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A novel method for rapid assessment of the performance and complexity of small wastewater treatment plants

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Abstract. The performance of wastewater treatment plants (WWTPs) depends on various technical, non-technical, and human factors. A total of 245 small and medium-size WWTPs were studied during 2014–2015 and evaluated according to a novel method for rapid assessment of their performance and complexity. The suggested method creates a comparable system of ratings for all treatment solutions by analysing simultaneously influential characteristics, system complexity, operational practices, and process parameters in comparison with designed and/or standardized values and their impact on the overall system performance. Total evaluation of complexity and total evaluation of performance are new unified tools, which were applied for comparing WWTPs that applied different technologies and had a wide variety of loadings.

The study revealed that the greater the designed loading, the more treatment steps were usually needed and employed. The complexity of these treatment steps can vary a lot depending on the plant capacity. There was a positive relationship between complexity and performance: a higher complexity provided a better performance of WWTPs. This suggests that combining automation as a tool for the process control with a more advanced equipment (higher complexity) could prevent many process disturbances and therefore improve the overall plant performance.

Key words: wastewater treatment, performance assessment, critical control points, total evaluation of complexity, total evaluation of performance.

1. INTRODUCTION

The main goal of wastewater treatment is to reduce the amount of pollutants below the admissible level in order not to pose any threat to the environment or to public health. Regardless of a large variety of wastewater treatment technologies (e.g. activated sludge, sequencing batch reactors, biofilm, or constructed wetlands), the performance of wastewater treatment plants (WWTPs) depends on various technical and non-technical factors

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such as characteristics of influent wastewater and how well the designed treatment process is in agreement with them, operational and management practices, reliability of equipment, and flexibility of the process (Hegg et al., 1979; Olsson, 2012; Hao et al., 2013). It is extremely difficult to compare fundamentally different treatment systems such as the biofilm process for 150 personal equivalents (PE) and a sequencing batch reactor for 10 000 PE. The former process relies on attached microorganisms, but the latter operates with free-swimming bacteria known as activated sludge. One is small and moderately automated, but the other is much larger and well automated. As a consequence, the two processes are designed on different bases. For example, substrate availability in biofilm processes can be considered to be diffusion-dependent, whereas floc diffusion limitation in activated sludge is not relevant. Still, both of these solutions contain similar design elements like pretreatment (e.g. sieves), biological treatment, sedimentation, and sludge handling. The function of sieves is to remove particles and objects from the flow of wastewater (ISO, 2014). The performance of the sieve depends on the quantity and quality of the influent, yet the configuration of sieving equipment may vary from hand-operated to multi-step and fully automated. Sedimentation is a process of settling and deposition, under the influence of gravity, of suspended matter carried by water or wastewater physical process that relies on gravity to remove suspended solids from water (ISO, 2014). Regardless of whether it is performed in the same tank of sequencing batch reactors or in a separate tank, the principle of the process is the same. Therefore, the evaluation of the overall efficiency of a WWTP constitutes a multi-objective decision chain (Hao et al., 2013).

It has been argued that implementation of the same method for comparative evaluation of overall treatment performance of different WWTPs is not possible due to the varying nature of treatment processes used and operational conditions applied (Hao et al., 2013; Chen et al., 2015). In many cases the process parameters in a WWTP can be modelled in detail based on designed values, characteristics of the influent, or even on the basis of metabolic reactions of the specific group of microorganisms (Copp, 2002; Henze et al., 2011). However, the actual situation on the plant can differ dramatically from the modelled result due to incorrect design parameters, inevitably changing input parameters, equipment failure, or neglect of maintenance. As there are many factors that can influence the effectiveness of a WWTP (e.g. infiltration, bulking sludge, broken sensors, or air diffusers), comparative evaluation is difficult to perform.

Some evaluation models and indexes have been proposed, but the aim of these models is quite different. Many authors focus on environmental or economic benefit evaluation and the models then are adaptations of life cycle assessments (De Faria et al., 2015; Fang et al., 2016), and the selection of treatment process is based on fuzzy analytical hierarchy process method (Karimi et al., 2011) or multi-criteria analysis (Jozwiakowski et al., 2015). The more universal models like treatment performance index proposed by Chen et al. (2015) and a similar model described by Hao and co-authors (2013) focus mainly on pollutant removal efficiencies in different treatment phases. Advantages of these models are that operational conditions are included in the assessment, but the variance of factors is still limited. In the above-mentioned studies the suggested models have been applied only on a handful of very large treatment plants. No studies treating small-scale WWTPs could be found.

The aim of this study was to create a comparable system of ratings for all wastewater treatment solutions by analysing simultaneously influential characteristics, system complexity, operational practices, and process parameters in comparison with designed and/or standardized values and their impact on the overall system performance.

