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

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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 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.

Keywords: Controller tuning; Mathematical modelling; Process control; Snow melt; Stormwater; Turbidity

Introduction

For years, the Saint-Charles River in Québec City (Canada) has suffered from around fifty combined sewers overflows (CSOs) annually. In an effort to regain recreational uses of the river and re-naturalize the riverbanks, fourteen 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 WWTP, named East and West, collect wastewater of the 540,000 inhabitants of Quebec 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 deteriorate the treatment process, especially primary clarification, inducing excessive fouling of the subsequent biofilter-based treatment stage and reducing its performance. The primary treatment has thus been enhanced by chemical addition on an event basis in order to respect the effluent regulation requirements.

A preliminary study based on lab experiments, confirmed by one full-scale test, recommended to use 70 mg/L of alum on a dry basis and 0.2 mg/L of polymer (Lajoie and Collin, 2008). However, other experiments have in the meantime shown that in many cases such alum dosage is excessive, resulting in operational problems and economical loss. This study aimed to solve this issue by optimizing the chemical dosage through automation with turbidity sensors. Experiments have been performed to model the primary clarifier (PC) behaviour without and with chemical addition. The modelling objective was to set up a real-time control system. This paper presents the successful model-based development and implementation of chemical addition control using on online turbidity data.

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 and especially activated sludge systems for carbon and nutrient removal. Next to flow and level meters, measurement equipment most relevant for primary treatment control consists of turbidity sensors. These robust sensors have shown to be reliable since the early 90s (Nyberg *et al*., 1996; Thomsen and Nielsen, 1992). 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 *et al.*, 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. This control system's objectives are to minimize chemical consumption while maintaining secondary treatment performance, especially under wet weather and snow melt conditions that challenge the primary treatment stage. To make the development as efficient as possible, a new PC model was first developed and this was then used to test different control strategies and tune the selected controller before its actual implementation.

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 in full-scale. Some practical implementation issues that were encountered are presented to the readers before the conclusions are drawn.

Material and Methods

Fieldwork

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 *et al.*, 2008) equipped with several sensors, in particular with turbidimeters, has been installed at the inlet of the PCs (Alferes *et al*., 2013). Figure 1 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 April 17th. At noon on April 18th the TSS-data indicate the 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, which allows us to conclude that turbidity measurements provide a suitable assessment of TSS concentration.

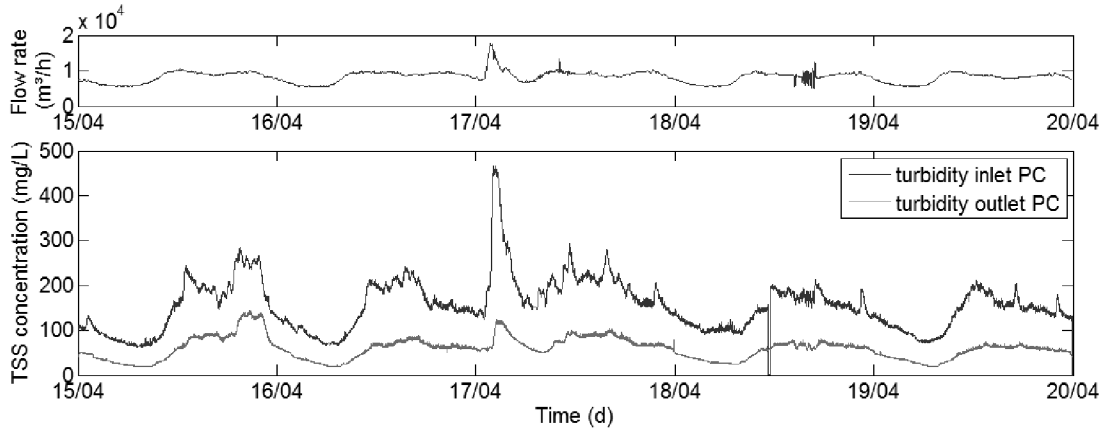

Figure 1 Daily dynamics of flow rate and turbidity at the inlet and at the outlet of the primary clarifier. On top, the WWTP influent flow rate.

