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Lessons learnt from evaluating full-scale ammonium feedback control in three large wastewater treatment plants

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ABSTRACT

Three large wastewater treatment plants in Sweden participate in a project evaluating different types of ammonium feedback controllers in full-scale operation. The goal is to improve process monitoring, maintain effluent water quality and save energy. The paper presents the outcome of the long-term evaluation of controllers. Based on the experiences gained from the full-scale implementations, a discussion is provided about energy assessment for the purpose of comparing control strategies. The most important conclusions are the importance of long-term experiments and the difficulty of comparing energy consumption based on air flow rate measurements.

Key words | aeration control, ammonium feedback control, full-scale evaluation, wastewater treatment

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INTRODUCTION

Between 2010 and 2014 Henriksdal, Käppala and Himmerfjärden wastewater treatment plants (WWTPs) in Sweden cooperated in a project with the aim to implement ammonium feedback control in the activated sludge process. Ammonium-based control determines the dissolved oxygen (DO) concentration in the aeration tank in a WWTP based on a measurement of ammonium. The project goals in this study are to save energy, to improve process supervision and to continue to reach sufficiently low ammonium concentrations in the effluent.

Ammonium control has been shown to contribute to energy savings of around 5–25% in full-scale installations (cf. Åmand *et al.* 2013b). The majority of full-scale evaluations of ammonium control are performed during a shorter time period than 2 months. Apart from the STAR controller (Nielsen & Önnerth 1995), Lindberg (1997) and Suescun *et al.* (2001) published early results with ammonium feedback control from pilot-scale experiments. Ingildsen *et al.* (2002) and Ayesa *et al.* (2006) published experiments with full-scale ammonium control performed in Spain and Denmark. Ingildsen *et al.* (2002) pointed out the importance of an even flow distribution between parallel lines to be able to compare controllers. Later on, Ayesa *et al.* (2006) discussed the difficulty of performing a quantitative assessment of a control strategy, due to variations in load and temperature. Rieger *et al.* (2012) emphasise the importance of data quality evaluation and present examples of where plant equipment limits the performance of process controllers. This paper continues on the path to further increase the knowledge from working with full-scale implementation and evaluation.

The structure of the paper is as follows. Background data about the plants are presented in the first section, followed by a method section describing the control strategies and experimental set-up. The results from the experiments are presented and discussed. Parts of the data in this study have previously been presented by Åmand *et al.* (2013a). This paper also includes more data, more statistics, a more comprehensive energy analysis and a cost-benefit analysis.

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THE PLANTS

The three plants in this study are situated in and around Stockholm (Sweden) and together they treat wastewater from around 1.5 million inhabitants. Data about the plants are presented in Table 1. Käppala and Henriksdal WWTPs have an annual average nitrogen limit of 10 mg/l and Himmerfjärden WWTP has since 2013 a limit of 8 mg/l. The compliance to the effluent permit is assessed based on weekly composite samples. The processes and instrumentation level in the experimental lines are depicted in Figure 1.

METHODS

Control strategies

In this project, ammonium cascade controllers have been used, see Figure 2. All controllers at the plants were discrete time implementations of proportional-integral (PI) controllers on the following form:

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau\right), \qquad u_{\min} < u(t) < u_{\max}$$

Table 1 | Basic data for the three treatment plants in the study. Data from 2012

	Henriksdal WWTP	Käppala WWTP	Himmerfjärden WWTP
Connected persons	782,600	454,409	294,419
Inflow (m^3/d)	284,000	160,000	114,800
Influent total nitrogen (mg/l)	41	41	33
Aerobic sludge age (d)	5	7	10–15
Total volume (m^3)	204,000	143,850	21,680
Aerobic volume (m^3)	94,500	80,296	21,680
Nitrogen removal process (DN = denitrification)	Pre-DN	Pre-DN	Nitrification with post-DN in fluidised bed
Reject water treatment			DeAmmon®

