

Improvement of multi-parameter-based feed-forward coagulant dosing control systems with feed-back functionalities

W. Liu and H. Ratnaweera

ABSTRACT

Coagulant dosing control in drinking and wastewater treatment plants (WWTPs) is often limited to flow proportional concepts. The advanced multi-parameter-based dosing control systems have significantly reduced coagulant consumption and improved outlet qualities. Due to the long retention time in separation stages, these models are mostly based on feed-forward (FF) models. This paper demonstrates the improvement of such models with feed-back (FB) concepts with simplifications, making it possible to use even in systems with long separation stages. Full-scale case studies from a drinking water treatment plant and a WWTP are presented. The model qualities were improved by the dosage adjustment of the FB model, ranging from 66% to 197% of the FF model. Hence, the outlet qualities became more stable and coagulant consumption was further reduced in the range of 3.7%–15.5%.

Key words | coagulation, feed-back, feed-forward, model

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INTRODUCTION

Background

Coagulation followed by separation is one of the most important treatment processes for drinking water treatment (DWT) and wastewater treatment (WWT). In WWT, after dosing a certain amount of coagulant, the destabilized particulate pollutants as well as precipitated phosphates will be converted into larger and heavier flocs and hence separated from liquid in subsequent separation processes. In DWT, colloids and particulate matter including natural organic matter (NOM) are separated. Pathogenic and toxic matters can also be removed similarly during the coagulation process. Practically in full-scale treatment processes, defining optimal coagulant dosage is a vital operation for performance of the coagulation process (Baxter *et al.* 2002; Ratnaweera *et al.* 2005). Therefore, model predictive control (MPC) of coagulant dosing has been studied in recent years

and a number of studies conclude that MPC is a more efficient way to gain stable treatment qualities than manual dosing control, which can lead to better economy (Yu *et al.* 2000; Zeng *et al.* 2003; Chu *et al.* 2004; Ashraf & Barry 2009; Maier *et al.* 2010).

However, the models commonly used in WWT are either flow proportional dosing or flow proportional dosing to achieve the optimal pH. Rathnaweera (2010) has shown that the efficiency of the coagulation process can be improved with significant saving of coagulants when including additional water quality parameters, even saving over 30% of the coagulants in WWT. Later this control concept was adopted to full-scale DWT and achieved constant treatment performance alongside 10% coagulant savings comparing to a parallel treatment line with the same inlet water qualities, where the dosage was proportional to the wastewater flow (Liu *et al.* 2013). However, along with the stringent treatment requirements for lower and more stable outlet qualities and different desired range of outlet qualities, the limitation of the current control system emerges. Moreover, the practical issue of unexpected inlet disturbance and increasing variation of treatment efficiencies are challenging the reliability of the current control highlighting the need to improve the system.

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Description of the coagulant dosing control model

Although coagulation process followed by settling tank belongs to a multivariate nonlinear system, it is well defined that outlet particle concentration highly depends on inlet particle concentration represented by turbidity (TU) and/or suspended solid (SS), pH, phosphate (for WWT), alkalinity, hardness, temperature and coagulant dosage. Because of non-proportional variation of these parameters and due to the complexity of the coagulation process as well as the lack of universally accepted theoretical models, empirical models have been widely used for full-scale coagulant dosing control comparing with the theoretical model (Maier *et al.* 2010; Ratnaweera & Fettig 2015). Instead of converting the theory to mathematical formulae and involving all related parameters, empirical models are able to establish the relationship between measured inlet variables and coagulant dosage by learning from a large amount of data. Based on current availability of online sensors, the model that author used for previous research is shown in the following equation, which is an empirical model and was validated in many full-scale WWT plants (WWTPs) and DWT plants (DWTPs) with the better results mentioned above (Rathnaweera 2010; Liu *et al.* 2013).

$$\text{Dosage} = f(\text{WW flow, inlet SS/TU, inlet pH, inlet conductivity, inlet phosphate, temperature, interaction among variables, variables squares}) \quad (1)$$

