Chemically enhancing primary clarifiers: model-based development of a dosing controller and full-scale implementation

Sovanna Tik and Peter A. Vanrolleghem

ABSTRACT

Chemically enhanced primary treatment (CEPT) can be used to mitigate the adverse effect of wet weather flow on wastewater treatment processes. In particular, it can reduce the particulate pollution load to subsequent secondary unit processes, such as biofiltration, which may suffer from clogging by an overload of particulate matter. In this paper, a simple primary clarifier model able to take into account the effect of the addition of chemicals on particle settling is presented. Control strategies that optimize the treatment process by chemical addition were designed and tested by running simulations with this CEPT model. The most adequate control strategy in terms of treatment performance, chemicals saving, and maintenance effort was selected. Full-scale implementation of the controller was performed during the autumn of 2015, and the results obtained confirmed the behaviour of the controlled system. Practical issues related to the implementation are presented.

Key words | controller tuning, mathematical modelling, process control, snow melt, stormwater, turbidity

Sovanna Tik (corresponding author)
Peter A. Vanrolleghem
Département de génie civil et de génie des eaux, model*EAU*, Université Laval,
1065 av. de la Médecine,
Québec,
QC,
Canada G1V 0A6
E-mail: *sovanna.tik.1@ulaval.ca*

INTRODUCTION

For years, the Saint-Charles River in Québec City (Canada) has suffered from around 50 combined sewer overflows (CSOs) annually. In an effort to regain recreational uses of the river and re-naturalize the riverbanks, 14 retention tanks (RT), totalizing a capacity of over 150,000 m^3, were constructed to reduce the CSOs. However, the RT emptying is currently only controlled on the basis of flow rate. At the end of a rain event, the RT are indeed emptied at the maximum acceptable flow rate at the inlet of the wastewater treatment plant (WWTP), with the aim of recovering the storage volume as fast as possible in case of a future rain event.

Two WWTPs, named East and West, collect wastewater from the 540,000 inhabitants of Québec City. They have respectively been designed to treat a mean flow rate of 9,625 m^3/h and 6,540 m^3/h, their acceptable peak flow rates being about 15,625 m^3/h and 13,125 m^3/h. With the current emptying management rules of the RT, the WWTPs have to operate at maximum capacity for an extended period of time after each major rain event. Such conditions can cause the treatment process to deteriorate, especially primary clarification, inducing excessive fouling of the subsequent biofilter-based treatment stage, reducing its performance. The primary treatment has thus been enhanced by chemical addition on an event basis in order to comply with the effluent regulation requirements. Figure 1 presents a flowsheet of the Québec City East WWTP. A preliminary study based on laboratory experiments, confirmed by one full-scale test, recommended the use of 70 mg/L of alum on a dry basis and 0.2 mg/L of polymer (Lajoie & Collin 2008). However, other experiments have in the meantime shown that in many cases such alum dosage is excessive, resulting in operational problems and economic loss. This study aimed to increase knowledge on chemically enhanced primary treatment (CEPT), which is a widespread process when the secondary treatment (as in our case the biofilters) needs to be protected. CEPT is also gaining attention in view of achieving energy neutrality, by increasing the capture of carbon to be fed to digesters (Meerburg *et al.* 2015) or in combination with novel processes that need low chemical oxygen demand (COD)/N-ratio influent to perform mainstream deammonification (Xu *et al.* 2015). To maintain good primary effluent quality, despite the large influent characteristics variation (rain, snowmelt, etc.), automatic control of the chemical addition based on effluent quality measurements is proposed in this paper.

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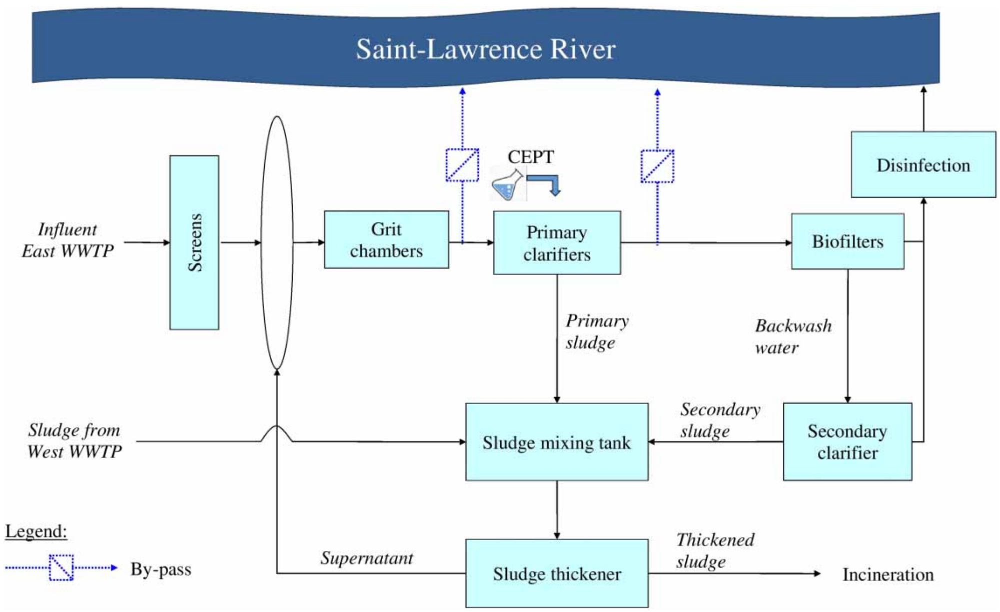

