H$_2$Open Journal


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doi: 10.2166/h2oj.2020.007

# Improving wastewater treatment plants operational efficiency and effectiveness through an integrated performance assessment system

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## Abstract

Optimizing the efficiency of urban water systems is a growing concern for water utilities worldwide. Wastewater treatment plants (WWTP) are crucial in maintaining water quality and resource recovery in a world facing growing challenges such as climate change, water-energy-food nexus and the increase of legal requirements and users' expectations. Thus, adopting a performance assessment system (PAS) is of the utmost importance to assess operating conditions and to identify critical aspects of the WWTP which can negatively affect its effectiveness, efficiency and reliability. This paper presents the global and operational performance assessment of an urban WWTP and identifies improvement measures. The WWTP presented a good performance in terms of effectiveness and reliability. Nevertheless, in terms of efficiency, relevant improvement opportunities were identified, specifically in the sludge treatment phase and in terms of energy management. PAS was proven to be successful in the identification and prioritization of rehabilitation needs in a systematic way which will continuously improve the efficiency and effectiveness of the WWTP as well as to support asset management decisions regarding their upgrade and retrofit.

**Key words:** key performance indicators, operational efficiency and effectiveness, performance indices, wastewater treatment plants

## Highlights

- A performance assessment system methodology was applied to an urban WWTP.
- The global and operational performance assessment based on indicators and indices is presented.
- The WWTP presented a good overall performance in terms of effectiveness.
- The performance assessment system allowed the identification of efficiency improvement measures.

## INTRODUCTION

Wastewater treatment plants (WWTP) play an important role in maintaining water quality and resource recovery in a world facing significant challenges such as climate change, water-energy-food nexus and the increase of legal requirements and user's expectations. As such, maintaining efficient systems is a growing concern for water utilities. However, WWTP are typically designed to solely meet wastewater quality discharge permits (effectiveness) and are not traditionally designed to maintain costs at a minimum (efficiency) (Panepinto *et al.* 2016 and references therein). Good

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doi: 10.2166/h2oj.2020.007

management of the WWTP is imperative to balance water pollution prevention and economic sustainability of these facilities. Adopting a preventive management will allow the achievement of the required levels of service (reliability) whilst optimally utilizing the available resources (efficiency). For this, a 'plan-do-check-act' approach is usually recommended (Cabrera *et al.* 2011; Silva *et al.* 2014b) for which performance assessment is of most importance. Thus, adopting a methodology for the performance assessment of WWTP is crucial to evaluate its efficiency and effectiveness as a starting point to identify the strengths and improvement measures in a continuous way.

Several performance assessment methodologies have been proposed and are typically based on life cycle analysis (LCA) and energy efficiency benchmarking. LCA methodologies mainly evaluate the potential environmental impact of products and services of WWTP, helping utility managers to maintain a sustainable water management (Arnell *et al.* 2017 and references therein). Energy benchmarking aims at providing key performance indicators (KPI) and methodologies to help increase energy efficiency diagnosis (Yang *et al.* 2010; Longo *et al.* 2016 and references therein; Panepinto *et al.* 2016; Di Fraia *et al.* 2018; Longo *et al.* 2019; Luo *et al.* 2019). Other benchmarking tools are based on assessing the effectiveness and economic efficiency of WWTP by analysing the effluent characteristics to guarantee compliance using KPIs and to identify potential economic savings (Molinos-Senante *et al.* 2014; Ebrahimi *et al.* 2017).

Even though these studies have brought great contributions to the field, typically they assess efficiency on a yearly basis. In addition, they lack a general overview and assessment of the WWTP in terms of both effectiveness and efficiency of energy and sludge management and adequacy of operational practice in each of the WWTP processes. Such an integrated assessment will allow the identification of improvement needs in terms of technical, economic and environmental performance (Silva *et al.* 2014a). In addition, the use of KPI is crucial as it allows understanding of the overall effectiveness and efficiency of a WWTP. However, such analyses fail at providing crucial information on the complexity of such systems. Individual processes in a WWTP will be influenced differently by dynamic parameters such as inlet flow, organic matter and nutrients concentrations or solid content (Di Fraia *et al.* 2018 and references therein). Thus, although KPI allow for an adequate assessment of any system, they should be used as a starting point for a more specific and detailed analysis of each element (Okwori *et al.* 2020 and references therein) or process.

AGS, owned by Marubeni, is a privately held company responsible for the operation and maintenance of several water and wastewater treatment facilities and for the management of 13 utilities in Portugal and Brazil under concession agreements, public–private partnerships and for the service provision of engineering services to water utilities in Europe, South America and Asia. Aiming at greater efficiency and effectiveness, AGS has applied a performance assessment system (PAS) (Rosa *et al.* 2011; Silva *et al.* 2014a, 2016), under the scope of the Portuguese benchmarking on Water Quality, Treatment and Energy initiative (iEQTA) (Silva & Rosa 2020), to evaluate the performance of several WWTP over the past years. Briefly, this methodology takes into account the overall effectiveness of WWTP to guarantee compliance and to identify areas which can be improved. Subsequently, a more detailed analysis of each process is performed which allows the pinpointing of specific improvements in the operation of each process of the WWTP. This paper describes the application of this methodology to a selected WWTP. Subsequently, the global and operational performance assessment is presented and improvement measures for this specific WWTP are identified.

## METHODS

### Performance assessment system

The PAS methodology was applied to a WWTP in order to obtain an indication of how the plant could be optimized in terms of efficiency and effectiveness. Briefly, the methodology involves two

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stages (global and operational performance assessment). The first consists of evaluating the WWTP's global performance (GP) using KPI in terms of its removal efficiency and reliability, energy efficiency and sludge management on an annual basis. The KPI selected to evaluate the chosen WWTP are depicted in Table 1.

The second stage evaluates the system in terms of the daily operational performance of treated wastewater quality, removal efficiency and operational conditions. Each individual operation/process is evaluated using performance indices (PX) which can vary between 0 and 300 where a PX of 100 corresponds to the minimum acceptable performance and 300 corresponds to an excellent performance. Values between 0 and 100 correspond to poor performance, values between 100 and 200 correspond to acceptable performance and values between 200 and 300 correspond to good performance. The PX are obtained by converting state-variable data, which express the relevant operational performance assessment aspects of the WWTP into dimensionless performance indices (Silva *et al.* 2016 and references therein) using performance functions (Figure 1). The type of performance function used depends on which parameter is being assessed (view subsections below).