In total, there are 1.35 million people and 664 municipal WWTPs in Estonia (VEKA, 2016). Between 2004 and 2014 about 49 million euros was invested into small-scale (less than 2000 PE) WWTPs and 115 million euros into 41 bigger plants. The main sources of investments were the Cohesion Fund of the European Union (2004 to 2007, 53.8 million euros, and 2007 to 2013, 61.7 million euros) and national investment programmes (approximately 16 million euros through the Estonian Environmental Investment Centre) (EIC, 2016). In total 288 WWTPs were constructed or modernized by using subsidies. According to national monitoring programmes, 45% of these WWTPs were not capable of meeting environmental requirements (Allas, 2014), and according to water enterprise self-monitoring programmes about 10% of the WWTPs were not capable of meeting these requirements most of the time even after the investments (VEKA, 2016). Reasons for their poor performance remained unclear. The difference between national programmes and self-monitoring programmes could be a result of differences in the sampling time (operators themselves could choose the sampling time for self-monitoring analyses) and the performance of the WWTP during that specific period, or caused by some other factors, e.g. sampling strategy and analytical methods, as highlighted by Prasse et al. (2015).

Prasse et al. (2015) showed that chemical and biological assessment of wastewater treatment technologies are influenced by the sampling strategy and analytical methods used, and therefore they suggested flow-proportional composite sampling. However, for us the flow-proportional composite sampling strategy for both influent and effluent of each WWTP was not realistic due to the funding and time limitations. Moreover, Estonian regulation on effluent quality (Vabariigi Valitsus, 2013) states that all wastewater effluents have to meet quality standards all the time. Therefore, a completely different approach to analyse the performance and effectiveness of WWTPs was chosen.

2. MATERIAL AND METHODS

2.1. Overview of the studied facilities

In total 245 WWTPs that had been built or modernized by using subsidies were evaluated (Fig. 1). Activated sludge process was the process most commonly used (163 conventional activated sludge treatment plants and 34 using sequencing batch reactors), followed by ecological wastewater treatment systems (incl. 13 oxidation ponds, 28 constructed wetlands for secondary treatment, and 104 maturation ponds for tertiary treatment) and biofilm reactors (21 plants). Most evaluated WWTPs are small: 109 WWTPs are designed for loadings less than 300 PE, 91 for 300–2000 PE, 26 for 2000–10 000 PE, 15 for 10 000–100 000 PE, and 4 WTTPs for more than 100 000 PE. Of all studied WWTPs 88 (24%) were prefabricated package plants and 157 WWTPs were of special design.

There were three aspects that significantly complicated assessment of the performance: (i) most of the WWTPs were very small (see Fig. 2); (ii) technical solutions for wastewater treatment were different, and (iii) no unified evaluation methodology was available.

The suggested integrated method creates a comparable system of ratings for all individual technological steps making it possible to simultaneously analyse several factors such as influent characteristics, system complexity, operational practices, and process parameters. It also simultaneously considers their impact on the overall system performance. In addition, sampling results were linked to this rating-based model.

