Automatic control of the effluent turbidity from a chemically enhanced primary treatment with microsieving

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ABSTRACT

For chemically enhanced primary treatment (CEPT) with microsieving, a feedback proportional integral controller combined with a feedforward compensator was used in large pilot scale to control effluent water turbidity to desired set points. The effluent water turbidity from the microsieve was maintained at various set points in the range 12–80 NTU basically independent for a number of studied variations in influent flow rate and influent wastewater compositions. Effluent turbidity was highly correlated with effluent chemical oxygen demand (COD). Thus, for CEPT based on microsieving, controlling the removal of COD was possible. Thereby incoming carbon can be optimally distributed between biological nitrogen removal and anaerobic digestion for biogas production. The presented method is based on common automation and control strategies; therefore fine tuning and optimization for specific requirements are simplified compared to model-based dosing control.

Key words | coagulation, control, flocculation, microsieving, turbidity

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INTRODUCTION

Municipal wastewater treatment plants (WWTPs) have been forced to become more efficient as a result of economic incentives and regulatory requirements (Olsson *et al.* 2014). One method that has gained interest in recent years is optimized primary treatment. It has been demonstrated that energy neutrality can be realized by maximizing the removal of carbon-utilizing chemically enhanced primary treatment (CEPT) (Remy *et al.* 2014). With maximized carbon removal, the possibility of conducting biological nitrogen removal with the carbon remaining can be limited and external carbon addition might be necessary. A controlled removal of the incoming carbon in the raw wastewater is therefore of interest for the performance and economics of WWTP.

Suspended solids (SS) and chemical oxygen demand (COD) removal of around 50 and 30% respectively are normally achieved with primary settling. To improve this, CEPT can be introduced to obtain SS removal in the range 60–90% (Kristensen *et al.* 1992; Ødegaard 1992). Common practice for the control of the chemical dose with CEPT and settling is dosing proportional to the flow (Morrissey & Harleman 1992; Ødegaard 1992; Ratnaweera *et al.* 1994). In CEPT based on settling, common proportional integral (PI) feedback control strategies have not been entirely successful. The problems are related to the retention time for settling, that is, introducing a long lag time (L) and a long time constant (T) in the range of 2–6 h, negatively affecting the stability by lowering the phase margin of the open loop system (Seborg *et al.* 2004). In addition to this, the variation in influent water composition during the same period increases the complexity (Ratnaweera *et al.* 1994). Other control strategies have been suggested, for example model predictive-based feedforward control relying on historical data or continuous laboratory scale flocculation experiments (Zhang *et al.* 1990; Ratnaweera *et al.* 1994; Huang & Liu 1996; Bello *et al.* 2014).

Microsieving as a separation method can, however, circumvent the problem related to retention time, and thus controlling the chemical dosing using feedback control can be applicable. Microsieving, here referred to as particle separation via physical straining processes (EPA 1975), in municipal wastewater treatment is mostly used for tertiary treatment (Wilén *et al.* 2012) but microsieving in primary

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treatment has gained more attention recently, also in combination with CEPT (Rusten & Ødegaard 2006; Ljunggren et al. 2007). The total retention time in the coagulation/flocculation and sieving process is around 5–20 minutes (Ewing 1976; Remy et al. 2014; Väänänen 2014). Moreover, particle separation via the sieving mechanisms in disc and drum microsieves seems predictable (Väänänen et al. 2016) and these aspects are favorable when implementing feedback control. For possible improvement in performance on occasions were a faster response is needed, feedback control can be combined with a feedforward compensator, which could be of interest for CEPT and microsieving.

In adition to flow-induced variation in lag time and time constant for CEPT and microsieving, the removal is non-linear in relation to the applied chemical dose (Väänänen et al. 2016). To improve control performance some modifications of a standard PI controller might be necessary. Scheduling of the proportional (P) and integral (I) control parameters, the proportional gain (K_p) and integration time (T_i) (or integral gain K_i) can be implemented. The parameters are then adjusted depending on process conditions (Seborg et al. 2004). These methods have been successful for example in automotive air/fuel mixture or aircraft autopilot control (Rugh & Shamma 2000) but also at WWTPs for ammonium feedback control (Åmand 2014). Thus, scheduling of the control parameters could be applicable to control the chemical dosing for controlled COD removal in CEPT with microsieving as well. Online measurement of the carbon content, directly or indirectly, is required and turbidity measurements have shown to correlate with sufficient accuracy with the particulate COD content (Mels et al. 2004). COD to turbidity correlations for wastewater have also been reported by others (Métadier & Bertrand-krajewski 2012; Nguyen et al. 2014).

Implementing controlled COD removal in wastewater treatment can vastly improve the performance of WWTPs (Bachis et al. 2015; Arnell 2016). The objective of this work was to obtain a controlled removal in primary treatment by maintaining a preset effluent water turbidity (NTU units) independent of load or flow variations, this in the broadest range possible and to show proof of concept in full scale. The method was developed and verified at a treatment capacity corresponding to 3,200 person equivalents utilizing coagulation, flocculation and discfiltration.

MATERIALS AND METHODS

A pilot plant was used for all experiments (Figure 1(a)). The plant was initially operated without chemical pretreatment to study general removal patterns and these results were used as a basis for the design of the control system. In the following section the test site and pilot plant are described and the general removal pattern is discussed. The design of a PI controller with gain scheduling and feedforward compensator is presented. The controllers are implemented in the programmable logic controller (PLC) shown in Figure 1(a).

Test site, pilot plant and analysis

The Källby WWTP in Lund, Sweden, treats, on average, 27,000 m^3/day from a combined sewer system. The WWTP consists of conventional primary sedimentation, activated sludge, including biological phosphorous and nitrogen removal, and a post precipitation process. A microsieve pilot plant with controlled coagulation/flocculation and discfiltration was installed, treating water after grit and sand removal. A schematic illustration of the pilot plant and a block diagram of the control structure are shown in Figure 1(a) and 1(b).