### Treated wastewater quality

The treated wastewater quality PX are determined using a performance function (Figure 1) where $R_{100}$ is the parametric value (PV), $R_{200}$ corresponds to half of the PV, i.e. 0.5 PV, and $R_{300}$ corresponds to 0.2 PV. $R_0$ is determined according to the maximum deviation allowed by the legislation for each parameter. For example, $R_0$ is 2 PV for chemical oxygen demand (COD) and biochemical oxygen demand ($BOD_5$) and 2.5 PV for total suspended solids (TSS). PX for COD, $BOD_5$ and TSS are determined using the performance function shown in Figure 1(a) whereas for pH, the performance function used is shown in Figure 1(b) since it is dependent on a range of values.

### Removal efficiency

Assessing facilities' performance based on typical removal efficiencies (Er) (Equation (1)) can be misleading since a given Er can either be insufficient, adequate or excessive to achieve effluent quality requirements, depending on influent quality.

$$Er = \left(1 - \frac{C_{out}}{C_{in}}\right) \times 100 \tag{1}$$

where $C_{out}$ is the effluent concentration and $C_{in}$ is the influent concentration.

Thus, to obtain a clear picture on how effective removal efficiencies are, PX on removal efficiencies (PX_Er) were determined according to the methodology presented in Silva *et al.* (2014b). The reference values and performance functions depend on the targeted pollutants and the specific operation or process and take into consideration the influent concentration ($C_{in}$) and limit value for effluent concentration, field data of Er vs $C_{in}$ (to obtain the Er model curves) and lower limit of Er vs $C_{in}$ typical curves which are determined based on literature review, taking into account the type of treatment. Consequently, the PX_Er are obtained by converting a 0–100% Er into a 0–300 performance indices using the increasing performance function depicted in Figure 1(c). The performance functions used for PX_Er were obtained for COD, $BOD_5$ and TSS removal considering a WWTP with activated sludge followed by secondary clarifiers.

### Operational conditions

The evaluation of operational conditions identifies the key state operational parameters for each process/treatment step which can be limiting the overall performance. Regarding operational conditions,

**Table 1** | Key performance indicators for the global performance assessment of the wastewater treatment plant

| Goal | Code, description and units | Formula | References |
|---|---|---|---|
| Effectiveness and reliability | WQ01 – Quality tests carried out (discharge permit regulation) (%) | $\frac{\text{Tests carried out (no.)}}{\text{Tests required (no.)}} \times 100$ | Quadros *et al.* (2010b); Silva *et al.* (2014a) |
| | WQ02 – Parameters analysed (discharge permit regulation) (%) | $\frac{\text{Parameters analysed (no.)}}{\text{Parameters required (no.)}} \times 100$ | Silva *et al.* (2014a) |
| | WQ03.1 – Compliance of discharged water quality discharge permit regulation (%) | $\frac{\sum_{i=1}^{m} Ji}{m}$<br>where $m$ is required parameters analysed (no.); $Ji$ is compliance of parameter $i$ (0 – no compliance or 1 – compliance) | Quadros *et al.* (2010b); Silva *et al.* (2014a) |
| | WQ03.3 – Compliance with Portuguese legislation (%) | $\frac{\sum_{i=1}^{p} \sum_{k=1}^{q} J_{ik}}{p\ x\ q} \times 100$<br>where $p$ is parameters analysed (no.); $q$ is months assessed in the reference period (no.); $J_{ik}$ is compliance of parameter $i$ in month $k$ (0 – no compliance or 1 – compliance) | Silva *et al.* (2014a) |
| | ER01 – Volumetric efficiency (%) | $\frac{\text{Volume of treated wastewater}}{\text{Volume of raw wastewater} - \text{volume of fresh water}} \times 100$ | Quadros *et al.* (2010b) |
| Energy efficiency | ER08 – Net use of energy from external sources (kWh/m$^3$) | $\frac{\text{Energy bought} - \text{energy sold}}{\text{Volume of treated wastewater}}$ | Silva & Rosa 2015 |
| | RU03.1 – Energy consumption (kWh/m$^3$) | $\frac{\text{Energy consumed}}{\text{Volume of treated wastewater}}$ | |
| | RU03.2 – Energy consumption (kWh/kg $BOD_5$ removed) | $\frac{RU03.1}{\text{BOD}_5\ \text{specific removal rate}}$ | |
| | BP18 – Energy production from biogas (kWh/m$^3$) | $\frac{\text{Energy produced from biogas}}{\text{Volume of treated wastewater}}$ | |
| Sludge management | BP01.1 – Sludge production (kg/m$^3$) | $\frac{\text{Produced sludge}}{\text{Volume of treated wastewater}}$ | Silva *et al.* (2016) |
| | BP01.2 – Sludge production (kg/kg $BOD_5$ removed) | $\frac{BP01.1}{FE03}$ | |
| | BP08 – Sludge dry weight (%) | Percentage of dry weight in the produced sludge | |

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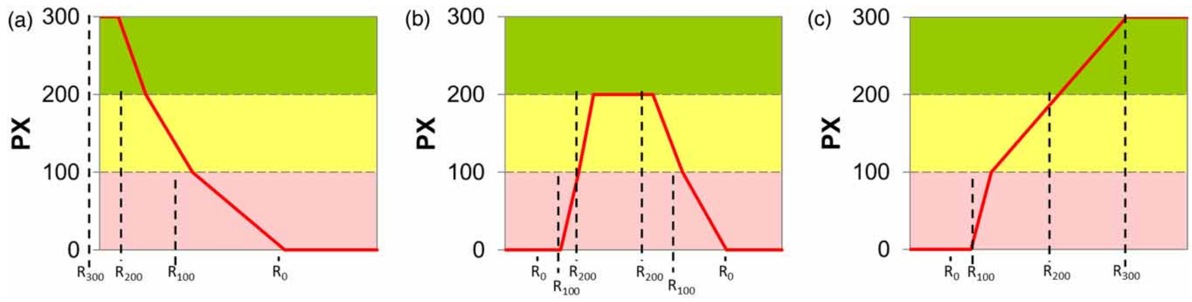


**Figure 1** | Performance functions used converting state variables of relevant operational performance assessment aspects of the WWTP into dimensionless performance indices. ($R_0$ to $R_{300}$ are reference values) (red – poor performance, yellow – acceptable performance, green – good performance).

