

Fault signatures and bias progression in dissolved oxygen sensors

Oscar Samuelsson, Anders Björk, Jesús Zambrano and Bengt Carlsson

ABSTRACT

Biofilm fouling is known to impact the data quality of sensors, but little is known about the exact effects. We studied the effects of artificial and real biofilm fouling on dissolved oxygen (DO) sensors in full-scale water resource recovery facilities, and how this can automatically be detected. Biofilm fouling resulted in different drift direction and bias magnitudes for optical (OPT) and electrochemical (MEC) DO sensors. The OPT-sensor was more affected by biofilm fouling compared to the MEC-sensor, especially during summer conditions. A bias of 1 mg/L was detected by analysing the impulse response (IR) of the automatic air cleaning system in the DO sensor. The IR is an effect of a temporal increase in DO concentration during the automatic air cleaning. The IRs received distinct pattern changes that were matched with faults including: biofilm fouling, disturbances in the air supply to the cleaning system, and damaged sensor membrane, which can be used for fault diagnosis. The results highlight the importance of a condition-based sensor maintenance schedule in contrast to fixed cleaning intervals. Further, the results stress the importance of understanding and detecting bias due to biofilm fouling, in order to maintain a robust and resource-efficient process control.

Key words | biofilm fouling, condition-based maintenance, dissolved oxygen sensor, fault detection, wastewater

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INTRODUCTION

The dissolved oxygen (DO) concentration is a key measured variable in water resource recovery facilities (WRRFs). Two measurement technologies are common, membrane electrochemical (MEC) and optical fluorescent (OPT) measurement techniques. The MEC type was originally described in [Clark \(1959\)](#) and the OPT type was introduced by [Demas *et al.* \(1999\)](#).

On-line DO measurements have been commercially available since the 1970s and have enabled the development of automatic DO control ([Olsson *et al.* 2005](#)). Typically, the DO concentration is maintained at different DO set-points at different zones using multiple DO sensors to enhance biological nitrogen removal. Moreover, multiple parallel treatment lines result in a large total number of installed DO sensors. As an example, the two WRRFs in this study,

Bromma (Sweden) WRRF (about 300,000 p.e. (population equivalent)) and Henriksdal (Sweden) WRRF (about 750,000 p.e.), make use of 30 and 21 DO sensors, respectively.

Regardless of measurement technology, a sensor has to be clean to provide accurate measurements. Inaccurate measurements used in a feedback control loop may result in an undesired DO concentration and potentially reduced treatment efficiency or unnecessary aeration (with associated increasing costs). Therefore, visually inspecting the sensor, its manual cleaning, and readings verification are needed on a regular basis to guarantee accurate readings. Current sensor verification practice, as in [International Organization for Standardization \(2012\)](#), rely on assessing sensor readings under predefined conditions. For DO sensors, oxygen free water solutions and water saturated air are commonly used. Such actions are, however, time-consuming, especially for WRRFs with many and possibly remotely located DO sensors. In sewage measurements, specific systems have been developed to resist biofilm fouling and prolong maintenance intervals ([Li *et al.* 2017](#)). The

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need for prolonged sensor maintenance is also highlighted in (Thürlimann *et al.* 2018), where a qualitative soft-sensor approach was developed to replace an ammonium sensor with high maintenance requirements.

There are multiple sensor fouling sources in WRRFs that originate both from the influent wastewater stream and the treatment process itself. The fouling sources include: solids deposition (biofilm formation, chemical precipitation, sludge, and plastic products), hair and fibres, and grease (WEF 2013). In this study we consider DO sensors located in the activated sludge process (ASP) where the main fouling substance is from biofilm formation. In the following we use the term biofilm fouling to distinguish fouling from biofilm formation and other fouling sources.