Figure 1 | Schematic process flow diagram of the Québec City East WWTP.

After 40 years of actual use, process control of wastewater treatment processes can be considered state of the art, even though its acceptance is still suffering from reluctance with operators (Olsson *et al.* 2014). Also, except for volume/level and flow rate control, the application of control systems has mainly been used to better operate biological processes, especially activated sludge systems for carbon and nutrient removal. Next to flow and level meters, the measurement equipment most relevant for primary treatment control consists of turbidity sensors. These robust sensors have been shown to be reliable since the early 1990s (Thomsen & Nielsen 1992; Nyberg *et al.* 1996). Indeed, these optical probes were soon equipped with autocleaning devices such as wipers, air brushes and now also ultrasonic cleaning systems to guarantee signal quality (Vanrolleghem & Lee 2003). Importantly, installation quality, maintenance procedures and data quality assurance have also improved significantly as experience was collected with these sensors in a variety of situations (Alferes *et al.* 2013).

This study thus takes advantage of the availability of reliable turbidity measurements to set up an automated chemical dosing system that is able to achieve a certain concentration of suspended solids (measured as turbidity) in the primary effluent. The objectives of the control system are to minimize chemical use while maintaining secondary treatment performance, especially under wet weather and snowmelt conditions that challenge the primary treatment stage. To make the development of the controller as efficient as possible, a new primary clarifier (PC) model taking into account chemical addition was first developed based on extensive laboratory- and full-scale experiments. This model was then used to test different control strategies and tune the optimal controller, which has been selected based on its performance as well as operational constraints. This turbidity-based CEPT controller has finally been implemented and tested at full scale.

The experimental work conducted to support the model development and to demonstrate the performance of the controller is described first. The developed PC model is then presented, followed by the presentation of the selected controller, its tuning and its performance, first in simulation and subsequently at full scale. Some practical implementation issues that were encountered are presented to the readers before the conclusions are drawn.

Data collection and analysis

Turbidity and total suspended solids measurements

To get a good understanding of the system's behaviour and to identify key parameters of the PC model, extensive field campaigns were carried out. The legislation standards relevant for this study are based on total suspended solids (TSS) concentration data, which are time-consuming and expensive measurements, even more if high frequency time series are needed. Using turbidity data recorded by a sensor as a substitute are thus very interesting. Unlike TSS, turbidity measurements are immediately available, allowing a real-time controller scheme to be considered.

The possibility to monitor influent and effluent quality of the PCs has been evaluated by the utility (Québec City), resulting in the permanent installation of a turbidimeter (Hach Solitax®) at the outlet of the PCs. Moreover, for the duration of the controller development project, a portable measuring station RSM30 (Primodal Systems, ON, Canada; Rieger & Vanrolleghem 2008) equipped with several sensors, in particular with turbidimeters, was installed at the inlet of the PCs (Alferes *et al.* 2013). Figure 2 shows typical recorded data of the daily dynamics in turbidity measurements at the inlet and outlet of the PC and the impact of a small rain event occurring on 17 April. At noon on 18 April, the TSS data indicate the manual cleaning activity that took place. Calibration tests confirmed that the correlation between turbidity and TSS can evolve depending on water characteristics, and further investigations may thus be needed in this area. Still, the two measurement dynamics seem alike (Tik & Vanrolleghem 2012), which allows us to conclude that turbidity measurements provide a suitable assessment of TSS concentration.

From an operational point of view, the long-term in-situ experiments that were conducted revealed that to ensure proper operation, the sensors' maintenance can be limited to one manual cleaning per week. This is an acceptable effort for the utility.

In order to be used as controller inputs, raw data given by the sensors need to be filtered to eliminate non-representative data, such as outliers, which are identified using statistical methods that are tuned on the basis of previously analysed data (Alferes *et al.* 2013). Moreover, a kernel smoother has been applied to decrease noise. This data treatment is important to ensure the development of a stable controller. With a five-second measuring interval, the sensor is recording a large amount of data, and a moving average is calculated and stored as one-minute interval data. These data were used to perform long-term simulations.

