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Eco-efficiency assessment of wastewater treatment plants using a weighted Russell directional distance model

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ABSTRACT

Improving the performance of wastewater treatment plants is essential to ensuring their long-term sustainability. Most of the previous studies on this topic have assessed the techno-economic efficiency of wastewater treatment plants and ignored the emission of greenhouse gases. For the first time, the weighted Russell directional distance model was applied to estimate the eco-efficiency of a sample of real wastewater treatment plants. Moreover, this approach allowed an inefficiency score to be obtained for each variable (cost factors, pollutant removal and greenhouse gases) involved in the model. Subsequently, a second stage of analysis was applied to identify factors influencing the previously computed inefficiency scores. The results illustrated that approximately half of the facilities assessed had significant room for improvement in their eco-efficiency. Moreover, the characteristics of over- and undersizing of the plants significantly affected their eco-efficiency. The methodology and results of this study are of great interest, not only for wastewater treatment plant managers and water authorities but also for citizens because there have been growing concerns regarding minimizing the ecological footprint in the urban water cycle.

1. Introduction

1.1. Background

Wastewater treatment is essential to protecting human health and environmental sustainability (IOC/UNESCO, 2011). Hence, several regulations concerning wastewater treatment have been developed such as the European Union Directive 91/271/ECC or the United States Clean Water Act. As a result, the number of wastewater treatment plants (WWTPs) worldwide has increased notably, and in developed regions, virtually the entire population (96%) has access to wastewater treatment services (WHO-UNICEF, 2014).

In this context, the performance assessment of WWTPs has gained the interest of WWTP managers and water authorities for improvement of the long term sustainability of these facilities (Piao et al., 2016). Moreover, comparative analysis (benchmarking) of WWTPs allows identification of the strengths and weaknesses of each plant (Molinos-Senante et al., 2014).

The urban water cycle is well-known to be the nexus of water-energy because water and wastewater facilities use between 30% and 60% of municipal government energy usage (US EPA, 2008). Focusing on WWTPs, energy consumption was approximately 15%–30% of the operation and maintenance costs of large WWTPs and 30%–40% at small WWTPs (WEF, 2009). Energy consumption involves indirect GHG emissions which are a major global environmental issue (Henriques and Catarino, in press; Li et al., 2016). The important role that the wastewater treatment industry could play in the reduction of GHG emissions has been already realized by

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a number of governments (Molinos-Senante et al., 2015a). Hence, it was essential to include GHG emissions in the efficiency assessment of WWTPs. However, to the best of our knowledge, only Lorenzo-Toja et al. (2015) has integrated emissions linked to energy use in the evaluation of the efficiency of a sample of WWTPs. Nevertheless, this author did not consider GHG emissions as undesirable outputs, instead integrating them as a negative environmental impacts through life cycle assessment.

The objectives of this paper were twofold. The first was to assess the eco-efficiency of a sample of WWTPs. In doing so, for the first time in the framework of WWTPs, a weighted Russell directional distance model (WRDDM), a non-radial DEA model that allowed an individual inefficiency score to be obtained for each input, desirable output and undesirable output at WWTP level, was applied. Hence, not only the total room for improvement of each WWTP's eco-efficiency but also the variables in which WWTP managers and water authorities should focus on to improve the performance of each facility were evaluated. The second objective of this paper was to explore the factors affecting the inefficiency scores of each previously computed input, desirable output and undesirable output. To illustrate the usefulness of the proposed methodological approach, an empirical application using data from real Spanish WWTPs was carried out.

This paper contributed to the current vein of literature in the field of WWTP performance assessment by computing, for the first time, the eco-efficiency of a sample of WWTPs by applying the WRDDM. It should be noted that although several previous studies' evaluations of the efficiency of WWTPs have used non-radial DEA models, none of them has integrated GHG emissions as undesirable outputs. Moreover, no studies have evaluated the efficiency of WWTPs to provide an individual score of inefficiency for each input, desirable output and undesirable output. Hence, this study provided a pioneering and novel approach to assess the eco-efficiency of WWTPs. Moreover, this study provided insights into the factors affecting individual inefficiency scores. We considered these topics to be very relevant and deserving of investigation.

