On the one hand, rapid population and industrial expansion in megacities would raise great concerns about water sufficiency. On the other hand, in developing countries, water safety issues are complicated by undeveloped infrastructure and the limited budgets of the public sector. For example, Delhi now suffers from water scarcity with 20% water shortage of 200 Million Gallons Daily (MGD) [1], and could not even ensure the minimum purification flow capacity of rivers [2]. In the past 20 years, the piezo-metric status of many places in Kolkata, Delhi, and Mumbai was found to be at an alarming level of 14–16 m below ground, and some untreated sewage was directly discharged into the river or sea [3]. City agglomerations are more fragile when encountering meteorological disasters and climate change. Since the end of 2013, southeastern Brazil has suffered the worst drought in 55 years, which was repeated in 2015 and 2016. Cities such as São Paulo, Rio de Janeiro, and Belo Horizonte have been under water shortage stress, putting a total of 40 million local people at risk [4]. Under the multiple influences of global climate change, city expansion, higher water demand, and environmental degradation, etc., water resources in city agglomeration may deteriorate even more [5–7]. If megacities in developing countries have no way to effectively combat the water crisis, global social and economic development would meet with great challenges.

To achieve sustainable development of urban water resources, scholars usually explore urban water management from two perspectives. One is the perspective of the water supply, mainly to discuss water supply management [8–12] and unconventional water resource utilization [13–16]. The other is the perspective of urban water demand, which mainly focuses on water conservation [17–20] and water use efficiency improvement [21–25]. In addition, there are some studies [26–28] on urban water management exploration from the perspectives of both supply and demand.

As cities expand in developing countries, industrial water use efficiency gets increasing attention. For one thing, the priority in the urban water supply goes to domestic water, for which demand grows with the population, so the supply for industrial water use would be further reduced. Moreover, unlike developed countries with advanced technology and management modes, comprehensive urban water management strategies partly fail to be applied to reducing water demand in developing countries [29]. However, industrial water use efficiency has been promoted by industrial centralization. Thus, industrial water use efficiency improvement can be seen as one of the basic strategies to solve urban water issues.

The subject of urban water management might seem to be limited to cities, but it requires comprehensive management of the whole basin or region [30]. For example, California, USA has included agricultural water use in urban water use management through coordinative management such as water rights trading, water supply, and emergency management, etc. [31,32]. In developing countries, agricultural water use efficiency must be optimized as soon as possible to satisfy increasing water demand in rapidly expanding city agglomerations. A comprehensive evaluation of industrial water use efficiency of city agglomerations and their surrounding areas can better reflect the urban water use prospect. In addition, considering water quantity and water quality are indispensable to a region's sustainable development [33]; this paper takes water resource input and industrial wastewater pollutant discharge into consideration.

From the perspective of city water demand, taking Bohai Bay region as an example, this paper adopts the non-radial Malmquist water use performance index method to explore industrial and agricultural water use efficiency for four years from the angles of water quantity and water quality. Also, it provides answers to policy makers in developing countries faced with water shortage and water pollution, who may encounter some practical problems: What is the current urban water use efficiency? What is the potential reduction of water input and water pollution under current environmental production technology? If water use were efficient, would the city meet its sustainable development goals? What is the best direction for water use efficiency improvement?

2. Reviews of Water Use Efficiency

There are different methods to measure water use efficiency [34]. Despite different definition levels, all water efficiency calculations aim to achieve more production with less water input. It was firstly measured from the perspective of the economy, thus being seen as the value of products produced per unit of water consumption [35]. However, Hu et al. [36] suggested calculating water use efficiency using a multi-input model, believing that water cannot produce anything as a single input.

Data envelopment analysis model (DEA), as a multi-input model, has been widely adopted in the field of water use efficiency evaluation [37–43]. However, these studies have ignored the undesirable output, wastewater discharge, which would cause some deviation from the water-use efficiency evaluation [44]. Later scholars begin to include undesirable outputs into DEA model efficiency, forming a unified environmental production technology research framework. In the field of water use efficiency, Sun et al. [22], Chen et al. [23], and Shi et al. [25] consider gray water footprint, wastewater discharge, and pollutants in wastewater, respectively, as undesirable outputs. However, the calculation result from the DEA model is a dimensionless value with no actual meaning, and policy makers focus more on water reduction potential and pollutant reduction potential. In recent years many scholars have just focused on water conservation and tried to explore the possibility of saving water from different perspectives of policy innovation, management strategy change, technology promotion, method improvement, energy control, etc. [45–50]. Likewise, studies on wastewater discharge reduction have also gained wide attention [51–59].

Some scholars perform integrated research on water use efficiency and water saving/waste pollutant reduction, to explore water use management more comprehensively. Bian et al. [24], using a three-stage DEA method, analyzed water use efficiency and the efficiency of a wastewater purification system in China's cities, and calculated the water savings potential and cyclic water use potential. Wang et al. [44] adopted the slacks-based measure DEA (SBM-DEA) method to investigate water use efficiency, water conservation potential, two pollutants' reduction potential, and the marginal abatement cost of industrial systems in China. Methodologically, both have adopted slacks adjustment. Coelli [60] pointed out that non-efficiency decision-making units in the DEA model were achieved through adjusting slacks by setting the most efficient point in environmental production frontier as the goal. The calculation of slacks variable could not only avoid the deviated efficiency estimation [61], but also help to reduce water resource input and pollutant discharge [24,44].

The above studies have covered water savings and pollutant reduction, but they are still examples of static analyses, which are, unlike time series data, difficult when using panel data to reflect historical trends [62]. Differently, this study would, from the perspective of time series, evaluate dynamic water use efficiency and the reduction space of water input and polluting emissions. This paper aims to evaluate industrial water use efficiency using the non-radial directional distance function method. To further evaluate dynamic water use efficiency, it adds Malmquist indexes, forming the evaluation method of non-radial Malmquist water use performance index (NMWUPI), which can be divided into technical efficiency change (EC) and technological change (TC), which can explain the reason for water use efficiency change. Then, based on the calculation of slacks variables, it estimates water use savings potential and pollutant reduction potential, to set objectives for improve water use efficiency and to evaluate influences on water resource environment after improving.

3. Methods

3.1. Environmental Production Technology Framework and Basic Assumptions

Production requires various inputs, such as labor (L), capital (K), and water resources (W), and then produces desirable output (Y), and undesirable output, namely pollution or wastewater discharge (P). The DEA reference technology, which includes undesirable output, is what Färe and Grosskopf [63] call environmental production technology. In other words, environmental production technology collection includes all the possible production collections of environmental production technology (T). The combinations of inputs and outputs in the environmental production technology frontier are efficiency. T can be defined as:

$$T = \{(K, L, W, Y, P) : (K, L, W) \text{ can produce } (Y, P)\}. \quad (1)$$

Many researchers, such as [64–67], have proposed assumptions or set constraints for environmental production technology, which are recognized by this study and can be categorized as follows:

1. Compactness: T is a bounded section. Limited inputs can only produce limited outputs.
2. Inactivity: in any section, there is the possibility that any given input vector may get no output.
3. Free disposability of inputs: inputs and desirable outputs have to meet free disposal conditions, which means the inputs of (K, L, W) can get the outputs of (Y, P). When $Y' < Y$, $(K,\ L,\ W,\ Y\prime,\ P) \in T$; when $(K\prime,\ L\prime,\ W\prime) > (K, L, W)$, $(K\prime,\ L\prime,\ W\prime, Y,\ P) \in T$.
4. Weak disposability of outputs: on the boundary curve of environmental production technology, desirable output (GDP) gets reduced in proportion to undesirable output (wastewater discharge).
5. Null-jointness: desirable output is paired with undesirable output.

Studying production water use efficiency requires not only environmental production technology, but also an environmental technology analysis framework, so this paper takes advantage of non-parametric DEA, a widely used linear programming function in static water use efficiency evaluation. Suppose that each water use department or area is regarded as a decision-making unit (DMU), and the DMU_i is the vector composed of inputs, desirable outputs, and undesirable outputs. The linear programming of environmental production technology should be as follows:

$$T = \{(K, L,\ W,\ Y,\ P) : \sum_{i=1}^{n}\lambda_i K_i \le K \sum_{i=1}^{n}\lambda_i L_i \le L \sum_{i=1}^{n}\lambda_i W_i \le W \sum_{i=1}^{n}\lambda_i Y_i \ge Y \sum_{i=1}^{n}\lambda_i P_i = P\ \lambda_i \ge 0,\ i = 1, 2, \ldots n\} \quad (2)$$

where T is a convex curve composed by variable λ_i. Then, based on environmental production technology, static water use efficiency can be calculated through a directional distance function (DDF).

3.2. Evolution from Static Water Use Efficiency to Dynamic Water Use Efficiency

Directional distance function (DDF) was improved from Shephard's input distance function and Luenberger's benefit function by Chambers et al. [68], and applied to environmental production technology by Chung et al. [69]. As a traditional DDF, it has also been called a radial directional distance function, which gets optimal inputs, desirable outputs, and undesirable outputs by enlarging desirable output and narrowing undesirable output or inputs proportionally. However, it has the hidden potential of non-zero slacks, which would fail the most efficient environment efficiency [61]. As a result, non-radial directional distance function (NDDF) is adopted by scholars [67,70,71]. Zhou et al. [70] give it a concrete definition as follows:

$$\vec{ND}(K,L,W,Y,P;g) = \sup\left\{\omega^T\beta : ((K,L,W,Y,P) + g\cdot\mathrm{diag}(\beta)) \in T\right\}, \tag{3}$$

where $\omega^T = (\omega_k, \omega_l, \omega_w, \omega_y, \omega_p)^T$ denotes the normalized weight vector relevant to the number of inputs and outputs, $g = \left(-g_k, -g_l, -g_w, g_y, -g_p\right)$ is the explicit directional vector, and $\beta = (\beta_k, \beta_l, \beta_w, \beta_y, \beta_p)^T \geq 0$ denotes the vector of scaling factors. When $\vec{ND}(K,L,W,Y,P;g) = 0$, the observation value of DMU in direction g is on the environmental technology production frontier, suggesting the most efficient observation value.

