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Water use efficiency and related pollutants' abatement costs of regional industrial systems in China: a slacks-based measure approach

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ABSTRACT

Water saving and wastewater cleaning are two important ways to alleviate water shortage crisis in China. This paper aims to examine water use efficiency and abatement costs of two main pollutants in wastewater, i.e., chemical oxygen demand (COD) and ammonia nitrogen (NH_4–N), of regional industrial systems in China. For this purpose, a slacks-based measure model based on the assumption of undesirable output weak disposability is developed. Based on the proposed model, the measures of water saving potential, COD reduction potential, NH_4–N reduction potential, COD abatement cost and NH_4–N abatement cost are presented. We apply the proposed approaches to investigate water use efficiency, water saving potential, the two pollutants' reduction potentials and their related abatement costs during 2009–2010. Results of the application show that there are great potentials to reduce water consumption and pollutants' discharges in China's regional industrial production process, and there exist evident geographic disparities in water saving potentials, pollutants' reduction potentials and their abatement costs. It is found that water use efficiency increases from 2009 to 2010, while pollutants abatement costs decrease. Some other findings and implications for efficiency improvement of China's regional industrial systems in water management and pollutants' abatement are achieved.

1. Introduction

The renewable water resource in China is estimated to be approximately 2812.4 billion m^3 per year, which accounts for about 6% of total fresh water resource of the whole world. Due to the largest population in the world (i.e., 1.3 billion inhabitants), China's per capita water resource capability is very limited. In 2012, its per capita water availability is about 2186.1 m^3, which is roughly one fourth of the world's average value. It is reported that more than half of the 667 cities in China are facing water shortage (He et al., 2001). On the other hand, rapid population growth, economic development and urbanization in recent years have caused significant increase in water consumption and wastewater discharge in China. For example, total wastewater discharged from industrial sectors and people's living in 2010 is about 61.73 billion t (ton), which is 1.49 times that of 2003. Great amount of pollutants (e.g., chemical oxygen demand and ammonia nitrogen) in wastewater has directly or indirectly discharged to the water supply sources, and this in turn has further aggravated the water scarcity problem in the country. Water resource has become a key restricting factor that influences the socio-economic development as well as urbanization process in China (Guan and Hubacek, 2007).

Industrial sector, as an important part in China's economy, has achieved remarkable progress in past 30 years and the country has been referred to as the “global factory” (Choi and Zhang, 2011). Industrial gross domestic product (GDP) is 16086.7 billion CNY in 2010, which accounts for about 39.89% of China's total GDP. Total water consumption in industrial sectors is about 144.7 billion m^3 in 2010, which is about 24.03% of total water consumption in the country. It is noteworthy that, total wastewater discharged from industrial sectors in 2010 is 23.75 billion t, and this is about 38.47% of the total wastewater generated from all sources except agricultural sectors in China. As a result, industrial

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water use management especially industrial wastewater treatment has played an important role in China's water resource management.

With the growing emphasis on water scarcity and environmental protection, the government has carried out various plans and strategies to keep sufficient water supply or to decrease pollutant discharges since the late 1990s, e.g., South-to-North Water Transfer Project, Three Gorges Dam and Total Amount Control of Pollutant Emissions (Bian et al., 2014). Nevertheless, water shortage and industrial pollutant problem are still severe. Therefore, the mode of economic development considering water resource limited and environmental constraints will become an inevitable choice. Under this situation, improving water efficiency and reducing pollutant emissions have been recognized as two better ways to support sustainable development.

To improve water efficiency and reduce pollutant discharges in industrial sectors, two important issues are raised: (1) how to harmonize the trade-off between industrial economic growth, water use and environment protection? (2) how to measure the pollutants' abatement costs of industrial wastewater?

In the literature, water efficiency (also called water use efficiency) has gained increasing attention in recent years. Marlow (1999) first defined economic water efficiency as the value of products produced per unit of water consumption. Following this definition, Mo et al. (2005) and Huang et al. (2005) have analyzed water efficiency and its impact on agriculture in North China by investigating crop yields or the amount of food per unit water consumption. However, as argued by Hu et al. (2006), water consumption alone as an input cannot produce any output through production processes, and a multiple-input model is required to examine water efficiency. It can be found in the existing studies that, data envelopment analysis (DEA) as a multi-factor efficiency evaluation approach has been widely used to cope with water efficiency measurement issues. Emmanuel (2000) applied the standard DEA approach to evaluate the efficiencies of UK water utilities to rearrange the water distribution. Byrnes et al. (2010) also employed the standard DEA models to investigate the efficiencies of urban water utilities in regional New South Wales and Victoria. Cruz et al. (2013) used a shared input (cost) DEA model to separately measure the efficiencies of drinking water and wastewater services in Portuguese water sector. Note that these studies mainly focused on examining the efficiency of public utilities. Hu et al. (2006) provided a total-factor water efficiency measure based on standard DEA model to examine regional water use efficiency in China. Lilienfeld and Asmild (2007) applied DEA approach to estimate the excess water use in irrigated agriculture in western Kansas during 1992–1999.