Jar test

The CEPT chemicals used are alum as coagulant (added at the inlet of the grit chamber) and an anionic polymer as flocculent (added at the inlet of the PC). Jar tests were carried out to determine the optimal dosage range. Since the main chemical supply cost comes from the coagulant, it was decided to use a relatively high polymer concentration (0.15 mg/L) and to modulate alum concentration to achieve the desired turbidity in the supernatant. Dosing between 25 and 65 mg/L of alum on a dry basis was found to be optimal. Below this concentration range, no effect of alum addition could be discerned and adding more alum did not yield any improvement in settling behaviour. These experiments suggested variation of the settling characteristics with alum addition following a sigmoidal function. Further experiments could be performed to better understand the effect of the wastewater temperature on the effectiveness of the alum addition. For instance, it was noticed that an increase in the alum concentration range could be useful during snowmelt periods.

Tracer test

Several tracer tests using rhodamine WT, which is an innocuous soluble and inert product that can be detected down to very low concentrations by fluorimetry, have been performed to determine the hydraulics of the grit chamber and PC under different incoming flow rates. The average

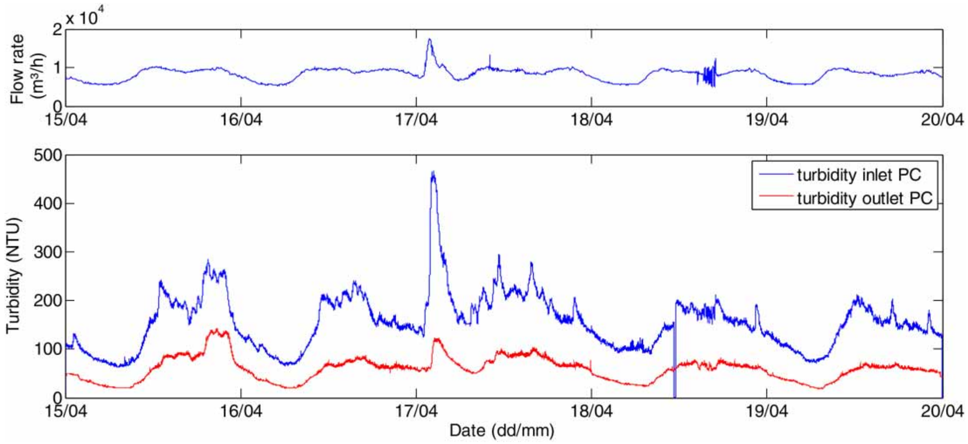

Figure 2 | Daily dynamics of WWTP flow rate (top graph) and turbidity (bottom graph) at the inlet (top line) and at the outlet (bottom line) of the PC. On top, the WWTP influent flow rate.

hydraulic retention time in each process unit has been determined. An extensive experiment performed simultaneously on the seven parallel PCs showed a not often seen agreement between effluent tracer concentrations (Figure 3), which indicates an excellent distribution of the influent flow over the seven PC units.

Full-scale experiments protocol

Full-scale experiments were conducted for calibration and validation of the model and for evaluation of the controller's performance. The calibration/validation experiments consisted of adding a constant dose of polymer and making step changes in the applied alum concentration. Each step change was continued for a period of about 40 minutes to ensure that the PC outlet concentration reached a new steady state. The calibration experiment was conducted under dry weather conditions, whereas more challenging wet weather conditions were monitored for the validation experiment. During the whole process, turbidity and TSS concentrations were measured at the inlet and the outlet of the PCs.

Model and controller development

New PC model for CEPT

The model used for developing the controller has been set up in the WEST® modelling software (mikebydhi.com). The tracer test results showed that the grit chambers, at the inlet of which alum is injected, can be modelled by four completely mixed reactors. The PC can be fairly well represented by a reactor composed of homogeneous layers, providing a 1D vertical profile of the TSS concentrations in the PC. In the present case, the tracer test indicated 11 layers were needed, with the reactor being fed in the sixth layer. Furthermore, since the tracer test was performed simultaneously on the seven parallel primary clarification units of the East WWTP (Figure 3), it was possible to deduce from the very similar tracer outlet profiles that an excellent hydraulic distribution over the seven units was achieved. This allowed simplifying of the model as the seven PCs could thus be modelled as a single lane with the combined settler surface. Finally, since the turbidity sensor at the PC outlet is located after a channel that all PCs flow into, the channel itself has been modelled by inserting an additional reactor to ensure that the resulting delay is properly covered. This results in the configuration presented in Figure 4.

The proposed PC model was based on the one presented by Gernaey *et al.* (2001). The effect of alum addition on sedimentation was modelled by making the fraction of non-settleable suspended solids (f_{ns}) depend on the alum concentration at the inlet (Figure 5(a)) and by extending the settling velocity model by a dependency of the settling velocity parameter (V_0) on the local alum concentration in the considered layer (Figure 5(b)). The time evolution of the alum concentration in the layers thus had to be modelled as an advective model of this soluble component throughout the different PC-layers.