In WRRFs, most sensor manufacturers provide optional automatic air cleaning that extends the required time interval for manual cleaning. The air cleaning results in a temporal increase in the DO concentration, which we further denote as an air cleaning impulse response (IR). Andersson & Hallgren (2015) showed that the IRs contain information about the degree of biofilm fouling. A similar approach was suggested by Spanjers & Olsson (1992), where a change in the time constant of the DO sensor was shown to be a good indication of an artificially fouled DO sensor.

Although there are reasons to believe that the IR of an automatic air cleaning system can be used to detect biofilm fouling, we lack knowledge about the robustness and sensitivity of using the IRs to detect different levels of biofilm thickness. Andersson & Hallgren (2015) detected a bias in an OPT-sensor of -0.6 and -0.8 mg/L due to biofilm fouling during two 1-month experiments. Additional experiments are required to study the IRs during clean and fouled conditions in order to extend the knowledge about IRs for biofilm fouling detection. In this study, we were therefore interested to investigate:

- the lowest detectable bias due to biofilm fouling using the response time method
- the variations in IR patterns of repeated biofilm fouling procedures and at different process conditions
- whether both MEC and OPT DO sensors are applicable to bias detection with IRs.

It is a common assumption that biofilm formation on a DO sensor affects its readings. As an example, Yoo *et al.* (2008) assumed that sludge clogging of the DO sensor can result in a complete sensor failure as a part of a simulation study. Hsu & Selvaganapathy (2013) used yeast and nutrient mixture in laboratory experiments to compare the effect of biofilm growth (in terms of protein absorption) on Teflon-

coated DO sensor membranes with silicone rubber alternative. Janzen *et al.* (2007) found indications of negative drift due to biofilm fouling in a redesigned MEC-sensor positioned in the ocean. Carlsson & Zambrano (2016) studied how bias in DO sensors could be detected by comparing the air-flow ratios. There are few studies, apart from Andersson & Hallgren (2015), that have investigated the effect of biofilm fouling on DO sensors under real conditions in WRRFs. Our general understanding about the effects of biofilm fouling is further complicated by WRRF-specific process conditions, seasonal variations, and differences between sensor types and brands. These aspects are fundamental to understand in order to design a cost-effective sensor maintenance schedule. Therefore, we were also interested to study the bias progression due to biofilm fouling under real conditions for MEC- and OPT-type DO sensors.

In this study, we conducted long-term experiments under full-scale conditions with artificial and real biofilm fouling with two sensor techniques: MEC and OPT DO sensors. Further, we studied the applicability of the response time method to detect biofilm fouling and worn-out sensor membranes.

MATERIALS AND METHODS

Two experiments were conducted, one with artificial biofilm fouling (grease) and one with real biofilm fouling. The purpose of evaluating both artificial and real biofilm fouling was to study two aspects: variation in IRs during different process conditions and long-term time effects on IRs and bias from biofilm fouling. The two aspects require different studies since long-term studies are difficult to repeat under different conditions. Both aspects need to be considered to evaluate the usefulness of IRs for fouling detection. The experimental set-ups differed between the two experiments and are detailed in the following two sections.

Experiment 1 – artificial biofilm fouling experiments in Henriksdal WRRF

The first experiment was conducted in Henriksdal WRRF with artificial biofilm fouling to investigate:

- the shape change of a fouled sensor's IR at a small bias (<0.2 mg/L), i.e. the detection sensitivity of using IR for biofilm fouling detection
- the effect of different process conditions on the IRs, including varying DO and suspended solids (SS) concentration

- variation in the response time during clean and fouled conditions during repeated experiments
- the difference between MEC- and OPT-sensors in terms of a response to artificial biofilm fouling.

The artificial biofilm fouling experiments were carried out in Henriksdal WRRF during summer conditions with a wastewater temperature about 19 °C. Four locations in the ASP, both in aerated and unaerated zones, were considered to study the impact of different DO concentrations. Parts of the measurements were conducted in the return sludge channel to study the impact of SS concentration on the IRs.