Considering that this study is mainly about water conservation and water ecological protection in city agglomerations, capital and labor are kept constant for the convenience of evaluating a region's water saving potential and pollution reduction potential. Based on the previous description, the direction variable can be set as $g = \left(0, 0, -g_w, g_y, -g_p\right)$. Economic growth and water ecological environment are supposed to be of equal importance, so the weight vector is set as (0, 0, 1/3, 1/3, 1/3). The non-radial directional distance function of any region in this study can be solved by piecewise linear DEA model as follows:

$$\begin{gathered}
\vec{ND}(K,\ L,\ W,\ Y,\ P) = \max \omega_w\beta_w + \omega_y\beta_y + \omega_p\beta_p \\
\text{s.t.} \quad \begin{cases}
\sum\limits_{i=1}^{n} \lambda_i K_i \leq K_j \\
\sum\limits_{i=1}^{n} \lambda_i L_i \leq L_j \\
\sum\limits_{i=1}^{n} \lambda_i W_i \leq W_j - \beta_w g_w \\
\sum\limits_{i=1}^{n} \lambda_i Y_i \geq Y_j + \beta_y g_y \\
\sum\limits_{i=1}^{n} \lambda_i P_i = P_j - \beta_p g_p
\end{cases} \\
\lambda_i \geq 0,\ i = 1, 2, \ldots n;\ \beta_k, \beta_l, \beta_w, \beta_y, \beta_p \geq 0.
\end{gathered} \tag{4}$$

The above methods have included slacks variables, but the evaluation of water use efficiency is still static, so the Malmquist index is adopted to achieve the evaluation of dynamic water use efficiency.

Malmquist [72] created a quantitative index with the ratio between two distance functions, and then the index was named after him. Caves et al. [73], based on the ratio between two distance functions during a period, described the production rate change and developed it into the Malmquist productivity index. Färe et al. [74] calculated the Malmquist productivity index with linear programming, and divided it into two indexes to analyze technological change (TC) and technical efficiency change (EC), respectively. Considering the possibility of technological inefficiency in production rate calculation, Färe et al. [74] furthered the development of Malmquist productivity index with a non-parametric framework. Chung et al. [69] took the initiative to apply the Malmquist productivity index to environmental production technology change evaluation. Førsund and Kittelsen [75] pointed out that the Malmquist productivity index could be explained as a total-factor productivity index, for it was a productivity technology function with constant returns to scale.

Under the analysis framework of a non-radial Malmquist water use performance index (NMWUPI), t and s are set as two different periods, and $t < s$. NMWUPI is composed of four different NDDF ratios of DMU_i, with the molecular items being $\vec{ND}^t(K_i^s, L_i^s, W_i^s, Y_i^s, P_i^s)$ and $\vec{ND}^s(K_i^s, L_i^s, W_i^s, Y_i^s, P_i^s)$, which respectively indicate DMU_i at period t and the distance of environmental productivity technology curve between period t and period s. NMWUPI is defined as follows:

$$\mathrm{NMWUPI_i(t,s)} = \left[\frac{\vec{\mathrm{ND}}^{s}(\mathrm{K_i^s, L_i^s, W_i^s, Y_i^s, P_i^s}) \cdot \vec{\mathrm{ND}}^{t}(\mathrm{K_i^s, L_i^s, W_i^s, Y_i^s, P_i^s})}{\vec{\mathrm{ND}}^{s}(\mathrm{K_i^t, L_i^t, W_i^t, Y_i^t, P_i^t}) \cdot \vec{\mathrm{ND}}^{t}(\mathrm{K_i^t, L_i^t, W_i^t, Y_i^t, P_i^t})}\right]^{1/2}. \tag{5}$$

In this paper, $\mathrm{NMWUPI_i(t,s)}$ measures total-factor productivity water use performance change of $\mathrm{DMU_i}$ from period t to period s. When $\mathrm{NMWUPI_i(t,s)} > 1$, it indicates water use efficiency has been improved during the period. When $\mathrm{NMWUPI_i(t,s)} < 1$, it indicates water use efficiency has declined during the period. Likewise, NMWUPI can be divided into technology efficiency change and technology change as follows:

$$\mathrm{EFFCH_i(t,s)} = \frac{\vec{\mathrm{ND}}^{s}(\mathrm{K_i^s, L_i^s, W_i^s, Y_i^s, P_i^s})}{\vec{\mathrm{ND}}^{t}(\mathrm{K_i^t, L_i^t, W_i^t, Y_i^t, P_i^t})}, \tag{6}$$

$$\mathrm{TECHCH_i(t,s)} = \left[\frac{\vec{\mathrm{ND}}^{t}(\mathrm{K_i^s, L_i^s, W_i^s, Y_i^s, P_i^s}) \cdot \vec{\mathrm{ND}}^{t}(\mathrm{K_i^t, L_i^t, W_i^t, Y_i^t, P_i^t})}{\vec{\mathrm{ND}}^{s}(\mathrm{K_i^s, L_i^s, W_i^s, Y_i^s, P_i^s}) \cdot \vec{\mathrm{ND}}^{s}(\mathrm{K_i^t, L_i^t, W_i^t, Y_i^t, P_i^t})}\right]^{1/2}. \tag{7}$$

$\mathrm{EFFCH_i(t,s)}$ is the relevant movement of $\mathrm{DMU_i}$ towards the environmental production technology curve from period *t* to period *s*, which indicates the catch-up effect of technical efficiency change (EC). $\mathrm{TECHCH_i(t,s)}$ is the quantization of $\mathrm{DMU_i}$'s technology boundary movement distance, showing the frontier-shift effect of technological change (TC). EC and TC suggest how close an observation and the whole, respectively, are to environmental production technology [71]. EC > (<) 1 means technical efficiency gain (loss), and TC > (<) 1 means technological progress gain (loss). The change direction of NMWUPI is determined by the integrated performance of EC and TC. From the perspective of water resource management, to improve water use efficiency, there are two behaviors: technological improvement, namely on-off behavior, such as the application of water-saving technology and the implementation of highly efficient water-use equipment; and institutional improvement, namely water-saving actions [76,77]. EC emphasizes the individual efficiency change, which is determined by institution. For example, the improvement of EC (EC > 1) can be regarded as the transformation from extensive production management to conservative management. TC describes the change of environmental production technology, namely technological change. So, the improvement of TC (TC > 1), results from an upgrade of production technology. In a word, water use efficiency can be improved through constitution construction and technology upgrades. According to the previous introduction, values of water use NMWUPI, EC, and TC in evaluated regions can only be obtained by calculation with $\vec{\mathrm{ND}}^{l_1}\left(\mathrm{K_i^{l_2}, L_i^{l_2}, W_i^{l_2}, Y_i^{l_2}, P_i^{l_2}}\right)$ $(\mathrm{l_1, l_2} \in \{\mathrm{t,s}\})$. Thus, based on environmental technology Equation (2) and Equation (4), this study tries to get the solutions to the following DEA model:

$$\vec{\mathrm{ND}}^{l_1}\left(\mathrm{K_i^{l_2}, L_i^{l_2}, W_i^{l_2}, Y_i^{l_2}, P_i^{l_2}}\right) = \max \omega_w \beta_w + \omega_y \beta_y + \omega_p \beta_p$$

$$\text{s.t.} \begin{cases} \sum\limits_{i=1}^{n} \lambda_i \mathrm{K_i^{l_1}} \le \mathrm{K_i^{l_2}} \\ \sum\limits_{i=1}^{n} \lambda_i \mathrm{L_i^{l_1}} \le \mathrm{L_i^{l_2}} \\ \sum\limits_{i=1}^{n} \lambda_i \mathrm{W_i^{l_1}} \le \mathrm{W_i^{l_2}} - \beta_w g_w \\ \sum\limits_{i=1}^{n} \lambda_i \mathrm{Y_i^{l_1}} \ge \mathrm{Y_i^{l_2}} + \beta_y g_y \\ \sum\limits_{i=1}^{n} \lambda_i \mathrm{P_i^{l_1}} = \mathrm{P_i^{l_2}} - \beta_p g_p \end{cases} \tag{8}$$

$$\mathrm{l_1, l_2} \in \{\mathrm{t,s}\};\ \lambda_i \ge 0,\ i = 1,2,\ldots n;\ \beta_k, \beta_l, \beta_w, \beta_y, \beta_p \ge 0.$$

NMWUPI, EC, and TC can be found from the four NNDFs in Equation (8), to analyze total-factor production water use performance and the reasons for EC's and TC's changes.

3.3. The Potential for Water Saving and Pollutant Reduction

Evaluation efficiency results cannot directly serve as water management targets. Based on the above model, it is known that water use can reach the environmental production technology frontier by input or output slack variables adjustment, for getting optimal inputs and outputs [24,44]. A slack variable in the linear programming model is a coefficient that adjusts inputs and outputs [74]. Apparently, the surplus input or undesirable output are what should be conserved or reduced to realize the savings potential and reduction potential in this paper. Conclusively, water use efficiency can be improved through water input and pollutant reduction, which are more perceptible than efficiency, so it is more appropriate to set them as water use management targets. Based on the non-radial distance function method in Section 3.2, water saving potential (WSP) and pollutant reduction potential (PRP) can be calculated. $\beta^* = \left(\beta_w^*, \beta_y^*, \beta_p^*\right)$ is assumed as the primal solution to Equation (4), and $\beta_w^*, \beta_y^*, \beta_p^*$ correspond to water resource inputs, desirable output GDP, and undesirable output, respectively. From free disposability and weak disposability, introduced in Section 3.1, it is known that inputs and desirable outputs can be freely disposed of while undesirable outputs cannot be freely disposed of, and that reduction of undesirable outputs may lead to desirable outputs. When exploring pollution reduction, Zhou et al. [70] clearly expressed the relationship between desirable outputs and undesirable outputs, which would be observed by this study as Equation (9):

$$\mathrm{MPRI} = \frac{(P - \beta_P^* P)/\left(Y + \beta_y^* Y\right)}{P/Y} = \frac{1 - \beta_p^*}{1 + \beta_y^*}. \tag{9}$$

Optimal solutions corresponding to pollution and GDP can be obtained from β_p^* and β_y^*. The ratio between potential intensity and actual intensity (P/Y) is the maximum potential reduction index of pollutants (MPRI), which calculates the minimum potential undesirable output.