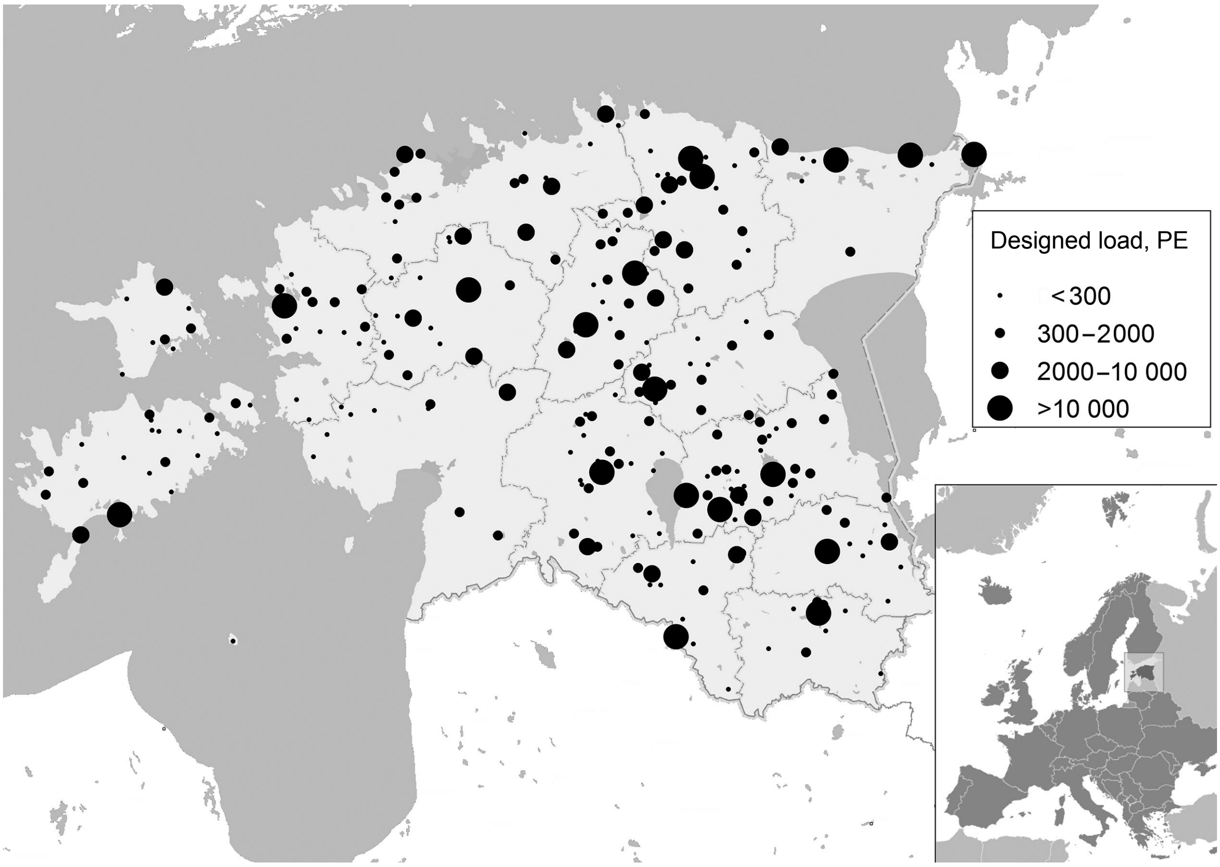

Fig. 1. Location and size of the evaluated wastewater treatment plants in Estonia.

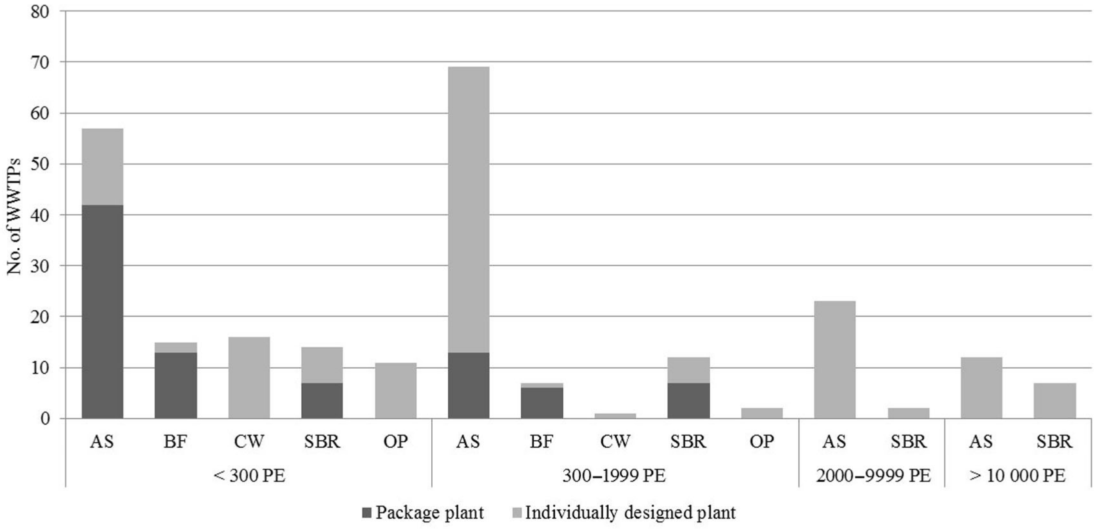

Fig. 2. Overview of treatment technologies in the studied facilities (<10 000 PE). Technologies applied: AS – activated sludge, BF – biofilm, CW – constructed wetlands, SBR – sequencing batch reactors, OP – oxidation ponds.

2.2. A novel method for evaluating performance

The overall assessment of the treatment performance of WWTPs was based on the performance of individual treatment phases, but unlike Chen et al. (2015), the individual treatment steps had to be evaluated separately due to the great variance in technologies used and environmental objectives set for the evaluated WWTPs. To ensure comparability of individual WWTPs, the following prerequisites were set:

- The steps of treatment processes (primary, secondary, and tertiary treatment) are characteristic of all WWTPs.
- Different equipment and processes have the same function in the same treatment step (e.g. the bar screen and screw screen are both devices for removing particles from wastewater).
- All the processes and equipment having the same purpose at the same treatment step have to be comparable by setting specific critical control points (CCPs) for each treatment step.

A questionnaire was developed to assess WWTPs in situ. The questionnaire was divided into five main categories and 21 subcategories (Table 1). For each subcategory (treatment step), a minimum of four CCPs were set. Depending on the complexity of the wastewater treatment process the number of CCPs to be evaluated varied between 37 (two treatment steps − septic tank and oxidation ponds) and 170 (9 treatment steps − primarily treated wastewater was divided into two parallel treatment lines using activated sludge process or sequencing batch reactors, and the sewage sludge was stabilized on site). To overcome the problem of assessment subjectivity, all the CCPs were formulated as multiple-choice questions with two to five alternative answers, but mainly in the form ‘yes’ or ‘no’.

During the assessment of WWTPs the following parameters were evaluated on a scale of 10 points (Fig. 3):

- **General complexity** describes the situation where the complexity of each individual treatment step is not taken into consideration, but the number of treatment steps in the specific WWTP is divided by all possible treatment steps described in the model. General complexity defines all treatment steps that are to be evaluated for performance and complexity.
- **Total evaluation of complexity (TEC)** describes how many different treatment steps are involved in the wastewater treatment process and how sophisticated the technology is.
- **Total evaluation of performance (TEP)** describes all the factors that can influence the wastewater treatment process (e.g. quantity and composition of the influent, difference between design values and actual conditions, functionality of equipment, operational problems).