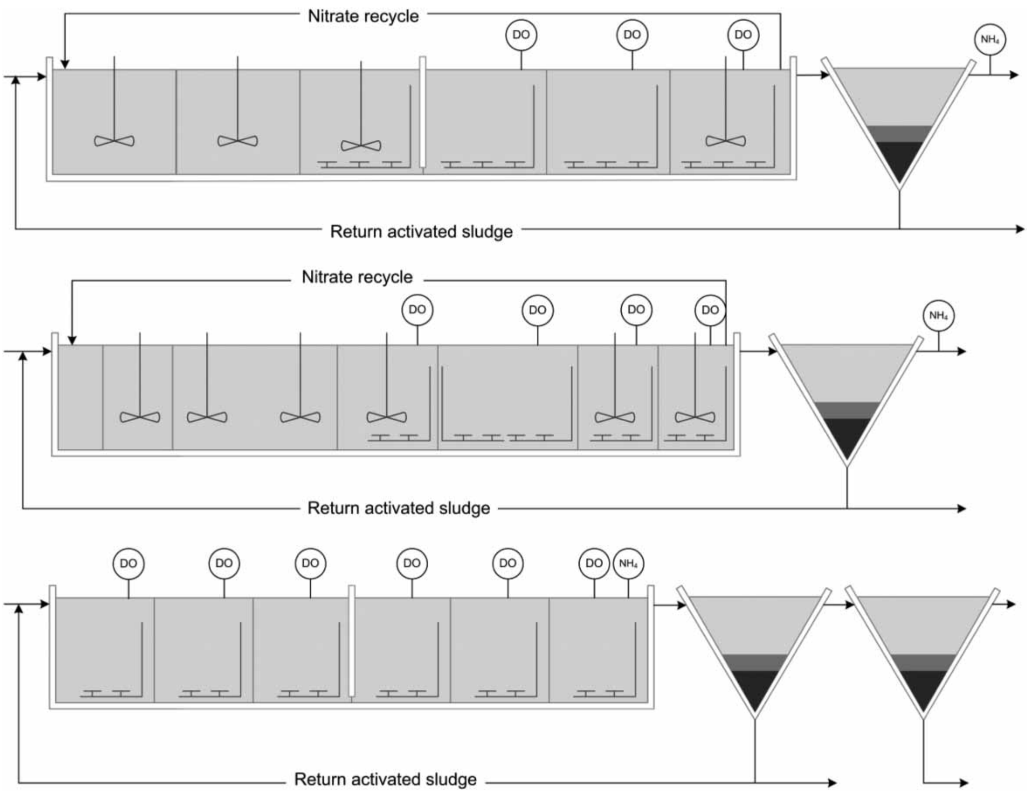

Figure 1 | The activated sludge processes and instrumentation in the experimental lines. Top: Henriksdal WWTP, middle: Käppala WWTP and bottom: Himmerfjärden WWTP.

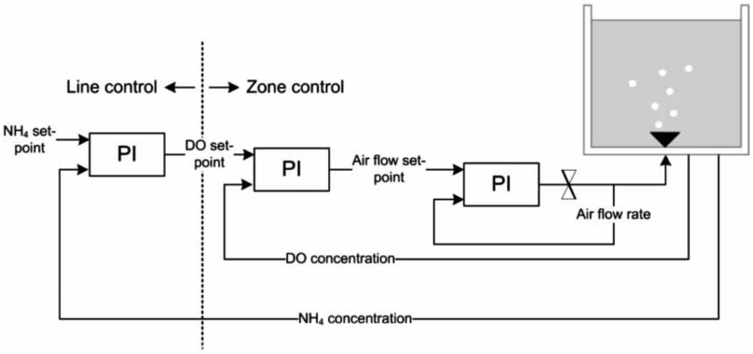

Figure 2 | Cascade control of ammonium. One ammonium controller determines the DO set-point of several aerated zones.

where $u(t)$ is the controller output, K is the controller gain, T_i is the integral time, $e(t)$ is the control error, and $u_{\min}$ and $u_{\max}$ are the minimum and maximum limitations of the controller output, respectively. All controllers have anti-windup, and the controllers at Henriksdal and Käppala WWTPs use tracking, making, for example, bumpless transfer available.

Ammonium feedback PI-control was chosen as the preferred control strategy in this study since it has been evaluated with success by others and was preferred over more advanced optimal and predictive controllers in order to try simple things first.

Henriksdal WWTP

Control structure

Six out of seven treatment lines at Henriksdal WWTP were used for controller evaluation. Ammonium feedback control was introduced in three lines, and the other three lines operated with constant DO control. The plant had ammonium sensors installed after the secondary settlers at the start of the project, and these were used for ammonium control. The DO set-point in the last aerobic zone was fixed (1–2 mg/l) to avoid the risk of elevated DO concentrations recirculating to the anoxic zones.