If the water use performance of a region is efficient, the slacks variable is zero, and there is no space for water savings and pollution reduction. If not, though, the potential for water resource and pollution reduction can be expressed as:

$$\left\{ \begin{array}{c} \mathrm{WSP} = (1 - \beta_w^*)W \\ \mathrm{PRP} = \left(1 - \frac{1-\beta_p^*}{1+\beta_y^*}\right)P = \frac{\beta_y^* + \beta_p^*}{1+\beta_y^*}P \end{array} \right. . \tag{10}$$

Equation (10) has achieved quantitation of water savings potential and pollution reduction potential.

3.4. The Influence of Water Savings and Pollution Discharge Reduction

To evaluate the room for water savings and the corresponding influence on the environment, this paper introduces water stress index (WSI) and water degradation possibility (WDP).

For different research subjects, scholars have adopted different calculation methods to describe the relationship between water use and water resources. Sun et al. [78] combined WSI and virtual water and calculated the water stress change in different regions in China after a blue water transfer. Núñez et al. saw WSI as a regionalized characterization factor and differentiated the water use pressure on sub-basins [79]. Miano et al. [80] considered the influences of climate and human change factors on regional water resources exploitation. Based on local water resource deficiency, Berger et al. investigated the possibility of water degradation from perspective of water consumption [81]. Boulay et al. believed WSI is the competition pressure among water users, and differentiated water sources and water quality [82]. This paper focuses on the relationship between regional water use and local water resources, so it follows the WSI calculation method of [80].

The water stress index is adopted to evaluate local water exploitation degree [80]. I can be determined by the ratio between the amount of water use and water resources (WR). WR includes surface water, underground water, and other water resources. WSI is as shown in Equation (11):

$$\mathrm{WSI} = \frac{\mathrm{W}}{\mathrm{WR}} \times 100\%. \tag{11}$$

The higher the WSI, the more water use stress the region is faced with. If WSI remains higher than 100% for many years in a row, it means the water resources of the region have been over-exploited. If WSI is higher than 80%, it means the region is confronted with severe water stress. If WSI is lower than 80% and higher than 40%, it means the region is faced with high water stress. If WSI is lower than 40%, it means the region is under no water use stress.

Normally, the evaluation index for water pollution is water quality, while wastewater discharge is quantitatively measured. It is difficult to quantitatively describe water quality change from wastewater discharge. Thus, gray water footprint has been introduced because it can describe the influence of water pollution on available water amount, achieving the evaluation of water quality from the perspective of water quantity [83,84]. Hoekstra et al. [85] give a clear definition of gray water footprint: based on current water quality environmental standards, it is the freshwater amount required to absorb the pollutant load, namely the freshwater volume needed to dilute wastewater to standard water quality. A common gray water footprint can be found as follows:

$$\mathrm{WF_{gray}} = \frac{\alpha \cdot \mathrm{L}}{\mathrm{C_{max}} - \mathrm{C_{nat}}} \tag{12}$$

where $\mathrm{WF_{gray}}$ is the gray water footprint, α is the leaching rate, L is the pollutant discharge load, $\mathrm{C_{max}}$ represents the pollutant's highest concentration in a standard water environment, and $\mathrm{C_{nat}}$ is the initial concentration of pollutants in the natural receiving water body. Considering that industrial pollution is point source pollution, its leaching rate can be set at 100%; agricultural pollution is non-point source pollution, and its leaching rate is set at 10%.

Generally, the gray water footprint can be directly compared with local water resources. When the gray water footprint is smaller than the local water quantity, it means there is enough water to dilute pollutants to a safe environmental water quality standard. When the gray water footprint is larger than the local water quantity, it means there is not enough water to dilute the pollutant to satisfy the safe environmental water quality standard, and the accumulative pollutant would cause water environment degradation. So, to express their quantitative relationship more directly, this paper adopts the ratio between gray water footprint and water resource as an evaluation index, which indicates water gradation possibility. As a result, the WDP index can be calculated as follows:

$$\mathrm{WDP} = \mathrm{WF_{gray}}/\mathrm{WR} \tag{13}$$

When WDP is smaller than 1, the water gray footprint is not supposed to affect water quality because the local water amount is enough to dilute pollutants to a standard water quality range [65–67]. Only when WDP is larger than 1 is there a possibility that the water body will be polluted, and the bigger it is, the higher the possibility.

4. Case Study and Data

4.1. Introduction to Bohai Bay City Agglomeration

As the center of the northeast Asian economic zone, Bohai Bay city agglomeration includes three sub-economic zones: Beijing-Tianjin-Hebei circle, Shandong peninsula circle, and Liaoning peninsula circle. It takes the two municipalities of Beijing and Tianjin as the center, coastal open cities like Dalian, Qingdao, Yantai, Weihai, etc. as the sector, and cities like Jinan and Shijiazhuang as the longitudinal fulcrum, and successfully connects all the urban and rural areas in the North China Plain, Huang-Huai-Hai Plain, and Liaohe Plain, thus constituting the most important, multi-functional city agglomeration of politics, economy, culture, and international affairs in China.

In Bohai Bay city agglomeration (Figure 1), there are many large cities and several super-cities with populations over 10 million. For example, the population in Beijing and Tianjin, two of the largest international cities, is 21.52 million and 15.17 million, respectively. The total population of Hebei province is 73.84 million, while six cities in it have a population of a million people. The population in Shandong province is close to 100 million, with two cities close to 10 million, five cities between 5 million and 8 million, and seven cities between 1 million and 5 million. Liaoning province has a population of about 43 million with two cities over 5 million and 12 cities between 1 million and 5 million.

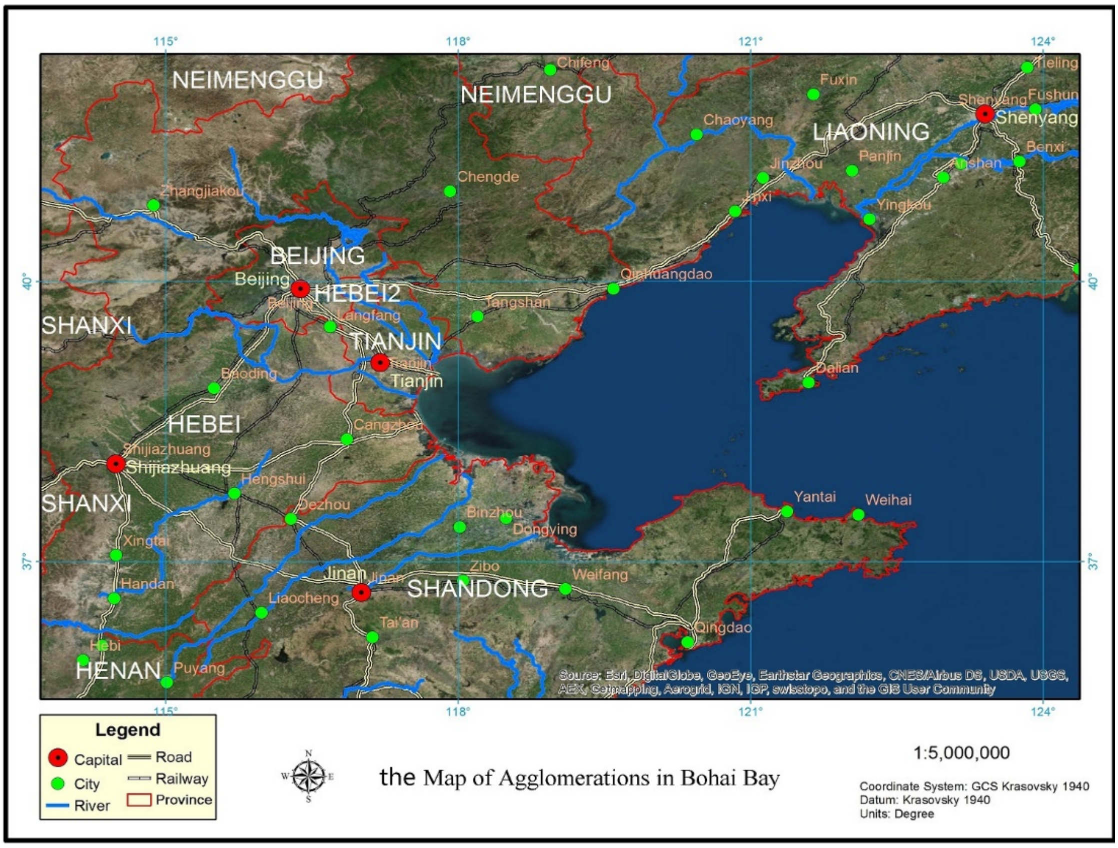


Figure 1. Map of agglomerations in the Bohai Bay city agglomeration.

Due to geological and political advantages, industry and agriculture in Bohai Bay region are comparatively developed. It, as the largest industrial concentration area in China, serves as a heavy industry base, chemical industry base, and export port. Covering North China Plain, the Huang-Huai-Hai Plain, and part of Liaohe Plain, agriculture here is rich in crops such as wheat, grains, cotton, oil seeds, fruit, etc. It has been the economic core zone in northern China and has a total population of 252.33 million with GDP about 15.44 trillion RMB.

However, the current water supply in Bohai Bay region accounts for only about 75% of annual average water resources. What is more, city expansion has brought industrial and agricultural growth, which require far more water. The water shortage issue is worsened by massive industrial and agricultural water pollution. As a result, water quality decline, due to long-time water shortage and water pollution accumulation [86,87], has been a serious impediment to the sustainable development of Bohai Bay city agglomeration.

4.2. Data

With NMWUPI calculation method, this paper has calculated the dynamic total-factor water use efficiency of Bohai Bay region in China during the "twelfth five-year" plan period (2011–2014). Since water is mainly consumed through industry and agriculture, this thesis would measure industrial and agricultural water use efficiency. This research set gross domestic production (GDP) as the desirable output, which is suitable for calculating efficiency at the industrial level.