Evaluations of performance and complexity in each treatment step were established on the basis of the evaluation of the CCPs in the same step. In this paper CCPs are defined as factors that (i) influence the performance of the treatment step (e.g. growth of filamentous micro-organisms), (ii) describe operational conditions (e.g. surface of final clarifier is kept clean, pumps are in

Table 1. Categorization of treatment steps used in assessment

Treatment step	Mandatory CCPs to be evaluated for all WWTPs	Selected steps of individual WWTPs
1. Wastewater characterization		
Characteristics of the influent	X	
Additional loading due to excess loading		X
Effluent quality	X	
2. Primary treatment		
Screens and sieves		X
Primary clarifier		X
Grit chamber and oil trap		X
Septic tank		X
3. Secondary treatment		
Activated sludge process		X
Sequencing batch reactor		X
Constructed wetlands		X
Biological filter		X
Submerged bed reactor		X
Biological contactor		X
Final clarifier		X
4. Tertiary treatment		
Nitrogen removal		X
Phosphorus removal		X
Effluent polishing		X
5. Other factors		
General aspects of wastewater treatment	X	
Automation		X
Sewage sludge treatment		X
Operator's competence	X	

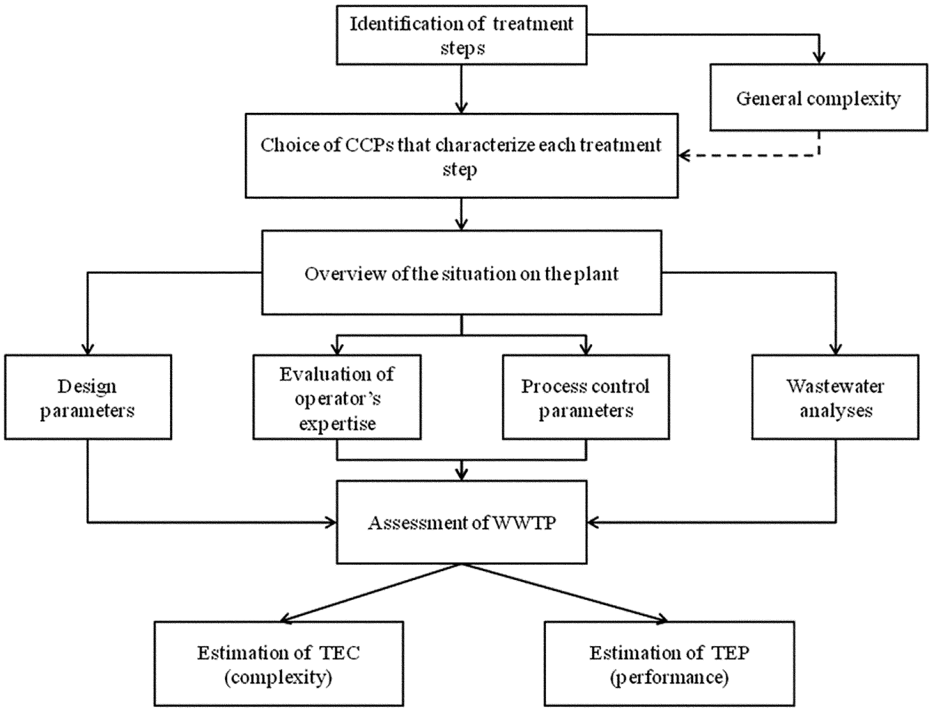

Fig. 3. Flow sheet of activities and data collection in WWTPs.

working order), or (iii) describe the complexity of the treatment step (e.g. screens are pressed and washed). For each wastewater treatment step, a minimum of two CCPs were defined. All CCPs were chosen by a group of experts following suggestions in the literature (Kuusik et al., 2001; Jenkins et al., 2004; Noorvee et al., 2007; Maastik et al., 2011; Baumann et al., 2012).

The relevance and values for each CCP that described the performance or complexity of a specific treatment step (P_i) were defined empirically. The following formula was used to calculate P_i:

$$P_i = \frac{\sum_{i=1}^{n} X_i \times Y_i}{\sum_{i=1}^{n} Y_i} \times 10, \tag{1}$$

where P_i is the harmonized assessment of the treatment step on the scale of 10 points, X_i is the score on the CCP (between 0 and 1), and Y_i describes the expert opinion on the importance of the given CCP in the treatment step.

Based on each treatment step, TEP and TEC were calculated. A summary of the evaluations was formed from the weighted scores of the different stages as follows:

$$\mathrm{TEP} = \left[\sum_{i=1}^{n} a_i + \frac{\sum_{i=1}^{n} \left(\frac{P_i}{10} \times b_i \right)}{\sum_{i=1}^{n} b_i} \right] \times 10, \tag{2}$$

where TEP is harmonized performance assessment of the total treatment process on the scale of 10 points, a_i addresses some general aspects for the overall process control, P_i is harmonized performance assessment of the treatment step on the scale of 10 points, and b_i describes the expert opinion on the importance of the given treatment step in the whole wastewater treatment process.