To describe the above mentioned sigmoidal dependency of the settling characteristics on the chemical concentration, the following mathematical functions, respectively for the non-settleable fraction of TSS, f_{ns} (Equation (1)) and the particle settling velocity, V_0 (Equation (2)) were used.

Equation (1): Evolution of the non-settleable fraction of TSS with alum addition

$$f_{ns} = f_{ns\_max} - (f_{ns\_max} - f_{ns\_min}) \frac{C^n_{alum\_inlet}}{K^n_{al} + C^n_{alum\_inlet}} \quad (1)$$

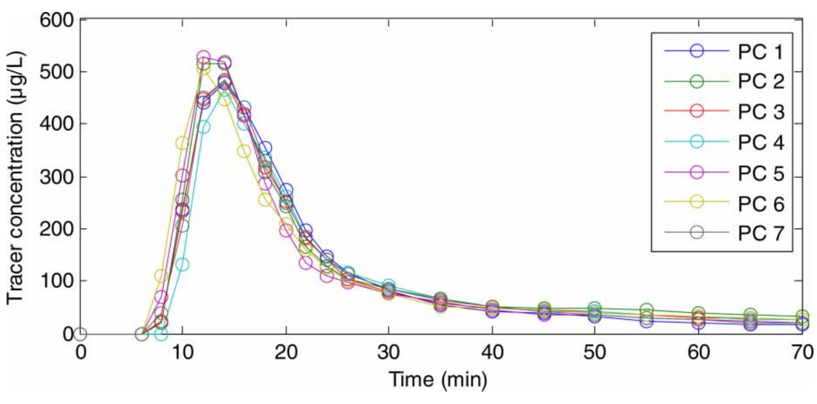

Figure 3 | Tracer concentration profiles collected at the outlet of each of the seven parallel PCs of the Québec East WWTP. The tracer test was conducted by injecting a pulse of rhodamine WT at the inlet of each PC at t = 0. The flow rate was maintained constant at about 10,000 m^3/h.

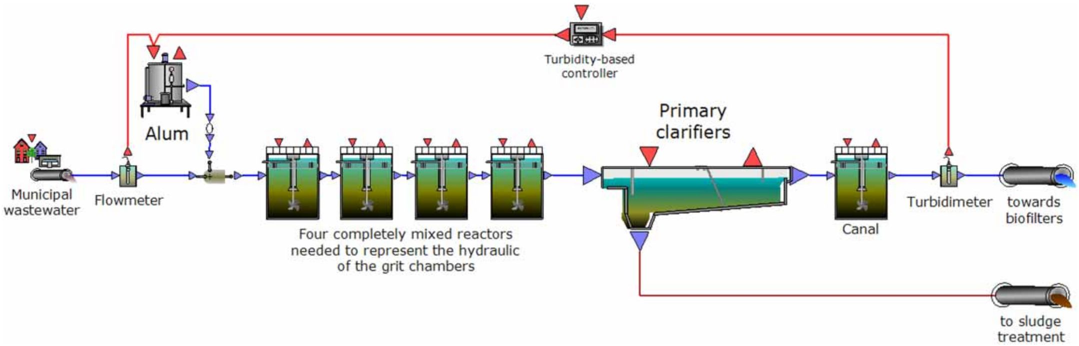

Figure 4 | Model configuration of the East WWTP PC in WEST® (mikebydhi.com).

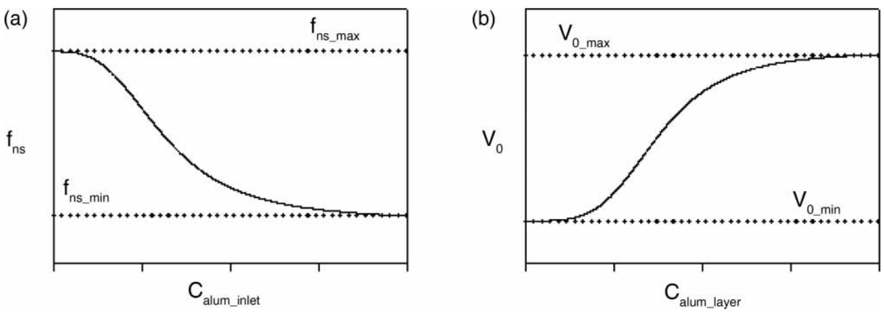

Figure 5 | Proposed evolution of (a) the non-settleable fraction of TSS, f_{ns}, and (b) settling velocity, V_0, depending on the alum concentration at the inlet of the PC and the local alum concentration in the considered layer, respectively C_{alum_inlet} and C_{alum_layer}.

