Water Science & Technology

Water Science & Technology Vol 87 No 3, 555 doi: 10.2166/wst.2023.018

Operational optimization at the Nenäinniemi wastewater treatment plant's tertiary disc filter phosphorus removal installation to reduce chemical consumption

Janne Väänänen[a,*], Markku Tuohimetsä[b], Kari Savolainen[c], Ville Sorsamäki[b], Sonja Pyykkönen[b], Petri Tuominen[b] and Carles Pellicer-Nacher[a]

[a] Hydrotech Veolia Water Technologies AB, Mejselgatan 6, Vellinge 235 32, Sweden
[b] Jyväskylän Seudun Puhdistamo Oy, Raivionsuntti 10, Jyväskylä 40520, Finland
[c] Insta Group Oy, Sarankulmankatu 20 (P.O. Box 80), Tampere FI-33901, Finland
*Corresponding author. E-mail: janne.vaananen@hydrotech.se

JV, 0000-0002-3769-1760

ABSTRACT

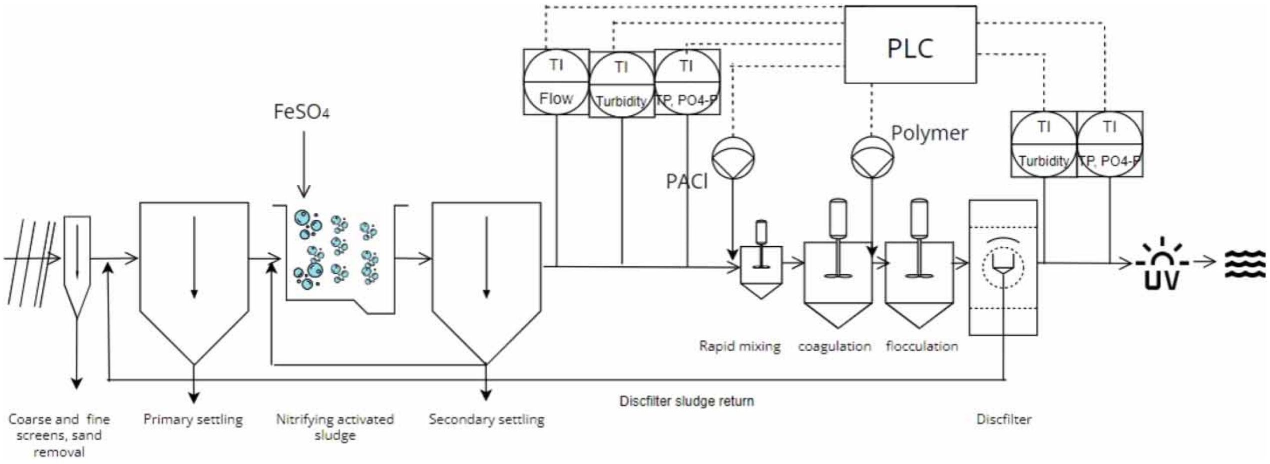
Instrumentation, automation and control in municipal wastewater treatment can result in large resource, cost and energy savings. Feedforward and feedback control algorithms were implemented together with turbidity and phosphorus analysers to control the chemical dose at the tertiary stage of the Nenäinniemi wastewater treatment plant, consisting of coagulation, flocculation and microsieve filtration. This optimization lowered the coagulant dose by 70% and the polymer dose by 36% compared to manual adjustments of the chemical dosing. Effluent total phosphorus (TP) and total suspended solids (TSS) concentrations were lowered by 20–30%. With the control system in operation, the annual savings in coagulant and polymer were in the range of 100 and 1.4 tons, respectively. Conducting automated CIP on the media at an economical break-even interval of approximately 20 days was also important to further lower energy usage and operational costs.

Key words: coagulation–flocculation, feedback control, feedforward control, full scale, microsieving, tertiary phosphorus removal

HIGHLIGHTS

- Online phosphorus analysers and turbidity sensors improve the P-removal performance of disc filters in tertiary treatment.
- Feedforward and PI feedback online dosing control reduced the annual chemical consumption by 70% at the Nenäinniemi WWTP (165,000 PE) tertiary disc filter treatment stage.
- 20 days of operation between chemical disc filter cleanings is recommended to minimize the total OPEX of the disc filter plant.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Municipal wastewater treatment plants (WWTPs) have the general driver of reducing operational costs while fulfilling effluent water quality requirements. Through optimization, processes become more efficient and consume fewer resources with the same or better level of treatment. Some optimization examples are the installation of more energy-efficient equipment or fine-tuning the control of the treatment processes at the plant. Usually, process optimization involves some form of adjustment of the control parameters. Adjustments can be carried out on the aeration regime to control the oxygen content in the activated sludge process or on the return sludge flow for sludge age control. Implementing advanced process control strategies has been a powerful and common approach to improve performances, such as dissolved oxygen (DO), nitrate recirculation, external carbon dosage and chemical dosing (Yuan *et al.* 2019) in wastewater treatment. Instrumentation control and automation (ICA) in the wastewater management sector has shown reductions in electricity usage by 10–30% (Olsson *et al.* 2005, 2014). The chemical usage for some applications was reduced by 25% with ICA (Ganigué *et al.* 2018).

There are examples where ICA has been implemented in municipal wastewater treatment in combination with coagulation and flocculation processes. Some WWTPs in Germany and Sweden have reported using orthophosphate (PO_4^{3-}–P) and pH analysers after coagulant addition or in the final effluent to control chemical dosing (Ingildsen 2002; Ratnaweera 2004). Mathematical models, neural networks or fuzzy logic have also been tested; however, flow-proportional dosing seems to be the dominant form of dosing control (Ratnaweera 2004; Nadeem *et al.* 2022). Feedback (FB) proportional–integral–derivative (PID) controllers have been used extensively in industrial processes for 100 years, but they are rarely used in wastewater treatment for coagulation dosing control. The main issue of using FB control seems to be the long and varying retention time in the separation stage (Olsson *et al.* 1973; Ratnaweera 2004; Ratnaweera & Fettig 2015). However, FB control of the iron dose in an activated sludge process with co-precipitation and tertiary settling has been proven to work to meet effluent requirements (Craig *et al.* 2014).

Feedforward (FF) and FB control, with turbidity sensors, has been used in chemically enhanced primary treatment with disc filtration to control the polymer dosing and operate at a consistent effluent turbidity set point (Väänänen *et al.* 2017). In principle, FB control seems possible in other applications with disc filters and chemical pre-treatment, such as tertiary treatment for phosphorus removal. The combination of online phosphorus analysers and turbidity sensors with FF and FB control loops should allow for lower chemical usage with a low-risk level. The FB controller allows for simple operation at the required effluent TP and turbidity concentrations. Effluent quality is continuously monitored and the dosing is adjusted automatically without the operator's involvement. The need to develop, calibrate and recalibrate coagulation/flocculation models is avoided. The additional use of a FF control loop can dampen the influences of disturbance variables (Liu *et al.* 2019) and can be implemented as a complement if needed.

Common activated sludge processes generally have a specific energy consumption of 300–600 Wh/m^3 (Silva & Rosa 2015; Gu *et al.* 2017). The specific energy consumption for the tertiary disc filter applications with coagulation and flocculation is in the range of 30–50 Wh/m^3. The dosing, rapid mixing and the coagulation and flocculation stirring stand for about 28% of the tertiary disc filter energy usage. The operation of the disc filter including the backwash (BW) and rotation is responsible for the remaining 72% (Kängsepp *et al.* 2016). In the long term, media fouling leads the filters to BW more often, which results in a significant increase in their energy consumption. To lower the disc filter energy usage in the tertiary treatment, fouling needs to be controlled. Fouling arises mainly from extracellular substances and inorganic compounds that build up on the surface and in the pores of the media (Iorhemen *et al.* 2017; Meng *et al.* 2017), reducing permeability over time. For disc filters, as well as for other filtration technologies, regular chemical media cleaning is needed to maintain the permeability over time. From a resource-saving perspective, conducting chemical cleaning is a trade-off between chemical costs and increasing operational costs. Effluent water quality can also be impacted by severe fouling. If filters are fouled, they can treat a lower water volume than originally designed for and untreated secondary effluent could bypass treatment and be discharged directly to the recipient.

The main objectives of this study were, first, to optimize the chemical dosing at the tertiary stage of the Nenäinniemi wastewater treatment plant (165,000 PE) by implementing online instrumentation for phosphorus and turbidity measurement and online FF and PI FB dosing control. Additionally, this paper investigates disc filter energy usage and proposes how to control long-term fouling and chemical cleaning in order to reduce even further the operational costs of the tertiary treatment stage.