PX 100 is obtained when the parameter values are within the range suggested in the literature. On the other hand, PX 200 corresponds to the values which guarantee the commitment between removal and economic efficiency. PX300 was not considered in most operational parameters as it cannot be based on literature values since excellent performance is very specific to each WWTP and its operational conditions. Thus, the assessment must identify case by case if there is potential for improvement or not (Quadros *et al.* 2010a).

Table 2 summarizes the specific key state operational parameters selected for the main treatment units in the studied WWTP and the reference values which were considered in the present study. The parameters were selected based on the specificity of the WWTP process and the available data.

**Table 2** | State variables/operational parameters selected to evaluate the operational conditions of the WWTP

| Treatment unit | Operational parameter | Performance function type | Reference values $R_0$ | $R_{100}$ | $R_{200}$ | $R_{300}$ | $R_{200}$ | $R_{100}$ | $R_0$ |
|---|---|---|---|---|---|---|---|---|---|
| Primary clarifier (no addition of coagulant) | HRT (d) | Figure 1(b) | 0.75 | 1 | 1.5 | n.a. | 2.5 | 4 | 5 |
| | Q/A ($m^3/m^2$.d) | Figure 1(b) | 18.75 | 25 | 30 | n.a. | 50 | 60 | 75 |
| Activated sludge | HRT_anaerobic (d) | Figure 1(b) | 0.3 | 0.5 | 0.7 | n.a. | 1.1 | 1.5 | 1.9 |
| | HRT_anoxic (d) | Figure 1(b) | 0.4 | 0.5 | 0.6 | n.a. | 0.8 | 1 | 1.2 |
| | HRT_aerobic (d) | Figure 1(b) | 3 | 3.5 | 4 | n.a. | 6 | 8 | 10 |
| | $R_{sludge}$ (%) | Figure 1(b) | 16 | 20 | 25 | n.a. | 50 | 100 | 120 |
| | $R_I$ (%) | Figure 1(b) | 80 | 100 | 120 | n.a. | 300 | 400 | 480 |
| | MLSS (mg/L) | Figure 1(b) | 1,600 | 2,000 | 3,000 | n.a. | 3,500 | 4,000 | 4,800 |
| | F/M ($kgBOD_5$/kgMLSS/d) | Figure 1(b) | 0.13 | 0.15 | 0.18 | n.a. | 0.22 | 0.25 | 0.3 |
| | SRT (d) | Figure 1(b) | 3 | 4 | 7 | n.a. | 20 | 27 | 34 |
| Secondary clarifier | Q/A ($m^3/m^2$.d) | Figure 1(b) | 11 | 15 | 20 | n.a. | 28 | 34 | 38 |
| | SLR (kgTSS/($m^2$.h)) | Figure 1(b) | 1.5 | 2 | 4 | n.a. | 6 | 10 | 12.5 |
| | HRT (d) | Figure 1(b) | 1.4 | 1.5 | 1.6 | n.a. | 2 | 4 | 5 |
| Anaerobic digestion | DM (% w/w) | Figure 1(c) | 1.125 | 1.5 | 2.5 | 3.5 | n.a. | n.a. | n.a. |
| | Alkalinity (mg $CaCO_3$/L) | Figure 1(b) | 1,500 | 2,000 | 3,000 | n.a. | 4,000 | 5,000 | 6,250 |
| | pH | Figure 1(b) | 6 | 6.6 | 7 | n.a. | 7.6 | 8 | 8.5 |
| | VFA/Alkalinity (mg VFA/mg$CaCO_3$) | Figure 1(b) | 0.075 | 0.1 | 0.2 | n.a. | 0.4 | 0.5 | 0.625 |
| Gravitational thickener | DM (% w/w) | Figure 1(c) | 3.75 | 5 | n.a. | 10 | n.a. | n.a. | n.a. |
| | Q/A ($m^3/m^2$.d) | Figure 1(b) | 11.625 | 15.5 | 23.75 | n.a. | 30.08 | 32 | 40 |
| | SLR (kgDM/($m^2$.h)) | Figure 1(b) | 67.5 | 90 | 120 | n.a. | 141 | 150 | 187.5 |
| | HRT (d) | Figure 1(b) | 0.75 | 1 | 1.2 | n.a. | 1.5 | 2 | 2.5 |
| Flotation | DM (% w/w) | Figure 1(c) | 2.25 | 3 | 4 | 5 | n.a. | n.a. | n.a. |
| Dewatering (centrifuge) | DM (% w/w) | Figure 1(b) | 11.25 | 15 | 17.5 | 20 | n.a. | n.a. | n.a. |

HRT – Hydraulic retention time; Q/A – Overflow rate; $R_{Sludge}$ – Sludge recirculation; $R_I$ – Internal recirculation; MLSS – Mixed liquor suspended solids; F/M – Food to microorganism ratio; SRT – Solids retention time; SLR – Solids loading rate; DM – Dry matter; VFA – Volatile fatty acids; n.a. non-applicable.

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## RESULTS AND DISCUSSION

### Case study

As a case study, a WWTP serving a 263,107 population equivalent with a treated flow of 27,922 $m^3$/day and an organic loading of 13,984 kg$BOD_5$/day is presented. The wastewater treatment includes primary clarification (two units), secondary activated sludge process ($A^2O$ – anaerobic/anoxic/aerobic) and secondary clarification (three units). The produced sludge is treated by gravitational thickening and flotation, anaerobic digestion with biogas production and centrifuge sludge dewatering.

The WWTP performance was evaluated for the period 2015–2018.

### Global performance assessment

The GP of the WWTP can be seen in Figure 2. Although an overall satisfactory performance is observed, the GP gave an indication that improvement is possible in all areas, especially in terms of energy performance and sludge management.