In the pilot plant a centrifugal pump controlled with a variable frequency drive with an operational window of 15–40 m^3/h was used to supply water to the coagulation/flocculation and the microsieve. Flow was monitored with a flowmeter from Siemens (Sitrans F M MAG 5100 W, Germany). The coagulation (1.7 m^3) and flocculation (2.4 m^3) tanks were circular and made of stainless steel with baffles and top-mounted frequency-controlled stirrers. The mixing intensity was estimated to be $G \approx 100\ s^{-1}$ in both the coagulation and the flocculation tanks. A microsieve (Hydrotech HSF 2202/1-1H discfilter) equipped with 100 μm woven polyester filter panels with a total surface area of 5.6 m^2 was used. Polymer preparation was done in a Tomal® Polyrex 0.6 automatic polymer station. The coagulant (polyaluminiumchloride, PACl, 9.3% Al^{3+}) was supplied by Kemira Kemi AB, Sweden. The polymer was a high molecular weight, medium-charged cationic powder polymer (100% active) from Veolia Water STI/Hydrex, France, and was found to be the most suitable after pre-screening in the laboratory. Coagulant and polymer dosing pumps were Alldos DDA and Alldos DME (Grundfos, Denmark), respectively. Online influent and effluent turbidities were measured with Hach Lange SC1000 controller and Hach Lange Solitax® sc sensors with automatic cleaning with wipers, wiping the glass of the sensor every 10 minutes. The Hach Lange SC1000 controller was calibrated for an operational window between 0 and 700 NTU for both influent and effluent turbidities. For the control of the process (P), influent turbidity (d) was used for the

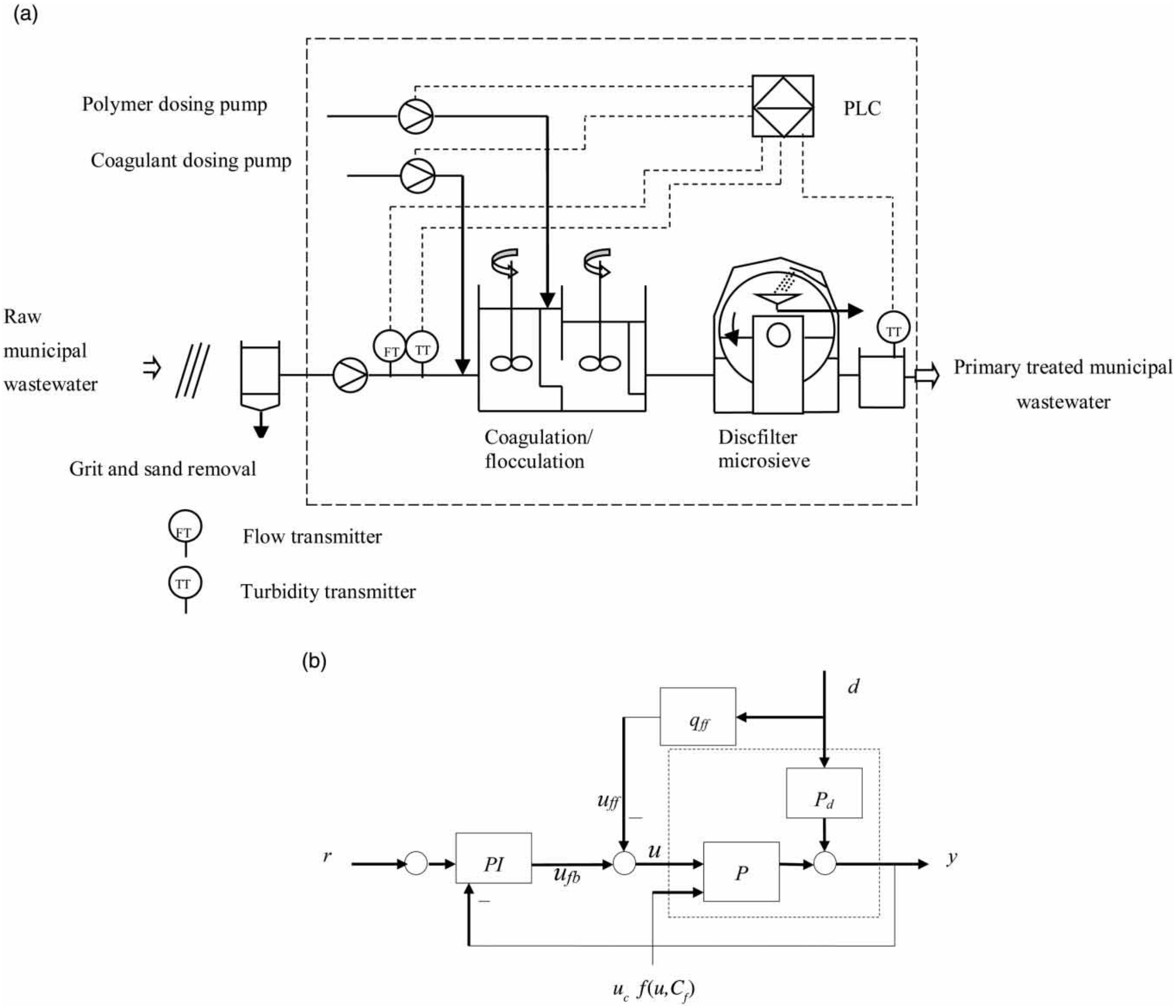

Figure 1 | (a) Schematic illustration of the pilot plant and control system and (b) block diagram of the control structure.

feedforward compensator and the effluent turbidity (y) was measuring the output and was used for feedback (Figure 1(b)). The influent turbidity sensor was positioned just after grit and sand removal, close to the influent pump. The effluent sensor was positioned in a 1 m^3 IBC equalization tank after the discfilter. The control system consisted of a Beijer Electronics iXT12B softcontrol PLC, and PLC programming was done in CoDeSys/IXdeveloper (Beijer Electronics AB, Sweden). Chemical parameters were analyzed from grab samples using colorimetric methods and Dr Lange cuvette test kits (COD, LCK 114/314; total phosphorus, LCK 348/349/350). SS were analyzed according to APHA/AWWA/WEF (2005). Additionally, turbidity was also measured with a portable turbidity meter (Hach Lange 2100P portable turbidity meter). The initial experimental phase consisted of general performance data acquisition (without chemical pretreatment) and performance evaluation with chemical pretreatment by adjusting the chemical dose manually. Verifying experiments for the evaluation of the control strategy were conducted with a duration ranging from 17 to 96 h depending on set point. The time on site was between April and November 2015.

