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Efficiency assessment of urban wastewater treatment plants in China: Considering greenhouse gas emissions

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ABSTRACT

Wastewater treatment plants (WWTPs) are high-cost facilities for improving the urban water environment and facilitating resource recycle but with inevitable negative externality. To comprehensively assess urban WWTP performance, a distance function approach was configured to quantify the efficiency with capital cost and energy consumption as inputs, removals of four types of pollutants as desirable outputs, and emission of greenhouse gases (GHGs) as undesirable output. Adding both direct and indirect GHG emissions into the efficiency metrics would help decision makers obtain a more profound understanding of urban WWTPs' contribution to both aquatic and atmospheric environments. The method was applied to 1079 urban WWTPs across China adopting eight major biological technologies. The average efficiency score was 0.322, implying that GHG emissions could decrease by 32.2% if all plants worked efficiently. Eight plants were deemed the most efficient and formed a frontier of the best practices, while 12 plants were the most inefficient with distances from the frontier larger than 0.650. The parameterized distance function could be used to set a benchmark system for the performance surveillance of urban WWTPs. The integrated efficiency assessment considering multiple dimensions and statistical analysis on a large sample allowed us to reveal reasons for efficiency gaps. Statistic test results showed that plants scale, technology, and capacity of tertiary treatment were significant for explaining efficiency disparities. Large-scale plants, plants with the bioreactors or the anaerobic-anoxic-oxic processes, and plants without tertiary treatment processes tended to be more efficient, showing the advantage in co-benefiting water pollutants and GHG control.

1. Introduction

Wastewater treatment plants (WWTPs) are recognized as fundamental tools for improving the urban water environment (Pasqualino et al., 2009). More than that, WWTPs also play an essential role in resource conservation and recycling in the ecosystem, in terms of wastewater reclamation and reuse (Pasqualino et al., 2009), nutrients recycling (Tidåker et al., 2006), and sewage sludge treatment and disposal (Suh and Rousseaux, 2002). However, the operation of WWTPs inevitably causes some negative externalities, such as acidification and eutrophication of recipient water bodies and emission of greenhouse gases (GHGs) (Flores-Alsina et al., 2011; Lassaux et al., 2007). When removing pollutants from raw wastewater to comply with effluent standards, the WWTP is also well known as an energy-intensive facility (Hernandez-Sancho et al., 2011a). Given that the constructions and technical upgrades of WWTPs always involve high costs (Dasgupta et al., 2001), plant managers and local governments have keen interests in simultaneously improving the performance and restricting costs of WWTPs (Molinos-Senante et al., 2010). Nevertheless, various aspects influence the behavior of WWTPs. To enhance the overall performance of WWTPs and reduce their negative impacts, an integrated assessment of WWTPs in which all technical, economic, and environmental aspects are considered is the first crucial step (Hoibye et al., 2008).

In a productive economy, efficiency is applied to describe the optimal use of available resources under existing technology (Hernández-Sancho and Sala-Garrido, 2009) and assess performances in different areas. Popular methods for efficiency analysis concerning WWTPs include life cycle assessment (LCA), multiple-objective evaluation, and indicator-based method. LCA takes the whole treatment process including sludge treatment into account and evaluates performance of case WWTPs from perspectives of cost, energy and chemical consumption, nutrient loading, and GHG

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emissions (Pasqualino et al., 2009; Dong et al., 2014; Lorenzo-Toja et al., 2015; Rahman et al., 2016). The approach of multiple-objective evaluation usually considers aspects such as operating cost, water quality, effluent standard, and microbiological risks as objective functions for ranking WWTPs (Flores-Alsina et al., 2010; Kalbar et al., 2012). As to indicator-based method, different hierarchical indicators, e.g. environmental, personnel, physical, operational, quality of service and economic and financial indicators are often selected to evaluate WWTP performance (Balkema et al., 2002; Matos and Association, 2003; Quadros et al., 2010). It can be difficult to apply these methods because they all require detailed inventory data and are technically complicated (Sala-Garrido et al., 2011). Additionally, when only partial cases are evaluated, using the results from these methods to make inferences about general conclusions requires extra caution (Zhong et al., 2011).

An alternative for WWTP assessment is the distance function approach, first proposed by (Pittman, 1983) and (Färe et al., 1989), through which pollution emissions are incorporated into the traditional Shephard's production function (Shephard et al., 1970) to measure productivity and efficiency. Since its proposal, the distance function approach has been widely used in the estimation of productivity indexes, technological efficiency, shadow prices of pollutants, and marginal abatement costs of pollutants, owing to its advantages, including joint modeling of both desirable and undesirable outputs (Diaz-Balteiro and Romero, 2008), easily obtained quantitative input/output data, and compact results of efficiency capturing interactions among technologies and side effects (Lee et al., 2014). Several studies used the distance function approach to assess WWTPs performances (Tupper and Resende, 2004; Molinos-Senante et al., 2010; Molinos-Senante et al., 2011b; Lorenzo-Toja et al., 2015) in which different technical, economic and environmental aspects were taken into consideration in an integrated model. Hence, the distance function approach was selected and employed in the present study because it can provide a more complete picture of production processes (Murty et al., 2006).