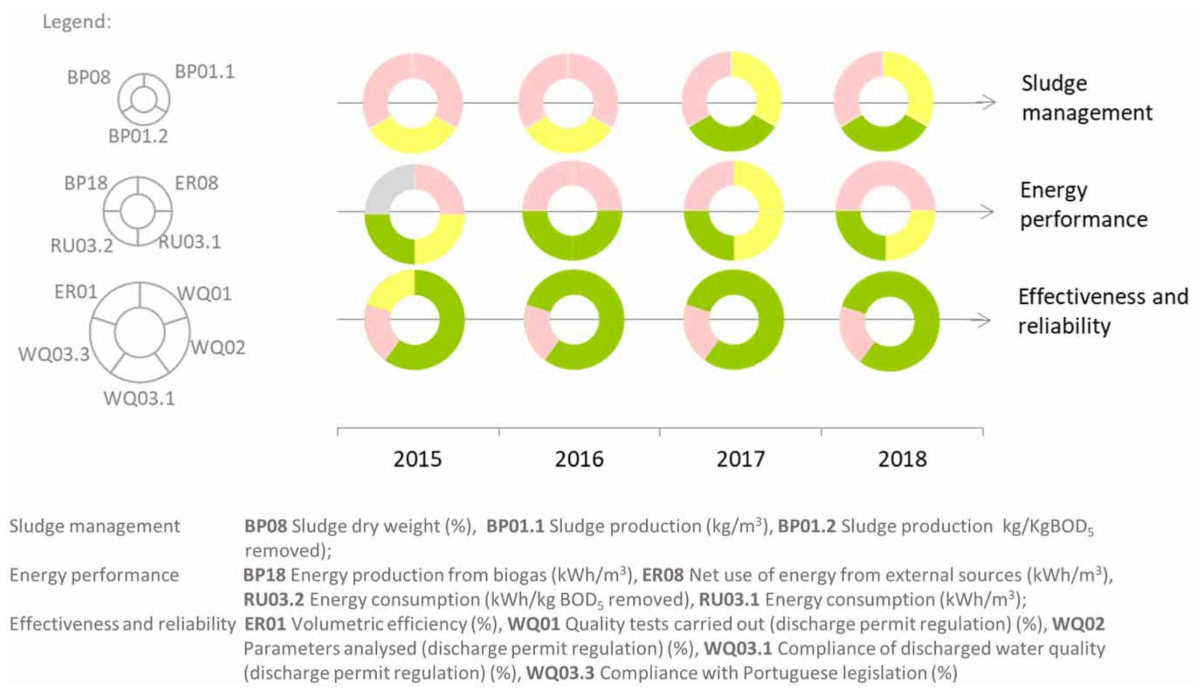


**Figure 2** | WWTP's global performance assessment (red – poor performance, yellow – acceptable performance, green – good performance, grey – non-applicable).

The KPI for effectiveness and reliability show that the WWTP consistently complies with the discharge permit regulation. Note that WQ3.3 was determined using all the operational control analyses and not only those required by the Portuguese regulation. Nevertheless, this WWTP shows efficiency problems by not consistently ensuring compliance in terms of $BOD_5$, COD and TSS (view section below). This is partly due to the discharge of non-permitted industrial wastewater to the WWTP.

Since WWTP are responsible for 1% of electricity consumption in European countries (Simon-Várhelyi *et al.* 2020) and 25–40% of operating costs in a WWTP are related to energy consumption (Panepinto *et al.* 2016 and references therein), it is crucial to evaluate the energy efficiency and to

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identify improvement measures. Regarding energy production, the results obtained for BP18 show that the WWTP could be producing higher volumes of biogas which could be converted to energy. Improving the parameter and decreasing energy consumption will have a direct impact on the results obtained for ER08. In terms of energy performance, RU03.2 presents good performance, showing an adequate energy efficiency in terms of mass removed. However, the performance indicator for energy consumption (kWh/m$^3$), RU03.1, presents poor performance resulting in an average consumption of 0.58 kWh/m$^3$. The result obtained is similar to that estimated for energy consumption (0.6 kWh/m$^3$) of a typical WWTP with activated sludge processes and anaerobic digestion of the sludge (Gude 2015). As such, and based on these results, energy measurement campaigns were identified as necessary and are currently being performed to understand which units/equipment are underperforming and can be optimized. These energy campaigns will focus on the main energy consuming equipment such as aeration of mixed liquor sludge pumping in primary and secondary settling and sludge dewatering which typically represent 55–70, 15.6 and 7% of total energy consumption, respectively (Metcalf & Eddy 2003).

The main indicators affecting the sludge management efficiency are the sludge dry weight (BP08) and sludge production (BP01.1), which indicates possible problems in the sludge treatment units (see section below). However, an improvement can be observed in the KPI BP01.2, which went from an acceptable performance in 2015–2016 to a good performance in 2017–2018, and KPI BP01.1, which went from a poor performance in 2015–2016 to an acceptable performance in 2017–2018.

## Operational performance

### Quality of the treated wastewater

Overall, the PX of $BOD_5$ and COD show that the WWTP can remove these pollutants to levels which are in compliance with the discharge permit (Figure 3). The lower performance around May 2018 was due to non-permitted industrial wastewater discharge and an anomalous increase in rainfall which increased the inflow. If recurrent, such non-permitted industrial discharges should be evaluated in terms of origin and characteristics to minimize the impact in the treatment effectiveness (Sánchez-Avila *et al.* 2009).