2. MATERIALS AND METHODS

2.1. The treatment plant

The Nenäinniemi WWTP is located in Jyväskylä, central Finland, and it is operated by Jyväskylän Seudun Puhdistamo Oy. The WWTP is designed for 165,000 PE and treats an average yearly flow of 13.6 million m^3/year and an average hourly flow rate of approximately 1,500 m^3/h. The process line (Figure 1) consists of coarse screens (25 mm), sand removal, fine screens (6 mm) and primary settling. The biological treatment is a nitrifying activated sludge process with simultaneous phosphorus precipitation using iron sulphate and secondary settling. Tertiary phosphorus removal is conducted by coagulation with polyaluminium chloride (Kemira Oyj, Finland), flocculation (high molecular weight low charged cationic powder polymer) and 6× Hydrotech HSF 2628-2F disc filters (10 μm pore size) with a total filtration area of 1,277 m^2.

The Nenäinniemi WWTP has quarterly effluent permits on TP, TSS, BOD_7, NH_4-N and COD_{cr} with no requirement for nitrogen removal. The treatment plant has the following environmental permit set by the Finnish Ministry of the Environment.

- $BOD_7 < 10$ mg/L and 96% reduction.
- Total phosphorus < 0.3 mg/L and 96% reduction.
- Ammonium nitrogen < 4 mg/L and 80% ammonium nitrogen reduction.
- TSS < 10 mg/L and 90% reduction.
- $COD_{Cr} < 80$ mg/L and 90% reduction.
- Pathogens 90% reduction.

Despite the limit prescribed on TP by law, the treatment plant management has set a production target for the final effluent TP concentrations to be around 0.1 mg TP/L in order to further reduce eutrophication potential in the receiving water body.

2.2. The tertiary treatment plant

The wastewater is fed into the tertiary stage of the treatment plant through a common rapid mixing zone (3–5 s retention time) where the coagulant is injected. The flow is then divided into two treatment lines, each consisting of one coagulation and one flocculation basin with top-mounted stirrers. The polymer is injected into the turbulent overflow zone between the coagulation and flocculation basins. The average hydraulic retention time, during dry weather daily flow variations, was 2–4 min for the coagulation stage and 8–12 min for the flocculation stage.

Two Phosphax Sigma P-analysers (LPV341.99.10000, Hach, USA) and Sigmatax 2 sampling preparation units (LXV215, Hach, USA) were used to measure TP and PO_4^{3-}P in the tertiary plant influent (secondary clarifier effluent) and disc filter effluent. Solitax SC sensors (LXG 423.99.00100, Hach, USA) were used to measure disc filter influent and disc filter effluent turbidity and TSS (Figure 1). SC200 control units were used with the turbidity sensors (LXV404.99.00551) (Hach, USA). The flow to the tertiary treatment stage was measured prior to the coagulant injection point by the WWTP's main control system.

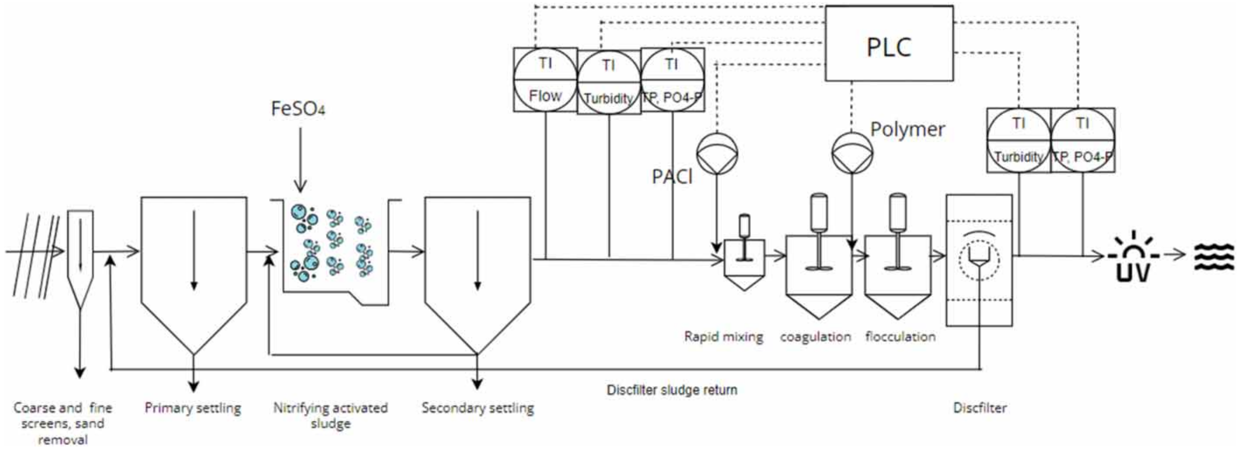


Figure 1 | Nenäinniemi WWTP process scheme and the tertiary phosphorus removal disc filter stage including the positioning of the instrumentation and dosing system.

The PLC was a Siemens S7-400 (CPU 412-2 PN) series, and the communication was with Siemens WinCC (WinCC V7.4 + SP1, Siemens AG, Germany)).

In parallel with the online monitoring, daily composite sampling and analysis were performed according to Nenäinniemi WWTP ordinary sampling routines.

The Nenäinniemi disc filter installation is designed hydraulically with bypass weirs prior to the disc filters. If the water level prior to the disc filters increases above these weirs, part of the wastewater leaving the treatment plant will not undergo tertiary treatment. To comply with the effluent requirements, bypass is to be avoided.

2.3. Dosing algorithms

In 2020, the coagulant and polymer concentrations were adjusted manually by the operators. In 2021, FF and FB control loops (Figure 2) were implemented to calculate the final applied doses of coagulant and polymer to achieve a certain effluent quality with the required chemical dose. The FF and FB control loop actions are added to set the total output without further adjustments.

The coagulant set point of the active material as mgAl^{3+}/L and the set point of active polymer (mg/L) of any system can be adjusted through the actual volumetric flow dose according to Equations (1) and (2).

$$\frac{\left(\frac{27}{31} * \text{Inf. } PO_4^{3-} - P * \text{molar ratio}\left(\frac{mgAl^{3+}}{L}\right) + PI\ \text{controll}(0-1) * \text{max FB coag. dose}\left(\frac{mgAl^{3+}}{L}\right)\right) * Q_{in}(m^3/h)}{Al^{3+}\text{content in product}\left(\frac{g}{g}\right) * \text{density of product}\left(\frac{g}{L}\right)} = QPACl\left(\frac{L}{h}\right) \tag{1}$$

$$\frac{\left(FF\left(\frac{mg}{L}\right) + PI\ \text{controll}(0-1) * \text{Max FB poly. dose}\left(\frac{mg}{L}\right)\right) * Q_{in}\left(\frac{m^3}{h}\right)}{\text{Content active polymer}\left(\frac{g}{g}\right) * \text{Polymer concentration in stock solution}\left(\frac{g}{L}\right)} = \text{Qpolymer}\left(\frac{L}{h}\right) \tag{2}$$

The above flow calculation was scaled to a 4–20 mA output signal in the PLC and sent to the dosing pumps. The dosing pumps were calibrated for the corresponding flow signals according to standard routines for signal transfer and dosing pump calibration. The coagulant product has an active Al^{3+} content of 9.3% and a density of 1,360 g/L. The powder polymer used is assumed to be 100% active polymer and the stock solution concentration was 1.5 g/L.

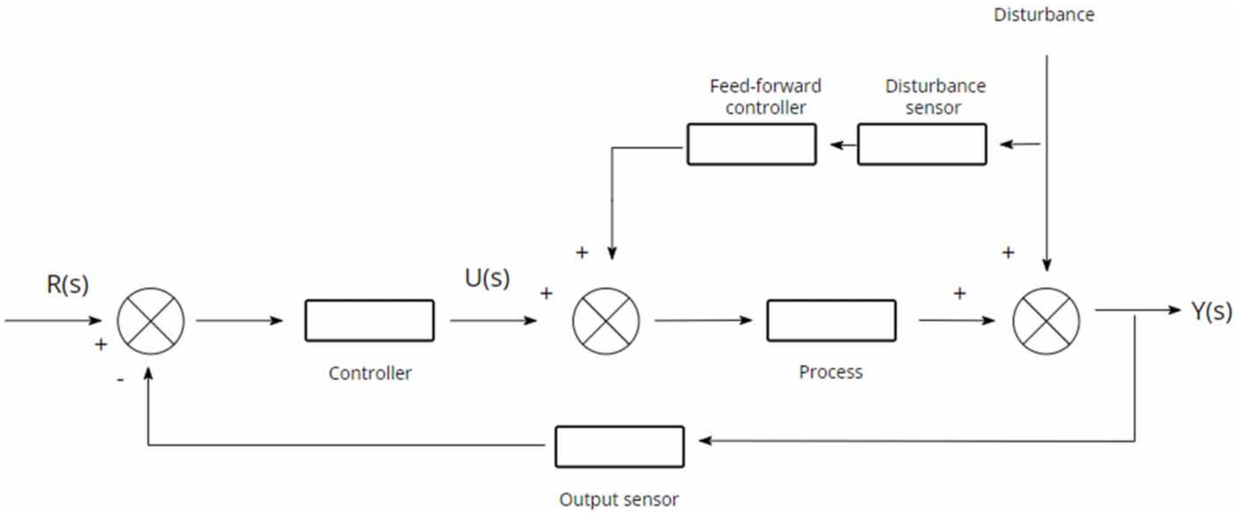


Figure 2 | Schematic illustration of the FF and FB coagulant and polymer control loops.