In view of the control strategy for the coagulation process, this model only uses the inlet qualities, not outlet qualities, as input variables, known as feed-forward (FF) systems or open-loop systems. Theoretically, a FF model can react instantly with any measured disturbing variables (inlet qualities measured by online sensors) through manipulated variables (coagulant dosage) and then controlled variables (CVs: outlet qualities) will be responding accordingly. In contrast, dosage variation from a pure feed-back (FB) model only depends on outlet variables instead of

inlet variables, which means ignoring both measured and unmeasured disturbance from inlet (Ogata 2001). In many situations, especially when the raw water source is a lake or a calm river, a FF model can work efficiently in WWT or DWT even with a treatment process with high hydraulic delays (Ingildsen *et al.* 2002). Furthermore, because a FF model is able to react at the very beginning of a process, it can lead to better economy by chemical and energy saving.

One disadvantage of a FF model is its low ability in handling situations with unmeasured disturbance, leading to unexpected outlet qualities. This is essentially because there is no compensation from outlet qualities to dosage prediction. Previous results of the authors show that a FF model cannot respond to unexpected outlet qualities during heavy rain (Liu *et al.* 2013). Conversely, the advantage of FB control is the ability to adjust dosage based on measured error between set point and CVs (Ogata 2001). As a result, the unmeasured disturbance and related inaccurate dosage can be compensated for (Vrecko *et al.* 2003). Therefore, it is very necessary to incorporate the advantages of these two control strategies with the purpose of improving model performance. Figure 1 shows the concept of the dosing control system combining FF with FB. FB signals like the streaming current and pH after coagulation are already used in some water works (Ratnaweera & Fettig 2015). Both of these signals provide valuable information on the status of colloidal charge. Because these two signals do not consider the flow variations and mixing conditions, they do not always represent the outlet quality and their applications are limited. Stanley *et al.* (2000) pointed out that streaming current detectors (SCDs) prove to be useful when the charge neutralization mechanism predominates. Dentel & Abu-Orf (1995) also pointed out that the output of the SCD sometimes exhibits a contradictory result for the coagulation activation, because surface charge of particles and the charge of the functional groups on NOM molecules are affected by pH. Although SCDs are available from a number of suppliers, there has been no standard calibration procedure so far (Ratnaweera & Fettig 2015). Hence, this

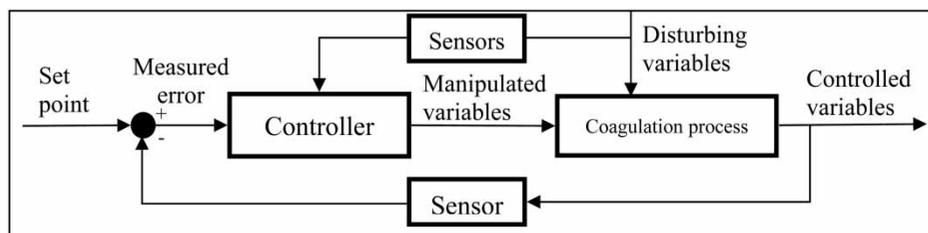


Figure 1 | Control strategy of combining FF and FB.

paper considers traditional outlet parameters such as outlet turbidity or SS as feed-back parameter of coagulant dosage control.

Challenges

In coagulation processes, inlet wastewater qualities and WW flow can vary rapidly even in less than 1 hour and the normal hydraulic retention time of a commonly used sedimentation tank is over 2 hours. Thus, it is often too late for outlet quality to provide timely FB to the dosing control system, which can lead to inaccurate and even wrong dosage during rapid inlet variation. It is also a weakness that a black box system, which the empirical model in this paper refers to, cannot display any theory, or logic between input and output. Namely, the internal equations cannot be explained and changed purposefully. Therefore, two difficulties provide challenges to combining FB variables with the FF system.

Objective

Focusing on the second challenge primarily, the objective of this paper is to improve dosage accuracy and stabilize outlet qualities by combining FB with the current FF model without considering the hydraulic retention time. Hence, this paper assumes that outlet qualities are measured immediately after dosing coagulant, and internal mixing during the separation process is negligible. The following equations show the concept of this objective.