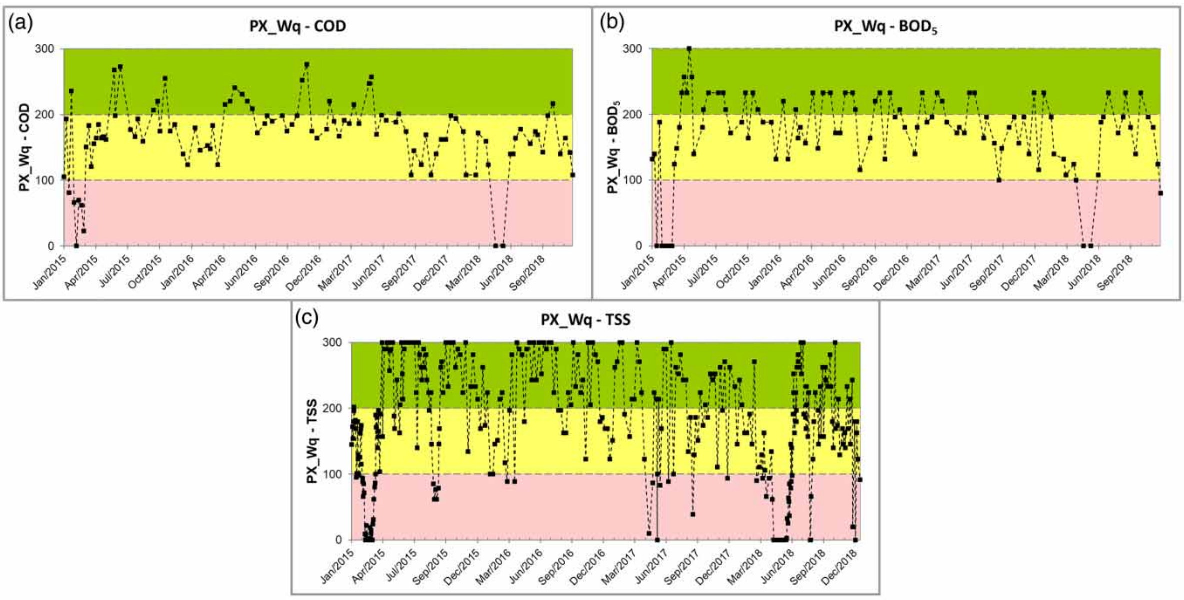


**Figure 3** | Daily performance indices of treated wastewater quality for COD, $BOD_5$ and TSS.

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On the other hand, TSS values showed great variability throughout the years of study (Figure 3). Albeit the effluent concentration values are compliant with the discharge permit, and this variability may indicate that there are some instabilities in the operational conditions which must be studied further to identify improvement measures and minimize the risks.

## Removal efficiency

Figure 4 presents the results obtained for the removal efficiency of COD, $BOD_5$ and TSS for the studied WWTP. Despite receiving wastewater with concentrations above the typical range in terms of COD and $BOD_5$ (Figure 4, left), the WWTP has been successful at removing these pollutants, keeping removal at an acceptable or good performance level (Figure 4, right). The only exception was the moment corresponding to the industrial wastewater discharge as mentioned above. Contrarywise, TSS levels in the influent were mostly within the typical range but showed lower performance levels, i.e. lower PX_Er. This is coherent with the results obtained in terms of quality shown above. As such, the operational conditions of the primary and secondary clarifier were studied and are presented and discussed in the following section.

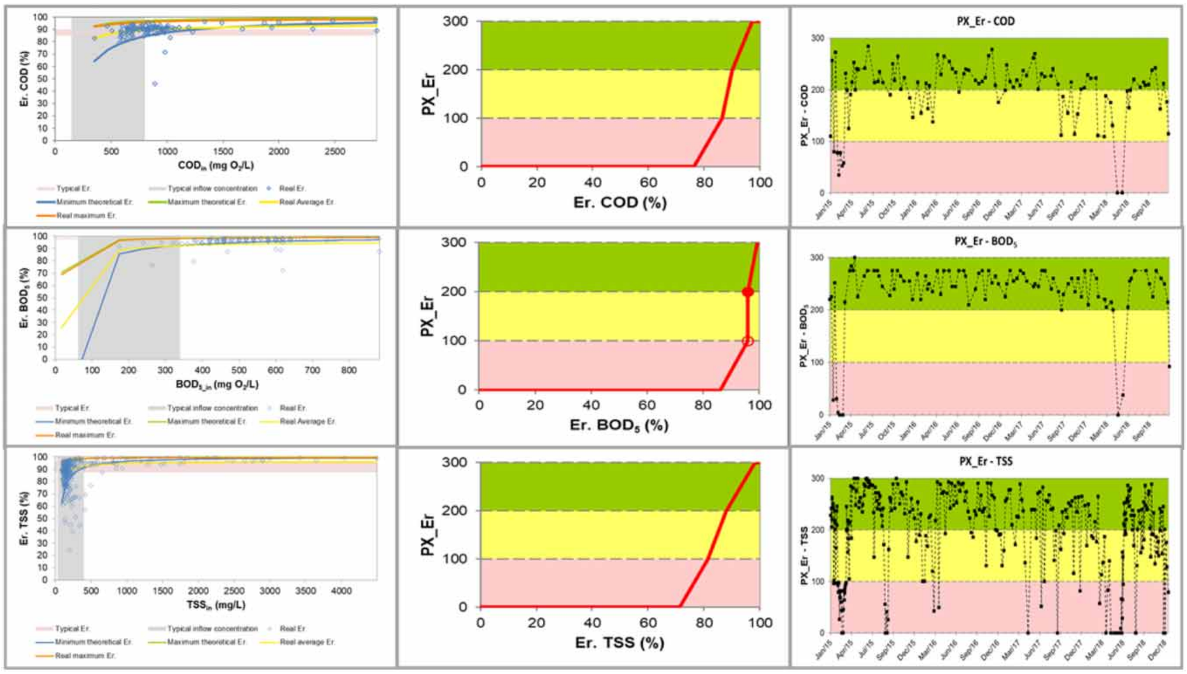


**Figure 4** | Er model curves (for theoretical and real Er), effect of $C_{in}$ on Er and typical $C_{in}$ range (left), examples of performance functions used converting removal efficiencies of COD, $BOD_5$ and TSS into PX_Er (middle) and PX_Er obtained for the studied WWTP (right).

## Operating conditions

To understand where the system is underperforming, each operational unit was studied using the data available in order to calculate the operational PX (Table 2). Since the main problems detected are related with the TSS (Figure 3) and sludge management (Figure 2), this section focuses mainly on the operational parameters associated with these issues.