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.

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 previous 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 5-second measuring interval, the sensor is recording a large amount of data, and a moving average is calculated and stored as 1-minute interval data. These data were used to perform long term simulation.

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 range of optimal dosage. 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 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.

Several tracer tests using rhodamine WT, which is an innocuous soluble and inert product which 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 hydraulic retention time in each unit process has been determined. An extensive experiment performed simultaneously on the 7 parallel PCs showed a not often seen agreement between effluent tracer concentrations (Figure 2), which indicates an excellent distribution of the influent flow over the 7 PC units.

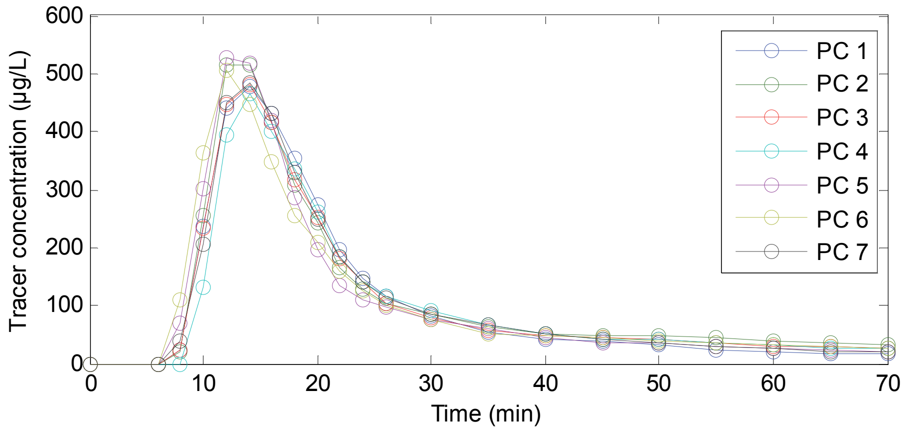

Figure 2 Rhodamine profiles collected at the outlet of the seven parallel PCs of the Quebec WWTP. The tracer test was conducted by injecting a pulse of Rhodamine WT at the inlet of each PC.

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 by 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 used for the validation experiment.

Results and Discussion

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 primary clarifiers 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 eleven layers were needed and the reactor was 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 the model as they could thus be modelled as a single lane with the combined settler surface. Finally, since the turbidity sensor at the primary clarifiers' outlet is located after a channel where all PCs flow into, the latter has also been modelled by inserting an additional reactor to ensure that the resulting delay is properly covered. This results in the configuration presented in Figure 3.

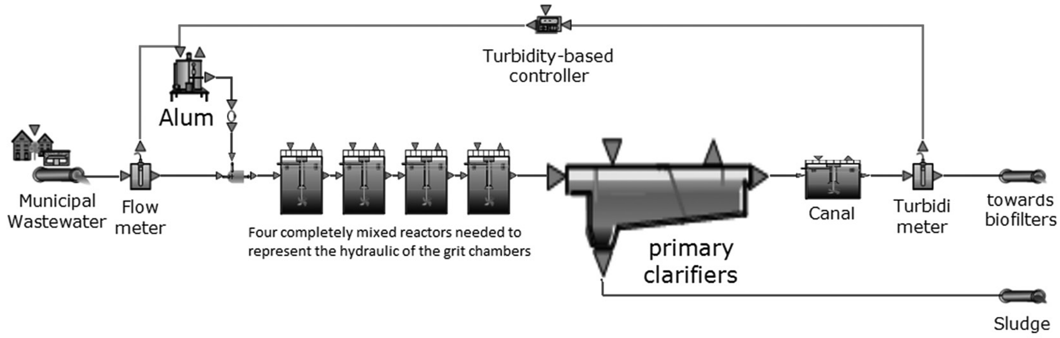

Figure 3 Model configuration of the East WWTP primary clarifier in WEST® (mikebydhi.com).