For TEC similar calculations were made.

As assessing the impact of performance and complexity on the effluent quality can be problematic due to the varying quality requirements for the WWTPs by size, the index of effluent violations (IVE) was developed. The value of IVE was set on the 10 point scale. With the purpose of ensuring comparability of different WWTPs on the same basis, the following prerequisites were set: (i) for the effluents performing by up to 25% better than required by the discharge consent, IVE = 10; (ii) for the effluents exceeding quality standards by more than 300%, IVE = 0.

IVE is formed as an average compliance with effluent quality standards that are regulated by the plant's discharge consent:

$$\mathrm{IVE} = \frac{\sum_{i=1}^{n} \left(\frac{x_i}{y_i} \times 8 \right)}{n}, \tag{3}$$

where x_i is the result of effluent analysis for the component i (e.g. $\mathrm{BOD_7}$), y_i is the effluent quality standard for the component i (e.g. $\mathrm{BOD_7}$), and n is the number of components that were analysed and regulated by discharge consent.

2.3. Data collection, sampling, and laboratory analyses

The selected WWTPs were visited and assessed according to a uniform method over a period of six months, between October 2014 and March 2015. A total of 541 grab samples were collected, of which 241 samples were taken from the effluent of secondary treatment units and 94 from the effluent of tertiary treatment units. For the determination of mixed liquor suspended solids (MLSS) 94 samples were collected. No effluent samples were taken from two WWTPs as there was no outflow during the plant visit. For these two WWTPs analysis results from a national monitoring programme were used. The average wastewater temperature during the sampling session was 8.9 ± 3.3 °C.

The assessment was performed in the presence of a local operator. The following actions were performed (Fig. 3): (i) design parameters (e.g. flow rate, solids retention time (SRT) sludge volume index) were collected; (ii) actual situation on the plant (e.g. flow rate, SRT, sludge volume index, equipment failures) was documented (taking photos, filling in Excel sheets of the model); (iii) samples were collected from the effluent and process reactors to determine biological oxygen demand, chemical oxygen demand, total suspended solids, Kjeldahl nitrogen, and total phosphorous. The parameters pH, conductivity, dissolved oxygen, and water temperature were determined in situ. In addition to the data needed for the TEC and TEP, some additional data were collected during the plant inspection. These included the operator's knowledge about the process and evaluation of the operator's competence, the operator's contentment with each treatment step, and additional data that were not used in any assessment but were expected to be relevant in the interpretation of results.

All the wastewater grab samples were collected from the effluents of secondary and tertiary treatment processes, where available, according to ISO 5667-10 (ISO, 1992). Wastewater samples were stored and transported to the accredited laboratory according to ISO 5667-3 (ISO, 2018) and immediately analysed according to the standard methods in the laboratory.

2.4. Statistical analyses

For studying the relationship between the plant performance and WWTP complexity, tools of correlation and regression analyses were applied. Together with the Pearson coefficient, the Spearman correlation coefficient was also applied in those cases where the dependence between study variables was of monotonic type instead of linear. For categorical variables, analysis of variances (ANOVA) was used for comparing the population means of performance in different groups. In some cases where assumptions of ANOVA were not satisfied, the Kruskal–Wallis test was applied as an alternative. It decides whether the population distributions of the performance are identical in study groups or not. The analysis was carried out using the software R.

3. RESULTS AND DISCUSSION

3.1. Effluent quality

Final effluents have to meet effluent standards. Estonian regulation on effluent quality standards (Vabariigi Valitsus, 2013) sets limit values for the disposed effluent. In treatment plants with a loading rate of less than 300 PE only constructed wetlands met consent effluent standards, whereas WWTPs with different technologies did not perform that well. As many as 70% of activated sludge, 79% of sequencing batch reactors, and only 60% of fixed film (biofilm) reactors and oxidation ponds met consent effluent standards. In the smallest settlements (WWTP 300–1999 PE), where total N and total P limit values are also set, the effect of these two parameters is easily observed. A large number of WWTPs failed in all categories: 67% of sequencing batch reactors, 57% of activated sludge plants, 50% of oxidation ponds, only 33% of biofilm reactors, and none of the constructed wetlands met the consent of the effluent standards in this study.

3.2. Relationship between the performance and complexity of WWTPs

As expected, the complexity of the WWTPs increased with plant size and specific treatment steps (e.g. screens, primary clarifiers, biological nitrogen removal).

Statistical analysis revealed that all four WWTPs with designed loading exceeding 100 000 PE caused statistically significant distortion in the overall tendencies of data interpretation. Therefore, some of the following results were submitted with and some without these four WWTPs.

There was a rather good positive relationship between general complexity and design loading rate for all WWTPs (Fig. 4a) ($R^2 = 0.434$, p-value = 1.863e^{-05}, Pearson's $r = 0.279$). For WWTPs with loading rates less than 100 000 PE, the relationship was more significant (p-value = 1.35e^{-11}, Pearson's $r = 0.432$) and monotonic (Spearman's $\rho = 0.631$, p-value = 2.2e^{-16}). This suggests that the structure of the wastewater treatment process tends to become more sophisticated with the growth of the design loading rate. It can easily be explained by the increasingly stricter requirements for effluent quality as plants (design) loading rates become higher.