Controller tuning

No improvements of the air flow and DO controller tunings were needed. In particular during cold periods of the year the effluent ammonium concentration varies on a daily basis. If the ammonium concentration has daily variations and the ammonium sensor is placed after the settler the ammonium controller should not react too quickly on these variations. The delayed ammonium reading will make a fast ammonium controller control the DO concentration to low levels close to the daily load peak. The ammonium controller was manually tuned to be slow, following weekly and monthly variations rather than daily.

Käppala WWTP

Control structure

Käppala WWTP had the possibility to operate with DO control and ammonium feedback control in several lines at the start of the project as reported by Thunberg *et al.* (2009). Two treatment lines were used in the project, operated interchangeably with constant DO control and with ammonium feedback control. The ammonium sensor was positioned after the secondary settler, and the DO set-point was constant in the last aerobic zone.

Controller tuning

Small improvements of the air flow and DO controllers were made during the project. At Käppala WWTP, nitrification is complete most of the time apart from during rain events. Since the ammonium concentration rarely reaches the ammonium set-point, the ammonium controller was tuned to be fast despite the fact that the sensor was placed after the settler.

Himmerfjärden WWTP

Control structure

Himmerfjärden WWTP does not have individual control of DO in the six aerated zones, but controls the air flow rate based on the DO in the second aerated zone and there is only one air flow valve for each treatment line. This leads to a sharp increase in DO in the last zones of the basin. One treatment line at Himmerfjärden was reconstructed to include zone control of DO and ammonium feedback control. The ammonium sensor was placed *in situ* in the last aerobic zone.

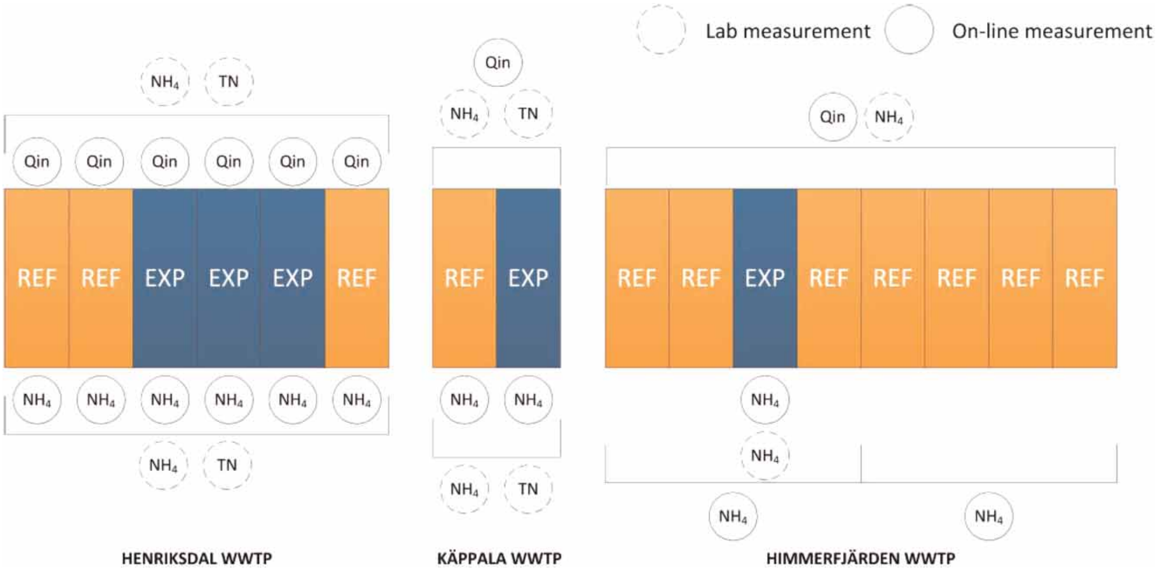

Figure 3 | Summary of experimental set-up and instrumentation for Henriksdal WWTP (left), Käppala WWTP (middle) and Himmerfjärden WWTP (right). REF = reference line, EXP = experimental line, Qin = inflow rate, TN = total nitrogen, NH_4 = ammonium.