PI controller with feedforward compensator

A feedback PI (Figure 1(b)) controller including integral anti-windup of the following type was used:

$$u_{fb}(t) = K_p\ e(t) + K_i \int_{t_0}^{t} e(t)dt$$

where K_p is the proportional gain, K_i the integral gain, and $e(t)$ the error, calculated as the difference between the set point or reference value (r) and the effluent turbidity (y) at time t as follows: $e(t) = r(t) - y(t)$. For the feedforward compensator, influent turbidities (d) > 200 NTU were considered as a disturbance and the feedforward compensator (q_{ff}) was to dose polymer (u_{ff}) according to algorithms presented below to obtain an effluent turbidity of around 140 NTU. The total polymer dose (u) was then the sum of the feedback (u_{fb}) and feedforward (u_{ff}) polymer dose:

$$u = u_{fb} + u_{ff}$$

The PI controller was to adjust the feedback polymer dose (u_{fb}) in the interval 0–4 mg polymer/L. The feedforward polymer dose (u_{ff}) was turbidity limited to 2.4 mg/L. The effluent set point was limited between 0 and 140 NTU. The coagulant (u_c) was dosed in proportion applying a factor (C_f) to the total polymer dose (u). The coagulant (u_c) was dosed proportional to the polymer dose (u) as follows: $u_c(t) = C_f \cdot u(t)$ where the proportional factor is chosen according to the operational set point.

Integral gain (K_i) scheduling

To simulate daily flow patterns in a treatment plant, influent flow to the pilot plant was varied between 15 and 40 m^3/h. The coagulation/flocculation/sieving process can be described as a time-delayed first order system. For time-delayed first order systems the lag time (L) and time constant (T) are inversely proportional to the flow (Q_{in}) (Åström & Wittenmark 1995). The variable flow introduces variations in L and T and with fixed tuning parameters the control would either become sluggish or have reduced stability (Haugen 2004). The Ziegler–Nichols step response method, described among others in Åström et al. (1993), is based on a time-delayed first order system for which tuning of the integration time (T_i) should be:

$$T_i = 3L$$

For the coagulation/flocculation and sieving process an increased flow will result in a reduced lag time (L) and time constant (T) and vice versa and therefore to improve stability the controller integral gain K_i was scheduled as follows:

$$K_i = \frac{Q_{in}}{k} = \frac{1}{T_i}$$

By scheduling K_i accordingly, sluggish or even unstable behavior is then avoided. The constant k was obtained from open loop experiments at 30 m^3/h (Q_{in}). A lag time (L) of 300 s was recorded and a corresponding appropriate integration time (T_i) of 900 s was selected according to the Ziegler–Nichols step response method. From the definition of K_i, the constant k was calculated to ≈27,000 and was thereafter used to schedule the integral gain (K_i) according to Q_{in}.

Proportional gain (K_p) scheduling

For microsieves in CEPT the polymer dosing is crucial to the treatment results and, to maximize the removal, polymer dosing is to be combined with coagulant dosing upstream (Väänänen et al. 2016). Maximum removal can be of interest for example during bypass situations where the wastewater is bypassed directly to the recipient instead of being directed to biological treatment. Moreover, previous research has shown that the removal is nonlinear in relation to the applied chemical dose (Sher et al. 2013; Väänänen et al. 2016) and that polymer in combination with metal salt coagulants gives a higher removal than polymer dosing alone. To account for this nonlinearity the proportional gain (K_p) was scheduled. Effluent set point and the coagulant factor (C_f) were used as input parameters. Scheduling of the proportional gain (K_p) was performed according to the following:

$$K_p = \begin{cases} 0.3 - (C_f \cdot 0.2) & \text{for } r \geq 90 \\ 0.3 + ((90 - r) \cdot 0.06) - (C_f \cdot 0.2) & \text{for } r < 90 \end{cases}$$

The scheduling factors for the proportional gain (K_p) 0.3, 0.06 and 0.2 were derived from trial-and-error closed loop experiments with the evaluation criterion of having an overshoot ≤25%. The factor 0.3 was derived from initial experimental conditions of $K_p = 1$, $r = 90$ NTU, $Q_{in} =$ 30 m^3/h and dosing polymer only ($C_f = 0$). This factor was kept for the following experiments. To scale K_p depending on the coagulant factor (C_f), similar closed loop experiments were performed. At set point of $r = 90$ NTU, $C_f = 1$, $Q_{in} =$ 30 m^3/h and starting from 0.1, the factor 0.2 was identified as the most appropriate. K_p was also scaled in relation to the operational regime, with a similar closed loop experiment. An effluent set point of $r = 60$ NTU was used. The experiment was initiated with a factor of 0.02 and moving upwards. The factor of 0.06 was shown to most closely fall within the evaluation criterion. All experiments started with the pilot plant operating without chemical dosing and with an influent turbidity in the range 200–400 NTU. For comparison the proportional gain of 0.3 is in the range of a calculated K_p of 0.45 obtained from step response analysis at $Q_{in} = 30$ m^3/h (L = 300 s; T = 600 s) and applying tuning rules according to the Ziegler–Nichols step response method described in Åström et al. (1993).

Feedforward control

The initial experiments without chemical pretreatment showed that the influent turbidity could change rapidly. This change could be difficult for the feedback controller to cope with and therefore a feedforward compensator was implemented. The objective of the feedforward compensator was to support the feedback controller to stabilize the effluent water turbidity to ≈140 NTU during occasions when the influent turbidity here defined as the process disturbance (P_d) (Figure 1(b)) was in the range 200–700 NTU. Results from pilot experiments indicated a similar turbidity reduction for the applied polymer dose with and without a low coagulant dose of <4 mg Al^{3+}/L (Figure 2). Thus it was considered appropriate to tune the feedforward compensator based on this general behavior. The obtained reduction curve (Figure 2) was linearized to obtain the dosing algorithms for the feedforward compensator. No significant difference between the experimental results in a one-way analysis of variance (ANOVA) test at $\alpha = 0.05$ level, $F = 1.1$ $F_{crit.} = 3.63$, $p_{value} = 0.35$ could be observed for the three experiments. For most cases the polymer dose from the feedforward compensator would be in the range 0.7–1.6 mg/L when considering the average influent turbidity range of 300–450 NTU.