Dosage =

$$f \left(\begin{array}{l} \text{WW flow, inlet SS/TU, inlet pH, coagulation} \\ \text{pH, inlet conductivity, inlet phosphate, temperature} \\ \text{+interaction among variables, variables squares + FB} \end{array} \right) \quad (2)$$

$$FB = (\text{outlet TU/SS, set point}) \quad (3)$$

MATERIALS AND METHODS

FF-FB model is calibrated respectively for a DWTP and a WWTP. The datasets include inlet flow, inlet turbidity, inlet conductivity, inlet pH (PHI), pH after coagulation (PHO), temperature, and outlet turbidity (TUO). These water qualities were measured by online sensors and recorded at 15 min intervals.

A programmable logic controller (PLC), as hardware of the dosing control system, can receive real time signals of water qualities via supervisory control and data acquisition (SCADA: plant control system). After dosage is calculated by the PLC, the real time dosage signal is sent out to the dosing pump via SCADA. In order to ensure the online sensors work as normal, plant workers clean and calibrate them once per week. Furthermore, several rules and criteria in the PLC apply to check measurement errors of online sensors, and various models with fewer input variables respond to different combinations of the measurement error (Rathnaweera 2010).

The model in this paper was calibrated by software Unscrambler[®] version 10.3, which is an efficient statistical tool to establish the relationship between many variables and response parameters. This software includes several regression methods including principal component regression, multiple linear regression and partial least squares regression (PLSR). Among these, the PLSR was tested to be the best method for coagulant dosage prediction by previous studies (Rathnaweera 2010). Furthermore, there are four methods for the PLSR, including classical PLSR, nonlinear iterative partial least squares, kernel PLSR and wide kernel PLSR. Since the kernel PLSR is best suited for a large number of samples (Dayal & MacGregor 1997) and the training data in this paper cover long-term samples, the kernel PLSR is selected as the calibration method. During the model calibration, the training data are standardized for equalizing the weight of each variable to the model. Cross-validation is implemented after the calibration. The software enables identification of the outlier data that do not fit to the model and to recalibrate the model without the outliers to ensure better coefficient of determination (R^2). The model calibration is completed when the R^2 is acceptable and suitable factors are selected accordingly.

This paper presents results from two treatment plants in China and Norway. The first plant is called 'number two DWT plant' (N2DWTP), located in Haining, China, with a treatment capacity of 100,000 m³/day, and the raw water is taken from the Changshan River where the water quality is relatively constant. Sequentially, the main treatment process includes an aeration tank, a coagulation process and a filtration process. The second plant, Nedre Romerike WWTP (NRA), has a capacity of 110,000 population equivalent, is situated in Lillestrøm, Norway, and has been using a FF-based dosing control system since 2009. The treatment process comprises a screen, pre-sedimentation, a moving bed biofilm reactor biological treatment and a coagulation treatment. WW comes from a combined sewer system, and the amplitude and the variation of WW flow become substantial after rain events.

A multi-parameter-based FF system started dosing control from May 2012 at the N2DWTP, and the dataset used for calibrating and validating the FF-FB model is from May 2012 to October 2013. Table 1 shows statistical data of water qualities.

The distribution of TUO measurement under the FF control system is shown in Figure 2, which includes 40,271 samples in the period of the data collection. Figure 2 shows TUO measurements usually varied within the expected variation (1.8–2.8 NTU) while undesirably high TUO (>3.8 NTU usually) was always observed during the heavy rain event. However, the inlet measured water qualities varied in normal range as before. Hence, the FF model showed no improvement after recalibration with these data. Although the sample percentage of high TUO is very low, the duration is not short enough to be accepted because of the large number of samples. For instance, total time of 0.1% of samples is about 10 hours under the 15 min interval of data recording.