Table 2 | Summary of ammonium controller settings (K, T_i) and evaluations performed at the three plants

	Period	NH_4 setpoint (mg/l)	K	T_i (s)	Reference controller	Temperature (°C)
Henriksdal	12 months	1.0	$K = 0.07$	$T_i = 10{,}000$	Constant DO all zones	16.7 (9.2–23.8)
Käppala	8 months	0.8	$K = 0.2$	$T_i = 1{,}000$	Constant DO all zones	11.5 (7.6–15.6)
Himmerfjärden	12 months	2.0	$K = 1.2$	$T_i = 1{,}200$	Constant DO zone 1	14.2 (9.4–18.2)

Controller tuning

The PI parameters in the air flow controllers and DO controllers were tuned with lambda tuning (Åström & Hägglund 2006). The ammonium controller was tuned manually, and the controller is relatively fast.

Summary of experiments

Outlet ammonium from the activated sludge process based on on-line measurements was used to estimate treatment performance at all plants, supplemented with composite weekly sampling at Himmerfjärden WWTP. Sensor maintenance was performed on a regular basis by the plant personnel. When calculations involved influent load, composite weekly samples taken from after primary sedimentation were used. The experimental set-up including instrumentation and sampling of nitrogen compounds is found in Figure 3. A summary of the evaluation and controller settings is found in Tables 2 and 3.

Evaluation methods

Energy estimation

An attempt was made to quantify the energy consumption from the measured air flow rates. More information is given in the 'Results' section.

Cost-benefit analysis

A cost-benefit analysis was carried out to look at the feasibility of using the ammonium controllers in full-scale.

Table 3 | DO limits in the ammonium controllers during the full-scale experiments

	Min. lower DO limit (mg/l)	Max. lower DO limit (mg/l)	Min. higher DO limit (mg/l)	Max. higher DO limit (mg/l)
Henriksdal	1.5	2	2.5	4
Käppala	1	1.3	2	2.2
Himmerfjärden	1	1.5	2.5	3

Reconstruction costs, installation of actuators and sensors, changes to control system and annual maintenance costs of sensors were included in the analysis. The depreciation of installations and sensors was 15 years on equipment and 30 years on constructions, with an interest rate of 4%.

Estimated energy savings (% of power consumption) was used to quantify the benefit of the ammonium feedback controllers. At Himmerfjärden WWTP part of the air to the aeration system is created from a gas motor run on biogas. A potentially higher sale of biogas was included in the benefit analysis. The benefit of improved process supervision has not been quantified. A cost-benefit ratio was calculated by dividing the annual costs with the annual benefits.

Statistical testing

Statistical testing was used to find out whether the difference between the experimental and reference line(s) was significant. The test was performed on daily averages of the DO concentration and daily (Henriksdal and Käppala WWTPs) and weekly (Himmerfjärden WWTP) averages of the effluent ammonium concentration. A two-sided paired Student *t*-test with significance level of 0.05 was used (Snedecor & Cochran 1989), with the following null hypotheses.

- H_0: The mean difference between the experimental line(s) and the reference line(s) is zero.
- H_1: The mean difference between the experimental line(s) and the reference line(s) is significantly different from zero.

RESULTS

Controller performance

Examples from ammonium controller operation at the three plants are found in Figure 4 and a summary of the results is presented in Table 4. There is a statistically significant reduction of DO concentration in the experimental lines of between 12 and 55%, since $p < 0.05$ for all experiments and the null hypothesis can be rejected. The *p*-value is the probability of achieving the observed results if the null hypothesis is true. The difference in ammonium concentration was not statistically significant ($p > 0.05$). At Henriksdal and Käppala WWTPs the ammonium peaks due to snow melting are removed from the effluent ammonium calculations, since this is not a representative period of operation and the ammonium sensors are not calibrated for the high concentration range (10–15 mg/l) obtained during these events. At all plants, periods of malfunctioning sensors or periods when the treatment lines had operational problems were not included in the summary in Table 4.