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 4a) 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 4b). 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 were used:

$$f_{ns} = f_{ns\_max} - \left(f_{ns\_max} - f_{ns\_min}\right) \frac{C_{al}{}^{n}}{K_{al}{}^{n} + C_{al}{}^{n}}$$

$$V_0 = V_{0\_min} + \left(V_{0\_max} - V_{0\_min}\right) \frac{C_{al}{}^{n}}{K_{al}{}^{n} + C_{al}{}^{n}}$$

where the minimum and maximum parameters are the minimum and maximum values attained at the extreme alum concentrations, the K_{al} parameter is the alum-concentration where the alum-effect is at 50% and the exponent n determines the sharpness of the sigmoidal shape (a larger n making the transition from minimum to maximum values sharper).

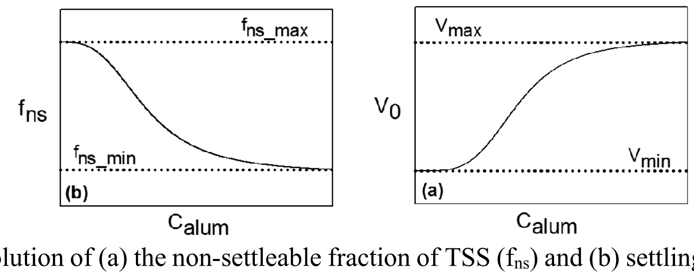

Figure 4 Proposed evolution of (a) the non-settleable fraction of TSS (f_{ns}) and (b) settling velocity, V_0, depending on alum concentration (C_{alum}).

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 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 5 (a) demonstrates that the proposed model enhancements allow a good simulation of the primary clarifiers' 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 3) 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 there 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 primary clarifiers since no evident impact on the outlet TSS concentration is observed.

The validation results are shown in Figure 5 (b). Even at these significantly higher flows, 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.