Table 1 | Statistical data of water qualities in Haining N2DWTP

Variables	Minimum	Maximum	Mean	Standard deviation
Inlet WW flow, m ³ /h	1,004	2,723	2,036	260
Inlet turbidity, NTU	20	251	105	54
Inlet conductivity, μ S/cm	163	882	359.9	120
Inlet pH	6.4	7.2	6.9	0.1
Inlet temperature, °C	4.5	36.7	22.8	9.2
pH after dosing coagulant	6.3	7.1	6.7	0.1
Outlet turbidity, NTU	0.7	6.8	2.0	0.6

Since TUO is much higher than the expected range, the operators often had to switch the dosing control to the manual mode until TUO was back in the expected range. In addition, in order to evaluate the relationship between TUO and backwash frequency of the filtration following coagulation, the FF model was requested to calibrate a few times aiming at different expected TUO ranges. On the other hand, Figure 2 also shows that >20% of situations have TUO <1.8 NTU, indicating possible over-dosages. Before calibrating FF-FB models for Haining N2DWTP, the set point in Equation (3) is fixed to TUO = 2.3 NTU according to the plant's usual desired value.

The dataset from NRA during December 2013 to December 2014 was used for the analysis presented here. The set point is fixed to TUO = 3.0 NTU as the usual desired value. The statistical data are shown in Table 2.

Figure 3 shows distribution of TUO measurement during the dosing control using the FF model at NRA and the figure is based on 32,124 data points. The expected TUO range is 1–4 NTU. It is also observed that 25% of TUO measurements were beyond the expected range, in which 18.4% of TUO measurements are higher than 4 NTU especially when inlet WW flow is varying in high level.

Data preparation is also necessary before feeding the dataset into the software Unscrambler[®] version 10.3. Firstly, the dataset was 'cleaned' for potential measurement errors, identified with sudden high variation, not changing for long time, out of normal variation range and not complying with logical rule, etc. For example, data with PHO higher than PHI is considered as measurement error and were excluded. Secondly, the retention time during the separation process and the non-plug flow conditions in the settling tank complicates direct comparison of inlet-dosage-outlet datasets. The possible error arising from the latter is probably

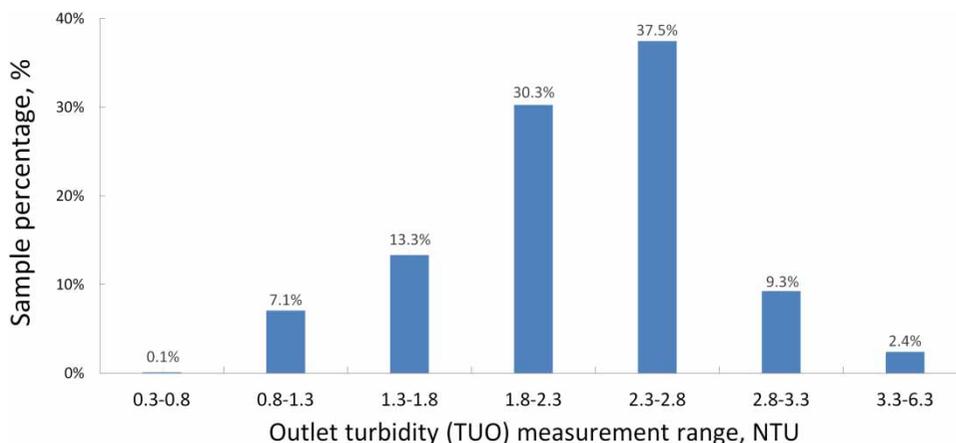


Figure 2 | Distribution of outlet turbidity measurement under FF system control in Haining number two DWTP.