During the evaluation period, no negative effects have been seen on the sludge properties due to ammonium control,

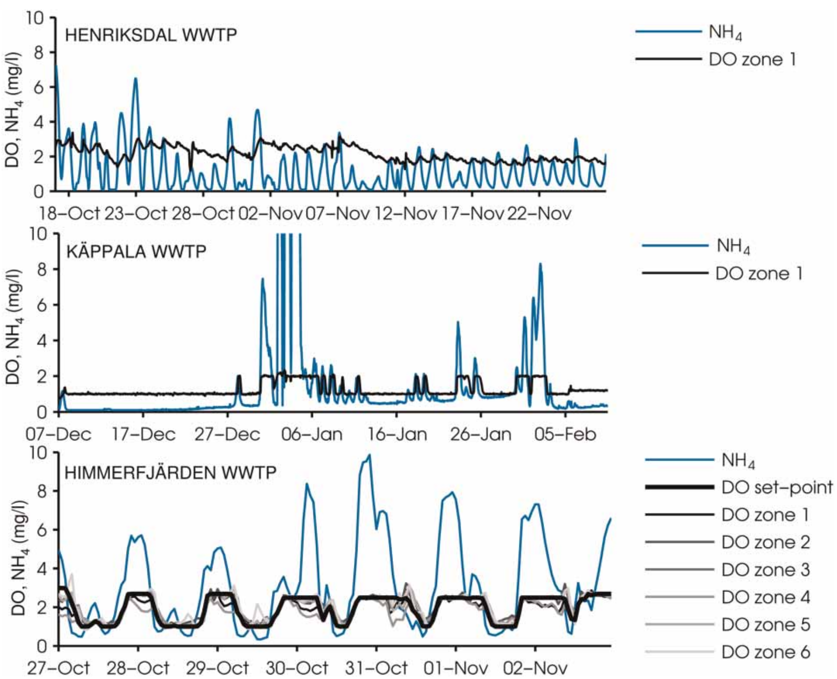

Figure 4 | Example of ammonium controller operation at Henriksdal, Käppala and Himmerfjärden WWTPs.

Table 4 | Process performance at Henriksdal, Käppala and Himmerfjärden WWTPs based on monthly averages and standard deviation. The result from the student *t*-test is based on daily mean values apart from at Himmerfjärden WWTP where the samples are weekly. Ammonium is measured at two points in the reference lines at Himmerfjärden WWTP: block A (^{A}) and block B (^{B}). ^{2}Second aerobic zone, ^{6}Sixth aerobic zone, ^{L}Lab sample

	DO (mg/l)				Outlet NH_4 (mg/l)		
	Reference (mg/l)	Experiment (mg/l)	Difference (%)	*p*-value *t*-test	Reference (mg/l)	Experiment (mg/l)	*p*-value *t*-test
Henriksdal	2.9 ± 0.7	2.5 ± 0.7	-12 ± 7.7	$p < 0.001$	1.4 ± 0.8	1.3 ± 0.7	$p = 0.51$
Käppala	2.0 ± 0.2	1.4 ± 0.3	-31 ± 9.5	$p < 0.001$	0.8 ± 0.3	0.7 ± 0.4	$p = 0.06$
Himmerfjärden	$2.2^{2} \pm 0.4$	$1.7^{2} \pm 0.2$	$-22^{2} \pm 10$	$p < 0.001^{2}$	2.0 ± 1.7^{A}	$2.2^{L} \pm 1.3$	$p = 0.39^{A}$
	$4.9^{6} \pm 0.5$	$2.2^{6} \pm 1.3$	$-55^{6} \pm 8.3$	$p < 0.001^{6}$	1.8 ± 1.9^{B}		$p = 0.73^{B}$

but it is still being investigated. No impact on denitrification has been observed at Henriksdal and Käppala WWTPs.

Estimation of energy consumption

At all plants there were systematic differences in air flow consumption in the treatment lines, making a direct comparison between experimental and reference lines difficult. The differences between the treatment lines were over 10% at all the plants, which is in the range of expected energy savings from ammonium control.

At Henriksdal WWTP a large decrease in DO of around 40% could result in a zero difference in air flow rate and vice versa. Since this is not reasonable, an analysis was made to compare each of the lines separately to each other. After normalising the air flow rate according to several periods when the DO concentration was the same in the lines, one experimental and one reference line was chosen for comparison. The air flow saving was 6.8% over 1 year, for an average difference in DO of −9.0%. A saving of 7% results in an annual cost-benefit ratio of 0.01 since the only cost is related to small changes in the control system.

At Käppala WWTP it became clear during the experiment that one of the two experimental lines had a non-functioning air flow meter. Therefore, a period of 4 weeks was chosen for evaluation in the other line. The weather, influent and temperature were stable since temperatures were below zero degrees and the ground was frozen. During this period the air flow reduction due to ammonium control was 13%, with a DO reduction of 40%. The DO reduction was larger than during most of the evaluation period, making the estimate optimistic. The cost-benefit ratio for Käppala WWTP is 0.32, assuming an energy saving of 10%. The energy reduction in terms of $Nm^3air/kgNH_4$ removed was 11% during the 4 week period.