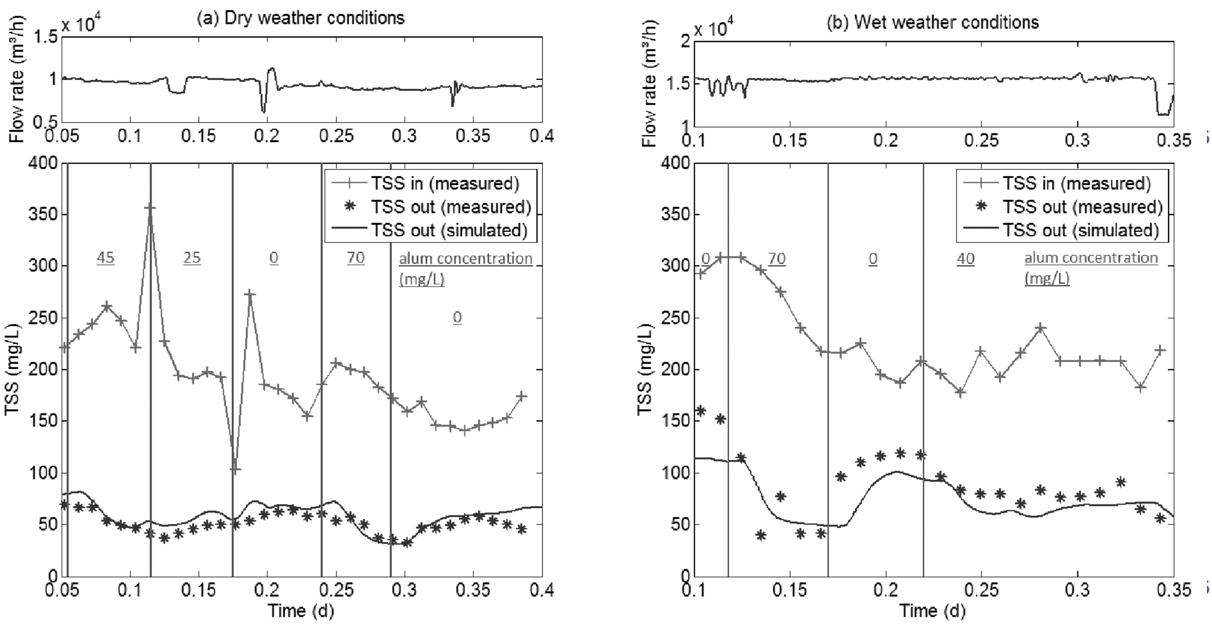

Figure 5 Inlet and outlet experimental TSS results of full-scale experiments performed **(a)** on August 25th during dry weather conditions and used for model calibration and **(b)** on January 14th during wet weather conditions and used for model validation. The solid blue line shows the simulation results. Values of alum concentration 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.

Controller design and tuning

Different control strategies were tested on the model. A PI-feedback controller based on the PC's outlet turbidity was retained, 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 an upstream turbidity sensor that would require an additional investment and more maintenance work. Still, a feedforward component is 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 3.

To evaluate the possible gain of installing a controller, a simulation study was conducted using recorded inlet turbidity data. Three scenarios were simulated:

1) open loop situation, no alum is added;
2) a constant dosage which ensures that the TSS concentration at the outlet of the primary clarifiers is below a given value most of the time;
3) a controlled system which aims at respecting the same TSS concentration.

Figure 6 shows that scenario 2 presents over-performance, which means that too much chemicals are used. Scenario 3 allows about 30% reduction in chemical addition while presenting similar performance in terms of the respect of the effluent TSS concentration objective. This 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 will not jeopardize the subsequent treatment process. They are thus considered not sufficient to warrant the burden of installing a turbidity sensor at the PC's inlet and adding a feedforward component to the controller.

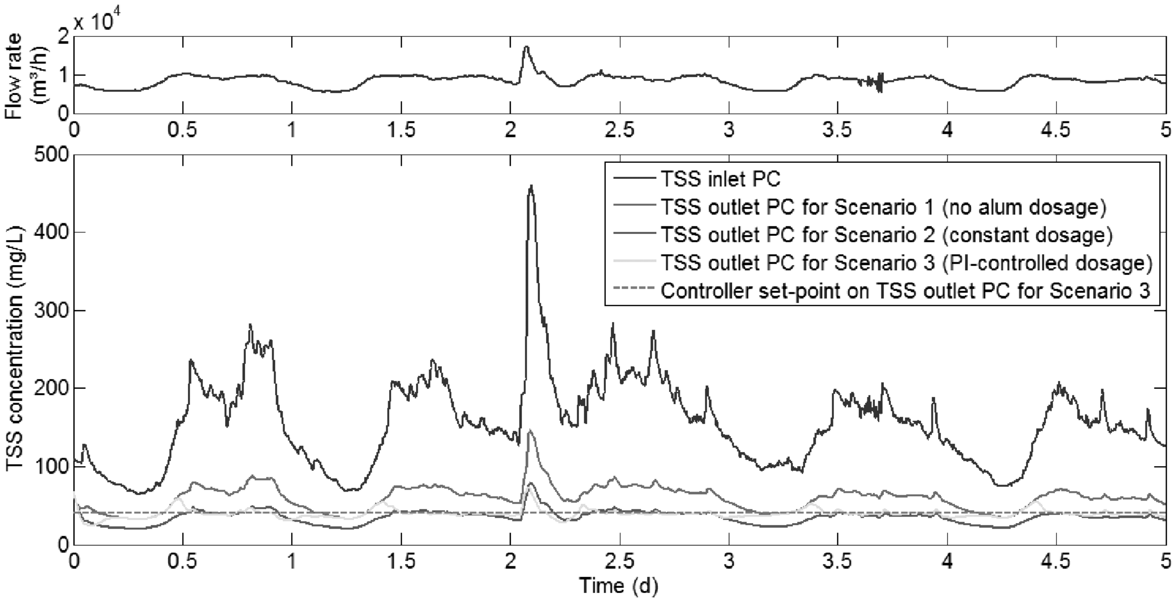

Figure 6 Primary clarifiers (PC) inlet and outlet TSS concentrations for the 3 simulated scenarios (no alum dosage, constant dosage and PI-controlled dosage). On top, the WWTP influent flow rate. On top, the WWTP influent flow rate.

