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Research article

The relevance of the design characteristics to the optimal operation of wastewater treatment plants: Energy cost assessment

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ABSTRACT

Operational parameters of the wastewater treatment process do not always fit the design ones for several reasons, such as the seasonality or an inaccurate estimation of the population connected. This fact has an effect on the performance of the Wastewater Treatment Plants (WWTPs) and their energy costs. The aim of this paper is to develop a cost function for the energy cost that takes into account the mismatching between the design and the operational inflow. For this purpose, a performance index is constructed in order to represent how far the operational inflow is from the design one, and will be included in the cost model. Moreover, three cost functions, depending on the size of the plants are developed in order to provide the managers of the WWTPs with valuable information that could be used to optimise the wastewater treatment process.

1. Introduction

Wastewater Treatment Plants (WWTPs) are intensive energy consumers (Racoviceanu et al., 2007), which can represent up to the 20% of the total energy consumed by the public utilities in a municipality (Means, 2004). The minimization of the energy consumption has become increasingly important for wastewater policy makers since the electricity tariffs increased (Bodik and Kubaská, 2013; Castellet-Viciano et al., 2018; Gikas, 2016), and the reduction of the greenhouse gases became one of the biggest global challenges (EU, 2010; Shao et al., 2014; Slingerland et al., 2015).

Even if already high, the energy consumption in WWTPs is supposed to increase in the next years for several reasons: new regulations, connected population increase and infrastructure ageing. Several authors (Bolong et al., 2009; Naidu et al., 2016; Noguera-Oviedo and Aga, 2016; Petrie et al., 2015) demonstrated that regulations have to be adapted to improve the standards concerning the discharge of new contaminants; this will require an increase in the energy consumption (Ahmed et al., 2017). Besides this, in different developed countries, the number of WWTPs is likely to rise because of the population growth; for example the urban population in Spain is supposed to rise 10.7% by 2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2015). On the other hand, experts of the wastewater treatment sector in Spain state that wastewater infrastructures are ageing and deteriorating (AEAS, 2014; AEAS, 2016), which will also contribute to enlarge the energy use of the WWTPs (Mo and Zhang, 2013).

The energy consumption of a WWTP is defined by both operational and design parameters, including the technology used in the process, the size of the plant, the volume and the contaminant load of the influent (Tchobanoglous et al., 1991). However, some of the characteristics mentioned above such as the volume of the treated wastewater and its contaminant load present fluctuations in time, depending on the hour of the day, between days or even in different periods of the year (Bragadin and Mancini, 2010; Butler, 1993; Campos and Von Sperling, 1996; Friedler and Pisanty, 2006; Krukowski et al., 2013; Wong and Mui, 2007), having an impact on the operating conditions.

Daily and weekly variations in the quantity and the quality of the wastewater treated are mostly defined by the domestic habits and the use of different appliances. Campos and Von Sperling (1996) found differences in the generation of domestic wastewater throughout socioeconomic variables, such as the salary of the population. Moreover, WWTP's performance can also be altered by storm conditions. In fact, a storm event can overflow the sewerage system, bring down the wastewater treatment process (Obaid et al., 2014), increase the energy demand and the sludge production, and negatively affect the contaminant removal efficiency (Stricker et al., 2003). Another important factor in generating variations in the production of wastewater is tourism. In accordance to Muñoz-Aulet and Caus-Pla (2005), the WWTPs of tourist areas only work at their maximum capacity during a short period of the year, being oversized for the most part of time. Accordingly, Sala-Garrido et al. (2012) found that WWTPs subjected to

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seasonality are less efficient than those that are not.

In order to guarantee the accomplishment of the quality parameters established in the Council Directive 91/271/EEC concerning urban wastewater treatment (EU, 1991), WWTPs are designed to treat those fluctuations in time. Wastewater treatment facilities are designed considering the peak flow and the peak mass loading rate (Mines et al., 2007). In many instances it is assumed a daily wastewater flow per capita using water consumption and socioeconomic information, and then a multiplier factor gives as a result the peak volume and the peak load (Butler et al., 1995).

Differences between the operational volume of the wastewater treated and the design one are responsible for inefficiencies in the process, since those facilities and equipment that are either oversized or undersized are likely to malfunction and fail (Campos and Von Sperling, 1996), decreasing the contaminant removal and increasing the operational costs in terms of energy, reagents, maintenance, and personnel. As far as the energy cost is concerned, Silva and Rosa (2015) report that those WWTPs that are operating at their 80% of their design capacity consume up to 28–53% less energy than those that are operating at half of their maximum capacity.

Due to the relevance of the energy cost in the wastewater treatment process, in the last decades different strategies have been developed to assess and improve the energy efficiency of the process. While most studies have used benchmarking methodologies (Castellet and Molinos-Senante, 2016; Hernández-Sancho et al., 2011; Longo et al., 2016; Panepinto et al., 2016; Torregrossa et al., 2016), the current research aims to contribute to the literature on reducing the energy inefficiencies in the wastewater treatment process from an economical approach based on cost functions.