At Himmerfjärden WWTP it is known that the flow distribution between the lines is not equalised and the variation between the eight lines is large. Therefore, all seven references lines were averaged before comparisons with the experimental lines. The air flow reduction in the experimental line during the evaluation period was 15%. The year before reconstruction the experimental line had a 4.7% higher air flow rate than the average of the other lines. If this is compensated for, the air flow reduction was 19%, resulting in an annual cost-benefit ratio of 0.31. A large part of the energy savings at Himmerfjärden WWTP is due to the implementation of DO zone control. The use of ammonium control has been estimated during a 2 week experiment to contribute a reduction in energy of up to 4% compared to constant DO control. Dynamic simulations suggest the energy saving is approximately 10%.

Henriksdal and Käppala WWTPs have decided to install ammonium control in all their treatment lines in the near future. Himmerfjärden WWTP will be reconstructed within the next few years and no changes to the aeration control will be made until then.

DISCUSSION

Lessons learnt from controller implementation

The three major causes of delays in the project were sludge issues, the control systems and sensor problems. With respect to sludge issues, delays were created when sludge scrapers broke down or during periods of poor sludge quality.

The project has been working with PI controllers, the most widely used controller for process control. Despite this, considerable time was spent to get the controller configuration correct. In the default controller implementation, all control signals did not have a maximum and minimum limitation. It is crucial for a good control performance to always be able to limit the control signal. At Henriksdal and Himmerfjärden WWTPs the integration time was initially not allowed to be large enough. Ammonium has a long response time to a DO change, which means integration times should be long.

Himmerfjärden WWTP does not have an industrial control system but uses stand-alone PID controllers connected to a SCADA (supervisory control and data acquisition) system. Therefore tracking of data between controllers was not available, resulting in cascade wind-up. If the air flow rate controller became saturated the DO controller experienced wind-up due to integration. This wind-up leads to unnecessary aeration since the DO concentration stays high for a period after the air flow controller stopped being saturated.

Despite weekly maintenance, the *in-situ* ammonium sensor at Himmerfjärden had the poorest performance of the ammonium sensors in the project. Most often the sensor showed too high values, which meant that nitrification was not at risk. When the ammonium sensors at Käppala WWTP were calibrated at very low ammonium concentrations (i.e. normal operation) the concentrations at the peaks were overestimated by the sensors. The ammonium sensors do experience drift and shift, especially after ammonium peaks. The sensors at Henriksdal WWTP were most often working satisfactorily. Other sources report that it is possible to make the sensors work satisfactory *in situ* at the plants (Rieger & Siegrist 2002; Kaelin *et al.* 2008).

Time aspects

For how long should a control experiment be carried out? Here it is useful to think about cycles. There are three main repetitive cycles at a treatment plant: daily, weekly and annual variations. Covering daily and weekly variations in a control experiment could be useful from a control engineering point of view – the experiment can give information about the dynamics of the controller and the response to short-time disturbances. But from an energy point of view the most important cycle to cover is the annual cycle.

Due to the effect of load, flow distribution, water temperature and the performance of equipment, the potential to save energy from ammonium feedback control varies over the year. Therefore the results from a control experiment are more vulnerable if short time periods are considered. One example is presented in Figure 5 showing DO concentrations at Henriksdal WWTP during the experiments. The main factor influencing the difference in DO concentration between experimental and reference lines is variations in the operation of the reference lines. In fact, during April and May 2013, there is no statistically significant difference between the two control strategies ($p = 0.61$). In around 75% of published full-scale or pilot-scale studies on ammonium-based control the time of experiment is 2 months or less (cf. Åmand *et al.* 2013b).