From policy and managerial points of view, computing an inefficiency score for each variable involved into the evaluation model, rather than a total inefficiency (TI) score could provide WWTP managers and policy makers with vital information. The results obtained could enable them to identify the variables in which the WWTPs need to improve the most for its eco-efficiency. Moreover, the identification of some factors which significantly affect inefficiency scores is essential to improving the long-term sustainability of WWTPs. Thus WWTP managers and policy makers could implement different strategies in the planning and designing of new facilities. It should be noted that improving eco-efficiency of WWTPs not only involves increasing the pollutant removal efficiency and reducing GHG emissions but also decreasing operational and maintenance costs. Thus, improving the eco-efficiency of WWTPs is a potential way to reduce wastewater treatment tariffs. Hence, improving the eco-efficiency of WWTPs also has marked repercussions from a social perspective.

The paper unfolds as follows. Section 1.2 describes briefly the literature already published on the topic analyzed. Section 2 presents the methodology employed in the paper. Section 3 describes the sample data used in the case study and the variables considered. Section 4.1 presents the main findings regarding inefficiency scores while Section 4.2 explores the factors affecting inefficiency in WWTPs. The final section concludes.

1.2. Literature review

In the framework of wastewater treatment, a series of research studies have aimed at assessing the so called "techno-economic efficiency" of WWTPs (e.g., Guerrini et al., 2015; Molinos-Senante et al., 2016a; Tomei et al., 2016). This approach is based on consideration of the operational and maintenance costs of WWTPs as inputs, while the pollutants removed from wastewater as outputs (Castellet and Molinos-Senante, 2016). Using the benchmarking methodology of data envelopment analysis (DEA), these previous studies computed an efficiency score for each WWTP. The great advantage of this methodology is that it enables integration of multiple inputs and outputs into a single index (Guerrini et al., 2013), which provides synthesized information regarding the total performance of each facility evaluated.

Within the framework of DEA methodology, several models have been developed to evaluate the eco-efficiency of the analyzed firms by integrating CO_2 and other greenhouse gas (GHG) emissions into the efficiency assessment as undesirable outputs (Shabani et al., 2014; Yu et al., 2016). Accordingly, it was considered that the production process carried out by the firms not only produced desirable outputs but also undesirable outputs (Chung et al., 1997; Fujii and Managi, 2013). Hence, the efficiency assessment involved variables to maximize (i.e., desirable outputs) and variables to minimize (i.e., inputs and undesirable outputs).

From a methodological point of view, most of previous studies have evaluated the efficiency of WWTPs using radial DEA models. Among other issues, they were characterized by adjustment of all variables to efficiency targets by the same proportion (Fujii et al., 2015). Hence, they only provided a score of total efficiency which involves that information regarding the efficiency of specific inputs, and outputs integrated in the analysis could not be obtained (Zhou et al., 2012). To overcome this and other limitations,[1] non-radial DEA models were developed. They allowed for the degree of inefficiency for each input and/or output to be different (Yagi et al., 2015). In other words, an efficiency score for each input and output was obtained in addition to the total efficiency score. Moreover, they allowed the preferences of decision makers to be integrated into the efficiency assessment by assignment of different weights to different variables (Wei et al., 2015).

While from a theoretical point of view, it has been demonstrated that non-radial DEA models are more effective than radial DEA models in assessing the performance of firms (Skevas et al., 2012) in the framework of WWTPs, to the best of our knowledge, only three previous studies have applied a non-radial DEA approach. Firstly, Hernández-Sancho et al. (2011), Molinos-Senante et al. (2014) applied a non-radial DEA model known as the Russell measure, which allowed an efficiency score to be obtained for each input involved in the analysis. However, this measure did not provide information regarding specific performance in the generation of outputs. Secondly, Castellet and Molinos-Senante (2016) used the weighted slack-based measure to evaluate the efficiency of a sample of Spanish WWTPs. However, they not only applied this non-radial DEA model to obtain an efficiency score for each input and output but also to assign different weights to the outputs based on their environmental impacts. Moreover, it should be noted that none of these previous studies evaluated the eco-efficiency of the WWTPs, i.e., none of them integrated the GHG emissions of the WWTPs as undesirable outputs.

2. Methodology

To compute an efficiency score for each input and output (desirable and undesirable) of WWTPs, the WRDDM was applied. It was based on a directional distance function combined with a non-

[1] More information about the differences between radial and non-radial DEA models can be consulted at Cooper et al. (2011).