Equation (2): Evolution of the settling velocity with alum addition

$$V_0 = V_{0\_min} + (V_{0\_max} - V_{0\_min})\,\frac{C_{alum\_layer}^{n'}}{K'^{n'}_{al} + C_{alum\_layer}^{n'}} \quad (2)$$

where:

- f_{ns_max} and V_{0_min} are, respectively, the non-settleable fraction of TSS and the particle settling velocity, when no alum is added.
- f_{ns_min} and V_{0_max} are, respectively, the non-settleable fraction of TSS and the particle settling velocity, when the amount of alum added is higher than the value at which a saturation effect on the improvement of settling characteristics is observed.
- K_{al} and K'_{al} are the alum concentration where the alum effect is at 50%.
- n and n′ are exponents that determine the sharpness of the sigmoidal shape (a larger n making the transition from minimum to maximum values sharper).
- C_{alum_inlet} and C_{alum_layer} are, respectively, the concentration of alum at the inlet of the PC and in the layer where the settling velocity is calculated.

The hydraulic configuration was reproduced using a series of completely mixed reactors. It was indeed essential to accurately represent the hydraulic retention time of the system, since the delay between the injection of chemicals and its actual effect has an important impact on the controller design. Indeed, a delay that is important compared to the process dynamics negatively affects the controllability of a system (Gujer 2008), and it is thus essential to accommodate for this by proper controller design and tuning (see below).

Calibration and validation of the PC model for CEPT

Figure 6(a) demonstrates that the proposed model enhancements allow a good simulation of the PC outlet during an experiment of full-scale alum addition with step alum concentration changes. In fact, the root mean square error between the data and the model results is only 9 mg/L, which is comparable to typical TSS measurement errors. The delay between changes in alum addition (located prior to the grit chamber, see Figure 4) and related outlet TSS concentration variations is clearly visible in the data and simulation results. The three peaks observed on the inlet TSS concentration data are probably due to operational conditions, as they were concomitant to sudden variations of the flow rate. The particle load generated with these flow rate changes seems to be captured well by the PC, since no evident impact on the outlet TSS concentration is observed.

The validation results are shown in Figure 6(b). Even at these significantly higher flows (about 15,000 m^3/h), the model is able to predict effluent TSS concentrations on the basis of flow rates, influent TSS concentrations and alum concentrations. The root mean square error, at 23 mg/L, is somewhat higher than for calibration, but this is still quite acceptable for a challenging model validation. Most importantly for controller design is that the dynamics (delay and step response) are well captured by the model. This will allow proper tuning of the controller's parameters.

Controller design and tuning

Different control strategies were tested with the model. Due to the fairly low residence time of the treatment units, a PI-feedback controller based on the PC's outlet turbidity was deemed sufficient, with an anti-windup component to deal with controller saturation. As the results will show, a relatively low gain controller can handle the relatively slow TSS-load variations without the need for a feedforward controller component based on an upstream turbidity sensor, which would require an additional investment and much more maintenance work. Still, a feedforward component is intrinsically present, since the actual control action is the inlet alum concentration and the amount of alum to be added to achieve the requested alum concentration in the wastewater is calculated using the measured incoming flow rate. The model configuration of the controlled system is given in Figure 4.

To evaluate the gain of installing this controller, a simulation study was conducted. Three scenarios were simulated:

(1) open loop situation, no alum is added;
(2) a constant alum concentration addition, which ensures that the TSS concentration at the outlet of the PC is below a given value most of the time;
(3) a controlled system which aims at respecting the same TSS concentration, defined as the set-point of the controller.

Figure 7 shows that scenario 2 presents over-performance during low-loaded periods, which means that too much alum is used. Scenario 3 allows about 20% reduction in chemical addition while presenting similar performance in terms of respecting the effluent TSS concentration objective. This set-point TSS value is based on the operators' expert knowledge in maintaining good secondary treatment efficiency by the biofilters. Hence, the short effluent TSS peaks due to the controller response delay are known not to jeopardize the subsequent treatment process. They are thus considered insufficient to warrant the burden of installing a turbidity sensor at the PCs inlet and adding a feedforward component to the controller.

Full-scale implementation and testing of the controller

Full-scale implementation of this controller was completed during the winter of 2015, and supervised tests were conducted during the snowmelt period and during rain events.