The feedforward compensator used a calculated value of the defined required reduction in percentage (RR) via the influent turbidity (d) and applied a polymer dose (u_{ff}) according to algorithms:

$$RR = 100 \cdot \left(1 - \frac{140}{d}\right)$$

$$u_{ff} = \begin{cases} 0.03 \cdot RR - 0.8 \text{ for } 30 \leq RR < 60 \\ 0.08 \cdot RR - 4.0 \text{ for } 60 \leq RR < 78 \\ 0.36 \cdot RR - 27 \text{ for } RR \geq 78 \end{cases}$$

For situations when RR was below 30%, then the polymer dose from feedforward compensation (u_{ff}) was 0.

RESULTS AND DISCUSSION

Treatment results without chemical pretreatment

During the experimental phase without chemical pretreatment turbidity removal was around 30% (45% SS removal) and the reduction was similar throughout the whole influent turbidity range of 100–700 NTU (Figure 3). For comparison the SS removal over the primary clarifier at Källby WWTP was 49% during the same period, which is typical for primary clarifiers (Tchobanoglous et al. 2002). Moreover, the influent turbidity was shown to periodically vary by approximately 100–200 NTU within 10 minutes. This rapid variation could cause instability to the feedback control and therefore supportive feedforward control was implemented.

COD and turbidity correlation

One of the aims with this study was to adjust COD removal to ensure a sufficient COD concentration for a subsequent biological nitrogen removal process. In general a recommended COD/N ratio of about 8 (Henze et al. 2002) should be maintained. The primary wastewater at Källby WWTP was containing 20–40 mg total nitrogen/L and a COD concentration of approximately 200–300 mg COD/L would then be required in the downstream biological nitrogen removal process. The general COD requirement of 200–300 mg COD/L was corresponding to an effluent turbidity of about 60–100 NTU (Figure 4). This turbidity interval was prioritized when tuning the control parameters and in the verifying experiments. Turbidity was measured with two different methods and the two methods displayed no significant difference in a one-way ANOVA test at $\alpha = 0.05$ level, $F = 3.3$ $F_{crit.} = 4.11$, $p_{value} = 0.076$. It was also important to assess the control system during bypass situations, i.e. for a scenario with potentially stricter removal

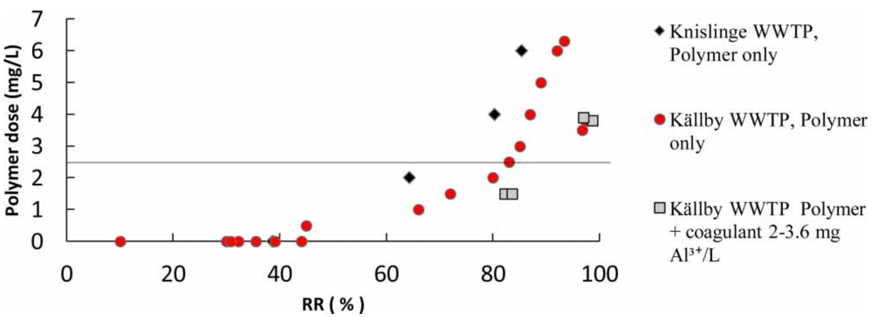

Figure 2 | Correlation between polymer dose and required reduction (RR). Knislinge WWTP (data retrieved from Väänänen et al. (2016)), Knislinge and Källby WWTP, Sweden. Straight line shows maximum feedforward polymer dose.

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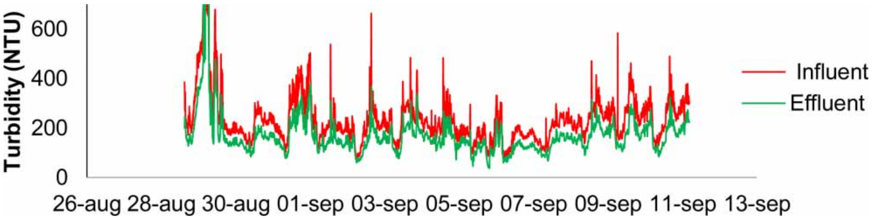

Figure 3 | Pilot experiment results; influent and effluent turbidity from 14 days of continuous operation without chemical dosing: 100 μm filter media, Q_{in} 40 m^3/h.

requirements and a set point lower than 60–100 NTU. Verifying experiments for this type of situation were therefore also performed. It should be noted that the same control parameters were used for all experiments.

Set point 40 NTU for low effluent carbon content

Figure 5(a)–5(c) shows the results from the experiments conducted with an effluent set point of 40 NTU, with C_f in the range 0–2 and flows of 15 or 40 m^3/h. The objective was to test the performance of the control system at the lower carbon content set point, which would correspond to a COD/N ratio of approximately 4–8. This set point was expected to produce an effluent water turbidity satisfying biological nitrogen removal processes with lower carbon requirements. It is seen that the effluent water turbidity was controllable to the desired set point and that the control system handled variations in influent turbidity and flow. Dosing of the polymer alone would be sufficient, at least if the influent water turbidity is approximately 200–250 NTU (400–600 mg SS/L) (Figure 5(c)). If the coagulant is applied and dosed in proportion to the polymer dose (C_f = 1), the control system can maintain an effluent turbidity of 40 NTU for influent turbidities up to 700 NTU (≈1,000 mg SS/L, Figure 5(b)). Moreover, due to the control design the controller was from around 19:12 operating with feedback control only (influent turbidity <200 NTU) and the results are indicating that only PI feedback control seems possible to use. Further experiments are necessary to verify if the controller can operate in pure PI feedback mode in the full influent turbidity range with similar performance as when combined with a feedforward compensator. During this experiment a storm water event occurred at the high flow of 40 m^3/h (Figure 5(b)), starting at around 22:00. One can observe a more concentrated influent than normal during this time of the day. The more concentrated raw wastewater was most likely due to the flushing of the sewer system as there had been a longer dry period previous to this event. During the storm water event the feedforward control had a greater impact on the turbidity reduction compared to the previous dry weather condition. The feedforward dosing was 1–2.2 mg polymer/L and 1–2.2 mg Al^{3+}/L and was sufficient to reach the desired set point. Noticeably the controller therefore became less stable (Figure 5(b)) but on average the effluent was maintained at 40 NTU. However, to improve stability, lowering the proportional gain (K_p) would have been applicable.