Table 2 | Statistical data of water qualities in NRA WWTP

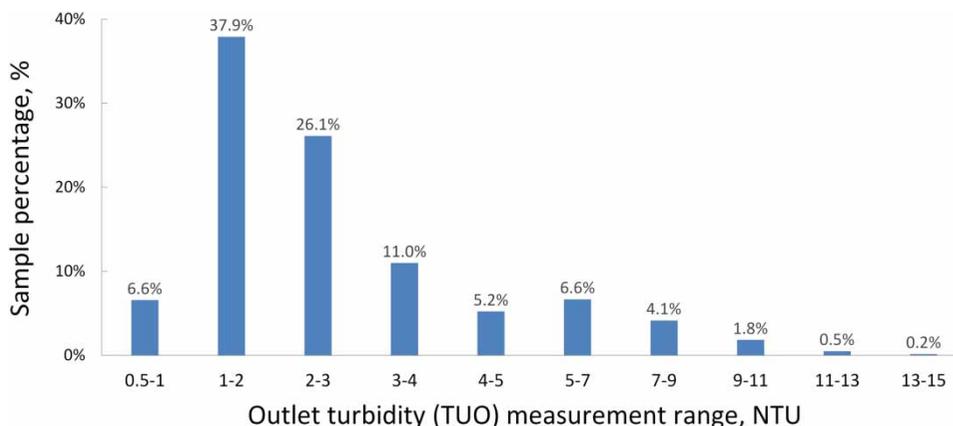
Variables	Minimum	Maximum	Mean	Standard deviation
Inlet WW flow, m ³ /h	109	1,466	644	294
Inlet turbidity, NTU	42	411	102	33
Inlet conductivity, μ S/cm	171	983	473	110
Inlet pH	5.9	6.8	6.4	0.1
Inlet temperature, °C	7.6	22.0	15.6	3.6
pH after dosing coagulant	5.3	6.7	6.1	0.2
Outlet turbidity, NTU	0.5	14.9	2.8	2.1

insignificant with high grade separation processes like Actiflo[®]. However, in this study we have assumed the error caused by non-plug flow conditions to be insignificant, thus only the average retention times served as pairing inlet and outlet datasets. Finally, the datasets were divided into two equal parts, the first of which is used for model calibration while the latter part is used for model validation.

RESULTS AND ANALYSIS

Case of DWTP – N2DWTP

The FF-FB model is calibrated by the first half of the data with $R^2 = 0.75$. Comparing with $R^2 = 0.71$ when FF model was calibrated without TUO input, it indicates that the calibration data with TUO provide better fitness to the model. Figure 4 shows the validation results; the upper figure shows distribution of TUO measurement in the validation data from

**Figure 3** | Distribution of outlet turbidity measurement under FF system control in Nedre Romerike WWTP.

February 2013 to October 2013, which include 20,108 samples. The statistics in the lower figure show the performance of FF-FB model to adjust dosage in different TUO measurement range. The percentage of average dosage adjustment is calculated by Equation (4). The FF-FB model seems to decrease the predicted dosage when TUO < 2.3 NTU (set point), while the dosage increases when TUO > the set point. Furthermore, the degree of this adjustment is increasing when TUO becomes further away from the set point. In the case of TUO > 3.8 NTU, dosage of the FF model could not be adjusted adequately and the TUO starts to increase. Then the plant operators switched to the original flow proportional dosing control, which is manually adjustment of the dosage. Otherwise, the dosage adjustment of the FF-FB model should be approximately shown as dot line bars in the range of 3.8–5.8 NTU.

Average dosage adjustment

$$= \frac{(\text{dosage from FF-FB model} - \text{real dosage from FF model})}{\text{real dosage from FF model}} \times 100\% \quad (4)$$

Therefore, the FF model after adding a FB variable seems able to compensate for variations of the inlet qualities, resulting in more stable TUO.

Case of WWTP – NRA

Regarding the FF-FB model in NRA WWTP, the data have shown a very good fitness to the model after adding a FB variable, because R^2 is improved to 0.87 from 0.61 of the FF model. Therefore, the model performance is much better than the FF model in the validation stage. Figure 5