The PX for surface overflow rate and HRT in the primary clarifiers were mostly below 100 (in the red area) (data not shown). This is mainly the case in the summer months where the inflow is lower. Most likely this occurs since the inflow is consistently lower than what was expected when designing

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the WWTP. Since the WWTP has two primary clarifiers, and given that the results indicate oversizing of the primary clarification phase, it could be advantageous to disable one of the units.

The secondary clarifiers also present potential for improvement (Figure 5). The performance indices show that there is no consistency in these operational parameters. The sludge recirculation rate ($R_{Sludge}$) is crucial to maintain a sufficient concentration of activated sludge in the aeration tank and the sludge blanket depth in the secondary clarifier (Metcalf & Eddy 2003). Currently, the secondary clarifier and the activated sludge unit are being operated at high $R_{Sludge}$. As such, it is suggested to decrease the $R_{Sludge}$ to values between 25 and 50% (Table 2). This will have a direct impact on the SLR and on the HRT. Similarly to the primary clarifiers, the low performance indices for the overflow rate are likely to be related with the oversizing of the WWTP. As such, it could be advantageous to work with only one or two units of the secondary clarifiers. By maintaining the best sludge recirculation rate would assure optimal operation of the secondary clarifiers, and it would be possible to maintain a stable high-quality effluent whilst reducing operational costs (Conserva *et al.* 2019).

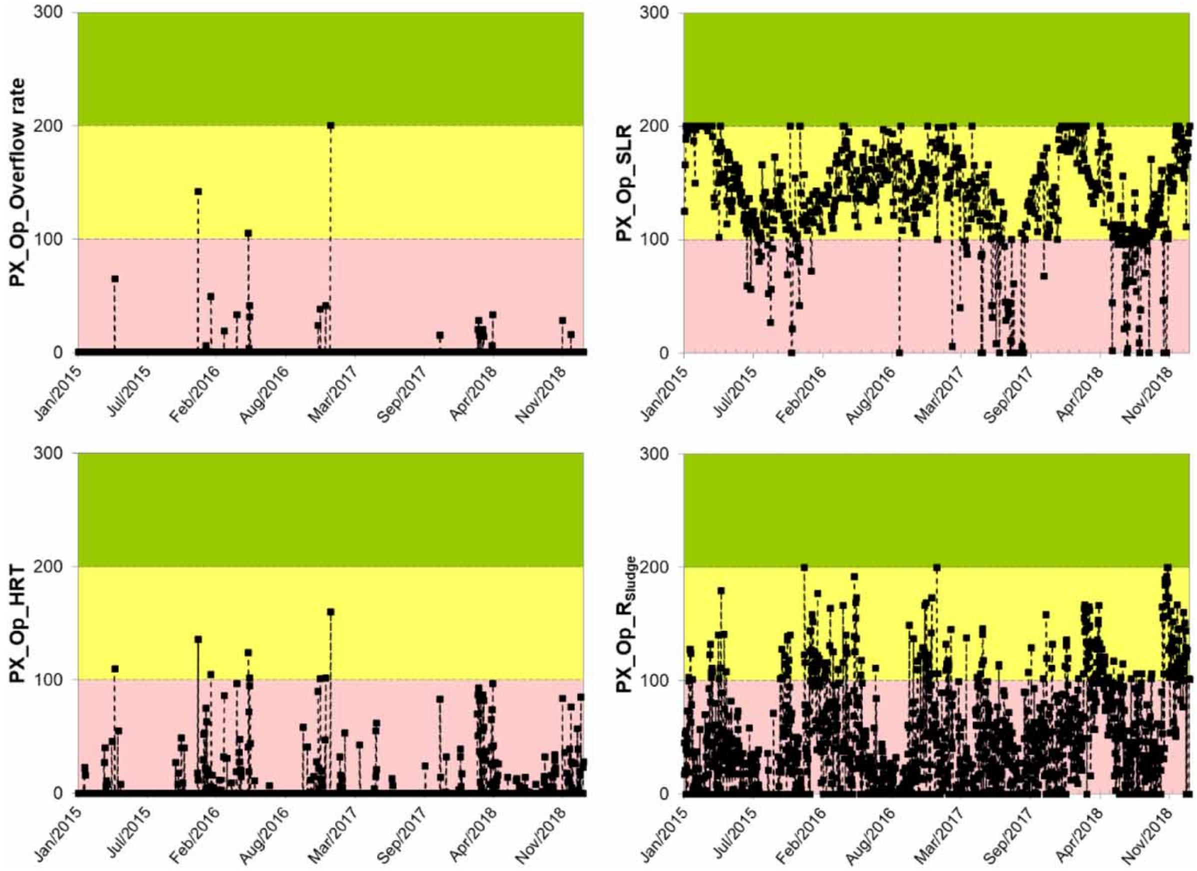


**Figure 5** | Performance indices for the secondary clarifier unit.

In terms of sludge management and analysing the dry solids PX, a good performance was observed for all stages of sludge treatment except for the sludge thickening phase which is presented in Figure 6. This underperformance could be associated with the low PX obtained for hydraulic and solids loading rates and hydraulic retention time (HRT) in the gravitational sludge thickening unit (Figure 6). In fact, the low hydraulic loading rates (Figure 6(b)) and high HRT observed (Figure 6(d)) can lead to floating sludge which may reduce the thickening efficiency (Metcalf & Eddy 2003). Since sludge management can cost between 20 and 60% of the total operating costs in wastewater treatment (IWA 2007), careful consideration should be taken in this field. Thus, improvement measures such as disabling one of the