Set point 80–90 NTU for high effluent carbon content and dynamic inflow

Another experiment was conducted to verify the performance during a sudden change in influent flow to simulate

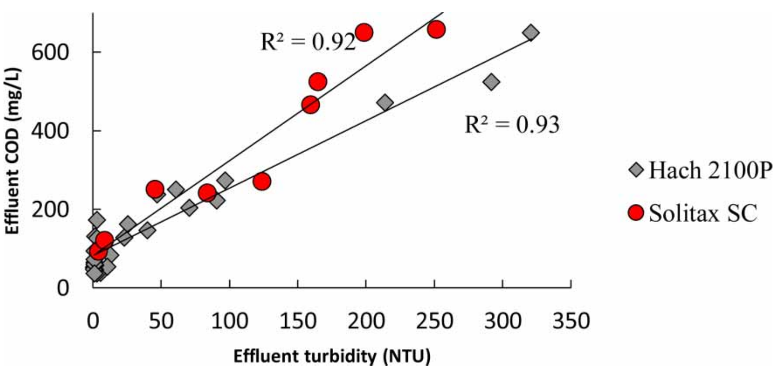

Figure 4 | Correlations between effluent turbidity (NTU) and effluent COD (mg/L). Grab samples measured either online by the Solitax SC or with Hach Lange 2100P portable turbidity meter.

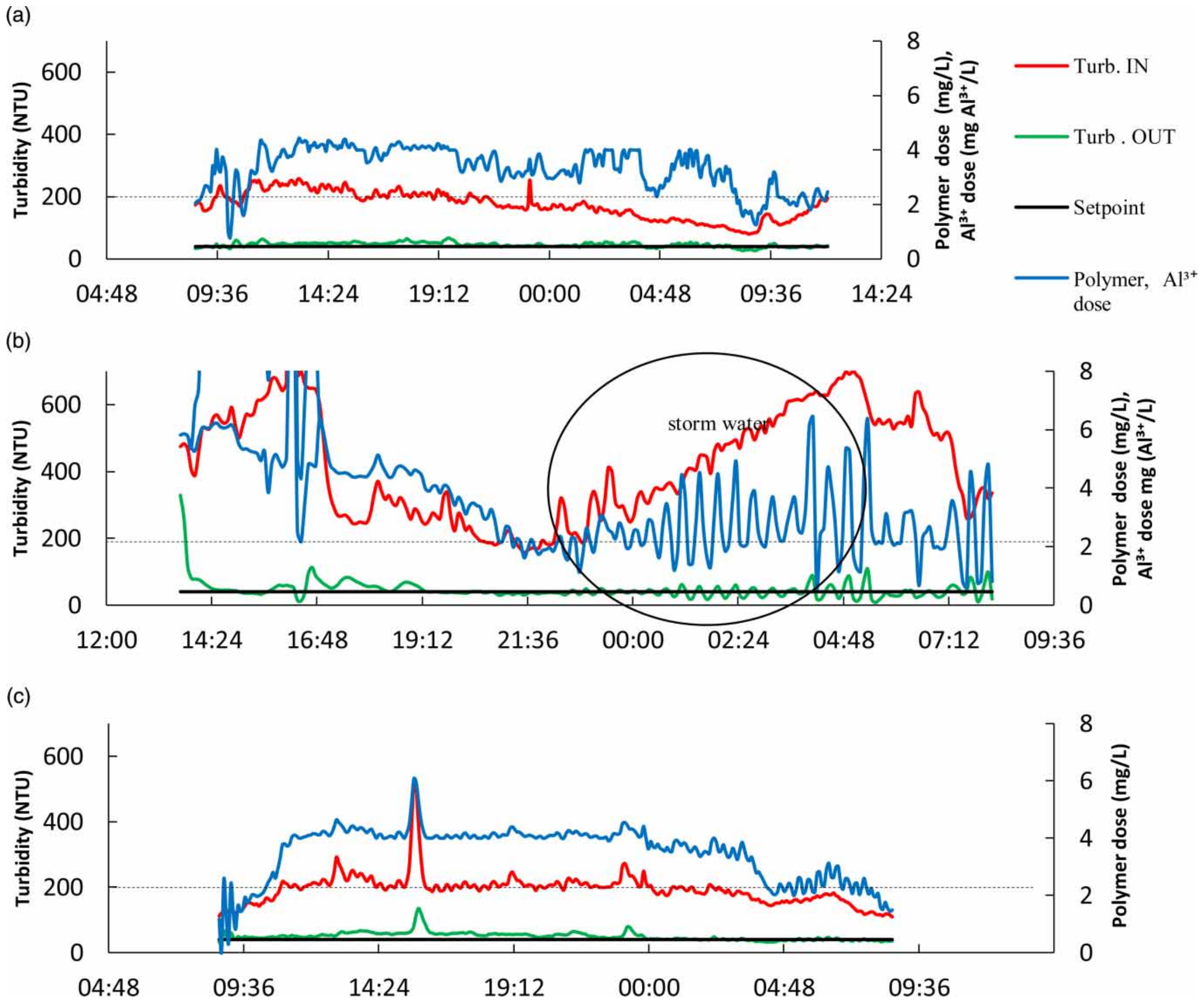

Figure 5 | 40 NTU tests: (a) 15 m^3/h, $C_f = 1$, (b) 40 m^3/h, $C_f = 2$ and reduced to 1 (@16:48), with storm water treatment during the night (00:00–05:00) and (c) 40 m^3/h, $C_f = 0$. Influent turbidities above the dotted line (200 NTU) show feedforward and feedback control simultaneously in operation and influent turbidities below the dotted line (200 NTU) show feedback control only.