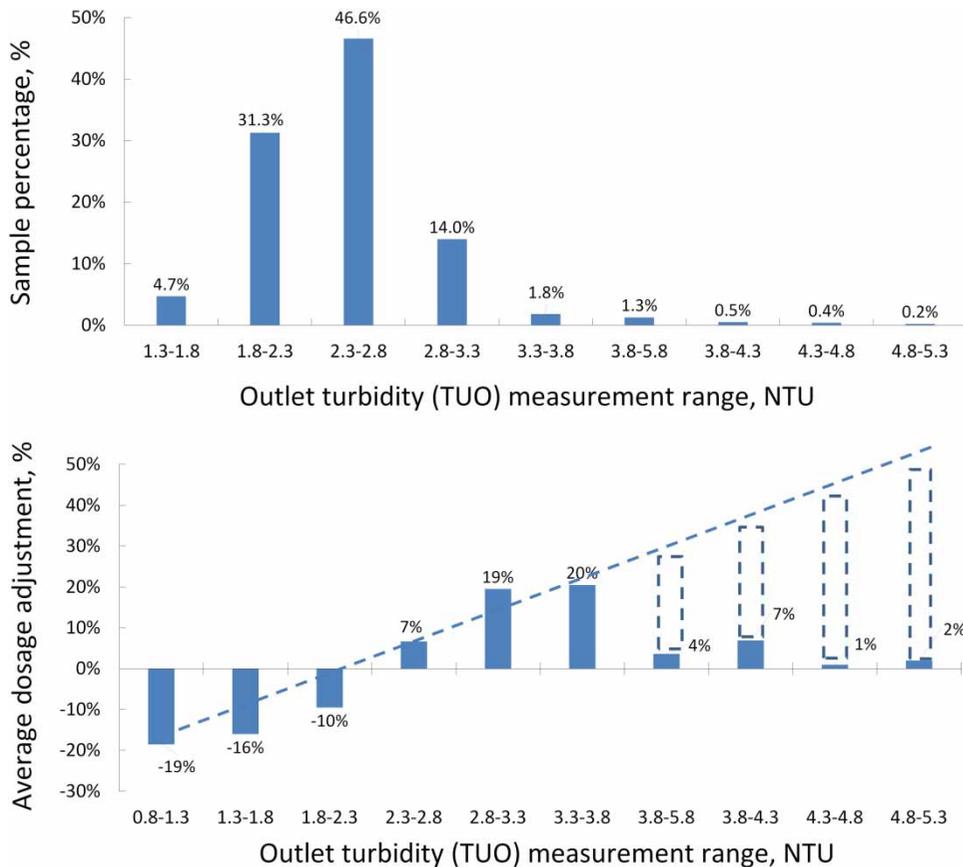


Figure 4 | Statistics on validation result of FF-FB model in Haining number two DWTP.

shows validation of the FF-FB model with 16,055 samples from June 2014 to December 2014, and FB proved to be more active to adjust the predicted dosage comparing to the FF-FB model of N2DWTP. Therefore, the FF-FB model has a strong capacity to stabilize outlet qualities for this WWTP.

FF and FB effects in the model

In practice, performance of FF-FB model depends on both inlet water qualities (FF) and outlet qualities (FB). Hence, this section is to analyse the combined effect of FF and FB. According to the above results, the FF-FB models of N2DWTP and NRA have the capability not only to predict dosage more accurately, but also to adjust it more efficiently when the outlet qualities are out of the expected range. Figure 6 shows the relationship between TUO deviation from set point (x-axis, presented by Equation (6)) and dosage adjustment percentage (y-axis, presented by Equation (5)). If pure FB control of dosage, the relationship

between dosage adjustment percentage and TUO deviation from set point should be a strict line like $y = ax$. In order to show the relationship with small amount of samples, Figure 6(a) and 6(b) contain 10% of total samples respectively, which are random-selected.

y-axis: dosage adjustment percentage

$$= \frac{(\text{dosage of FF - FB model} - \text{real dosage})}{\text{real dosage}} \times 100\% \quad (5)$$

x-axis: Outlet deviation = outlet measurement

$$- \text{set point} \quad (6)$$

Figure 6(a) is from N2DWTP and Figure 6(b) is from NRA WWTP. The relationship between outlet quality deviation and dosage adjustment is not as linear as the strict line ($y = ax$). This indicates that strengths of the dosage adjustment are not identical when the same TUO deviations from the set point happen. This is because inlet water qualities are different even under the