The use of cost functions is widespread in the literature. In the WWTP field, different authors propose this approach, for example: Hernandez-Sancho et al. (2011) who estimate the costs for different wastewater treatment technologies, Molinos-Senante et al. (2013), to estimate the cost of the sludge and waste management, Plumlee et al. (2014) to analyse the cost of the advanced treatment, and more recently Yumin et al. (2016), for the operational cost estimation of WWTPs in rural areas. Most of the cost functions developed for the wastewater treatment process have been used to estimate the operational and maintenance cost of the process. However, it is very difficult to find studies focused on the energy cost estimation.

The definition of the operational costs of the process can vary among authors. Two approaches can be identified in the existing literature depending on the variables used to explain the costs. Several studies show that it is possible to use operational parameters such as the volume of wastewater treated (Hernandez-Sancho et al., 2011), the load charge expressed as the population equivalent (Sipala et al., 2003; Tsagarakis et al., 2003) or the contaminant removal expressed in Kg of BOD, COD, N or P (Hernandez-Sancho et al., 2011) to explain the costs. In contrast, a second group of authors prefer using design parameters such as the capacity of the plant according to the volume of wastewater they are able to treat (Berbeka et al., 2012; Friedler and Pisanty, 2006; Pannirselvam and Gopalakrishnan, 2015).

The novelty of this paper is to include the effects of the mismatching between the operational and design inflow in the energy cost function since the fact that the equipment does not work at their optimum can have an impact on the energy cost. For instance, Torregrossa et al. (2017) show how the overestimation of inflow can produce avoidable energy costs in pump systems. The use of index has been reported to be very useful in the literature for different purposes since they can provide valuable information (dos Santos Simões et al., 2008; Paruch and Mæhlum, 2012; Shao et al., 2014). In order to achieve our purpose, a performance index is calculated to represent the distance between the operational condition and the design one. Moreover, due to the existence of scale economies in the wastewater treatment process, different energy cost functions depending on the size of the plant have been considered. The equations provided by this paper could be used by the managers of the WWTPs, public authorities and designers in order to estimate and predict the energy cost of the wastewater treatment, obtaining valuable information that would be very useful for the process optimization.

2. Material and methods

Most of the cost functions used to estimate the costs of the wastewater treatment process take the form of an exponential equation (Friedler and Pisanty, 2006). In this paper, the estimation of the energy cost of the wastewater treatment process is based on the model developed by Hernandez-Sancho et al. (2011):

$$EC = AV^{b}e^{(\sum \alpha_i \cdot x_i)} \tag{1}$$

where EC is the energy cost of the plant per year; V is the volume of wastewater treated per year; and x_i are different kinds of variables representative of the treatment processes; A, b and α are parameters.

It seems that treatment costs might be more related to the volume of wastewater treated and the quantity of contaminants removed from the wastewater than the capacity of the plant (Hernandez-Sancho et al., 2011). However, wastewater treatment facilities are designed to treat a specific volume or contaminant load, so all the equipment including technological elements, pumping systems, and other devices will be in accordance to these initial characteristics. It is considered that the closer would be the operational volume to the design one, the more efficient would be the process (Silva and Rosa, 2015). The fact that the equipment does not work at their optimum will have an impact on the energy cost.

To include this phenomenon into the cost function a performance index (Z) is constructed. It represents the difference between the designed capacity of the plant (m^3/day) and the real volume of wastewater treated (m^3/day), as follows:

$$Z = \frac{|\, q - Q \,|}{Q} \cdot 100 \tag{3}$$

where Z is the performance index; q is the volume of wastewater treated; and Q is the design flow of the plant.

When the WWTP is treating the same volume of wastewater established in the design condition the value of Z is 0. On the contrary, as the difference between the operational volume of wastewater and the design one increases, the value of Z will rise. Consequently, Z can be used as an indicator of the operational performance of the plants.

According to Eq. (3), a performance index per day will be obtained for each WWTP. However, a representative index per year is needed in order to relate it to the energy cost (€/year) throughout the cost function. Hence, instead of using the average of the daily index, we consider that the use of the median is more appropriated, since it reflects how much time the plant is working at its optimum.

Finally, the parameters of the model are obtained empirically through an ordinary least squares regression analysis, which includes those variables that better explain the energy cost. It should be noted, that the variables in the regression equation are significant at the 95% confidence level. Due to the nature of the process, problems of multicollinearity between the variables could be found, for this reason special attention will be paid to the variance inflation factor (VIF). Moreover, to guarantee the robustness of the model, the behaviour of the residuals will be analysed, throughout different statistical tests that would prove their normality, independence and the homoscedasticity of the model.

The methodology has been applied using empirical data from 156 WWTPs located in the Spanish region of Valencia. This area attracts lots of tourists during the summer, which makes that some cities double the usual population in this season (Rico Amorós, 2007). In order to cope with seasonality, WWTPs are designed to treat the maximum volume of wastewater that they could receive in this period, hence, the volume of wastewater that they usually treat the most part of the year differs from