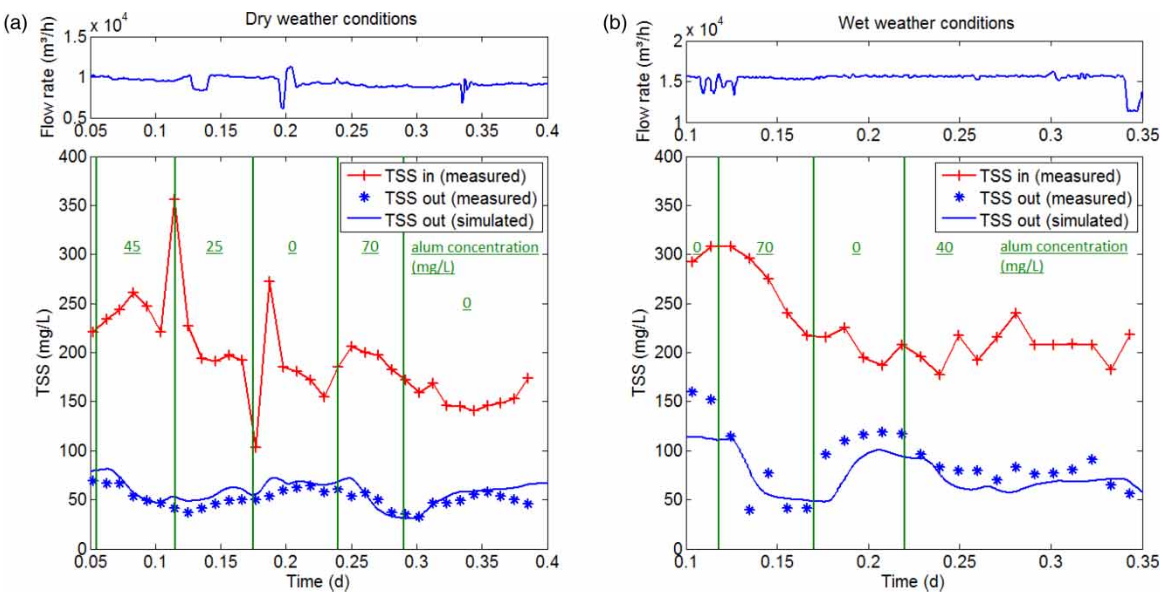

Figure 6 | Inlet and outlet experimental TSS results of full-scale experiments performed (a) on 25 August during dry weather conditions and used for model calibration and (b) on 14 January during wet weather conditions and used for model validation. The solid blue line shows the simulation results. Values of the concentration of alum added are underlined and the times of the step changes in the alum concentration are marked by the vertical lines. Graphs on top represent the WWTP influent flow rate measured during the experiments.

Under normal dry weather conditions, CEPT is not currently needed to maintain the treatment process performance. In order to use the turbidity signal as input for the feedback controller, a kernel average smoother is used to remove noise (see Figure 8).

In Figure 8, a demonstration run of the operational controller is presented. During the first hour, when the turbidity-based controller is switched on, a constant dosage of alum at 45 mg/L is applied (Figure 8, red line). The measured turbidity results (green line) clearly show that it takes some time after the dosing was started (12:30) before the beneficial effect of alum dosing becomes visible in the effluent turbidity (around 13:00). This delay of about 30 minutes is due to the retention time in the grit chamber and PC. After one hour the alum addition controller is activated, allowing it to modulate the alum concentration in the influent within the range of 25 mg/L to 65 mg/L. In case the required dosage were to drop below 25 mg/L, the alum dosage is stopped completely as the jar tests have shown that below 25 mg/L no enhancement of settling is to be expected. Similarly, a dosing above 65 mg/L is not useful since that does not bring about any further improvement in PC performance. The controller's action is visible in the slow decrease in alum dosing, which is due to the integral action of the PI-controller that reacts on the off-set (bias) that exists between the measured turbidity and the set-point.

The controller performance on two set-point changes at 14:21 and 15:37, respectively (Figure 8, pink dashed line) is illustrated in Figure 8. The obtained turbidity results (green line) clearly show the ability of the controller to modulate alum injection to reach and maintain the set-point despite the considerable time delay in the system. The actual alum pump flow rate results (Figure 8, light blue line) reflect the feedforward of the influent flow rate variations around 15:10 and 16:00. It is noteworthy that the delay after the second set-point change is shorter than the first one. This is probably due to the reduced retention time caused by the increased influent flow rate.

Practical issues of full-scale implementation

During the implementation of the developed controller into the treatment plant's SCADA system, two practical issues surfaced that we feel worth sharing. First of all, the turbidity data that were fed into the controller were data that were filtered using a moving average with a sample and hold feature updated only every five minutes, while the order of magnitude of the dynamics of the noise observed on the turbidity signal is seconds. Hence, an artificial delay was observed between the measured turbidity and the value used by the controller. The controller performance was thus initially very poor. After changing the SCADA filter's settings to a faster filtering and updating scheme, the performance anticipated by the model simulations could be reached. However, this was only possible after another implementation problem had been solved. A time unit problem was detected after it was observed that the implemented controller was reacting very slowly to deviations from the set-point. Settings of the controller's parameters in hours rather than minutes were the cause of the sluggish response. We deemed it worth mentioning that a careful check of the consistency of the data