extreme diurnal flow variations. In Figure 6(a) it is shown that control is maintained despite a step change in influent flow from 40 to 15 after a minor overshoot. Moreover, Figure 6(b) and 6(c) show the results from experiments conducted at the set point of 80 NTU and a flow of 15 or 40 m^3/h. This set point was expected to produce an effluent satisfying biological nitrogen removal processes with higher carbon requirements of about 10–15 COD/N ratio. This higher carbon content was also confirmed by measurements of COD from grab samples taken during one of the experiments and were in agreement with the obtained correlations. In this case, polymer dosing alone is sufficient to obtain the desired effluent water turbidity for influent wastewater with turbidities ≈700 NTU (1,000 mg SS/L), independent of flow. The control system also displays a higher degree of stability compared to a set point of 40 NTU. During this experiment, the influent turbidity was shown to be 5,600 NTU on two occasions; however, the output signal from the turbidity measurement was limited in the Hach Lange SC-1000 unit to 700 NTU, so probably this error was computational. Again, during night-time (≈04:48–09:36) the influent turbidity was below 200 NTU and the controller was operating in pure feedback mode. The feedback controller was maintaining the desired set point also during occasions with rapid variations in the influent turbidity (Figure 6(b)).

Set point step test for very low carbon content (12 NTU)

The effluent water turbidity from the discfilter was shown to be controllable to a desired set point of 40 or 80 NTU

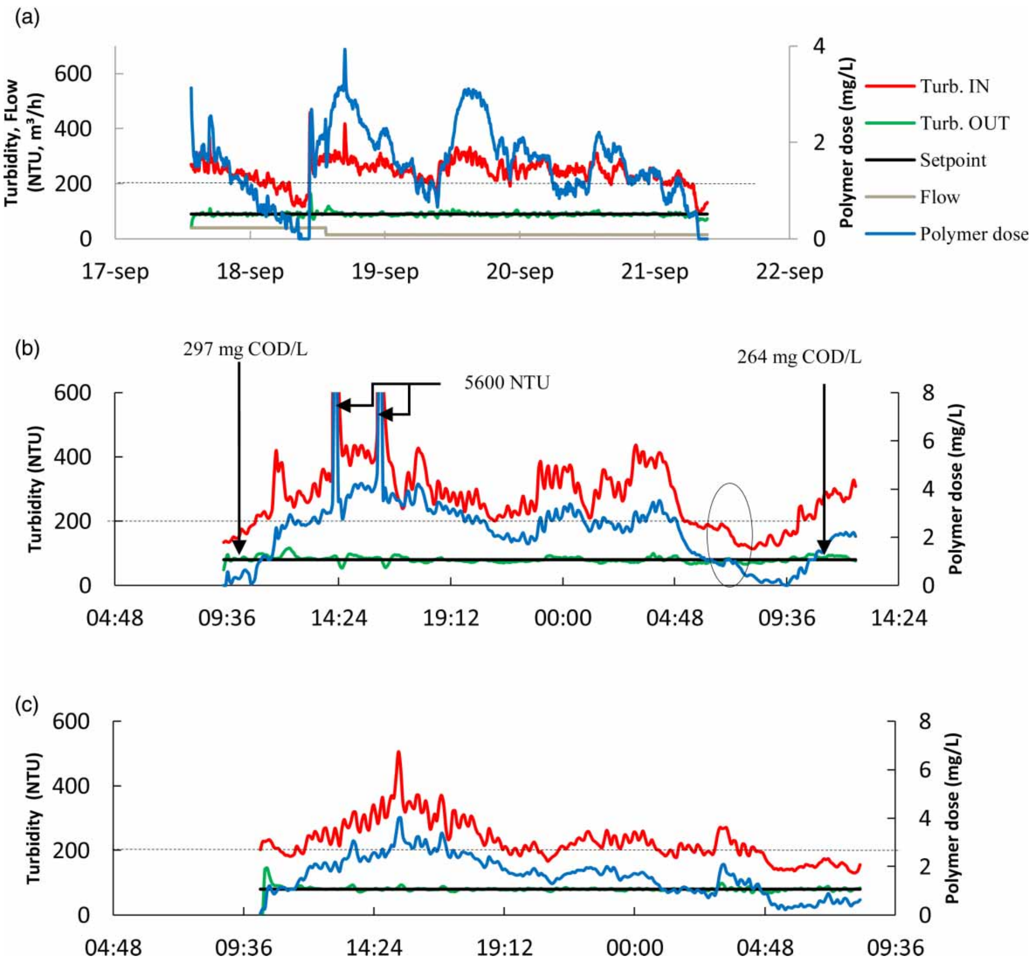

Figure 6 | 90 NTU test: (a) stepwise decrease in flow from 40–15 m^3/h. Set point experiment with 80 NTU and two flow regimes: (b) 15 m^3/h, $C_f = 0$, effluent COD from grab samples are shown, and (c) 40 m^3/h $C_f = 0$. Influent turbidities above the dotted line (200 NTU) show feedforward and feedback control simultaneously in operation and influent turbidities below the dotted line (200 NTU) show feedback control only.

identified as an appropriate range to provide an effluent sufficient in carbon for biological nitrogen removal at the Källby WWTP, independent of the variation in flow or influent water turbidity. However, it was also interesting to investigate how sudden step changes in the set point affect the system and to see how the system behaves at set points far away from the prioritized operational window. In Figure 7(a), the results from the set point step test are shown. It is shown that within the set point interval 20–80 NTU, the control system adjusts the chemical dosing to obtain the desired result. The dosing was stopped manually at around 13:00 and thereafter effluent water turbidity rapidly increased, indicating the rapid dynamics of the system. A final experiment was also performed with a set point of 12 NTU, with a flow of 40 m^3/h and $C_f = 2$ to simulate a supposed occasion where maximum treatment is required, for example, during bypass conditions. It is seen that even though the system is operating far away from the originally intended operational window, the control system shows reasonable stability (Figure 7(b)).