Bohai Bay city agglomeration includes Beijing City (BJ), Tianjin City (TJ), and part of Shandong province (SD), Liaoning province (LN), and Hebei province (HB). Data on cities of the last three provinces have been partly missed, so they can only be calculated based on currently available data, while data on industrial labor, fixed industry investment, industry water use amount, and industry added value from 2011 to 2014 are from the National Bureau of Statistics of China. To transfer fixed industry investment volume into fixed capital stock, the paper follows the perpetual inventory method, provided by [71]. Capital depreciation is set at 5%. For convenience of comparison, all monetary variables, including added value and capital stock, are converted into 2011 prices. There are many pollutants in discharged wastewater, with COD (chemical oxygen demand) and NH_3-H (ammonia nitrogen) being the two most important. For easier calculation and analysis, this study follows the perspective of gray water footprint, and finds that COD gray water footprint poses a greater threat to water environment in Bohai Bay region, so pollutant COD is selected as the unexpected output. The main part of COD discharge is contributed by agriculture in China [88]. Data on industrial and agricultural wastewater COD discharge from 2011 to 2013 come from China's Environmental Statistics Yearbook, and data in 2014 are measured from the year's average growth rate. Referring to the National Environmental Quality Standards for Surface Water, this paper sets the water standard as the minimum environment water quality requirement for biological survival, namely the National Water Quality Grade III, in which the COD standard concentration is 20 mg/L [89]. Table 1 shows summary statistics of industrial and agricultural inputs and outputs.

Table 1. Summary statistics of inputs and outputs for industry and agriculture, 2011–2014.

Sectors		Units	Max	Min	Mean	Std. Dev
Industry	Capital	Billion CNY	6120.54	75.09	1759.32	1649.37
	Labor	10^4 persons	1762.34	245.12	747.72	544.99
	Water	10^9 m^3	29.75	4.89	17.48	10.53
	GDP	Billion CNY	3202.34	375.25	1366.96	859.95
	COD	Thousand t	194.00	5.58	88.41	67.88
Agriculture	Capital	Billion CNY	358.51	4.72	120.79	113.51
	Labor	10^4 persons	1982.86	56.24	839.33	775.45
	Water	10^9 m^3	154.23	8.18	80.28	61.70
	GDP	Billion CNY	447.42	13.63	193.15	167.24
	COD	Thousand t	1379.73	71.46	654.12	503.43

Notes: unit "t" means metric ton; Std. Dev means Standard Deviation.

5. Results and Discussion

5.1. Results of Water Use Efficiency in Bohai Bay City Agglomeration

NMWUPI in Bohai Bay region shows that industrial and agricultural total-factor water use efficiency have grown during the twelfth five-year plan period, and the industrial average growth rate, which stays around 14.1%, is higher than the average agricultural growth rate of 9.0%. Table 2 has described NMWUPI values of different regions in different periods.

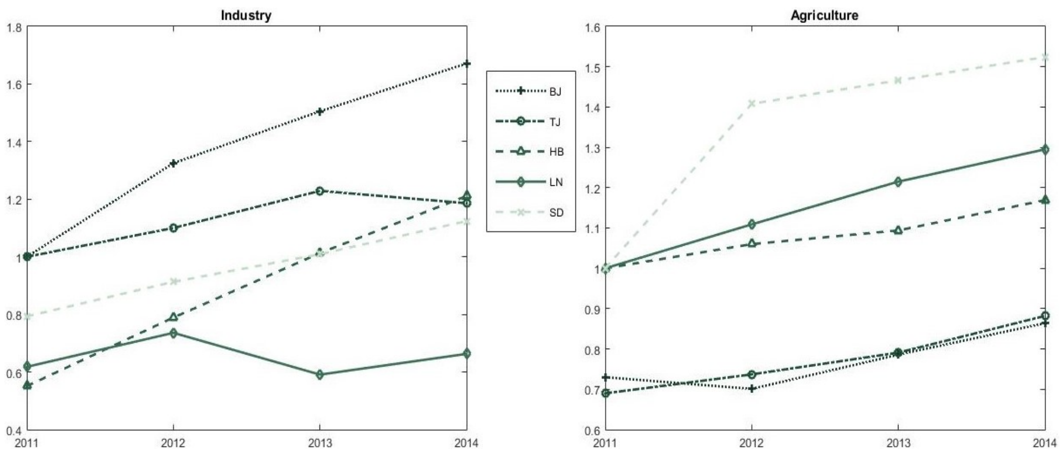
Table 2. Changes in NMWUPI of industry and agriculture, 2011–2014.

	2011–2012		2012–2013		2013–2014		G_{mean}	
	In	**Ag**	**In**	**Ag**	**In**	**Ag**	**In**	**Ag**
BJ	1.325	0.960	1.136	1.120	1.110	1.099	1.187	1.058
TJ	1.100	1.064	1.117	1.073	0.965	1.115	1.059	1.084
HB	1.433	1.060	1.283	1.031	1.196	1.069	1.300	1.053
LN	1.190	1.109	0.803	1.095	1.122	1.066	1.024	1.090
SD	1.151	1.408	1.106	1.042	1.113	1.040	1.123	1.151
Bohai Bay	1.240	1.120	1.089	1.072	1.101	1.078	1.141	1.090

Notes: G_{mean} represents geometric mean; Bohai Bay refers to arithmetic mean of five sub-regions.

Annual industrial water use efficiency grows faster than annual agricultural water use efficiency. The results show that, compared to agricultural water use, there is more technological support for and investment in industrial water use. On the one hand, developing countries are transforming from an agricultural society to an industrial society. Limited water resources are mainly allocated to agricultural water users with priority use rights, so industrial water use has to resort to water saving technology advancement. On the other hand, industry can afford water-saving technology input, and the technology is easy to make widespread. On the contrary, agricultural users' perception of water use is outmoded and stubborn. To make things worse, inefficient agricultural water users are dispersed, which requires the government to assist with agricultural water conservation technology promotion.

The static efficiency in 2011 is regarded as the base point, which is calculated based on Equation (4). Figure 2 has shown industrial and agricultural water use efficiency among sub-regions, which have demonstrated regional water use efficiency and growth speed differences. Generally, when it comes to industrial or agricultural water use efficiency, the five regions can be divided into three groups. Interestingly, regions with a relatively high efficiency usually present faster growth towards efficiency.



(**a**) (**b**)

Figure 2. (**a**) shows changes in industrial water use efficiency among sub regions in Bohai Bay Region; (**b**) shows changes in agricultural water use efficiency among sub regions in Bohai Bay Region.

In terms of industrial water use efficiency, BJ has the best performance, followed by TJ, HB, and SD, while LN's is the worst. Compared with the other four regions, LN has the richest water resources, so there is no motivation for it to improve efficiency.

However, in terms of agricultural water use efficiency, BJ and TJ have the worst performance; SD's is the best, followed by the other two provinces. Agricultural water use efficiency improvement could be directly connected to industrial structure. Agricultural water use in BJ and TJ accounts for just a small portion in the industrial structure. Comparatively, HB and SD lack water, but their agriculture require a large percentage of production, so it is necessary for them to improve agricultural water use efficiency.

For city agglomerations in most developing countries, industrial water use abilities show a distinct technology diffusion effect, especially in city agglomerations with scarce water. In an area with scarce water resources but high agricultural water use, agricultural water use efficiency would be high. This is because agricultural water use efficiency improvement would be driven by the increase of urban and industrial water use supply, represented by cases of agricultural water use efficiency in Xianjiang, China and California, USA. Otherwise, there perhaps would not be enough policy motivation to push agricultural water use efficiency improvement.

This paper evaluates the room for water savings and the corresponding impact on the environment in the following two sections.

5.2. Can Water Use Efficiency Improvement Adapt to Industrial Expansion?

Would regional water resource be sufficient for the rapid expansion of industrial production and increase of population in Bohai Bay? It depends on whether the industrial water use stress can be alleviated over the period. Figure 3 compares water resource amount, total water use amount, and water use amount after maximum water savings of Bohai Bay region during the twelfth five-year plan period. The maximum water savings potential of Bohai Bay region can be seen in Table 3, which suggests that the annual average maximum water savings potential should reach up to 3.371 billion cubic meters.

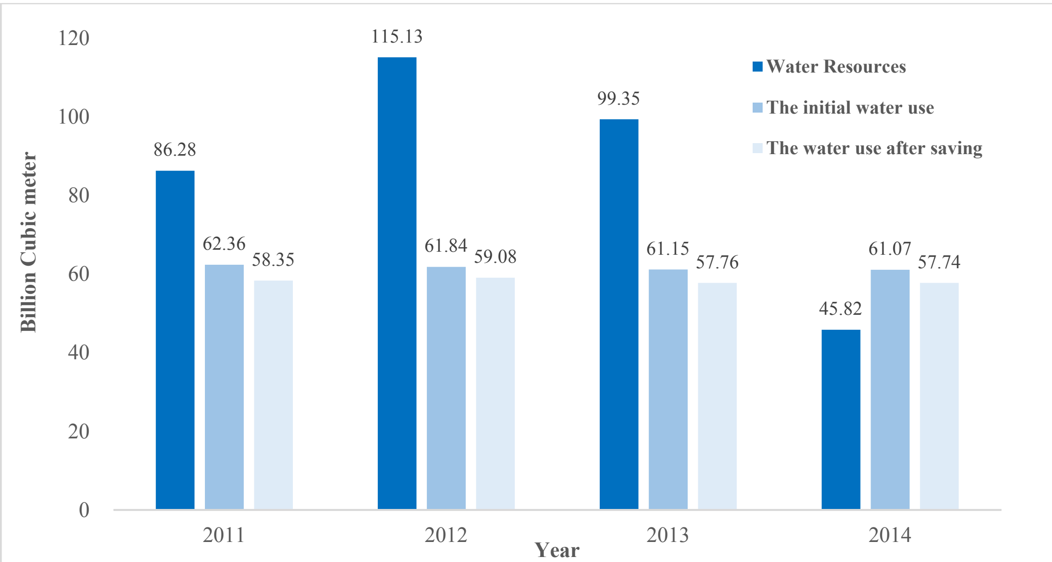


Figure 3. Comparison of water resources amount, initial water use amount, and water use after curtailment of Bohai Bay city agglomeration from 2011 to 2014.