The common feature of the above mentioned studies is that they model water resource as an input to explore economic efficiencies while ignoring discharged wastewater or pollutants. As we know, pollutants are the by-products of any economic production process. The efficiency evaluation without considering the pollutants may bias the efficiency results. Thus, to effectively measure the industrial water use efficiency, water consumption, pollutants such as chemical oxygen demand (COD) and ammonia nitrogen (NH_4–N) and other factors (e.g., labor, capital and GDP) should be taken into consideration simultaneously. Bian et al. (2014) provided a two-stage DEA approach to measure the efficiency of regional urban water use and wastewater decontamination systems in China by taking wastewater into consideration. They focused on evaluating water use efficiency of urban area rather than industrial sector, and they did not examine pollutant abatement costs.

Since the prices or costs for pollutants' abatement cannot be directly obtained in practice, researchers usually apply the shadow prices of pollutants to estimate their abatement costs. DEA approach is widely used to estimate the shadow prices of pollutants in the literature (Zhou et al., 2014). However, most of the extant studies mainly focused on examining the shadow prices of waste gases (i.e., sulfur dioxide, carbon dioxide and nitrogen oxides), e.g., Ke et al. (2008), Lee and Zhang (2012) and Wang and Wei (2014). Ke et al. (2010) in their study have explored the shadow prices of industrial waste gas, wastewater and solid waste in China, but they have not investigated water efficiency and the shadow prices of main pollutants in wastewater (i.e., COD and NH_4–N). In addition, the most previous studies use the radial efficiency measures that cannot capture all the technical inefficiency in inputs, desirable outputs and pollutants. The two exceptions are Choi et al. (2012) and Wei et al. (2012). They applied slacks-based measure (SBM) DEA models to examine the shadow price issues in China. However, they only focused on carbon dioxide emission efficiency and its abatement costs for regions in China. To our best knowledge, no study has well examined water efficiency and the abatement costs of main pollutants in wastewater simultaneously for regional industrial sectors in China.

The purpose of this study is to apply a slacks-based measure DEA approach to investigate regional industrial water use efficiency and the abatement costs of main pollutants in wastewater in China. The described DEA approach is constructed based on environmental DEA technology (Färe and Grosskopf, 2004), in which pollutants are incorporated based on the assumption of weak disposability. Based on the proposed approach, the measures of water efficiency, water saving potential and pollutants' reduction potentials are presented. The rest of this paper is organized as follows. Section 2 introduces the efficiency evaluation DEA model and the abatement cost estimation approach. In Section 3, the proposed approach is used to examine water use efficiency and pollutants' abatement costs for regional industrial sectors in China. Conclusions are presented in Section 4.

2. Methodology

In this section, we first present the slacks-based measure DEA model for measuring the water use efficiency of regional industrial systems in China. Based on the proposed approach, the method for estimating the shadow prices of pollutants is derived.

2.1. The efficiency evaluation model

Consider that there are n regions in China. Each region has its own industrial system, namely RIS_j ($j = 1,2,\ldots,n$). Each regional industrial system consumes multiple inputs including labor (XL), capital (XK) and water (XW) to produce desirable output GDP (YG) along with two main pollutants, i.e., COD (YC) and NH_4–N (YN).

To model the efficiency evaluation problem of units, traditional DEA or directional distance function approaches apply the radial measures to conduct it. The radial measure allows for the equal and proportionate adjustments for all inputs or outputs. Thus, it cannot identify the inefficiency information for specific inputs or outputs, and this in turn may result in a biased estimation (Fukuyama and Weber, 2009; Hernández-Sancho et al., 2011). To overcome the weakness of the radial measure, Choi et al. (2012) and Wei et al. (2012) used the standard slacks-based measure DEA model to evaluate energy efficiency, carbon dioxide efficiency