2.4. Coagulant

The applied coagulant dose from the FF coagulant control loop was based on the floating average of five consecutive influent PO_4^{3-}–P measurements and a pre-set molar ratio of 0.6 or 2.5 mol Al^{3+} dosed/mol influent PO_4^{3-}–P. The purpose of the FF coagulant controller was to set a base dose of coagulant. The use of an FF controller improves the response time as it will directly adjust the dosing in relation to the incoming PO_4^{3-}–P. The final adjustment of the coagulant dose to target the effluent TP set point was controlled by the FB coagulant PI dosing control loop, which was a factor ranging from 0 to 1 (Equations (3) and (4)), multiplied by a maximum FB dose of 0.5 mg Al^{3+}/L. The PI FB controller output was determined from the floating average of five consecutive effluent TP measurements according to standard PI controller operational principles (Urrea-Quintero *et al.* 2021). The PI controller was a standard inverted operating PI controller according to Equations (3) and (4) with bumpless transfer and anti-windup functions from Siemens software (Siemens Step 7 Classic; Step 7 V5.6 + SP1, CFC V9.0). The approximate sampling time (Δt) was set to 1 s. The controller gain (K_c) was set to -0.16 (%/%) (reverse action), and the integration time constant (τ_I) was set to 700 s.

$$e(t) = SP - PV \tag{3}$$

$$u(t) = K_c e(t) + \frac{K_c}{\tau_I} \sum_{i=1}^{n_t} e_i(t)\Delta t \tag{4}$$

SP = set point
PV = process variable
$u\ (t) = PI$ controller output (0-1)

Initially the effluent TP set point was 0.18 mg/L then lowered to 0.15 and finally to the targeted 0.1 mg/L. The maximum total coagulant dose FF + FB was limited to 1.2 mgAl^{3+}/L.

2.5. Polymer

The applied FF polymer dose was determined using the influent turbidity and the three linear equations (Figure 3). The FF polymer dosing equations $A_{1–3}$, $B_{1–3}$ and $C_{1–3}$ (Figure 3) were tuned by iteration to either minimize polymer use or to improve

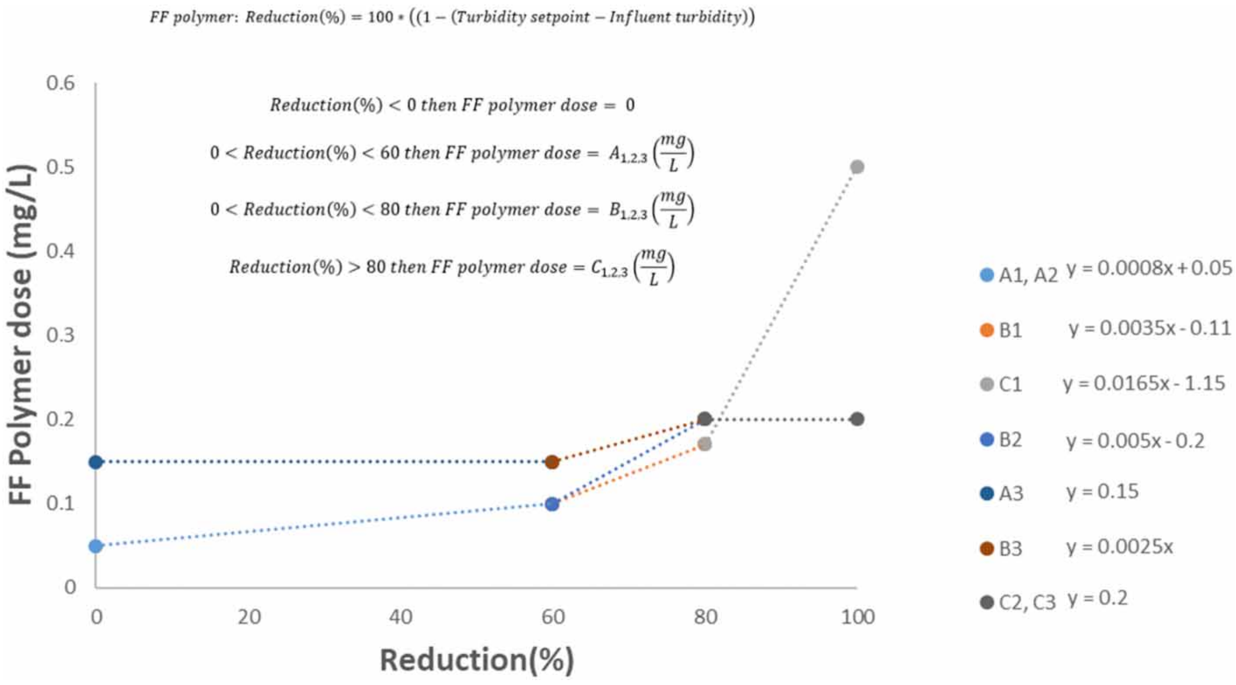


Figure 3 | FF polymer dosing equations.

process stability. The FF polymer dosing equations were adjusted more frequently during the first weeks until a first set of equations (A_1, B_1, C_1) was identified. The first set of equations (A_1, B_1, C_1) was used from February 22 to May 2, 2021. The second set of equations (A_2, B_2, C_2) was used from May 3 to August 23, 2021. The third set of equations (A_3, B_3, C_3) was used from August 24, 2021 onwards.

The applied FB polymer dose was determined by the Siemens software PI controller output (0–1) multiplied by the FB maximum polymer dose of 0.4 mg/L. In this case, the controller gain (K_c) was set to -0.2 (%/%) (reverse action, fixed). The integration time constant (τ_I) was first set to 720–0.16*Qin (m^3/h) and re-tuned from May 3 (2021) to -1.5 (%/%) and 6,800–0.63*Qin (m3/h). A variable integration time constant was applied to create an adaptive controller with gain scheduling to have an appropriate integration time constant (Leith & Leithead 2000) within the flow interval to the tertiary treatment stage.

By iteration, an appropriate set point value of effluent TSS or turbidity was identified. The goal was to find a TSS/turbidity set point value that matches the effluent TP set point. Initially when the effluent TP set point was 0.18 mg/L an effluent that was more turbid and contained a larger fraction of particulate P was allowed. With a lower effluent TP set point less particulate P was allowed in the effluent and subsequently the effluent turbidity set point was set lower. The TSS set point was initially 3.7, then increased slightly to 4, then reduced to 3.8 and finally 2.7 mg/L as online turbidity measurements were scaled to measure TSS. The FB turbidity sensor was replaced due to a noisy signal on July 1 2021. The new sensor was calibrated to measure turbidity and the set point was fixed at 1.7 NTU.

The maximum allowed total polymer dose (FF + FB) was initially limited to 0.6 mg/L and after tuning the control parameters, the maximum allowed total polymer dose was lowered to 0.4 mg/L.

2.6. Energy and cost calculations

The disc filter installation consists of six filters, each equipped with a BW pump. Each pump is rated at 22 kW and produces BW water for the rinsing of the accumulated particles on the media. The daily total BW pump operational time for each of the six units was logged with the daily flow to the tertiary treatment stage. The specific energy (Wh/m^3) was calculated with the logged BW pump daily operational time multiplied by the rated power of the BW pump divided by the daily flow.

Chemical cleaning of the six disc filters was conducted with diluted hydrochloric acid (HCl, 7–8% v/v) and sodium hypochlorite (NaClO, 3–4% v/v). The cleaning was semiautomatic including a pump and a chemical cleaning spray bar placed inside the filters and a preprogrammed cleaning sequence in the filtering software. One CIP of the six-disc filters consumes 100 kg of hydrochloric acid (HCl, 30%) and 100 kg of sodium hypochlorite (NaClO 15%). The price for the cleaning chemicals was 0.33€/kg for HCl (30%) and 0.65€/kg NaClO (15%) (internal communication).

For the economical break-even point between chemical cleanings the electricity price was 100€/MWh (Nord Pool). The daily average flow of 38,000 m^3 was used in the economy and energy calculations. The calculations were compared with the online data from 2020 and 2021 for a second estimate.