Table 3. Changes of maximum potential savings of water use in Bohai Bay city agglomeration (in billion cubic meters), 2011–2014.

	2011	2012	2013	2014	Mean
BJ	0.464	0.367	0.353	0.291	0.369
TJ	0.516	0.532	0.612	0.544	0.551
HB	0.901	0.798	0.651	0.623	0.743
LN	1.174	1.059	0.942	1.038	1.053
SD	0.949	0	0.838	0.833	0.655
Total	4.005	2.755	3.396	3.329	3.371

It was found that the whole region's industrial water use was reduced over the years, and the region constantly developed towards a resource-conservation community. However, compared to the maximum water savings potential, there is still a need for more improvement in terms of water use reduction. For example, in the drought year of 2014, the total water use amount still surpassed the water resources quantity, showing the fragility of the current so-called sustainability.

As calculated by Equation (13), the results show that water resources in Bohai Bay region are not equally distributed and that local areas face severe water resources shortages. As shown in Table 4, water resources in BJ, TJ, and HB have been over-exploited most of the time, with an average WSI of 105.74%, 131.54%, and 121.58% respectively. After the maximum water use reduction potential, water stress can be greatly alleviated, especially in BJ and TJ, whose WSI have declined by about 10% and 30%. However, the water savings situation is so severe in HB that it is necessary to transfer water from other places, while there are no effective ways to control industrial water use.

Table 4. Changes of water stress index in Bohai Bay city agglomeration, 2011–2014.

	2011		2012		2013		2014		Mean	
	WSI_0	WSI_r	WSI_0	WSI_r	WSI_0	WSI_r	WSI_0	WSI_r	WSI_0	WSI_r
BJ	106.36%	92.63%	76.29%	68.48%	110.78%	100.04%	129.54%	119.50%	105.74%	95.16%
TJ	145.22%	112.74%	66.87%	51.50%	144.17%	107.07%	169.89%	131.51%	131.54%	100.70%
HB	122.65%	117.01%	81.95%	78.61%	106.60%	102.97%	175.10%	169.44%	121.58%	117.01%
LN	48.44%	44.51%	25.83%	23.91%	30.44%	28.42%	94.98%	88.02%	49.92%	46.22%
SD	63.11%	60.44%	79.01%	79.01%	73.18%	70.36%	137.76%	132.41%	88.26%	85.55%
Mean	97.16%	85.46%	65.99%	60.30%	93.03%	81.77%	141.45%	128.18%	99.41%	88.93%

Notes: WSI_0 is the ratio between the total water consumption and water resources before saving; WSI_r is the ratio between the total water use and water resources after maximum potential savings.

5.3. Can Pollution Be Controlled by Water Use Efficiency Improvement?

Water pollution has not only put pressure on water use, but also constrains sustainable development of Bohai Bay region, so pollution reduction in wastewater is of great significance. As shown in Table 5, it is possible to greatly reduce COD discharge. On the whole, it can be reduced by as much as 306 thousand tons on average each year, accounting for about 16% of the total annual average. During the sample period, COD in HB steadily reduced, with an annual average reduction rate of about 4%. However, it has failed to effectively control pollutant discharge so far. City sewage disposal equipment has already been much advanced in BJ and TJ, so there is limited space for COD discharge reduction in two highly urbanized cities whose COD reductions are mainly connected to agriculture. Thus, they must focus more on agricultural non-point pollution. On the contrary, COD reduction in HB, LN, and SD mainly comes from industry, so they should strengthen industrial point pollution emissions control, and commit to sewage treatment development and pipeline building. These findings indicate that the tendency of the COD discharge reduction maximum potential keeps on declining, whether in the whole Bohai Bay region or in individual cities or provinces, which indicates that the government has gradually controlled the pollution discharge.

Table 5. Changes after maximum potential reduction of COD discharge in Bohai Bay city agglomeration (in kilotons), 2011–2014.

	2011	2012	2013	2014	Mean
BJ	28.91	27.51	24.68	24.54	26.41
TJ	54.35	57.14	53.78	52.84	54.53
HB	147.73	139.67	123.64	113.00	131.01
LN	60.76	50.38	49.03	37.10	49.32
SD	42.38	77.83	32.74	25.69	44.66
Total	334.13	352.53	283.86	253.16	305.92

Further, the impact of pollutant discharge change on water environment is discussed. Figure 4 demonstrates changes in total water resource amount, gray water footprint, and gray water footprint after curtailment. It is found that the gray water footprint is on the decline year by year, but it still has a reduction potential of about 10 billion cubic meters. On the whole, wastewater discharge management has attracted great attention, which caused a decline in pollutants in waste discharge. Unfortunately, it cannot meet the requirements of regional sustainable development, especially in the low flow year of 2014, even considering the potential amount of pollution reduction.

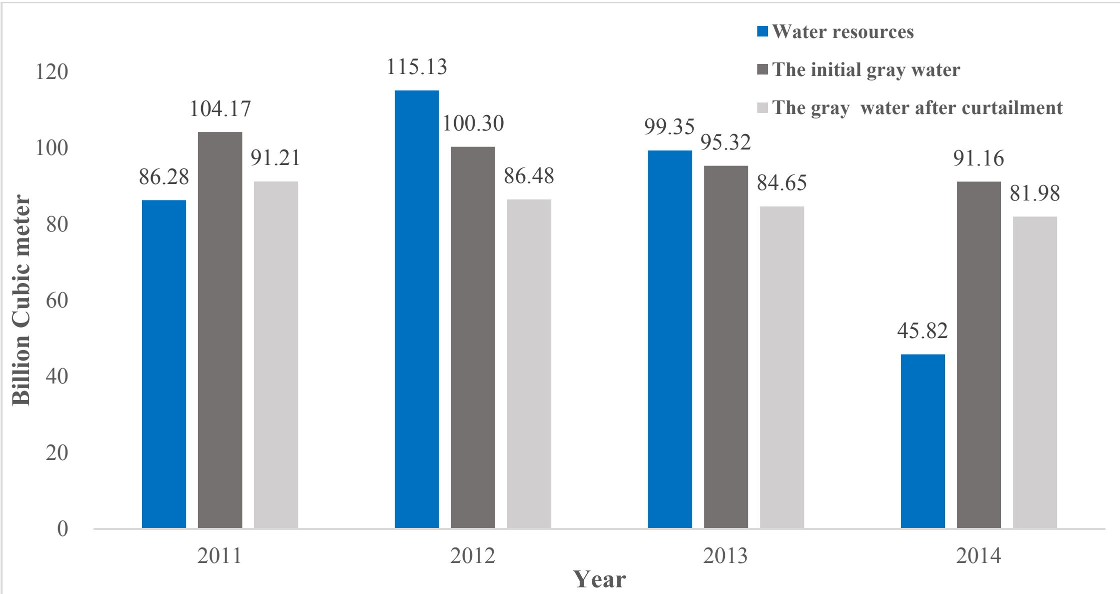


Figure 4. A comparison of water resources amount, the initial gray water footprint, and gray water footprint after curtailment of Bohai Economic Zone from 2011 to 2014.

In general, from the perspective of the individual city or province, water pollution is still serious, as shown as Table 6. Except for LN, there is a great water pollution threat in the other four cities and provinces, whose comprehensive water resource degradation possibilities are 3.47 (TJ), 1.63 (BJ), 1.60 (HB), and 1.39 (SD), respectively. Even after the maximum reduction potential, water degradation threats are still there. The reasons are the lack of wastewater disposal facilities in most rural areas, the inefficiency of city wastewater disposal facilities, and a failure to reach safe discharge standards even after disposal [90,91]. The situation is complicated by national low water quality standards [92]. Cumulatively, a large quantity of wastewater has been directly discharged, resulting in water body pollution and water environment degradation [91]. More seriously, low water quality and insufficient water quantity for a long time would lead to two grave consequences. One is that the water demand for agricultural production can only be met by wastewater irrigation, which poses a great threat to food safety [93,94]. The other is that rural drinking water safety cannot be ensured because underground water is the only drinking water source for many rural areas [92].

Table 6. Changes of water gradation possibility in Bohai Bay city agglomeration, 2011–2014.

	2011		**2012**		**2013**		**2014**		**Mean**	
	WDP_0	**WDP_R**	**WDP_0**	**WDP_R**	**WDP_0**	**WDP_R**	**WDP_0**	**WDP_R**	**WDP_0**	**WDP_R**
BJ	1.77	1.73	1.23	1.20	1.69	1.66	1.81	1.76	1.63	1.59
TJ	4.17	4.00	1.83	1.75	3.72	3.56	4.14	3.95	3.47	3.31
HB	1.70	1.23	1.10	0.80	1.41	1.06	2.19	1.68	1.60	1.19
LN	0.92	0.82	0.48	0.43	0.52	0.47	1.56	1.44	0.87	0.79
SD	1.04	0.98	1.27	1.13	1.14	1.09	2.09	2.01	1.39	1.30
Mean	1.92	1.75	1.18	1.06	1.70	1.57	2.36	2.17	1.79	1.64

Notes: WDP_0 and WDP_R represent the value of water gradation possibility before reducing and after reducing, respectively.

Therefore, a constant improvement of wastewater management is required in the Bohai Bay region. First, it is urgent to spread wastewater disposal facilities in rural areas and improve the efficiency of cities' wastewater disposal facilities. Second, the construction of rural drinking water projects and monitoring of water quality should be improved as soon as possible, to ensure rural drinking water safety. Third, the pollutant sources should be strictly controlled through strengthening recycling of industrial waste and reducing the use of chemical fertilizers and pesticides. Fourth, besides technological improvements, institutions should be leading with social, political, economic, and behavioral changes to ensure water quality and water quantity [95].

5.4. Directions to Improve Water Use Efficiency in the Bohai Bay Region

In the above, for calculating the potential reduction of water use and pollutants, the research has assumed that inefficient water use could be improved. But how to improve water use efficiency? Based on Equations (8) and (9), NMWUPI in Bohai Bay region can be explained from the two aspects of EC and TC. So, there are two directions to improve water use efficiency, which are institutional construction and technological upgrades.