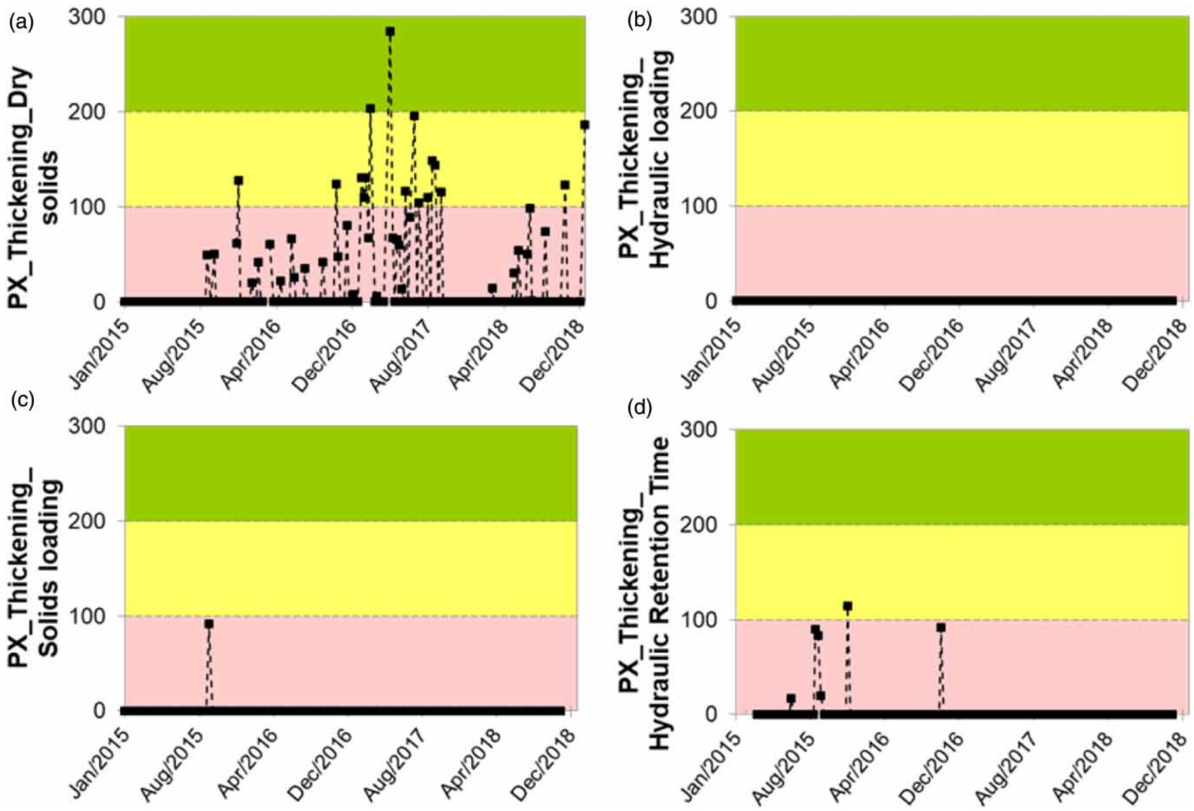


**Figure 6** | Performance indices for the sludge thickening unit.

units, decreasing the HRT, optimizing the sludge blanket depth, increasing loading rates and adding chemicals are currently being contemplated, also taking into account the effects on the subsequent digestion process.

The PX associated with the anaerobic digestor is shown in Figure 7(a). All present acceptable to good performance except for the PX associated with the VFA/alkalinity ratio. Since alkalinity levels are consistently within the typical range (Figure 7(a)), special care must be taken to maintain the VFA concentration at acceptable levels. The reference values for VFA concentration should be defined for each WWTP as it will vary with the sludge quality. The sludge quality will affect the bioavailability of the substrate and/or the thermodynamic conditions (Carvalheira *et al.* 2018). Analysing Figure 7(b), it seems that this unit could operate best by maintaining the VFA concentration above 0.4 g/L, taking care to maintain the other PX within acceptable levels. Further detailed studies

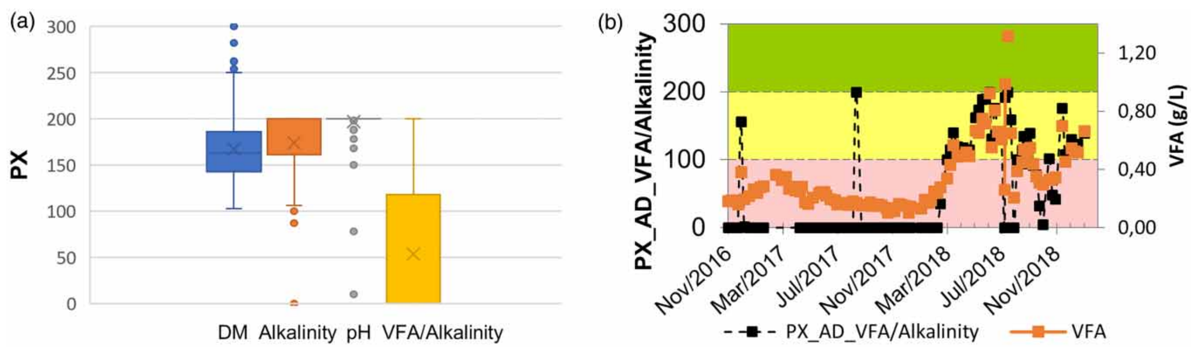


**Figure 7** | Performance indices for the anaerobic digestion unit (2016–2018).

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should be carried out to fully understand how to optimize this process as it could potentially increase the biogas production efficiency, improving the indicator BP18 (Figure 2).

## CONCLUSIONS

The studied WWTP presents an overall good performance in terms of effectiveness and reliability. However, improvement measures are needed in terms of sludge management and energy performance. To understand how to improve the energy performance, energy measurement campaigns were suggested and are currently being performed to understand which equipment is underperforming. In addition, a more in-depth critical analysis to the activated sludge unit will be performed to pinpoint improvement opportunities.

In terms of operation, this study showed that the oversizing of the WWTP is resulting in lower efficiency. To overcome this, operational improvements were identified for sludge management, particularly in the primary and secondary clarifier, the gravitational sludge thickening and anaerobic digestion unit.

The application of the PAS to the WWTP allowed the identification of improvement measures in both liquid and solid treatment stages. Besides supporting the facility's operational management, this system provides meaningful information that is used for decision-making purposes in terms of the utility's asset management system by identifying the most critical assets that require intervention, rehabilitation or upgrade (equipment or technology) as part of an integrated and on-going process that aims to continuously improve the facilities' efficiency and effectiveness.

## REFERENCES

Arnell, M., Rahmberg, M., Oliveira, F. & Jeppsson, U. 2017 Multi-objective performance assessment of wastewater treatment plants combining plant-wide process models and life cycle assessment. *J. Water Clim. Change* **8**, 715–729.