For the return on investment the cost for the turbidity and phosphorus instrumentation is 95,000€. The price for PACl coagulant was assumed 4€/kg Al^{3+} and for the polymer, 3€/kg polymer. The calculations were further based on the yearly treated flow (13.9 million m^3) and the average arithmetic coagulant and polymer dose for 2020 and 2021.

3. RESULTS AND DISCUSSION

The novel FF and PI FB dosing control system and energy usage were evaluated during approximately 1 year of operation. We compared online and laboratory data from two scenarios: one with manual control (2020) and the other with automatic control (2021). The comparison objective is to reveal the possible savings in the amount of coagulant and flocculant added for the removal of TP and TSS in a disc filter system.

3.1. Influent water quality and flows in 2020 and 2021

For both 2020 and 2021, the influent PO_4^{3-}–P was approximately 0.04–0.05 mg/L at the beginning of the year, with a decreasing trend to 0.02 mg/L until the end of March. Beginning in April to September the influent PO_4^{3-}–P concentration increased to approximately 0.08 mg/L. A minor increase could also be seen from the end of September before the low levels of 0.02–0.03 mg/L were observed at the end of December (Figure 4(a) and 4(b)). Generally, the PO_4^{3-}–P concentrations in the secondary effluent do not require coagulant addition to achieve the target TP concentrations. However, during summer the PO_4^{3-}–P

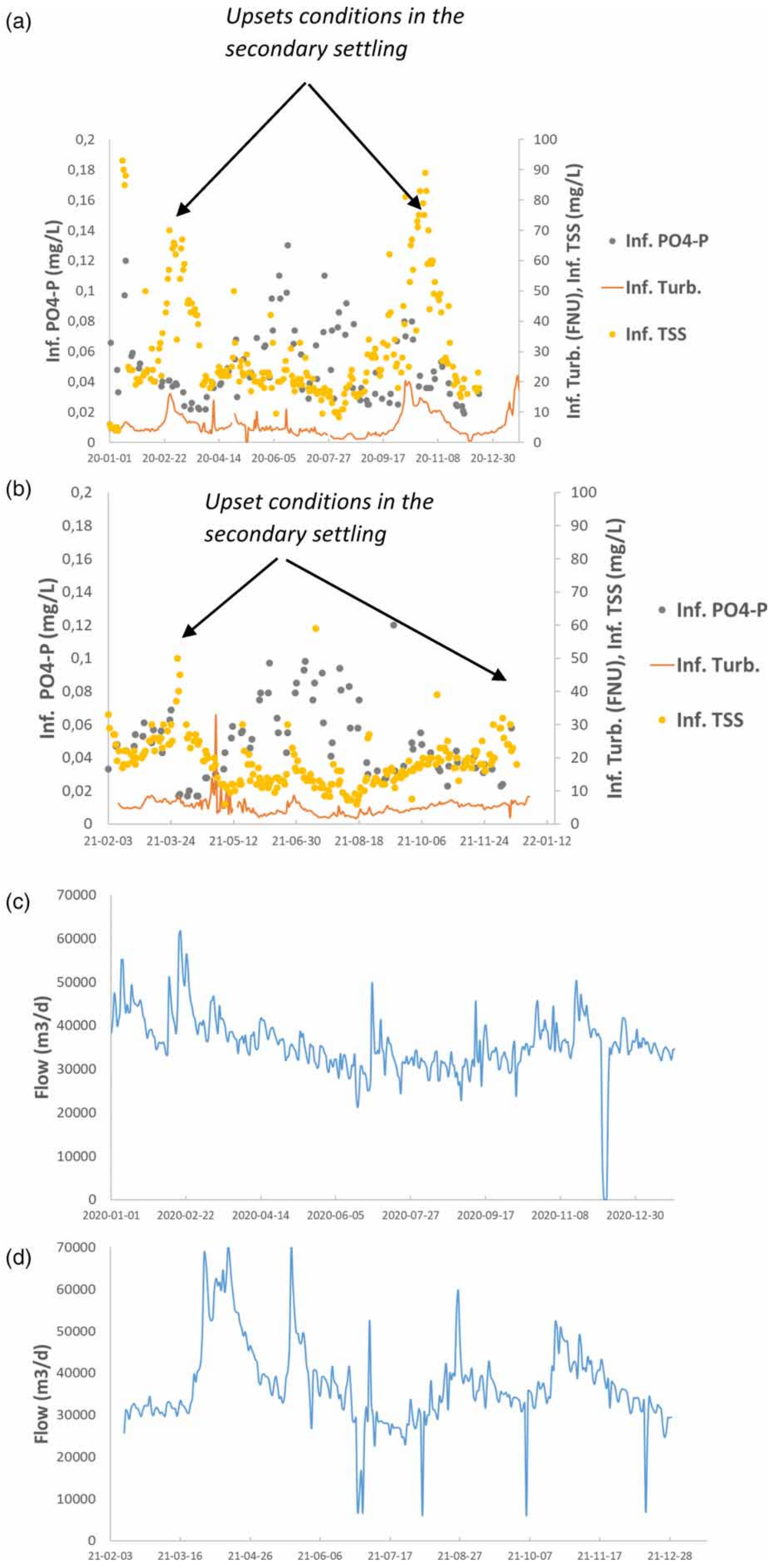


Figure 4 | Influent water quality to the tertiary treatment (the secondary effluent) (FNU-online, PO_4–P, TS- laboratory composite samples) for (a) 2020 and (b) 2021 and flows (m^3/d) for (c) 2020 and (d) 2021.

concentrations tend to increase to around 0.1 mg PO_4^{3-}–P/L and to be able to operate at a TP set point of 0.1 mg/L it is necessary to also dose some coagulant during these periods.

In 2020, influent laboratory TSS data show two periods from mid-January to the end of March and one from the end of September to mid-November with increased TSS concentrations. The common phenomenon of bulking sludge under cold-activated sludge conditions could be one reason (Bakos *et al.* 2022; Safder *et al.* 2022). The rise in flows (Figure 4(c) and 4(d)) with increased surface loading on the secondary settling could be another reason that contributed to the increasing TSS concentrations. During these periods, the influent TSS to the tertiary treatment stage increased to approximately 60 mg/L with some peaks up to 85 mg/L. In 2021, two periods of upset conditions could also be observed: one at the end of March and one at the end of December. The influent TSS during these periods was between 30 and 50 mg/L, lower than the peaks observed in 2020 (Figure 4(a) and (b)). Online turbidity measurements show a similar trend as the laboratory TSS measurements, which was considered important for control purposes.

For both 2020 and 2021, a consistent increase in flow could be observed around February–March due to snow melting. A minor increase in mid-November due to rainfall can also be observed together with some peaks during summer due to thunderstorms. The snow melting period in 2021 led to flows up to 70,000 m^3/day, which resulted in some bypass of the disc filters. The bypassed water was mixed with treated effluent and it gave rise to unrepresentative measurements from a dosing control point of view. This issue was addressed on April 28th by reprogramming the dosing control algorithm to a fixed flow proportional dosing set point during bypass.

3.2. Comparison of effluent water quality, average dosing for 2020 and 2021

The average chemical dosing, water qualities and relative dosing for 2020 and 2021 are summarized in Table 1. In 2020, chemical dosing was controlled by manually setting the flow proportional dose. In the beginning of 2020, the coagulant dose was set to approximately 1.0 mg Al^{3+}/L, and in mid-May, the coagulant dose was lowered to approximately 0.7 mg Al^{3+}/L; simultaneously, the polymer dose was lowered marginally from 0.3 to 0.25 mg/L. During this time, effluent TP was approximately 0.1–0.2 mg/L. After a trend with increasing effluent TP levels, the dosing at the end of July increased to 1 mg Al^{3+}/L and 0.3 mg/L polymers. The coagulant dose was further increased to 1.8 mgAl^{3+}/L as effluent TP showed a further increasing trend in mid-August. The coagulant dosing was lowered back to 1 mg Al^{3+}/L end of September when effluent TP concentrations were improved to approximately 0.1 mg/L. The dosing was then left unchanged for the rest of the year (Figure 5(a)). The arithmetic average coagulant dose for 2020 was 1.0 mgAl^{3+}/L, and for the polymer 0.28 mg/L. On average, effluent TP was 0.14 mg/L, and effluent TSS was 5.6 mg/L (laboratory composite samples). The online average values were 0.13 and 4.2 mg/L TP and TSS, respectively. The laboratory and online measurements showed good agreement; thus, the online instrumentations have the accuracy needed for in real-time dosing control.