On the one hand, urban water use efficiency improvement depends on new technology investment. Table 7 presents the results of TC. In the whole Bohai Bay region, the annual average growth rates of industrial and agricultural TC are 11.1% and 8.6%, respectively, which suggests that technological upgrades have occurred during the period of the twelfth five-year plan, but the speed of industrial technological progress is faster than that of agriculture. Industrial TC of BJ increased the fastest, with an annual average growth rate of 18.7%, followed by HB with an annual average growth rate of 13.1%. While the annual average growth rate of agricultural TC of SD is 15.1%, the fastest among the five cities and provinces, the rest were 2.7% for BJ, 9.6% for TJ, 5.3% for HB, and 9.0% for LN.

Table 7. TC components of NMWUPI of industry and agriculture, 2004–2013.

	2011–2012		**2012–2013**		**2013–2014**		**G_{mean}**	
	In	**Ag**	**In**	**Ag**	**In**	**Ag**	**In**	**Ag**
BJ	1.325	0.912	1.136	1.097	1.110	1.082	1.187	1.027
TJ	1.100	1.100	1.117	1.099	0.965	1.090	1.059	1.096
HB	1.188	1.060	1.119	1.031	1.087	1.069	1.131	1.053
LN	1.046	1.109	1.126	1.095	1.083	1.066	1.085	1.090
SD	1.101	1.408	1.090	1.042	1.078	1.040	1.090	1.151
Bohai Bay	1.152	1.118	1.118	1.073	1.065	1.069	1.111	1.086

Notes: G_{mean} represents the geometric mean; Bohai Bay refers to the arithmetic mean of the five sub-regions.

On the other hand, water use institution construction would directly affect water use efficiency. As shown in Table 8, the average EC indexes of industrial and agricultural are larger than 1, and their annual average increase rates are 2.8% and 0.4%, respectively, which indicates a slight improvement in industrial and agricultural technical efficiency in the whole region. Each year, industrial EC is better than agricultural EC. In 2011–2012 and 2012–2013, agricultural EC in TJ showed a slightly negative growth, thus affecting the whole region's agricultural EC.

Table 8. EC components of NMWUPI of industry and agriculture, 2011–2014.

	2011–2012		2012–2013		2013–2014		G_{mean}	
	In	Ag	In	Ag	In	Ag	In	Ag
BJ	1.000	1.053	1.000	1.021	1.000	1.016	1.000	1.030
TJ	1.000	0.967	1.000	0.977	1.000	1.023	1.000	0.989
HB	1.206	1.000	1.147	1.000	1.100	1.000	1.150	1.000
LN	1.138	1.000	0.713	1.000	1.036	1.000	0.944	1.000
SD	1.045	1.000	1.015	1.000	1.032	1.000	1.030	1.000
Bohai Bay	1.078	1.004	0.975	1.000	1.034	1.008	1.028	1.004

Notes: G_{mean} represents the geometric mean; Bohai Bay refers to the arithmetic mean of the five sub-regions.

From the perspective of individual cities or provinces, industrial EC in HB and SD have increased by 15.0% and 3.0%, respectively, while LN has declined by 5.6%, mainly for its negative growth in the whole period from 2011 to 2014. Industrial EC in BJ and TJ showed no change because their industry is the most developed in the Bohai Bay region, so there is little room for improvement. As to agriculture, contrary to industry, HB, LN, and SD, which have a mature agricultural industry, show no sign of EC. Therefore, it is believed that BJ and TJ should attach more importance to the improvement of agricultural water use technological efficiency change, while HE, LN, and SD should attach more importance to industrial water use technological upgrades.

Overall, water use efficiency in Bohai Bay region keeps on growing from 2011 to 2014. NMWUPI, whether of the whole Bohai Bay region or of the individual city or province, is more affected by TC than by EC. This means that the Bohai Bay city agglomeration has failed to improve water use efficiency through institutional reform, but relied more on investment in water use infrastructure and upgrades of water use technology. Theoretically and practically, water issues in developing countries have something in common: during the construction of city agglomeration, water use stress can be temporarily alleviated by investment in technological upgradation rather than institution construction. At the current environmental production technology frontier, there is little space for industrial water savings in BJ and TJ, and future water saving mainly depends on agriculture. On the contrary, water saving in HB, LN, and SD is from industry, but there is little space for further savings. With the rapid urbanization and industry modernization in China, water conservation technology has also been applied step by step, such as cycling use of water and improvement of pipeline administration, etc., so HB, LN, and SD perhaps achieve their industrial water conservation objectives.

Theoretically, the best way to solve the water shortage problem in the Bohai Bay region is to control agricultural water use by promoting technological input, but the potential for water savings is limited in the current system. The twelfth five-year plan has long suggested agriculture modernization, but water conservation hardware facility and advanced management have failed to prevail in agriculture. Rural water conservancy facilities in China are not enough to meet the growing demand for food production. Compared with developed countries, the irrigated land area is far more smaller [90] and water irrigation management ability is undeveloped in China [94]. What is more, surface water in Bohai Bay region cannot support agricultural production. Much underground water has been exploited, and the underground funnel from over-exploitation poses a great threat to the local water ecological environment, represented by TJ. Thus, in Bohai Bay region with its large-scale agriculture, it is urgent to promote the application of agricultural water conservation technology and institution construction, which would reduce water use stress to a large extent.

In China, agricultural water management develops slower than industrial water management, and agriculture consumes more water and produces more pollution in wastewater discharge than industry [90]. After the twelfth five-year plan, much importance was attached to agricultural modernization, to solve the problem of high water consumption and pollution. Stricter supervision and regulations are placed on water utilization and pollutant discharge in the process of agricultural production. China's National Statistics Bureau has improved regulative surveys and statistics on pollutants in agricultural wastewater since 2011 [96].

6. Conclusions

With the rapid expansion of city agglomeration, only a joint effort of government, market units, and the public can ensure sustainable development. This paper takes the NMWUPI method, constructed by non-radial directional distance function and the Malmquist production index, to evaluate industrial water use against a backdrop of expanding city agglomeration. Water savings potential and pollutant discharge reduction potential are measured through adjusting slacks, while water use efficiency change is explained by the two indexes of EC and TC.

In terms of NMWUPI, there are two limits to calculating water use efficiency. The efficiency, calculated by the multi-input model, is a relative value. Given the assumption of potential space of water saving and pollutants reduction, the water use efficiency is harder to be improved in the model. However, in practice, this may not be the case. In addition, the heterogeneity of DMUs is not considered in the method. So, some DMUs' maximum potential reduction could be overestimated or underestimated.

As a representative of city agglomeration in a developing country, Bohai Bay region in China is taken as a case study, and the research results can be applied to water demand management in other city agglomerations.

1. Rapid economic and social development of city agglomeration has generated water use crises and pollutant emissions crises, which lead to severe water degradation stress, especially in undeveloped areas where the water resources are not rich enough to support the developing of a city agglomeration, while technological progress alone cannot fully solve a local water crisis issue.
2. With the rapid expansion of the city agglomeration, under the great water use stress, industry water use efficiency would be greatly improved because newly added industry water use would be limited while agricultural water consumers compete with each other for water. During the sample periods, water use efficiency in Bohai Bay region has grown, but agricultural water use efficiency is not as good as the industrial one. As industry improves, administrators should place more attention on agricultural water use.
3. Technological investment and institution innovation are of the same importance when solving water problems in city agglomerations. Ignoring any one of them would pose potential risks to sustainable development. The water use efficiency of each city and province in Bohai Bay region is found to be greatly influenced by TC but lightly by EC, which shows that water use efficiency improvement in Bohai Bay region depends more on technological upgradation than on institution improvement.
4. Available water reduction caused by pollution is a serious threat to rapidly developed city agglomerations. Due to massive waste in those city agglomerations, water and soil resources have been severely polluted, endangering sustainable development. As to water pollution in Bohai Bay region, the pollution is so striking that even after the maximum reduction potential the effects are still not satisfactory. Also, agriculture contributes more pollutants than industry. So, resolving non-point pollution is the key to preventing environmental degradation.