In Figure 7(a) it is shown that, from around 04:48–11:00 during the 20, 40, 80 NTU experiment, feedback control was only in operation. Again, feedback control alone was shown to control effluent water turbidity to the desired set point. During this stage the set point was also changed and consequently the proportional gain (K_p), without a loss in control performance, indicating that scheduling of the K_p was an appropriate method.

Summary of the experimental results

It is demonstrated that control of effluent water turbidity from CEPT with microsieving offers the opportunity to

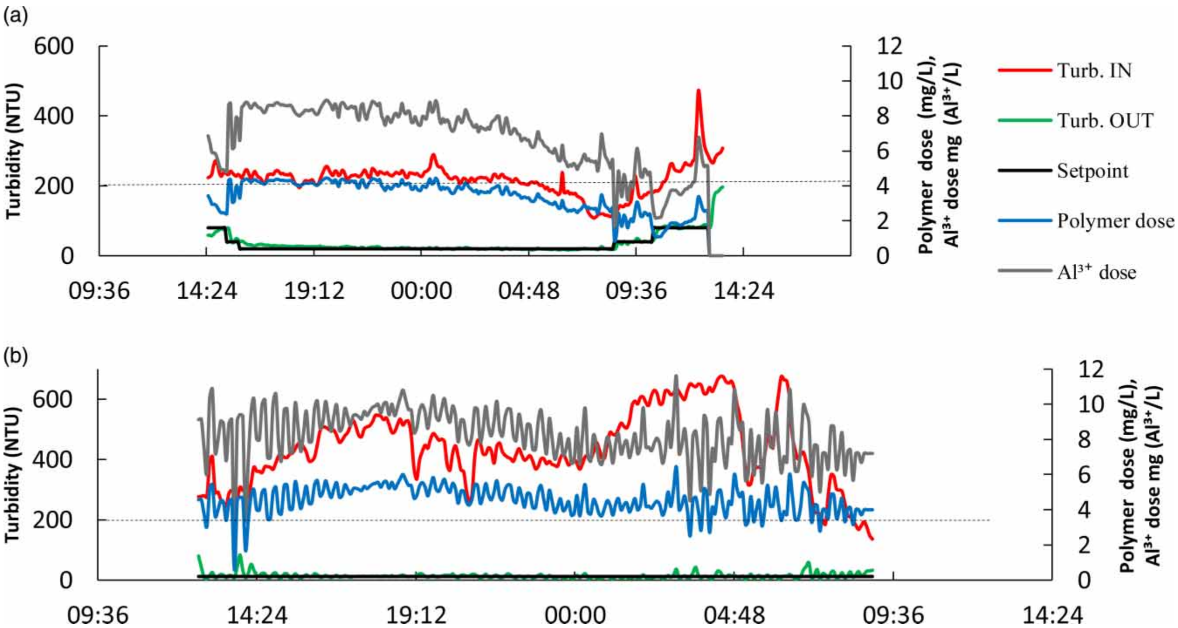

Figure 7 | Result from set point step test, (a) 80, 40, 20, 40, 80 NTU, $C_f = 2$, 40 m^3/h; and (b) 12 NTU test, $C_f = 1.8$, 40 m^3 /h. Influent turbidities above the dotted line (200 NTU) show feedforward and feedback control simultaneously in operation and influent turbidities below the dotted line (200 NTU) show feedback control only.

successfully implement common PI control with scheduling combined with a feedforward compensator. This is due to a short lag time and a predictive particle separation. Scheduling of the proportional gain (K_p) and integral gain (K_i) was implemented for stability reasons and was shown to be an appropriate method to get the system to operate within the entire operational window with sufficient stability and response quickness. Experimental results showed that with influent turbidities <200 NTU, effluent turbidity was maintained at the desired set point only with scheduled feedback control. Further experiments are needed to verify if this is also valid for the whole influent turbidity range and then feedforward compensation could be omitted, simplifying the control system further. Step response methodology was used to obtain the scheduled P and I control parameters. Hence, general PI tuning methodology was sufficient. Moreover as the results showed that the control system was able to operate in a broad operational window, this can be useful in for example overflow situations where maximum removal is necessary, simply by changing the set point. A correlation between effluent COD and turbidity was demonstrated, which is in accordance with other studies. The removal of COD in CEPT with microsieving was controllable, meaning that the biogas production at the treatment plant can potentially be increased without reducing nitrogen removal performance.

It was shown that during storm water events the removal effect of the applied chemical dosing is increased. Therefore, one could implement a proportional gain (K_p) damping function for these events in order to increase stability. The control program also had a fixed coagulant dose related to the polymer dose by a factor (C_f). It was shown that depending on the set point and influent water turbidity, polymer dosing only was sufficient, and thus, the coagulant factor (C_f) could be varied accordingly, in order to optimize chemical dosing further.

CONCLUSIONS

It was demonstrated that it is possible to use common PI control with scheduling combined with a feedforward compensator to control the effluent water turbidity to a desired set point by CEPT with microsieving. By implementing process-dependent scheduled P and I control parameters the system can operate within the entire operational window with sufficient stability. The method is based on scheduled feedback supported by feedforward control algorithms and online turbidity and flow measurements. With the proposed system, changes in effluent requirements for such reasons as to optimize the carbon content for biological nitrogen removal and biogas production or to maximize treatment results in case of storm water events are possible simply by changing the set point of the control system. Thereby performance of a municipal WWTP can be improved. The method and the design of the control system are based on traditional PI control, flow and turbidity measurements. The results also indicate that only scheduled feedback control can be sufficient and accurate enough to maintain the desired set point, simplifying the control system even further.

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REFERENCES

Åmand, L. 2014 *Ammonium Feedback Control in Wastewater Treatment Plants*. PhD Thesis, Department of Information Technology, Division of Systems and Control, Uppsala University, Sweden.

APHA/AWWA/WEF 2005 *Standard Methods for the Examination of Water and Wastewater*, 21st edn. American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC, USA.

Arnell, M. 2016 *Performance Assessment of Wastewater Treatment Plants: Multi-objective Analysis Using Plant-wide Models*. PhD Thesis, Division of Industrial Electrical Engineering and Automation, Department of Biomedical Engineering, Faculty of Engineering, Lund University, Lund, Sweden.