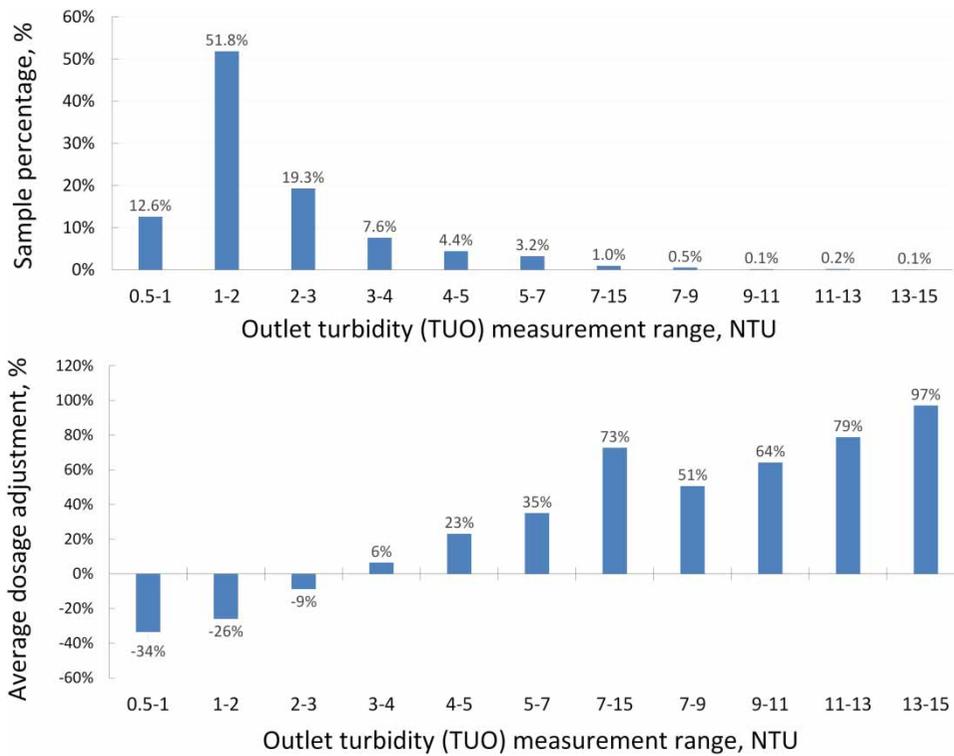


Figure 5 | Statistics on validation result of the FF-FB model in Nedre Romerike WWTP.

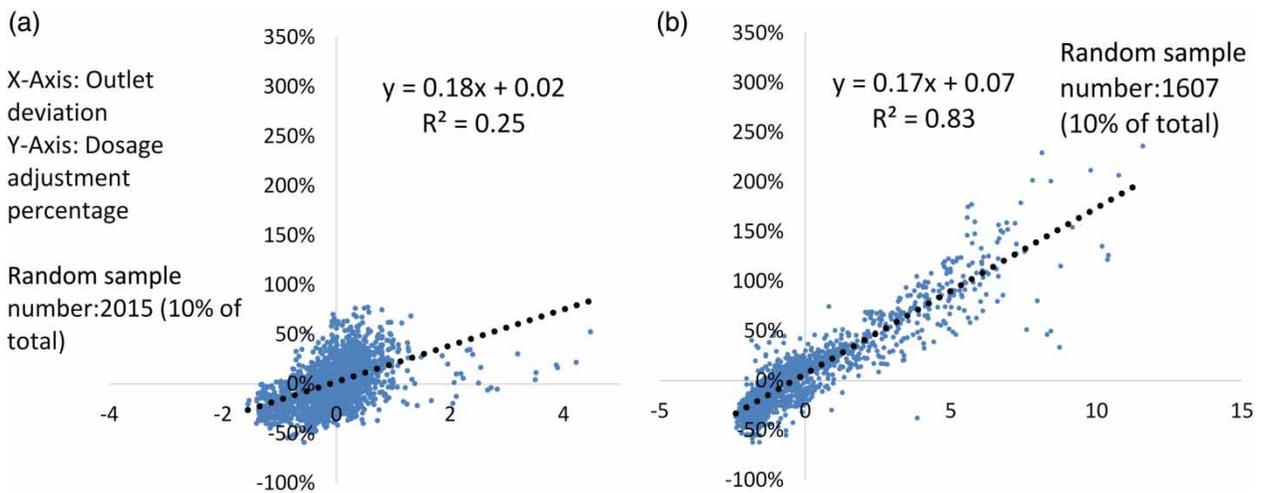


Figure 6 | Relationship between outlet quality deviation from set point and dosage adjustment percentage. (Dosage adjustment percentage = (dosage prediction – real dosage)/real dosage*100%.) (a) Haining number two DWTP and (b) Nedre Romerike WWTP.

same TUO deviations, which should generate various FF contributions to dosage prediction and differ the strengths of the dosage adjustment. Thus, the relationship in Figure 6(a) and 6(b) presents as the shape of a belt but not the strict line.