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References

1. Brar, R.; Brar, S. Causes, Characteristics and Solutions to the Water Crisis in Delhi. *J. Dev. Manag. Commun.* **2014**, *1*, 163–173.
2. Kumar, P. *Micro-Zonation of Environmentally Stressed Areas, Due to Air and Water Pollution in Delhi, Using Remote Sensing and GIS Techniques*; Jawaharlal Nehru University: New Delhi, India, 2014; Available online: http://shodhganga.inflibnet.ac.in:8080/jspui/handle/10603/16245 (accessed on 22 September 2016).
3. Adhya, S. Vulnerability of groundwater in three megacities of India. *Int. J. Ecosyst.* **2015**, *5*, 93–96.
4. Nobre, C.A.; Marengo, J.A.; Seluchi, M.E.; Cuartas, L.A.; Alves, L.M. Some characteristics and impacts of the drought and water crisis in Southeastern Brazil during 2014 and 2015. *J. Water Resour. Prot.* **2016**, *8*, 252–262. [CrossRef]
5. Varis, O.; Vakkilainen, P. China's 8 challenges to water resources management in the first quarter of the 21st Century. *Geomorphology* **2001**, *41*, 93–104. [CrossRef]
6. Liu, C.; Xia, J. Water problems and hydrological research in the Yellow River and the Huai and Hai River basins of China. *Hydrol. Processes* **2004**, *18*, 2197–2210. [CrossRef]
7. Wang, W.; Gao, L.; Liu, P.; Hailu, A. Relationships between regional economic sectors and water use in a water-scarce area in China: A quantitative analysis. *J. Hydrol.* **2014**, *515*, 180–190. [CrossRef]
8. Vairavamoorthy, K.; Gorantiwar, S.D.; Pathirana, A. Managing urban water supplies in developing countries–Climate change and water scarcity scenarios. *Phys. Chem. Earth Parts A/B/C* **2008**, *33*, 330–339. [CrossRef]
9. Bach, P.M.; Rauchb, W.; Mikkelsenc, P.S.; McCarthya, D.T.; Deletica, A. A critical review of integrated urban water modelling—Urban drainage and beyond. *Environ. Model. Softw.* **2014**, *54*, 88–107. [CrossRef]
10. Hadipuro, W.; Wiering, M.; van Naerssen, T. The sustainability of urban water supply in low income countries: A livelihoods model. *J. Water Sanit. Hyg. Dev.* **2013**, *3*, 156–164. [CrossRef]
11. Pincetl, S.; Porse, E.; Cheng, D. Fragmented flows: Water supply in Los Angeles County. *Environ. Manag.* **2016**, *58*, 208–222. [CrossRef] [PubMed]
12. Agudelo-Vera, C.M.; Mels, A.R.; Keesman, K.J.; Rijnaarts, H.H. Resource management as a key factor for sustainable urban planning. *J. Environ. Manag.* **2011**, *92*, 2295–2303. [CrossRef] [PubMed]
13. Steffen, J.; Jensen, M.; Pomeroy, C.A.; Burian, S.J. Water supply and stormwater management benefits of residential rainwater harvesting in US cities. *JAWRA J. Am. Water Resour. Assoc.* **2013**, *49*, 810–824. [CrossRef]
14. Hoff, H.; Döll, P.; Fader, M.; Gerten, D.; Hauser, S.; Siebert, S. Water footprints of cities–indicators for sustainable consumption and production. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 213–226. [CrossRef]
15. Manzardo, A.; Loss, A.; Fialkiewicz, W.; Rauch, W.; Scipioni, A. Methodological proposal to assess the water footprint accounting of direct water use at an urban level: A case study of the Municipality of Vicenza. *Ecol. Indic.* **2016**, *69*, 165–175. [CrossRef]
16. Paterson, W.; Rushforth, R.; Ruddell, B.L.; Konar, M.; Ahams, I.C.; Gironás, J.; Mejia, A. Water footprint of cities: A review and suggestions for future research. *Sustainability* **2015**, *7*, 8461–8490. [CrossRef]
17. Jiang, Y.; Chen, Y.; Younos, T.; Huang, H.; He, J. Urban water resources quota management: The core strategy for water demand management in China. *Ambio* **2010**, *39*, 467–475. [CrossRef] [PubMed]
18. Makki, A.A.; Stewart, R.A.; Panuwatwanich, K.; Beal, C. Revealing the determinants of shower water end use consumption: Enabling better targeted urban water conservation strategies. *J. Clean. Prod.* **2013**, *60*, 129–146. [CrossRef]
19. Malinowski, P.A.; Stillwell, A.S.; Wu, J.S.; Schwarz, P.M. Energy-water nexus: Potential energy savings and implications for sustainable integrated water management in urban areas from rainwater harvesting and gray-water reuse. *J. Water Resour. Plan. Manag.* **2015**, *141*, A4015003. [CrossRef]
20. Lee, M.; Tansel, B.; Balbin, M. Urban sustainability incentives for residential water conservation: Adoption of multiple high efficiency appliances. *Water Resour. Manag.* **2013**, *27*, 2531–2540. [CrossRef]
21. Huang, C.L.; Vause, J.; Ma, H.W.; Yu, C.P. Urban water metabolism efficiency assessment: Integrated analysis of available and virtual water. *Sci. Total Environ.* **2013**, *452*, 19–27. [CrossRef] [PubMed]
22. Sun, C.; Zhao, L.; Zou, W.; Zheng, D. Water resource utilization efficiency and spatial spillover effects in China. *J. Geogr. Sci.* **2014**, *24*, 771–788. [CrossRef]

23. Chen, Y.T.; Chen, C.C. An analysis of domestic water management performance across regions in Taiwan. *Water Policy* **2014**, *16*, 704–719. [CrossRef]
24. Bian, Y.; Yan, S.; Xu, H. Efficiency evaluation for regional urban water use and wastewater decontamination systems in China: A DEA approach. *Resour. Conserv. Recycl.* **2014**, *83*, 15–23. [CrossRef]
25. Shi, T.; Zhang, X.; Du, H.; Shi, H. Urban water resource utilization efficiency in China. *Chin. Geogr. Sci.* **2015**, *25*, 684–697. [CrossRef]
26. Dong, H.; Geng, Y.; Sarkis, J.; Fujita, T.; Okadera, T.; Xue, B. Regional water footprint evaluation in China: A case of Liaoning. *Sci. Total Environ.* **2013**, *442*, 215–224. [CrossRef] [PubMed]
27. Gurung, T.R.; Stewart, R.A.; Beal, C.D.; Sharma, A.K. Smart meter enabled water end-use demand data: Platform for the enhanced infrastructure planning of contemporary urban water supply networks. *J. Clean. Prod.* **2015**, *87*, 642–654. [CrossRef]
28. Noiva, K.; Fernández, J.E.; Wescoat, J.L. Cluster analysis of urban water supply and demand: Toward large-scale comparative sustainability planning. *Sustain. Cities Soc.* **2016**, *27*, 484–496. [CrossRef]
29. Sharma, S.K.; Vairavamoorthy, K. Urban water demand management: Prospects and challenges for the developing countries. *Water Environ. J.* **2009**, *23*, 210–218. [CrossRef]
30. Niemczynowicz, J. Urban hydrology and water management—Present and future challenges. *Urban Water* **1999**, *1*, 1–14. [CrossRef]
31. Newlin, B.D.; Jenkins, M.W.; Lund, J.R.; Howitt, R.E. Southern California water markets: Potential and limitations. *J. Water Resour. Plan. Manag.* **2002**, *128*, 21–32. [CrossRef]
32. Hanak, E. *Who Should Be Allowed To Sell Water in California? Third-Party Issues and the Water Market*; Public Policy Institute of California: San Francisco, CA, USA, 2003.
33. Araujo, R.S.; Alves, M.D.; de Melo, M.T.C.; Chrispim, Z.M.P.; Mendes, M.P.; Silva, G.C. Water resource management: A comparative evaluation of Brazil, Rio de Janeiro, the European Union, and Portugal. *Sci. Total Environ.* **2015**, *511*, 815–828. [CrossRef] [PubMed]
34. Qureshi, M.E.; Grafton, R.Q.; Kirby, M.; Hanjra, M.A. Understanding irrigation water use efficiency at different scales for better policy reform: A case study of the Murray-Darling Basin, Australia. *Water Policy* **2011**, *13*, 1–17. [CrossRef]
35. Marlow, R.J. Agriculture water use efficiency in the United States. In Proceedings of the US/China Water Resources Management Conference, Tucson, Arizona, USA, 19–23 April 1999.
36. Hu, J.L.; Wang, S.C.; Yeh, F.Y. Total-factor water efficiency of regions in China. *Resour. Policy* **2006**, *31*, 217–230. [CrossRef]
37. Thanassoulis, E. The use of data envelopment analysis in the regulation of UK water utilities: Water distribution. *Eur. J. Oper. Res.* **2000**, *126*, 436–453. [CrossRef]
38. Lilienfeld, A.; Asmild, M. Estimation of excess water use in irrigated agriculture: A data envelopment analysis approach. *Agric. Water Manag.* **2007**, *94*, 73–82. [CrossRef]
39. Yilmaz, B.; Yurdusev, M.A.; Harmancioglu, N.B. The assessment of irrigation efficiency in Buyuk Menderes Basin. *Water Resour. Manag.* **2009**, *23*, 1081–1095. [CrossRef]
40. Veettil, P.C.; Speelman, S.; Van Huylenbroeck, G. Estimating the impact of water pricing on water use efficiency in semi-arid cropping system: An application of probabilistically constrained nonparametric efficiency analysis. *Water Resour. Manag.* **2013**, *27*, 55–73. [CrossRef]
41. Ananda, J. Evaluating the performance of urban water utilities: Robust nonparametric approach. *J. Water Resour. Plan. Manag.* **2013**, *140*, 04014021. [CrossRef]
42. Ali, M.K.; Klein, K.K. Water use efficiency and productivity of the irrigation districts in Southern Alberta. *Water Resour. Manag.* **2014**, *28*, 2751–2766. [CrossRef]
43. Azad, M.A.; Ancev, T. Measuring environmental efficiency of agricultural water use: A Luenberger environmental indicator. *J. Environ. Manag.* **2014**, *145*, 314–320. [CrossRef] [PubMed]
44. Wang, Y.; Bian, Y.; Xu, H. Water use efficiency and related pollutants' abatement costs of regional industrial systems in China: A slacks-based measure approach. *J. Clean. Prod.* **2015**, *101*, 301–310. [CrossRef]
45. Molden, D.; Bin, D.; Loeve, R.; Barker, R.; Tuong, T.P. Agricultural water productivity and savings: Policy lessons from two diverse sites in China. *Water Policy* **2007**, *9*, 29–44. [CrossRef]
46. Zhong, R.; Dong, X.; Ma, Y. Sustainable water saving: New concept of modern agricultural water saving, starting from development of Xinjiang's agricultural irrigation over the last 50 years. *Irrig. Drain.* **2009**, *8*, 383–392.