As it is not always financially rational or feasible to choose the most complex solution for each wastewater treatment facility, the total evaluation of complexity showed a wide variation. Similarly to general complexity, the TEC was logarithmically growing in accordance with the design loading rate (Fig. 4b), but the variance was greater ($R^2 = 0.225$, p-value = 1.023e^{-06}, Pearson's $r = 0.317$). There was no great difference in Pearson's r ($r = 0.339$ and p-value = 2.025e^{-07}) and Spearman's ρ ($\rho = 0.386$, p-value = 2.249e^{-09}) for WWTPs with loading rates less than 100 000 PE. This suggests that although the number of treatment steps increases with the plant size, the technical solution chosen for a certain treatment step might not be very sophisticated. For example, there were no screens in 11 out of 99 WWTPs with a design loading rate of less than 300 PE. In other WWTPs, the screening equipment was screw screens (27), step screens (26), bar screens (11), and also various other devices or solutions (24). The complexity of the screens varied between 0 and 8 points, which indicates clearly that the choice of treatment steps complexity was made in compliance with the availability of financial resources.

A statistically significant but weak relationship ($R^2 = 0.062$, p-value = 5.566e^{-4}, Pearson's $r = 0.227$) was detected between TEP and the design loading rates (Fig. 4c). There was only a weak correlation between TEP and the design loading rate for WWTPs with the loading rate less than 100 000 PE (Pearson's $r = 0.148$, p-value = 0.027, and Spearman's $\rho = 0.144$, p-value = 0.031), which could be due to the capability to react to process disturbances in these plants. Three out of four WWTPs exceeding 100 000 PE had operations and maintenance personnel available 24/7, but among smaller WWTPs there was only one where this personnel were available all the time. At most of the small plants (less than 300 PE) such personnel were available for only 2–4 hours per week (during the scheduled supervision), and their ability to react to process disturbances was highly dependent on the discovery of a malfunction.

Figure 4d shows that there was a positive and moderate correlation between TEC and TEP ($R^2 = 0.228$,

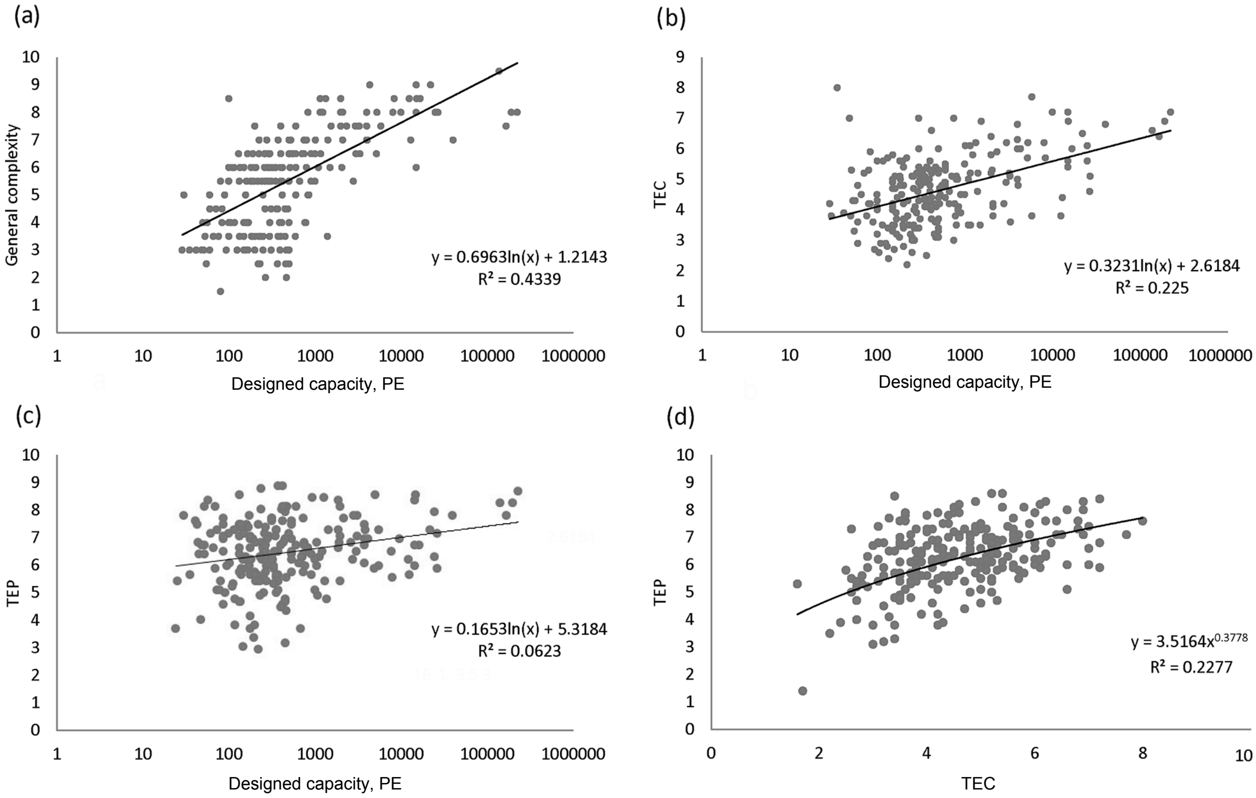

Fig. 4. Relationships between complexity, performance, and design loading rates.