Regarding the undesirable output of the WWTP, GHG emissions have drawn greater attention recently since it is identified as one of the largest minor sources (Doorn et al., 1997). Since the International Panel on Climate Change (IPCC) stated that wastewater treatments are biogenic sources, few studies investigating WWTP performance involving GHG emissions (Tupper and Resende, 2004; Molinos-Senante et al., 2010; Lorenzo-Toja et al., 2015) have been conducted. With the increasing criticism that the GHG emission of WWTPs was underestimated, paying more attention to this specific source is necessary (Bani Shahabadi et al., 2009; Foley et al., 2010; Yoshida et al., 2014). Adding the GHG emission into the assessment of WWTPs leads to a rethinking of the results of traditional methods. By adding this new angle, we could obtain an integrated analysis of WWTPs and perform comparisons of different WWTP performances to facilitate the reduction of GHG emissions.

In China, the number of WWTPs has increased dramatically during the last three decades in urban area. By 2013, 3513 urban WWTPs had been built and the total treatment capacity had reached 1.25×10^8 m^3/d. The demand for future constructions and technical upgrades of urban WWTPs is still significant. Despite the extensive literature on WWTP assessments, integrated analyses of urban WWTPs in China from economic and environmental perspectives remain scarce. Therefore, any attempt to address additional evidence to improve urban WWTP performance is vital and timely. With the distance function approach, this paper aims to assess the current efficiency of China's urban WWTPs by considering the reduction of pollution load, as well as related costs, energy consumption, and GHG emissions. Factors that affect efficiency scores are discussed as well, because a large sample of 1079 urban WWTPs and a parameterized distance function allow us to reveal reasons for efficiency gaps.

2. Methods

2.1. Definition of input and output

The assessment unit for computation with the distance function approach was each urban WWTP. In this study, the wastewater treatment process was considered as a joint-product process by certain inputs, while the output set with both desirable and undesirable outputs led to positive and negative environmental impacts accordingly. According to specific research aims and scopes, different inputs (e.g. cost, energy, chemicals, staff), positive impacts (e.g. treated water, pollutants removal), and negative impacts (e.g. effluent loads, pharmaceutical and personal care products) of urban WWTPs were chosen flexibly, when applying the approach of distance function (Tupper and Resende, 2004; Molinos-Senante et al., 2010; Lorenzo-Toja et al., 2015). This study sought to capture the efficiency of urban WWTPs with the aim of obtaining vital information for improving environmental performance and valuing the reduction potential of GHG emissions, resulting in the determination of two inputs, four desirable output and one undesirable output.

Two inputs were considered: fixed-asset investment per volume of treated wastewater (x_1, RMB Yuan/m^3) and energy consumption per volume of treated wastewater (x_2, kWh/m^3). Electricity (energy consumption) is actually the largest operation cost of WWTPs in China (Jin et al., 2014). These two inputs could represent both capital cost and operational expenditure for WWTPs.

Desirable outputs were defined with the concentration differences of pollutants between the influent and effluent, because the pollutant removal from WWTPs is a primary function of the treatment process and contributes a positive effect to the environment. Four types of pollutants were involved, including chemical oxygen demand (COD), suspended solids (SS), total nitrogen (TN), and total phosphorus (TP), and the corresponding outputs were denoted as y_1 (mg/L), y_2 (mg/L), y_3 (mg/L), and y_4 (mg/L), respectively.

To measure the negative environmental impact of urban WWTPs, GHG emissions per volume of treated wastewater (z_1, mg/L) was treated as an undesirable output in this study. WWTPs produce GHGs during the treatment process and through energy consumption, called direct (or on-site) and indirect (or off-site) emissions respectively. Both direct and indirect GHG emissions were calculated when quantifying the undesirable outputs.

Previous studies have shown a wide range of intensities of GHG emissions in WWTPs, affected by influent load, temperature, treatment process, and operating conditions (Kampschreur et al., 2009; Corominas et al., 2012). As a result, high uncertainty tends to exist when determining the GHG emissions, although various quantification methods are reported in the literature including the modeling approach (Bani Shahabadi et al., 2010; Rodriguez-Garcia et al., 2012), onsite observation (Wang et al., 2011), and estimation with emission factors statistically (Pan et al., 2011). In this study, for the large sample size and lack of data, the method using emission factors was more suitable, though the plant-specific emissions factors were not practically available. Consequently, GHG emissions including both direct emissions (GHG_{direct}, mg CO_2-eq/L) and indirect emissions ($GHG_{indirect}$, mg CO_2-eq/L) were estimated following the method derived from IPCC guidelines (CHANGE, 2006), so that the undesirable output can be determined as $z_1 = GHG_{direct} + GHG_{indirect}$.

The equation for estimating direct GHG emissions is as follows:

$$GHG_{direct} = (TOW \times B_0 \times MCF\text{-}R) \times 25 + TN \times EF_{N_2O} \times 298 \qquad (1)$$