47. Christian-Smith, J.; Cooley, H.; Gleick, P.H. Potential water savings associated with agricultural water efficiency improvements: A case study of California, USA. *Water Policy* **2012**, *14*, 194–213. [CrossRef]
48. Ahmad, M.U.D.; Masah, I.; Giordano, M. Constraints and opportunities for water savings and increasing productivity through Resource Conservation Technologies in Pakistan. *Agric. Ecosyst. Environ.* **2014**, *187*, 106–115. [CrossRef]
49. Horst, M.G.; Shamutalov, S.S.; Goncalves, J.M.; Pereira, L.S. Assessing impacts of surge-flow irrigation on water saving and productivity of cotton. *Agric. Water Manag.* **2007**, *87*, 115–127. [CrossRef]
50. Gu, A.; Teng, F.; Lv, Z. Exploring the nexus between water saving and energy conservation: Insights from industry sector during the 12th Five-Year Plan period in China. *Renew. Sustain. Energy Rev.* **2016**, *59*, 28–38. [CrossRef]
51. Ripa, M.N.; Leone, A.; Garnier, M.; Porto, A.L. Agricultural land use and best management practices to control nonpoint water pollution. *Environ. Manag.* **2006**, *38*, 253–266. [CrossRef] [PubMed]
52. Pillay, A.E.; Yaghi, B.; Williams, J.R.; Al-Kindy, S. Mercury pollution from irrigation with treated sewage water (TSW). *J. Water Health* **2007**, *5*, 315–322. [CrossRef] [PubMed]
53. Wang, M.; Webber, M.; Finlayson, B.; Barnett, J. Rural industries and water pollution in China. *J. Environ. Manag.* **2008**, *86*, 648–659. [CrossRef]
54. Maxted, J.T.; Diebel, M.W.; Vander Zanden, M.J. Landscape planning for agricultural non–point source pollution reduction. II. Balancing watershed size, number of watersheds, and implementation effort. *Environ. Manag.* **2009**, *43*, 60–68. [CrossRef] [PubMed]
55. Panagopoulos, Y.; Makropoulos, C.; Mimikou, M. Reducing surface water pollution through the assessment of the cost-effectiveness of BMPs at different spatial scales. *J. Environ. Manag.* **2011**, *92*, 2823–2835. [CrossRef] [PubMed]
56. Zhang, R.; Qian, X.; Li, H.; Yuan, X.; Ye, R. Selection of optimal river water quality improvement programs using QUAL2K: A case study of Taihu Lake Basin, China. *Sci. Total Environ.* **2012**, *431*, 278–285. [CrossRef] [PubMed]
57. Smith, L.E.D.; Siciliano, G. A comprehensive review of constraints to improved management of fertilizers in China and mitigation of diffuse water pollution from agriculture. *Agric. Ecosyst. Environ.* **2015**, *209*, 15–25. [CrossRef]
58. Wardropper, C.B.; Chang, C.; Rissman, A.R. Fragmented water quality governance: Constraints to spatial targeting for nutrient reduction in a Midwestern USA watershed. *Landsc. Urban Plan.* **2015**, *137*, 64–75. [CrossRef]
59. Pu, Z.; Wang, H.; Bian, H.; Fu, J. Sustainable lake basin water resource governance in China: The case of Tai Lake. *Sustainability* **2015**, *7*, 16422–16434. [CrossRef]
60. Coelli, T. *A Guide to DEAP Version 2.1: A Data Envelopment Analysis (Computer) Program*; Centre for Efficiency and Productivity Analysis: Armidale, New South Wales, Australia, 1996.
61. Fukuyama, H.; Weber, W.L. A directional slacks-based measure of technical inefficiency. *Socio-Econ. Plan. Sci.* **2009**, *43*, 274–287. [CrossRef]
62. Zhou, P.; Ang, B.W.; Han, J.Y. Total factor carbon emission performance: A Malmquist index analysis. *Energy Econ.* **2010**, *32*, 194–201. [CrossRef]
63. Färe, R.; Grosskopf, S. Modeling undesirable factors in efficiency evaluation: Comment. *Eur. J. Oper. Res.* **2004**, *157*, 242–245. [CrossRef]
64. Färe, R.; Grosskopf, S.; Lovell, C.K.; Pasurka, C. Multilateral productivity comparisons when some outputs are undesirable: A nonparametric approach. *Rev. Econ. Stat.* **1989**, *71*, 90–98. [CrossRef]
65. Färe, R.; Grosskopf, S. *New Directions: Efficiency and Productivity*; Springer Science & Business Media: New York, NY, USA, 2006; Volume 3.
66. Färe, R.; Grosskopf, S.; Pasurka, C.A. Environmental production functions and environmental directional distance functions. *Energy* **2007**, *32*, 1055–1066. [CrossRef]
67. Macpherson, A.J.; Principe, P.P.; Smith, E.R. A directional distance function approach to regional environmental–economic assessments. *Ecol. Econ.* **2010**, *69*, 1918–1925. [CrossRef]
68. Chambers, R.G.; Chung, Y.; Färe, R. Benefit and distance functions. *J. Econ. Theory* **1996**, *70*, 407–419. [CrossRef]
69. Chung, Y.H.; Färe, R.; Grosskopf, S. Productivity and undesirable outputs: A directional distance function approach. *J. Environ. Manag.* **1997**, *51*, 229–240. [CrossRef]

70. Zhou, P.; Ang, B.W.; Wang, H. Energy and CO_2 emission performance in electricity generation: A non-radial directional distance function approach. *Eur. J. Oper. Res.* **2012**, *221*, 625–635. [CrossRef]
71. Zhang, N.; Zhou, P.; Kung, C.C. Total-factor carbon emission performance of the Chinese transportation industry: A bootstrapped non-radial Malmquist index analysis. *Renew. Sustain. Energy Rev.* **2015**, *41*, 584–593. [CrossRef]
72. Malmquist, S. Index numbers and indifference surfaces. *Trab. Estad. Investig. Oper.* **1953**, *4*, 209–242. [CrossRef]
73. Caves, D.W.; Christensen, L.R.; Diewert, W.E. Multilateral comparisons of output, input, and productivity using superlative index numbers. *Econ. J.* **1982**, *92*, 73–86. [CrossRef]
74. Färe, R.; Grosskopf, S.; Norris, M.; Zhang, Z. Productivity growth, technical progress, and efficiency change in industrialized countries. *Am. Econ. Rev.* **1994**, *84*, 66–83.
75. Førsund, F.R.; Kittelsen, S.A. Productivity development of Norwegian electricity distribution utilities. *Resour. Energy Econ.* **1998**, *20*, 207–224. [CrossRef]
76. Gardner, G.T.; Stern, P.C. *Environmental Problems and Human Behavior*; Allyn & Bacon: Boston, MA, USA, 1996.
77. Lee, M.; Tansel, B. Water conservation quantities vs. customer opinion and satisfaction with water efficient appliances in Miami, Florida. *J. Environ. Manag.* **2013**, *128*, 683–689. [CrossRef] [PubMed]
78. Sun, S.; Wang, Y.; Engel, B.A.; Wu, P. Effects of virtual water flow on regional water resources stress: A case study of grain in China. *Sci. Total Environ.* **2016**, *550*, 871–879. [CrossRef] [PubMed]
79. Núñez, M.; Pfister, S.; Vargas, M.; Antón, A. Spatial and temporal specific characterisation factors for water use impact assessment in Spain. *Int. J. Life Cycle Assess.* **2015**, *20*, 128–138.
80. Milano, M.; Reynard, E.; Köplin, N.; Weingartner, R. Climatic and anthropogenic changes in Western Switzerland: Impacts on water stress. *Sci. Total Environ.* **2015**, *536*, 12–24. [CrossRef] [PubMed]
81. Berger, M.; van der Ent, R.; Eisner, S.; Bach, V.; Finkbeiner, M. Water accounting and vulnerability evaluation (WAVE): Considering atmospheric evaporation recycling and the risk of freshwater depletion in water footprinting. *Environ. Sci. Technol.* **2014**, *48*, 4521–4528. [CrossRef] [PubMed]
82. Boulay, A.M.; Bulle, C.; Bayart, J.B.; Deschênes, L.; Margni, M. Regional characterization of freshwater use in LCA: Modeling direct impacts on human health. *Environ. Sci. Technol.* **2011**, *45*, 8948–8957. [CrossRef] [PubMed]
83. Hoekstra, A.Y.; Mekonnen, M.M. The water footprint of humanity. *Proc. Natl. Acad. Sci.* **2012**, *109*, 3232–3237. [CrossRef] [PubMed]
84. Mekonnen, M.M.; Hoekstra, A.Y. Global gray water footprint and water pollution levels related to anthropogenic nitrogen loads to fresh water. *Environ. Sci. Technol.* **2015**, *49*, 12860–12868. [CrossRef] [PubMed]
85. Hoekstra, A.Y.; Chapagain, A.K.; Aldaya, M.M.; Mekonnen, M.M. *The Water Footprint Assessment Manual: Setting the Global Standard*; Earthscan: London, UK, 2011.
86. Cai, X. Water stress, water transfer and social equity in Northern China—Implications for policy reforms. *J. Environ. Manag.* **2008**, *87*, 14–25. [CrossRef] [PubMed]
87. Jiang, Y. China's water scarcity. *J. Environ. Manag.* **2009**, *90*, 3185–3196. [CrossRef] [PubMed]
88. National Bureau of Statistics; Ministry of Environmental Protection; Ministry of Agriculture. *The First National Pollution Census Bulletin*; China Statistics Press: Beijing, China, 2010.
89. *Environmental Quality Standards for Surface Water, GB3838-2002*; China Environmental Science Press: Beijing, China, 2002.
90. Jin, L.; Zhang, G.; Tian, H. Current state of sewage treatment in China. *Water Res.* **2014**, *66*, 85–98. [CrossRef] [PubMed]
91. Jiang, Y. China's water security: Current status, emerging challenges and future prospects. *Environ. Sci. Policy* **2015**, *54*, 106–125. [CrossRef]
92. Yu, X.; Geng, Y.; Heck, P.; Xue, B. A review of China's rural water management. *Sustainability* **2015**, *7*, 5773–5792. [CrossRef]
93. Hassan, N.U.; Mahmood, Q.; Waseem, A.; Irshad, M.; Pervez, A. Assessment of heavy metals in wheat plants irrigated with contaminated wastewater. *Pol. J. Environ. Stud.* **2013**, *22*, 115–123.
94. Lu, Y.; Song, S.; Wang, R.; Liu, Z.; Meng, J.; Sweetman, A.J.; Wang, T. Impacts of soil and water pollution on food safety and health risks in China. *Environ. Int.* **2015**, *77*, 5–15. [CrossRef] [PubMed]

95. Moore, M.L.; von der Porten, S.; Plummer, R.; Brandes, O.; Baird, J. Water policy reform and innovation: A systematic review. *Environ. Sci. Policy* **2014**, *38*, 263–271. [CrossRef]
96. National Bureau of Statistics; Ministry of Environmental Protection. *China Statistical Yearbook on Environment*; China Statistics Press: Beijing, China, 2014.