Artificial biofilm fouling

In the artificial biofilm fouling experiments, the goal was to decide and apply a fouling substance to the DO sensor that fulfilled the following three criteria:

- It should be simple to repeatedly apply and remove without damaging the sensor.
- It should be similar to organic biofilm, or at least result in a small negative bias.
- It should remain fixed to the sensor during repeated air cleaning impulses.

During one experiment, the fouling procedure consisted of the following three steps:

1. compare test sensor measurements with reference DO sensors
2. repeat IR measurements with clean test sensor
3. manually foul test sensor with an artificial biofilm fouling substance and repeat IR measurements during fouled conditions.

Sensor set-up and data collection

Five DO sensors (Cerlic O2X DUO) were connected to a data acquisition system with hardware and software from National Instruments, with the software LabVIEW. Data were stored in a PostgreSQL database in the same laptop computer. Each DO sensor could be switched between MEC and OPT measurement technology by simply changing the top part of the sensor. A photograph of the experimental equipment is given in the Supplementary materials (available with the online version of this paper).

Two of the DO sensors, one OPT- and one MEC-sensor, were used to study IRs (test sensors) and two were used as references (both MEC-sensors). The third reference sensor

was used as a back-up in case of a failing sensor. All sensors were mounted on rods according to the manufacturer's instruction at a slight angle (5–30°) and at 0.5 m depth. All membranes were replaced with new ones and calibrated in the beginning of the experiments. The length of an air cleaning impulse was set to 15 s at 2 bar for the two test sensors, which was expected to be sufficient to obtain a clear IR, even for high DO concentrations (4 mg/L).

Data pre-processing

Data were sampled with 8 Hz and later down-sampled to resemble full-scale conditions. First, the data were low-pass filtered (anti-alias filter) and afterwards down-sampled to 1 Hz. Details about the data pre-processing are given in the Supplementary materials.

A reference DO concentration was calculated from the two reference sensors by their weighted least squares (WLS) estimate, see for example [Kay \(1993\)](#). Then, the bias for a test sensor for a given IR was calculated as the difference between the test sensor and WLS estimate for the time interval between two IRs.

Measurements

The measurements were conducted at two positions in the aerated zone, in the anoxic zone, and in the return sludge channel. At each position, the three-step fouling procedure was repeated multiple times.

Experiment 2 – real biofilm fouling on a full scale in Bromma WRRF

In the second experiment conducted in Bromma WRRF, real biofilm growth was studied during 7 months to investigate:

- fault progression in terms of bias due to biofilm fouling
- difference in bias magnitude between MEC- and OPT-type sensors due to biofilm fouling
- sensitivity to detect bias using the response time of an IR
- variation in the response times for IRs, both for normal and fouled conditions
- impact of seasonal variations on biofilm growth and bias.

Bromma WRRF has a conventional ASP operated at six parallel lines with seven zones per line. The sensors in the ASP experience severe biofilm growth compared to other facilities in the city. Despite the automatic air cleaning system in the DO sensors, manual cleaning is required and

conducted between once a week and once a month, depending on the biofilm growth magnitude.

Sensor set-up and data collection

One MEC- and one OPT-sensor were used as test sensors. The sensors were positioned in the ASP in zone 5 (OPT-sensor) and zone 6 (MEC-sensor) about 1 m from the existing DO sensors that were used as references (MEC-sensors, Cerlic O2x DUO). Both zones were continuously aerated, but their DO set-points differed slightly (4.0 mg/L in zone 5 and 3.5 mg/L in zone 6).

Both test and reference sensors were equipped with an automatic air cleaning system, performing a cleaning cycle every second hour. The air pressure was set between 0.8 and 1.1 bar for each sensor. Both test and reference sensors in each zone were cleaned simultaneously so that their initial DO concentration would be equal.

Data from test and reference sensors were stored in the existing process database with 1 s sampling time.

Measurements

Each experimental period consisted of monitoring the biofilm growth on two test sensors until both received a bias larger than 0.3 mg/L. The bias was calculated as the mean difference in DO concentration between the reference and test sensor during the period bounded by two consecutive IRs, i.e. 2 hour mean values. The reference sensors were manually cleaned and inspected in addition to the automatic air cleaning, which was assumed to be sufficient to remove biofilm growth on the reference sensor. We expected a

time between 1 and 4 weeks to obtain a bias above 0.3 mg/L in the test sensor.