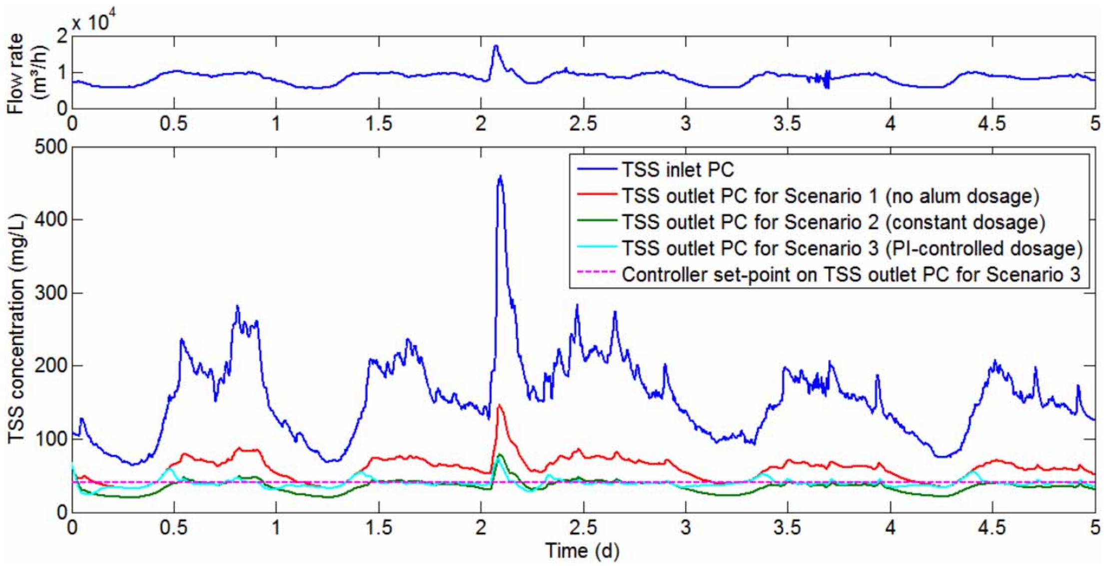

Figure 7 | PC inlet and outlet TSS concentrations for the three simulated scenarios (no alum dosage, constant dosage and PI-controlled dosage). On top, the WWTP influent flow rate.

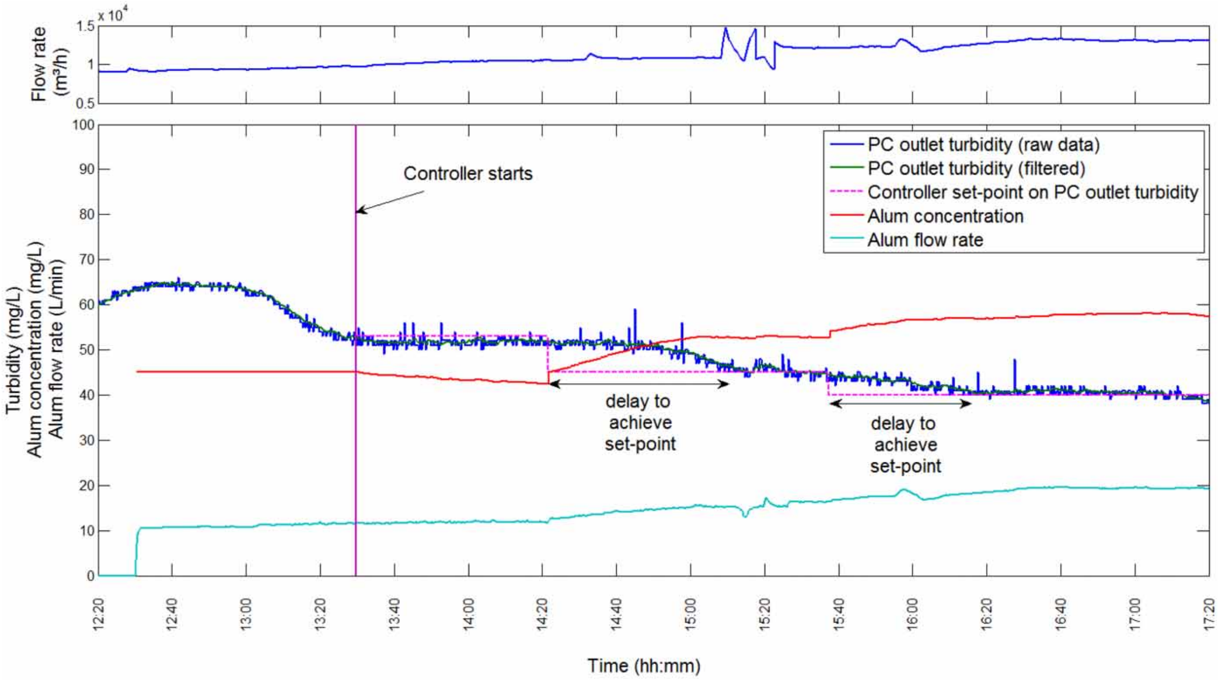

Figure 8 | Full-scale experiment performed on 9 April 2015. The turbidity-based control is switched on at 12:30 starting with a 1h-constant dosage of alum; at 13:30, the controller went into action and slowly decreased the amount of alum added. Two set-point changes were imposed: 45 mg/L of TSS at 14:21 and 40 mg/L of TSS at 15:37, which are both reached after a delay. The full colour version of this figure is available in the online version of this paper, at http://dx.doi.org/10.2166/wst.2016.600.

used is a crucial point, all the more in multidisciplinary projects involving automation and process engineers. Once these two issues were solved, the performance demonstrated in Figure 8 was reached.