Åström, K. J. & Wittenmark, B. 1995 *Adaptive Control*, 2nd edn. Addison-Wesley Publishing Company, USA.

Åström, K. J., Hägglund, T., Hang, C. C. & Ho, W. K. 1993 Automatic tuning and adaptation for PID controllers – a survey. *Control Engineering Practice* **1** (4), 699–714.

Bachis, G., Maruéjouls, T., Tik, S., Amerlinck, Y., Melcer, H., Nopens, I., Lessard, P. & Vanrolleghem, P. A. 2015 Modelling and characterization of primary settlers in view of whole plant and resource recovery modeling. *Water Science and Technology* **72** (12), 2251–2261.

Bello, O., Hamam, Y. & Djouani, K. 2014 Fuzzy dynamic modelling and predictive control of a coagulation chemical dosing unit for water treatment plants. *Journal of Electrical Systems and Information Technology* **1**, 129–143.

EPA 1975 EPA 625/1-75-003a: Process design manual for suspended solids removal. U.S. Environmental Protection Agency, Technology Transfer January 1975. Available from: http://nepis.epa.gov/Exe/ZyPDF.cgi/9101AVYN.PDF?Dockey=9101AVYN.PDF (accessed 15 March 2017).

Ewing, L. 1976 Design criteria for microscreening biological wastewater plant effluents. *Water & Sewage Works* **123** (April), R94–R101.

Haugen, F. 2004 *PID Control*. Tapir Academic Press, Trondheim, Norway.

Henze, M., Harremoës, P., la Cour Jansen, J. & Arvin, E. 2002 *Wastewater Treatment; Biological and Chemical Processes*, 3rd edn. Springer, Heidelberg, Germany.

Huang, C. & Liu, C. B. 1996 Automatic control for chemical dosing in laboratory-scale coagulation process by using optical monitor. *Water Research* **30** (8), 1924–1929.

Kristensen, G. H., Jørgensen, P. E., Strube, R. & Henze, M. 1992 Combined pre-precipitation, biological sludge hydrolysis and nitrogen reduction – a pilot demonstration of integrated nutrient removal. *Water Science and Technology* **26** (5–6), 1057–1066.

Ljunggren, M., Alm, L.-G., Nilsson, B., Persson, E., Strube, R., Svensson, L. & la Cour Jansen, J. 2007 Microscreening in chemically enhanced primary treatment. In: *Chemical Water and Wastewater Treatment IX* (H. H. Hahn, E. Hoffmann & H. Ødegaard, eds). IWA Publishing, UK, pp. 49–58.

Mels, A. R., Spanjers, H. & Klapwijk, A. 2004 Turbidity-based monitoring of particle concentrations and flocculant requirement in wastewater pre-treatment. *Water Science and Technology* **50** (11), 173–178.

Métadier, M. & Bertrand-Krajewski, J.-L. 2012 The use of long-term on-line turbidity measurements for the calculation of urban stormwater pollutant concentrations, loads, pollutographs and intra-event fluxes. *Water Research* **46**, 6836–6856.

Morrissey, S. P. & Harleman, D. R. F. 1992 Retrofitting conventional primary treatment plants for chemically enhanced primary treatment in the USA. In: *Chemical Water and Wastewater Treatment II* (R. Klute & H. H. Hahn, eds). Springer, Heidelberg, Germany, pp. 401–416.

Nguyen, L., Ward, A. J. & Lewis, D. 2014 Utilisation of turbidity as an indicator for biochemical and chemical oxygen demand. *Journal of Water Process Engineering* **4**, 137–142.

Ødegaard, H. 1992 Norwegian experiences with chemical treatment of raw wastewater. *Water Science and Technology* **25** (12), 255–264.

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, 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., Blom, H. & Aasgaard, G. 1994 Coagulant dosing control using a model for wastewater coagulation. In: *Chemical Water and Wastewater Treatment III* (R. Klute & H. H. Hahn, eds). Springer, Heidelberg, Germany, pp. 105–116.

Remy, C., Boulestreau, M. & Lesjean, B. 2014 Proof of concept for a new energy-positive wastewater treatment scheme. *Water Science and Technology* **70** (10), 1709–1716.

Rugh, W. J. & Shamma, J. S. 2000 Research on gain scheduling. *Automatica* **36**, 1401–1425.

Rusten, B. & Ødegaard, H. 2006 Evaluation and testing of fine mesh sieve technologies for primary treatment of municipal wastewater. *Water Science and Technology* **54** (10), 31–38.

Seborg, D. E., Edgar, T. F. & Mellinchamp, D. A. 2004 *Process Dynamics and Control*, 2nd edn. John Wiley & Sons, Hoboken, NJ, USA.

Sher, F., Malik, A. & Liu, H. 2013 Industrial polymer effluent treatment by chemical coagulation and flocculation. *Journal of Environmental Chemical Engineering* **1**, 684–689.

Tchobanoglous, G., Stensel, D. H., Burton, F. L. 2002 Physical unit operations. 5–7 Primary sedimentation. In: *Wastewater Engineering: Treatment and Reuse*, 4th edn (Metcalf & Eddy, eds). McGraw-Hill, New York, USA.

Väänänen, J. 2014 *Applying Coagulation, Flocculation and Discfiltration in Tertiary Treatment*. Licentiate Thesis, Water and Environmental Engineering, Department of Chemical Engineering, Lund University, Lund, Sweden.

Väänänen, J., Cimbritz, M. & la Cour Jansen, J. 2016 Microsieving in primary treatment: effect of chemical dosing. *Water Science and Technology* **74** (2), 438–447.

Wilén, B.-M., Johansen, A. & Mattsson, A. 2012 Assessment of sludge particle removal from wastewater by disc filtration. *Water Practice and Technology* **7** (2), wpt2012037. DOI:10.2166/wpt.2012.037.

Zhang, J., Wiesmann, U. & Grohmann, A. 1990 Process control of chemical water treatment plant by continuous flocculation test. In: *Chemical Water and Wastewater Treatment* (R. Klute & H. H. Hahn, eds). Springer, Heidelberg, Germany, pp. 257–270.

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