Software calculations and data availability

The response time of an IR was defined as the time to reach 63% of the peak amplitude, see Figure 1(a) for an illustration. The initial DO concentration was calculated as the average DO concentration 5 s before the IR. A short function computing the response time is provided in the Supplementary materials. All calculations and data pre-processing were performed off-line in MATLAB.

The pre-processed data from both artificial and real biofilm growth experiments are available at www.ivl.se/english/startpage/pages/publications (Report number: C343) under Creative Commons license CC BY 4.0.

RESULTS

The results from the experiments in Henriksdal and Bromma WRRFs are described in separate sections.

Experiment 1 – artificial biofilm fouling experiments in Henriksdal WRRF

The results include illustrations of the selected artificial biofilm fouling substance, motivation for discarding experimental data, and graphs showing variations in IRs during non-faulty and different faulty conditions.

A wide variety of fouling agents were evaluated. A mixture of ball-bearing grease and floating grease from the pre-precipitation fulfilled the three criteria for artificial biofilm

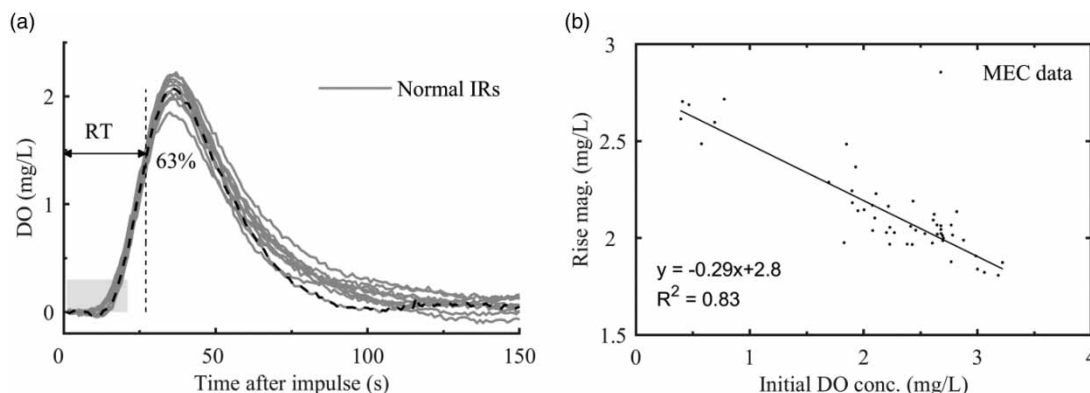


Figure 1 | (a) Ten IRs from a non-faulty MEC-sensor (solid grey lines) and the estimation of the response time for one of the curves (dashed black line). All IRs were normalised by subtracting the initial DO concentration of its IR for illustrative purposes. The response time (RT) is indicated as the time from the start of the cleaning procedure (time after impulse = 0) to reach 63% of the peak value. (b) Correlation between the initial DO concentration and the IR rise magnitude of clean MEC-sensors. The straight line, which is the least squares fit, indicates a small negative correlation (−0.29 mg/L per 1 mg/L).

fouling described in the ‘Materials and methods’ section. Both MEC- and OPT-sensors obtained a negative bias when fouled with the grease mixture. The same effect was seen for the OPT-sensor with organic biofilm fouling (Andersson & Hallgren 2015). Similarly, our own (unpublished) experience suggests that a completely fouled MEC-sensor displays 0 mg/L, thus a negative bias as well. Photos of artificially fouled sensors can be compared with real biofilm fouling in Figure 2.

During the experimental start, the OPT-sensor was damaged and data from the OPT-sensor were not further considered. Instead, both test sensors were of MEC type which allowed the simultaneous comparison of fouled and clean MEC-sensors.