Changes on coagulant consumption

Since the FF-FB model is able to adjust dosage to constant TUO, the coagulant consumption will be changed accordingly. Based on statistics data in Tables 3 and 4, this

Table 3 | Parameters of changes in coagulant consumption in Haining N2DWTP

TUO measurement range, NTU	0.8–1.3	1.3–1.8	1.8–2.3	2.3–2.8	2.8–3.3	3.3–3.8	3.8–5.8
Sample percentage, %	0.2%	4.7%	31.3%	46.6%	14.0%	1.8%	1.3%
Average dosage adjustment, %	–19%	–16%	–10%	7%	19%	20%	4%
Average pump frequency, Hz	26.81	25.19	24.46	24.91	25.21	26.83	36.88

Table 4 | Parameters of changes in coagulant consumption in NRA WWTP

TUO measurement range, NTU	0.5–1	1–2	2–3	3–4	4–5	5–7	7–15
Sample percentage, %	12.6%	51.8%	19.3%	7.6%	4.4%	3.2%	1.0%
Average dosage adjustment, %	–34%	–26%	–9%	6%	23%	35%	73%
Average real time dosage, ml/m ³	56.33	58.88	57.82	60.06	59.31	57.92	60.13
Average WW flow, m ³ /h	428	493	644	984	1,206	1,271	1,114

section estimates potential changes on coagulant consumption under the FF-FB model control. In Table 3, the pump frequency as the system output is an indicator of coagulant flow, which is proportional to the coagulant dosing flow. For N2DWTP, during the period of validation (9 months), the FF-FB model used 3.7% less coagulants to prevent over-dosage. However, the overall coagulant consumption with the FF-FB model to secure more stable TUO was 2.6% more than the FF model, because 12,809 data points originally had an under-dosage resulting in TUO > 2.3. However, in NRA the total consumption of the FF-FB model became less, which could save 9.2% coagulant during the validation period (6 months). If the FB-FF model's task was to only reduce the over-dosage, the savings would be 15.5%. Therefore, if inlet qualities are similar to validation data and TUO can work as a non-delayed FB variable, the FF-FB model can provide approximately 9.2% coagulant savings in future applications.

CONCLUSIONS AND DISCUSSION

The options for the use of FF and FF combined with feedback (FF-FB) were discussed.

A concept to integrate the FB values to the existing FF models was presented. The results of dosing control strategies based on the FB-FF models were superior to strategies based on the FF models. The increased efficiency of the model was documented with data from full-scale tests both from DWTPs and WWTPs.

The FF-FB models generated algorithms with better qualities compared with the FF-only models. If the objective of the control based on the FF-FB model was only to avoid over-dosage, it is possible to achieve savings in the range of 3.7–15.5%.

The possibility to generate more stable outlet qualities with the controls based on the FF-FB model were demonstrated. The outlet qualities became more stable but the overall coagulant consumption became only 9% less in WWTP while it increased by 3% in N2DWTP. The latter was a result of longer periods with under-dosage leading to poor outlet qualities, and an increase in dosage was often required to produce better and consistent outlet qualities.

Since the empirical model has a strong ability to establish the relationship between variables from historical data, the model performance can be improved by the data with more accurate dosages. The common retention time of sedimentation tanks and the associated internal are considered as challenges to the FF-FB model. However, a simplification applied in this study shows a significant trend to improve the outlet quality. With reduced retention times in separation stages, the model accuracy will obviously be better as it can include measured outlet values in the models. Another solution could be the use of FF-based soft sensors for outlet qualities, enabling the use of the FF-FB models in the separation stages with longer retention times (Liu & Ratnaweera submitted). However, the FF-FB model can still apply to DWTPs because inlet quality changes are often scaled by hours and days rather than minutes in most cases. The model could also apply to WWTP with high rate settling tanks such as lamella and

Actiflo, which reduce the settling time from hours to minutes.

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