During the experiment at Käppala WWTP, ammonium control contributes a consistent reduction of DO concentration of between 0.7 and 0.8 mg/l during all months

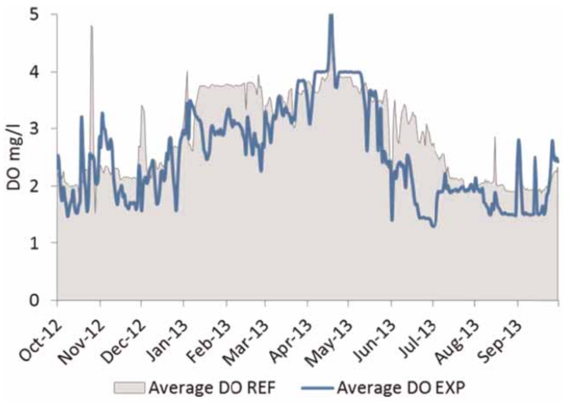

Figure 5 | Daily DO concentration in reference lines (REF, constant DO control) and experimental lines (EXP, ammonium feedback control) at Henriksdal WWTP during the 1 year experiment.

except during peak-flow periods such as snow melting. Under such circumstances a reasonable energy assessment can be made with a shorter evaluation period.

Energy estimation

How should the effect of a control strategy be quantified in terms of energy? The most straightforward way should be to look at the air flow rate or power consumption, but as this paper has shown this is often not simple in reality. Therefore, there is seldom a true number representing the energy saving from a full-scale control strategy comparison. If a precise estimate of the difference in energy demand between control strategies is needed, a well-calibrated dynamic model can be expected to give a better estimation.

If air flow rate measurements should be used as the main measure of energy cost, there should be a linear relationship between the power consumption and the air flow rate, and the energy tariff should be flat, i.e. no daily peak charge. These two criteria have been met at the plants in this study.

When looking at energy consumption during evaluation of control strategies, the core task is to capture only effects on energy consumption that could be related to changes caused by implementing a different control strategy. It is tempting to relate the air flow rate to variations in the process. Factors that could impact the energy consumption are removal rate of, for example, ammonium, inflow and suspended solid concentration in the aeration tank. By normalising with any of these factors, one could infer a correlation on the data not related to the control strategy itself. As an example, there is a correlation between the influent load and the removed amount of ammonium (Figure 6). It costs relatively more to treat less nitrogen. This type of normalisation should be used with care since, if two points in Figure 6 are compared, the

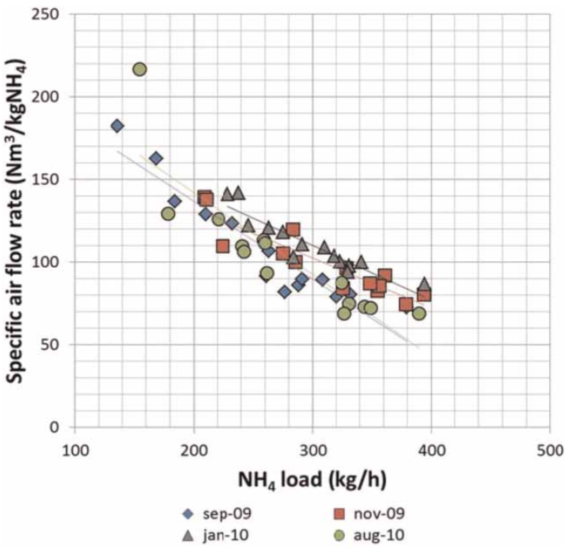

Figure 6 | Specific air flow rate as a function of ammonium load for 2 cold and 2 warm months. Data from Henriksdal WWTP.

comparison will include not only the effect of the choice of control strategy, but also the effect of the different load situations. Due to this reason, 1 week was removed from the estimation of energy consumption at Käppala WWTP since the influent ammonium concentration was around 10 mg/l lower than during the other 4 weeks. If this week was included the saving from using ammonium feedback control was only 1% based on specific air flow rate ($Nm^3/kgNH_4$ removed).

CONCLUSIONS

Ammonium feedback control has been operated for up to a year at three large wastewater treatment plants in Sweden. The estimated energy saving is in the range of 7 to 19% and the cost-benefit analyses suggest it is beneficial to implement ammonium feedback control at all plants. The evaluation process has revealed several lessons learnt from the project:

- Statistical hypothesis testing can be a tool to test if the difference between two control strategies is statistically significant, which has been the case in this study.
- Long-term experiments are needed to fully assess the impact of a control strategy in full-scale operation.
- It is important to always be attentive to circumstances that add systematic differences to the experimental treatment lines and that do not relate to the control strategies under study.
- Quantifying the energy savings potential from air flow measurements is challenging in full-scale plants.
- There are benefits from implementing cascade PID controllers in an industrial control system compared to working with stand-alone PID controllers in cascade.

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