Pearson's $r = 0.413$, p-value = $1.658e^{-11}$). This suggests that automation as a tool for the process control and equipment complexity in each treatment step could prevent many process disturbances and therefore improve the overall plant performance. For example, if the screens are not removed, either automatically or manually by an operator, clogging can happen, and as a result, the next biological process could be affected.

3.3. Relationship between the performance and complexity of treatment steps

For each treatment step, Pearson's correlation r, Student's t-test, and p-value were found for weighted complexity and performance in the given step (Table 2). In Table 2, r represents Pearson's product-moment correlation, t represents the values of Student's t-distribution, df represents the number of WWTPs where statistical analyses could be made (e.g. not all WWTPs had screens), and p-value shows the significance of this relationship.

Our study did not reveal any statistically significant (p-value < 0.05) correlation between the values of complexity and performance for some treatment steps (Table 2). This can be explained by the characteristics of the influent. In this step the performance assessment is based on the condition of the sewer system, rate of infiltration, variations in the influent flow rate due to seasonal or weather fluctuations, and the influence of industrial wastewaters. The complexity assessment in this step is based on the available loading control methods in the WWTP (e.g. use of balancing tanks or overflows, difference between actual and design loadings). Pearson's product-moment correlation between complexity and performance in this treatment step is statistically not significant (p-value = 0.56) and very weak ($r = 0.037$) as the quality and quantity of the influent have a great impact on the following treatment steps; however, the possibilities for balancing and loading control of wastewater are not directly connected to the origin of the wastewater.

The complexity of a certain treatment step has a great impact on the performance of several treatment steps. The most significant relationships between complexity and performance were detected for automation (p-value $< 2.2e^{-16}$), screens (p-value = $6.08e^{-12}$), final clarifier (p-value = $1.39e^{7}$), and nitrogen removal (p-value = $1.33e^{-6}$). The performance of a treatment step

Table 2. Pearson's product-moment correlation between TEC and TEP for each treatment step

Treatment step	*t*	*df*	*p*-value	*r*
Characteristics of the influent	0.582	243	0.561	0.037
Additional loading due to exhaustion	0.481	69	0.632	0.058
Screens and sieves	7.274	220	$6.083e^{-12}$	0.440
Primary clarifier	2.270	55	0.027	0.293
Grit chamber and oil trap	3.616	12	0.004	0.722
Septic tank	1.121	49	0.268	0.158
Activated sludge process	3.330	160	$1.263e^{-4}$	0.297
Sequencing batch reactor	0.775	32	0.444	0.136
Constructed wetlands	1.898	26	0.069	0.349
Biological filter	–0.856	15	0.406	–0.216
Submerged bed reactor	NA	2	NA	NA
Biological contactor	NA	1	NA	NA
Nitrogen removal	5.124	107	$1.333e^{-06}$	0.444
Phosphorus removal	1.051	199	0.295	0.074
Final clarifier	5.496	171	$1.394e^{-7}$	0.387
Automation	12.783	205	$< 2.2e^{-16}$	0.666
Effluent polishing	3.424	142	$8.059e^{-4}$	0.276
Sewage sludge treatment	2.862	30	0.008	0.463

NA – not applicable.

depended most strongly on the complexity in the given step for grit and oil removal ($r = 0.72$) and automation ($r = 0.67$). This suggests that for some treatment steps the complexity of equipment has a significant impact on their performance. For example, the risk for clogging and flooding of the screens can be reduced by using automatic removal of screens.

3.4. Relationship between performance and effluent quality

Performance assessment indexes proposed by Hao et al. (2013) and Chen et al. (2015) mainly focus on the effectiveness of pollutant removal, but they do not give any information about the overall situation on the plant. While Hao et al. (2013) took the operational situation into consideration (evaluation index K9), they did not specify what the 39 items that were inspected were and what their impact on the overall plant performance was. Although TEP does not give any specific information about problematic CCPs in the plant, conducting an assessment gives an operator a good indication how to start identifying problematic treatment steps within the WWTP.