Full-scale implementation 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. Under more normal 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 7).

On Figure 7 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 7, 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 1 hour the alum addition controller is activated, allowing it to modulate the dosage to bring the alum concentration in the influent within the range of 25 mg/L to 65 mg/L. In case the required dosage would drop below 25 mg/L the alum dosage would stop completely as the jar tests have shown that below 25 mg/L no enhancement of settling is to be expected. Similarly, no dosing above 65 mg/L is permitted 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 7, pink dashed line) is illustrated on Figure 7. 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 7, light blue line) reflect the feedforward of the influent flow rate variations around 15:10 and 16:00. Noteworthy is 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.

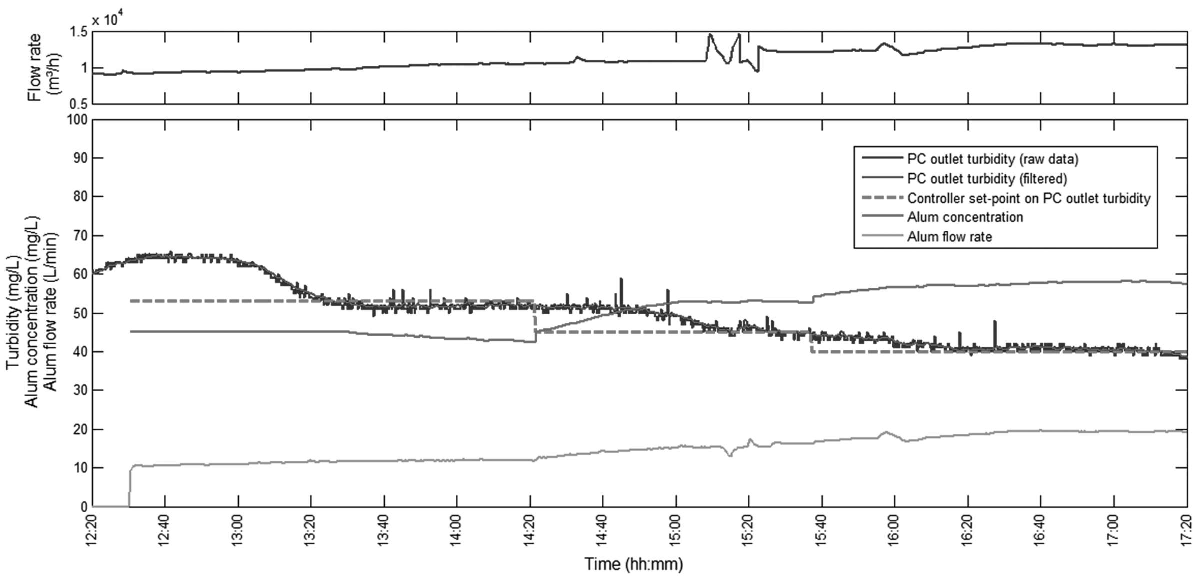

Figure 7 Full-scale experiment performed on April 9th 2015. The turbidity-based control is switched on at 12:30 starting with a 1h-constant dosage of alum; at 13:30, the controller went into action and slowly decreased the amount of alum added. Two set-point changes were imposed: 45 mg/L of TSS at 14:21 and 40 mg/L of TSS at 15:37, which are both reached after a certain delay.

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 5 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. Once these two issues were solved, the performance demonstrated in Figure 7 was reached.

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 chemically enhanced primary treatment. On the other hand, operational management ideas have been tested and evaluated on the model before its full-scale implementation, resulting in significant subsequent resource and time savings. Finally, with only minimal adjustments, an operational system was obtained.

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