DISCUSSION

An innovative controller based on online turbidity measurements allowing maintenance of the desired turbidity at the outlet of the PC has been presented. To quantify the benefit of the controller in comparison to constant alum addition, in terms of TSS removal efficiency versus chemical savings, we took advantage of having a process model to perform a scenario analysis. Simulations using the input data presented in Figure 7 were run with alum addition at different constant concentrations. For each scenario, the potential adverse effect of a high TSS concentration at the outlet of the PC was evaluated by calculating the cumulative mass of TSS discharged above the set-point over the 5-day evaluation period presented in Figure 7. Indeed, since the set-point has been defined to ensure proper operation of the secondary treatment, only the excess TSS load is detrimental. This cumulative mass of TSS has been plotted against the total amount of alum used during the evaluation period for each occurrence of the scenario analysis, resulting in the blue line in Figure 9. These indicators have also been calculated for scenarios 2 and 3 (defined in the 'Controller design and tuning' paragraph) and have been indicated on the same graph, showing:

- the gain in terms of water quality when the same amount of alum is used (Figure 9, red vertical arrow);
- the additional amount of alum needed under the constant concentration addition mode to achieve the same water quality as the controller mode (Figure 9, red horizontal arrow).

A simple PI feedback control was sufficient in this case thanks to the relatively small delay in the treatment unit. This choice allows avoidance of the need to install a turbidity sensor at the inlet of the treatment plant, which would have needed a high maintenance effort to provide reliable data. However, in the case of a CEPT system with a higher residence time, it may be worth considering a water quality based feedforward component.

Once a critical situation such as wet weather events or a snowmelt period is anticipated by the WWTP staff, this automatic controller can be activated and has been shown both in simulation and in full-scale application to be able to maintain an efficient primary treatment process while optimising the chemicals' consumption. However, to be effectively used, it

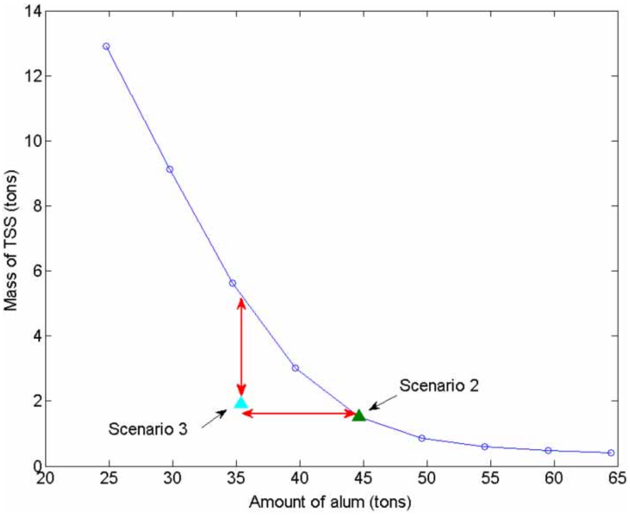

Figure 9 | Evolution of the cumulative mass of excess TSS, i.e. when the TSS concentration is higher than the controller set-point over the 5-day evaluation period presented in Figure 7, for different constant alum concentration additions. Scenario 2 (green triangle) and 3 (blue triangle) have been highlighted. The full colour version of this figure is available in the online version of this paper, at http://dx.doi.org/10.2166/wst.2016.600.

has to be trusted by the operators, the first-line users (Rieger & Olsson 2012). In this particular case, the issue of the reliability of turbidity sensors, which can be subject to fouling, has been raised. To address this issue, fault-detection methods can be applied to ensure the reliability of the turbidity measurements (Alferes *et al.* 2013), since, when a fault is detected, the system can automatically be switched to the less optimal but still useful constant concentration addition mode that does not rely on the potentially faulty signal.

CONCLUSIONS

A successful collaboration between water utility and university was presented, leading to both scientific and technical progress in the CEPT field. On the one hand, the large number of collected operational data supported the development of an innovative simple model of CEPT. On the other hand, operational management ideas have been tested and evaluated on the model before its full-scale implementation, ultimately resulting in significant resource and time savings. Finally, with only minimal adjustments, an operational system was obtained.

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