The arithmetic average coagulant dose for 2021 with the online dosing control system in operation was 0.3 mgAl^{3+}/L and polymer 0.18 mg/L. The arithmetic average effluent TP concentration was 0.11 mg/L, and the effluent TSS was 3.7 mg/L (laboratory composite samples). The online analysers measured 0.11 and 3.2 mg/L TP and TSS, respectively (Figure 5(b)); thus laboratory and online results showed good agreement also in 2021. The average coagulant and polymer doses were 70 and 36% lower, respectively, than those doses in 2020. The relative dosing of Al^{3+} to the amount of removed TP was higher in 2020 than 2021 both as a yearly average and for the summer months of April–September. For the polymer, the relative amount of polymer dosed to the amount TSS removed was similar to the yearly average but was for April to September higher in 2020 than 2021.

Table 1 | Laboratory composite sample arithmetic average influent and effluent water qualities and chemical dosing for the whole year of 2020 and 2021 and for the period April 1–September 2020 and 2021

Arithmetic average laboratory composite samples	Influent TSS (mg/L)	Influent TP (mg/L)	Influent PO_4^{3-}–P (mg/L)	Effluent TSS (mg/L)	Effluent TP (mg/L)	Coagulant dose (mgAl^{3+}/L)	Polymer dose (mg/L)	mgAl^{3+}/mg TP removed	mg polymer/ mgTSS removed
January–December 2020	31	0.66	0.05	5.6	0.14	1	0.28	1.9	0.01
April–September 2020	22	0.54	0.06	4.8	0.15	1.1	0.28	2.85	0.02
January–December 2021	22	0.48	0.05	3.7	0.11	0.3	0.18	0.79	0.01
April–September 2021	15	0.38	0.05	4.0	0.12	0.36	0.17	1.43	0.01

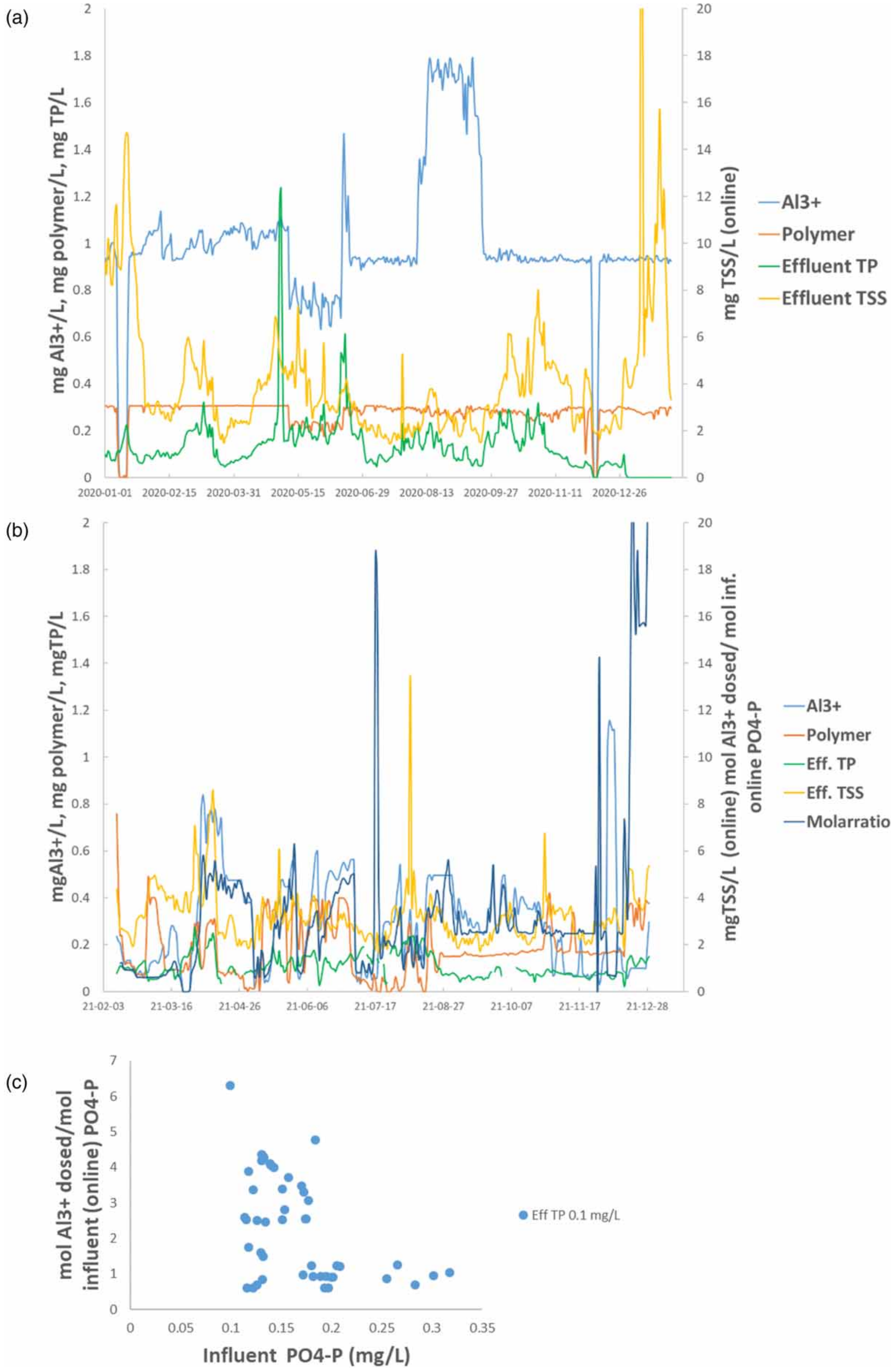


Figure 5 | Dosing requirements and effluent water quality for (a) 2020 and (b) 2021. (c) Relative coagulant dosing requirements for various influent PO_4^{3-}–P concentrations to obtain an effluent water quality with a TP concentration of 0.1 mg/L.

3.3. Chemical savings after the implementation of the controller

The effluent water quality after the implementation of the proposed control algorithms improved by 21% regarding TP concentration and 34% regarding TSS concentration on a yearly average. The yearly savings in chemicals were estimated to be approximately 1.4 tons of polymer and 100 tons of coagulant product based on average daily flow calculations. In 2020 from February to December, 3.34 tons of polymer and 126 tons of coagulant were dosed. In 2021 from February to December, 2.22 tons of polymer and 42 tons of coagulant were dosed. Thus, the online data show a saving of 1.12 tons of polymer and 85 tons of coagulant for the same period February–December 2020 and 2021.

The required coagulant and polymer dose to achieve an effluent TP similar to the one in 2020 of 0.10–0.15 mg/L was approximately 0.1–0.5 mg/L (Al^{3+} or polymer). To operate at a TP concentration of 0.1 mg/L in the disc filter effluent, the molar ratio of total dosed Al^{3+} to influent online PO_4^{3-}–P ranged from 0.6 to 6 (Figure 5(c)).

In general, higher dosing of both coagulant and polymer was observed to be required during the early summer. From May to mid-July, the dosing was highest at approximately 0.35–0.4 mg/L polymer and 0.5 mg/L Al^{3+} (or 5–6 in online molar ratio). The lowest chemical dosing was generally observed in February and July, but periods ending in April and beginning in June with a dose of approximately 0.1 mgAl^{3+}/L for the coagulant and 0.1 mg/L polymer could also be observed (Figure 5(b)). After the end of August, the FF control loop was retuned allowing for some overdosing lest low chemical dosing occurred. To achieve overdosing, the controller was tuned to allow for a higher dose than necessary. Effluent water quality could be below the set point without controller adjustment of the applied doses.

The increase in chemical dosing from May to mid-July could, to some extent, be explained by the increased influent PO_4^{3-}–P concentrations during summer. However, the lower dose in July and August with similar influent PO_4^{3-}–P suggests there be other factors involved. Other parameters that are known to influence coagulation processes and dosing requirements such as alkalinity and pH (Henze *et al.* 2002) were measured between 1.5 and 2 mmol$CaCO_3$/L and 6.9–7.2, respectively (data not shown) throughout 2021. The wastewater temperature was rather consistent during the summer, 15–17 °C (data not shown). These variations in alkalinity, pH and temperature were minor and would not influence the coagulation process to such a large extent explaining the increase in the chemical dosing. Another factor that was suspected to influence the coagulation process was maintenance. The maintenance was done in August about the same time when the dosing requirement was lower. During maintenance, treatment lines are taken out of operation and the loading of the existing treatment lines is higher. This was suspected to influence the water matrix so that the dosing requirements changed. The plant observed a similar behaviour during the maintenance period in 2020. The effluent water quality worsened and, therefore, the coagulant dosing was increased to 1.8 mg Al^{3+}/L (Figure 5(a)). The problem is very complex, as many factors influence coagulation-flocculation processes (Nadeem *et al.* 2022). Future investigations are required to find proof that there is a link between maintenance and dosing requirements.