Interpreting the results of statistical analyses of CCPs and studying their impact on the effluent quality revealed that several CCPs were extremely critical for effluent quality. For example, 50% of the WWTPs where effluents did not meet quality standards had a scum layer on the surface of the final clarifier. Analysis of the factors that influence the IVE in activated sludge plants showed that IVE was dependent on three factors: the performance of the final clarifier ($P_{\text{final clarifier}}$), the CCP that describes whether the results of effluent analyses meet the quality standards ($P_{\text{effluent analyses}}$), and the CCP that describes whether there are any sensory indicators (colour, turbidity, smell) of poor effluent quality ($P_{\text{visual-organoleptic assessment of effluent}}$). The following model is used to estimate a WWTP's IVE:

$$\begin{aligned} \text{IVE} = 5.00 + 0.29\, P_{\text{final clarifier}} + 0.21 \cdot P_{\text{effluent analyses}} \\ + 0.60 \cdot P_{\text{visual-organoleptic assessment of effluent}}. \end{aligned} \quad (4)$$

It has to be underlined that low ratings for $P_{\text{effluent analyses}}$ and $P_{\text{visual-organoleptic assessment of effluentt}}$ could be a direct result of a poor performance of the final clarifier. This empirical model ($r = 0.48$, p-value $2.72e^{-10}$) showed clearly that for activated sludge plants the final clarifier could be the weakest point as its effluent quality was directly dependent on several operational and maintenance aspects (e.g. whether the surface of the clarifier was clean or the floating scum was discharged together with the effluent, whether there were any hydraulic problems or a malfunction of activated sludge pumps that influenced the sludge volume surface loading rate). In addition, as it was shown in Table 2, Pearson's product-moment correlation between TEC and TEP was significant (p-value $= 1.39e^{-7}$) for the final clarifier. It can be concluded that several problems could be prevented in the initial design phase or by using more automated facilities. For example, using balancing tanks for the reduction of fluctuations in the wastewater flow could prevent hydraulic problems in the final clarifier.

4. CONCLUSIONS

A novel method was developed to rapidly assess the performance and effectiveness of a large number of small WWTPs. The objective of the integrated assessment method was to create a comparable system of ratings for all types of wastewater treatment technologies and steps. Evaluations of performance and complexity were formed on the basis of treatment steps used in each WWTP and assessment of specific CCPs in the treatment steps.

Based on the evaluations of performance and complexity of all 245 inspected WWTPs, the following conclusions were drawn:

- The greater the design loading rate, the more treatment steps are usually needed, but the complexity of these treatment steps can vary significantly depending on plant size;
- No direct relationship was detected between the plant capacity and its performance. This suggests that operation and maintenance practices play an important role in the performance of a WWTP regardless of its size;
- There was a positive relationship between TEC and TEP: increasing complexity provided better performance of the WWTPs. This suggests that combining automation as a tool for the process control with a more advanced equipment (higher complexity) could prevent many process disturbances and therefore improve the overall plant performance (e.g. infiltration to the sewer system during the rainy period can cause bulking by lowering food to microorganisms ratios if no automatic bypasses had been built);
- In particular, the complexity of equipment of some treatment steps (e.g. screens, final clarifier) has a highly significant impact to the performance of the whole facility.

The proposed performance assessment method makes it possible to simultaneously analyse several factors such as influent characteristics, system complexity, operational practices, and process parameters, and so their impact on the overall system performance can be taken into consideration. The new standardized tools TEC and TEP make it possible to compare a wide range of WWTPs using different technologies and treating different loadings. In further analyses the impact of several factors (e.g. operator's competence, level of automation, different wastewater treatment strategies) on the performance and effluent quality of the WWTP can be modelled.

Since the development process of TEC and TEP involved data from small-scale WWTPs only in Estonia and because of the varying maintenance and operational practices, further work would be suggested to apply these indexes in other regions and climatic conditions as well as to larger-scale WWTPs. It can also be suggested that the usage of the new assessment method be introduced on a large variety of WWTPs to improve the daily maintenance and operational practices (CCPs are always checked and critical parameters for system control are calculated simultaneously) and to develop a wide-ranging database that gives scientists and designers inputs for further research.

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Uudne meetod väikeste reoveepuhastite tõhususe ja komplekssuse kiireks hindamiseks

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Reoveepuhastite (WWTP) tõhusus sõltub mitmest tehnilisest, mittetehnilisest ja inimlikust faktorist. Aastatel 2014–2015 uuriti 245 väikest ja keskmise suurusega reoveepuhastit, mida hinnati uudse tõhususe ning komplekssuse hindamise metoodikaga. Meetod võimaldab samadel alustel hinnata erinevaid puhastustehnoloogiaid ja analüüsib reovee omadusi, süsteemi komplekssust ning käitamispraktikaid ja võrdleb protsessi reaalseid parameetreid projekteeritud väärtuste suhtes. Üldine komplekssus (TEC) ja tõhusus (TEP) on uued universaalsed tööriistad, mida rakendati erinevate koormuste ning tehnoloogiliste lahenduste hindamiseks.

Uuringu käigus selgus, et mida suurem on puhasti koormus, seda rohkem puhastusastmeid rakendatakse. Nende puhastusastmete komplekssus võib varieeruda suures ulatuses sõltuvalt puhasti koormusest. Tõhususe ja komplekssuse vahel tuvastati positiivne korrelatsioon: suurema komplekssusega puhastid olid tõhusamad. See näitab, et kui protsessi juhtimisel võtta kasutusele automaatika ja suurema keerukusastmega seadmed, on võimalik ennetada mitmeid protsessi seisakuid ning parandada kogu puhasti tööd.