Cabrera Jr, E., Dane, P., Haskins, S. & Theuretzbacher-Fritz, H. 2011 *Benchmarking Water Services. Guiding Water Utilities to Excellence*. The IWA Specialist Group on Benchmarking and Performance Assessment. AWWA and IWA Publishing, London.

Carvalheira, M., Cassidy, J., Ribeiro, J. M., Oliveira, B. A., Freitas, E. B., Roca, C., Carvalho, G., Oehmen, A. & Reis, M. A. M. 2018 Performance of a two-stage anaerobic digestion system treating fruit pulp waste: the impact of substrate shift and operational conditions. *Waste Manage.* **78**, 434–445.

Conserva, S., Tatti, F., Torretta, V., Ferronato, N. & Viotti, P. 2019 An integrated approach to the biological reactor–sedimentation tank system. *Resources* **8**, 94.

Di Fraia, S., Massarotti, N. & Vanoli, L. 2018 A novel energy assessment of urban wastewater treatment plants. *Energy Convers. Manage.* **163**, 304–313.

Ebrahimi, M., Gerber, E. L. & Rockaway, T. D. 2017 Temporal performance assessment of wastewater treatment plants by using multivariate statistical analysis. *J. Environ. Manage.* **193**, 234–246.

Gude, V. G. 2015 Energy and water autarky of wastewater treatment and power generation systems. *Renew. Sustain. Energy Rev.* **45**, 52–68.

IWA 2007 Biological wastewater treatment series. In: *Sludge Treatment and Disposal, vol. 6* (Andreoli, C. V., Sperling, M. & Fernandes, F., eds). IWA Publishing, London.

Longo, S., d'Antoni, B. M., Bongards, M., Chaparro, A., Cronrath, A., Fatone, F., Lema, J. M., Mauricio-Iglesias, M., Soares, A. & Hospido, A. 2016 Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement. *Appl. Energy* **179**, 1251–1268.

Longo, S., Mauricio-Iglesias, M., Soares, A., Campo, P., Fatone, F., Eusebi, A. L., Akkersdijk, E., Stefani, L. & Hospido, A. 2019 ENERWATER – a standard method for assessing and improving the energy efficiency of wastewater treatment plants. *Appl. Energy* **242**, 897–910.

Luo, L., Dzakpasu, M., Yang, B., Zhang, W., Yang, Y. & Wang, X. C. 2019 A novel index of total oxygen demand for the comprehensive evaluation of energy consumption for urban wastewater treatment. *Appl. Energy* **236**, 253–261.

Metcalf & Eddy 2003 *Wastewater Engineering – Treatment and Reuse*, 4th edn. McGraw-Hill Inc., New York.

Molinos-Senante, M., Hernandez-Sancho, F. & Sala-Garrido, R. 2014 Benchmarking in wastewater treatment plants: a tool to save operational costs. *Clean Technol. Environ. Policy* **16**, 149–161.

Okwori, E., Viklander, M. & Hedström, A. 2020 Performance assessment of Swedish sewer pipe networks using pipe blockage and other associated performance indicators. *$H_2Open$ J.* **3**, 46–57.

$H_2$Open Journal Vol 3 No 1
doi: 10.2166/h2oj.2020.007

Panepinto, D., Fiore, S., Zappone, M., Genon, G. & Meucci, L. 2016 Evaluation of the energy efficiency of a large wastewater treatment plant in Italy. *Appl. Energy* **161**, 404–411.

Quadros, S., Rosa, M. J., Alegre, H., Silva, C. & Ramalho, P. 2010a *Operational performance assessment of urban wastewater treatment plants*. 14.° Encontro Nacional De Saneamento Básico (National Meeting on Basic Sanitation) (ENASB) – Silubesa (in Portuguese).

Quadros, S., Rosa, M. J., Alegre, H. & Silva, C. 2010b A performance indicators system for urban wastewater treatment plants. *Water Sci. Technol.* **62**, 2398–2407.

Rosa, M. J., Silva, C., Ramalho, P. & Alegre, H. 2011 *PASt21 – National Initiative for the Performance Assessment of WTP and Urban WWTP*. Final Report 277/2011 NES, LNEC, Lisbon, p. 101, June (in Portuguese).

Sánchez-Avila, J., Bonet, J., Velasco, G. & Lacorte, S. 2009 Determination and occurrence of phthalates, alkylphenols, bisphenol A, PBDEs, PCBs and PAHs in an industrial sewage grid discharging to a municipal wastewater treatment plant. *Sci. Total Environ.* **407**, 4147–4167.

Silva, C. & Rosa, M. J. 2015 Energy performance indicators of wastewater treatment: a field study with 17 Portuguese plants. *Water Sci. Technol.* **72**, 510–519.

Silva, C. & Rosa, M. J. 2020 Performance assessment of 23 wastewater treatment plants – a case study. *Urban Water J.* **17**, 78–85. doi:10.1080/1573062X.2020.1734634.

Silva, C., Quadros, S., Ramalho, P. & Rosa, M. J. 2014a A tool for a comprehensive assessment of treated wastewater quality. *J. Environ. Manage.* **146**, 400–406.

Silva, C., Quadros, S., Ramalho, P., Alegre, H. & Rosa, M. J. 2014b Translating removal efficiencies into operational performance indices of wastewater treatment plants. *Water Res.* **57**, 202–214.

Silva, C., Saldanha Matos, J. & Rosa, M. J. 2016 Performance indicators and indices of sludge management in urban wastewater treatment plants. *J. Environ. Manage.* **184**, 307–317.

Simon-Várhelyi, M., Cristea, V. M. & Luca, A. V. 2020 Reducing energy costs of the wastewater treatment plant by improved scheduling of the periodic influent load. *J. Environ. Manage.* **262**, 110294.

Yang, L., Zeng, S., Chen, J., He, M. & Yang, W. 2010 Operational energy performance assessment system of municipal wastewater treatment plants. *Water Sci. Technol.* **62**, 1361–1370.

First received 17 January 2020; accepted in revised form 16 April 2020. Available online 7 August 2020