3.4. Insights into controller design

As indicated previously, the purpose of the FF control loops was to set a base chemical dose, generally not enough to obtain effluent water quality targets. The FB control loop supplemented the base chemical dose with additional amounts of coagulant and polymer to achieve the desired effluent concentrations of TP or TSS.

The tuning of the FF and FB control loops followed two main stages (Figure 6). The first stage (February–end of August 2021) had an FF control strategy, which added a low base chemical dose. The second stage (end August–December) allowed for a higher FF dose that deliberately resulted in some overdosing but this was to increase process stability and circumvent operational issues (Figure 6(a) and 6(b)).

The appropriate molar ratio for the FF coagulant control loop for the first tuning stage was 0.6 mol Al^{3+} dosed/influent PO_4^{3-}P concentration. The FF polymer control loop was set for the first strategy to add approximately 0.06 mg/L polymer (Figure 6(b)). An offset issue between effluent turbidity and TP was observed during a 2-week period from July 25 onwards. This situation was new and had not been observed during the previous 5 months of operation. The offset was characterized by the effluent TP concentration increasing to approximately 0.2 mg/L, while both influent and effluent turbidity remained very low, below the set point (<1.8 NTU), and this situation was of some concern. Even though the FB polymer control loop was active from time to time during this period lowering the effluent TP, it was considered necessary for operational and effluent permit reasons to deal with this offset. This type of offset between turbidity and effluent TP resulted in zero FF and FB polymer dosing and caused instability in the process. Coagulant dosing alone created flocs that were not retained on the woven media, resulting in worsened effluent water quality.

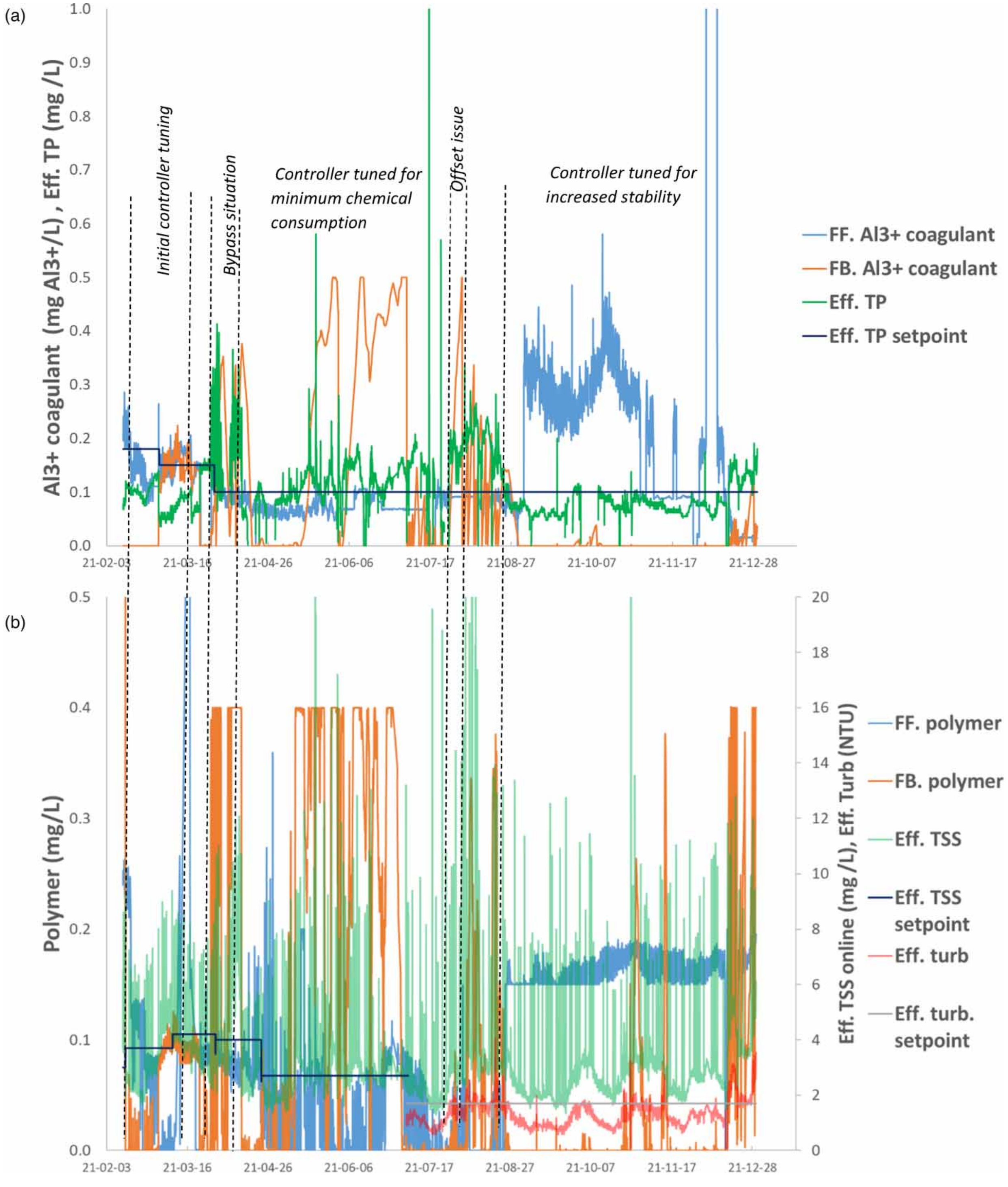


Figure 6 | Feedforward (FF) and feedback (FB) average hourly controller action: (a) coagulant (mg Al^{3+}/L) and (b) polymer (mg/L). (a) Effluent TP and effluent TP set point and (b) effluent TSS/turbidity and TSS/turbidity set point (2021 data).

From the end of August 2021 onwards (Figure 6(a)), the FF coagulant control loop was tuned for increased process stability. The FF coagulant control loop molar ratio was increased to 2.5 mol Al^{3+} dosed/influent PO_4^{3-}P concentration. This resulted in a mostly inactive FB coagulant control loop. This situation was deliberately causing some overdosing but the results show that the process was stabilized. The increased dosing also solved two operational issues with clogged coagulant pipes due to

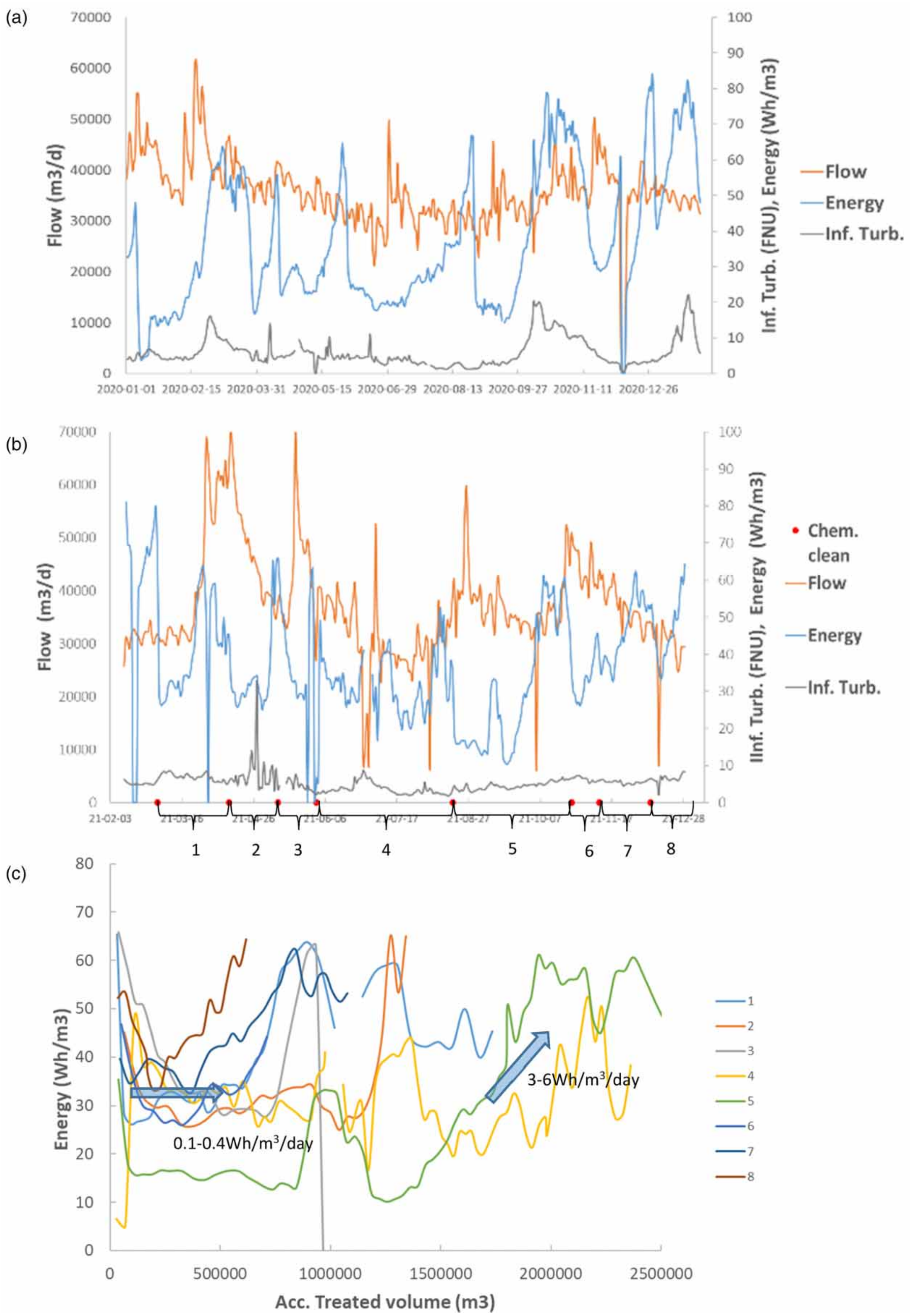


Figure 7 | Influent flow (m^3/d), specific disc filter (Df), energy consumption (Wh/m^3), chemical cleanings (only for 2021) and influent turbidity for (a) 2020 and (b) 2021. (c) Accumulated treated volume from the latest chemical cleaning (1–8) of the disc filter installation and specific energy consumption (Wh/m^3) and the specific energy consumption increase rate Wh/m^3/day.

low pipe flows and zero dosing during the night under low influent flow conditions that had been identified when the first dosing strategy was evaluated. These two operational issues were most likely contributing to some of the instability that was observed.

The FF polymer dosing control loop for the second stage was adjusted to increase the minimum dose from 0.06 to 0.15 mg polymer/L to increase the process stability (Figure 6(b)). With this setting, effluent turbidity was below the set point. The FB polymer control loop was activated periodically when effluent quality worsened and was above the set point (Figure 6(b)). The FB polymer control loop added approximately up to another 0.3 mg polymer/L in shorter periods to maintain effluent water quality at the turbidity set point.

To have a fully adaptive system and avoid overdosing, some auto-tuning of the FF control parameters can be implemented. One can, for example, add a correction factor on the applied FF dose based on the measured difference between measured effluent TP and effluent TP set point similar to a method described by Bertanza *et al.* (2021). Another method to improve the controller to avoid overdosing would be to rescale the FB controller range of variation output to also allow negative values. This would allow the FB control loop to reduce the influent coagulant and polymer concentrations imposed by the FF controller when it is excessive. Auto-tuning and optimization of the controller is a topic for future research.

The main conclusion is that with an active FB control loop (lower contribution of the FF control loop), the target effluent water quality could be achieved on average. Effluent water quality was oscillating around the set point for both effluent TP and TSS, minimizing the amount of chemical usage. With the more aggressive FF controller action, the effluent water quality was generally below the target TP and turbidity (Figure 6(a) and 6(b)). However, the result indicates that the process was more consistent. Despite some overdosing, a more active FF control resulted in an effluent water quality below the set point, while the coagulant and polymer consumption remained on average significantly lower (around 65% compared to 2020).

The required molar ratio on a daily average showed variation that, to some extent, indicated to be seasonal ranging between 2.5 and 20 mol Al^{3+}/mol influent PO_4^{3-}–P(Lab.) (0.6–6 if online PO_4^{3-}–P) to achieve 0.1 mg/L TP in the effluent. In the work presented by Langer & Schermann (2013) for disc filters, a molar ratio of around 15–30 mol Al^{3+}/mol influent PO_4^{3-}–P was used and Fundneider *et al.* (2020) reported molar ratios in the range of 5–20 to achieve similar 0.1 mg/L effluent TP concentrations in advanced tertiary treatment and cloth-filtration. Bertanza *et al.* (2021) also reported large variations by a factor up to 10 in the required relative dosing between coagulant and influent PO_4^{3-}–P to operate at a target effluent PO_4^{3-}–P set point in a full-scale coagulation/flocculation and lamella sedimentation tertiary treatment stage. One can expect that the optimal relative dosing is variable and that some form of FB control strategy is needed to be able to optimize the chemical used in a tertiary treatment stage from the results presented in this paper the FB control strategy should preferably be based on real-time online measurements.

The results from this paper conclude that FF control strategies can be used to improve controller and process performance in disc filter installations for the tertiary P removal. For the highest possible savings in chemical usage, it is most advantageous to use a FF control loop that contributes less to the final chemical dose and allows the FB control loop to be active most of the time. This will result in effluent water quality oscillating around the set point with the average effluent concentrations complying with requirements and with minimal chemical usage. With a slightly more active FF control loop, the process stability can be improved. The challenge is to find the balance for the two controller loops by a few iterations and analyse the FB and FF controller actions step by step.

3.5. Energy

For a disc filter installation, the major energy-consuming component is the BW (Kängsepp *et al.* 2016). Reducing the operational time of BW pumps is an important contribution to lower operational costs (Nunes *et al.* 2013; Kängsepp *et al.* 2016).

The operational time of the BW in the short timeframe (minutes) is determined by the solid loading. This means that the operational time of the BW pumps increases with increasing flow, increasing coagulant dose and/or increasing influent TSS concentrations or a combination. In the longer timeframe though (days–weeks), the fouling of the media will become significant for the BW operational time. Therefore, an effective measure to reduce energy usage in a disc filter installation is to control media fouling. The fouling is caused by the buildup of inorganic scaling and organic deposits around and within the structure of the media and is of similar nature as membrane fouling that is extensively described in the literature.

The results presented in Figure 7(a) and 7(b) show that the specific energy consumption in 2020 and 2021 for the disc filter installation varied between 10 and 80 Wh/m^3 (Figure 7(a) and 7(b)), with an average of 37 Wh/m^3 for both 2020 and 2021. In 2021, eight chemical cleanings were conducted, and the cleaning interval was approximately 30 days. During summer, the interval was extended to 45–50 days. The cleanings were conducted around a specific energy consumption of 60 Wh/m^3 (Figure 7(b)), which occurred when the water level prior to the bypass weir showed a significant rising trend with a risk of bypass events of the tertiary stage. Chemical cleanings were also conducted in 2020, but a track record was not available.

The specific energy is lowest a few days after a chemical clean and is the result of chemical residues. After the residues from the cleaning chemicals are rinsed off completely, the specific energy usage is initially showing a slow increase. After about 15 days of operation on average, the specific energy increases at a significantly faster rate. The results indicate that long-term fouling generally follows a two-stage pattern (Figure 7(c)). In this study, the daily increase rate during stage one was approximately 0.1–0.4 Wh/m^3/day from day 0 to approximately day 15 after a chemical cleaning. This corresponded to a total treated volume of 0.5–0.7 million m^3 but could be up to 1.5 million m^3 during summer. For stage two, from day 15 to approximately $>$25 days after a chemical cleaning, the rate in specific energy consumption increased to 3–6 Wh/m^3/day corresponding to the treated total volume of about $>$0.7–1 million m^3 or a bit more. A similar two-stage fouling pattern was observed previously in a study by Langer & Schermann (2013).

The breakeven point for a chemical cleaning to pay off was calculated to be approximately every 20 days (a bit longer over the summer periods). It was calculated that the additional cost per day for the increase in electricity consumption due to fouling was about 1€/day during the first 15 days and 15€/day from day 16 onwards. This interval can vary depending on electricity prices and the price for chemicals but the results show that initially, the fouling is slow with a minor increase in energy usage to rather rapidly change and that it is early in this stage of rapid increase it is beneficial to do the chemical cleaning from a cost perspective.

Potentially, energy usage can be further reduced. The disc filter installation at the site operates at a varying head loss of approximately 70–150 mm, this is governed by the control software. Head loss or transmembrane pressure influences the flux (Field *et al.* 1995), and the energy required to run the BW pump is head loss-independent. Operating at a higher head loss would increase the flux and lower the specific energy requirement. Currently, all filters are in use with the overlapping operation, they are also generally not over-loaded, operating at a relatively low average head loss. From an energy consumption perspective, it would be more beneficial to take some of the units out of operation and increase the load of the remaining units. This would increase the average head loss and lower the specific energy usage. However, in practice, this is not easily implemented.

3.6. Return on investment

The return on investment is approximately 2 years. The result also suggests that the dosing could have been lower from the end of August to mid-December, but for the discussed reasons, the FF controller settings did not allow for lower dosing. A lower dose would impact the investment calculations somewhat. However, the return on investment is short.

4. CONCLUSIONS

Chemical usage at the tertiary TP removal installation of the Nenäinniemi WWTP was lowered by around 85–100 tons of coagulant and 1.1–1.4 tons of polymer by using online turbidity sensors and phosphorus analysers and implementing simple FF and PI FB dosing control loops. Improvement in chemical usage related to the incoming TP and TSS was also observed. Despite the lower chemical dosing, the effluent water quality improved by 20–30% regarding TP and TSS concentration. Therefore, implementation of the required ICA to control the chemical dosing in a tertiary disc filter TP removal installation can render substantial savings in chemical use and improved effluent water quality with a payback time of 2 years for a medium-sized treatment plant.

To further improve energy usage, proper maintenance of the disc filter installation is of great importance. The optimal interval between chemical cleanings of the filter media from an energy and economical point of view was approximately 20 days long.

To have the lowest chemical consumption, the FF control loops for coagulant and polymer dosing should be tuned to dose low amounts of chemicals during normal operation and aim at having an active FB control loop most of the time. With the wastewater characteristics found in this study, an FF control loop dosing approximately 1 mol Al^{3+}/per mol influent PO_4^{3-}–P and 0.1 mg/L polymer seems to be a good starting point. The FB PI control loops adjust the necessary dosing to maintain effluent water quality around the set point. Generally, it is also initially preferable to have a more feedback-oriented controller action to be able to tune the FF control loop from the operational data. A strategy with a more active FF control loop and minor overdosing can be a risk for operational stability with the lowest chemical use. Combining both FF and PI FB control loops is highly recommended.

ACKNOWLEDGEMENTS

This work is supported by the funding from the cosponsors Hydrotech Veolia Water Technologies AB, Jyväskylän Seudun Puhdistamo Oy and Insta Group Oy.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Bakos, V., Gyarmati, B., Csizmadia, P., Till, S., Vachoud, L., Nagy Göde, P., Tardy, G. M., Szilágyi, A., Jobbágy, A. & Wisniewski, C. 2022 Viscous and filamentous bulking in activated sludge: rheological and hydrodynamic modelling based on experimental data. *Water Research* **214**, 118–155.

Bertanza, G., Baroni, P., Garzetti, S. & Martinelli, F. 2021 Reducing energy demand by the combined application of advanced control strategies in a full scale WWTP. *Water Science and Technology* **83** (8), 1813–1823.

Craig, K., Minnema, R., Dabkowski, B. & Gironi, M. S. 2014 Evaluation of an ‘Off the Shelf’ automated chemical phosphorus removal system. *Procedia Engineering* **70**, 363–368.

Field, R. W., Wu, D., Howell, J. A. & Gupta, B. B. 1995 Critical flux concept for microfiltration fouling. *Journal of Membrane Science* **100**, 259–272.

Fundneider, T., Alejo, L. & Lacker, S. 2020 Tertiary phosphorus removal to extremely low levels by coagulation –flocculation and cloth-filtration. *Water Science and Technology* **82** (1), 131–143.

Ganigué, R., Jiang, G., Liu, Y., Sharma, K., Wang, Y., Gonzalez, J., Nguyen, T. & Yuan, Z. 2018 Improved sulfide mitigation in sewers through on-line control of ferrous salt dosing. *Water Research* **135**, 302–310.

Gu, Y., Yue Li, Y., Li, X., Luo, P., Wang, H., Robinson, Z.-P., Wang, X., Wu, J. & Li, F. 2017 The feasibility and challenges of energy self-sufficient wastewater treatment plants. *Applied Energy* **204**, 1463–1475.

Henze, M., Harremoës, P., LaCour Jansen, J. & Arvin, E. 2002 *Wastewater Treatment: Biological and Chemical Processes*. Springer, Heidelberg.

Ingildsen, P. 2002 *Realising Full-Scale Control in Wastewater Treatment Systems Using in Situ Nutrient Sensors*. PhD Thesis, Industrial Electrical Engineering and Automation, Lund University, Lund, Sweden.

Iorhemen, O. T., Hamza, R. A. & Tay, J. H. 2017 Membrane fouling control in membrane bioreactors (MBRs) using granular materials. *Bioresource Technology, Special Issue on Challenges in Environmental Science and Engineering, CESE-2016* **240**, 9–24.

Kängsepp, P., Väänänen, J., Örning, K., Sjölin, M., Olsson, P., Rönnberg, J., Wallebäck, F., Cimbritz, M. & Pellicer-Nàcher, C. 2016 Performance and operating experiences of the first Scandinavian full-scale discfilter installation for tertiary phosphorus polishing with preceding coagulation and flocculation. *Water Practice and Technology* **11** (2), 459–468.

Langer, M. & Schermann, A. 2013 *Feasibility of the Microsieve Technology for Advanced Phosphorus Removal*. Kompetenzzentrum Wasser Berlin gGmbH. Available from: https://publications.kompetenz-wasser.de/pdf/Langer-2013-626.pdf (accesses 25 April 2022).

Leith, D. J. & Leithead, W. E. 2000 Survey of gain-scheduling analysis and design. *International Journal of Control* **73** (11), 1001–1025.

Liu, L., Tian, S., Xue, D., Zhang, T. & Chen, Y. Q. 2019 Industrial feedforward control technology: a review. *Journal of Intelligent Manufacturing* **30**, 2819–2833.

Meng, F., Zhang, S., Oh, Y., Zhou, Z., Shin, H.-S. & Chae, S. R. 2017 Fouling in membrane bioreactors: an updated review. *Water Research* **114**, 151–180.

Nadeem, K., Alliet, M., Plana, Q., Bernier, J., Azimi, S., Rocher, V. & Albasi, C. 2022 Modeling, simulation and control of biological and chemical P-removal processes for membrane bioreactors (MBRs) from lab to full-scale applications: state of the art. *Science of The Total Environment* **809**, 151109.

Nunes, J., Fredriksson, O., Lindqvist, P. & Mattsson, A. 2013 Experiences of full scale operation of discfilter as a final treatment step at Gryaab. In: *The Nordic Wastewater Conference NORDIWA*, October 8–10, Malmö, Sweden.

Olsson, G., Eklund, K., Dahlqvist, K. I. & Ulmgren, L. 1973 *Control Problems in Wastewater Treatment Plants. (Research Reports TFRT-3064)*. Department of Automatic Control, Lund Institute of Technology (LTH).

Olsson, G., Nielsen, M., Yuan, Z., Lynggaard-Jensen, A. & Steyer, J. P. 2005 *Instrumentation, Control and Automation in Wastewater Systems*. IWA Publishing, London.

Olsson, G., Carlsson, B., Comas, J., Copp, J., Gernaey, K. V., Ingildsen, P., Jeppsson, U., Kim, C., Rieger, L., Rodríguez-Roda, I., Steyer, J.-P., Takács, I., Vanrolleghem, P. A., Vargas Casillas, A., Yuan, Z. & Åmand, L. 2014 Instrumentation, control and automation in wastewater – from London 1973 to Narbonne 2013. *Water Science and Technology* **69** (7), 1373–1385.

Ratnaweera, H., 2004 Coagulant dosing control – a review. In: *Chemical Water and Wastewater Treatment VIII* (Hahn, H. H., Hoffmann, E. & Ødegaard, H., eds). IWA Publishing, London, UK, pp. 10–18.

Ratnaweera, H. & Fettig, J. 2015 State of the art of online monitoring and control of the coagulation process. *Water* **7**, 6574–6597.

Safder, U., Loy-Benitez, J., Nguyen, H. T. & Yoo, C. K. 2022 A hybrid extreme learning machine and deep belief network framework for sludge bulking monitoring in a dynamic wastewater treatment process. *Journal of Water Process Engineering* **46**, 102580.

Silva, C. & Rosa, M. J. 2015 Energy performance indicators of wastewater treatment: a field study with 17 Portuguese plants. *Water Science and Technology* **72** (4), 510–519.

Urrea-Quintero, J. H., Fuhg, J. N., Marino, M. & Fau, A. 2021 PI/PID controller stabilizing sets of uncertain nonlinear systems: an efficient surrogate model-based approach. *Nonlinear Dynamics* **105**, 277–299.

Väänänen, J., Memet, S., Günther, T., Lilja, M., Cimbritz, M. & la Cour Jansen, J. 2017 Automatic control of the effluent turbidity from a chemically enhanced primary treatment with microsieving. *Water Science and Technology* **76** (7–8), 1770–1780.

Yuan, Z., Olsson, G., Cardell-Oliver, R., van Schagen, K., Marchi, A., Deletic, A., Urich, C., Rauch, W., Liu, Y. & Jiang, G. 2019 Sweating the assets- The role of instrumentation, control and automation in urban water systems. *Water Research* **155**, 381–402.

First received 2 September 2022; accepted in revised form 11 January 2023. Available online 24 January 2023