A majority of the fouling procedures for the MEC test sensor resulted in the desired bias magnitude between 0 and 0.2 mg/L with clear IRs. However, for two of the initial fouling procedures, the average bias was larger (-1.7 and -0.35 mg/L). Similarly, a negative bias between -0.27 and -0.51 mg/L was also seen for the clean test sensor during the same time period. The data were studied in detail, which revealed that part of the bias was an effect of large

variations in the reference measurements (see the Supplementary materials, available with the online version of this paper). Since it was not possible to explain the reason for the variations, data with an absolute bias larger than 0.2 mg/L were not further evaluated. Also, seven IRs showed deviating shape with double peaks. Those IRs were discarded and removed from the normal dataset. The double peak behaviour was noticed after repeated manual fouling and subsequent cleaning, which could have affected the membrane. The potentially damaged membrane was replaced after noticing the double peak behaviour.

The remaining data were pre-processed and the IRs were extracted from the pre-processed data and grouped according to their status (normal or fouled). This resulted in 50 normal IRs and 2,628 IRs for fouled conditions.

Variations in IRs during normal conditions

Well-defined IRs were obtained for the MEC-sensor. A typical set of IRs at non-faulty conditions are shown in Figure 1. The rise magnitude variation (the difference between initial and maximum DO concentration during one IR) was about



Figure 2 | (a) Artificially fouled MEC-sensor with a mixture of ball-bearing grease and pre-sedimentation grease before an experimental procedure (24 July 2015). (b) MEC- and (c) OPT-sensor after repeated air cleaning impulses (4 August 2015). Note the effect of the three air cleaning nozzles that resulted in a partly cleaned MEC-sensor in (b). Different stages of biofilm fouling on MEC-sensor (d–f) and OPT-sensor (g). Fouling time: (d) 12 days (18 October), (e) 27 days (14 November), (f) 62 days (19 December), and (g) 62 days (19 December). Note that the biofilm starts to grow in the circular gap between the sensor and the sensor body (d), and further expands over the entire sensor and rod (e, f).

0.5 mg/L (Figure 1(a)). Part of this variation was a consequence of a changing initial DO concentration (Figure 1(b)).

Identification of common sensor faults

In addition to the artificial biofilm fouling, accidental faults occurred over the experimental period, common faults that could happen during everyday operations. The accidental faults resulted in distinct changes in the IRs, specific to the different accidental faults. The mean of the faulty IRs are visualised in Figure 3.

Fouling the MEC-sensor with grease mixture resulted in a dampened IR with an extended time to regain the original DO concentration (Figure 3(a), solid and dashed black lines). The small tweak during the impulse rise was not a typical pattern, but was merely an effect of combining IRs with two different shapes: one part of the dataset of the fouled IRs displayed a ‘double peak behaviour’ similar to Figure 3(d), whereas one set had a straight increase with dampened IRs similar to Figure 3(b).

In the end of the experimental period, a long-term test for 11 days was conducted, where the MEC-sensor was

fouled and subject to repeated cleaning events about 200 times per day. This was far more than the recommended amount of cleaning procedures, which resulted in a gradual change of the IR, potentially due to wearing out the membrane (Figure 3(d)). It is interesting that the shape of the IR changed from a dampened IR to exhibit an increasingly pronounced double peak behaviour. A double peak was also seen for the damaged membrane (perforated during manual cleaning) (Figure 3(e)). We have no clear explanation for the double peaks although they were present more frequently in faulty data, especially where the membrane was mechanically damaged. The first peak coincided with the duration of the air cleaning impulse whereas the second peak was delayed compared to a normal IR.

A decreased air pressure for the automatic air cleaning system resulted in a dampened peak (Figure 3(b)). Measurements in the return sludge channel with high SS only indicated a slight increase in the peak height of the same order of magnitude as the normal variation (compare Figures 1 and 3(c)). This indicates that the SS-level had none or minor impact on the IR. A large increase of the IR’s peak value after cleaning the MEC-sensor with harsh

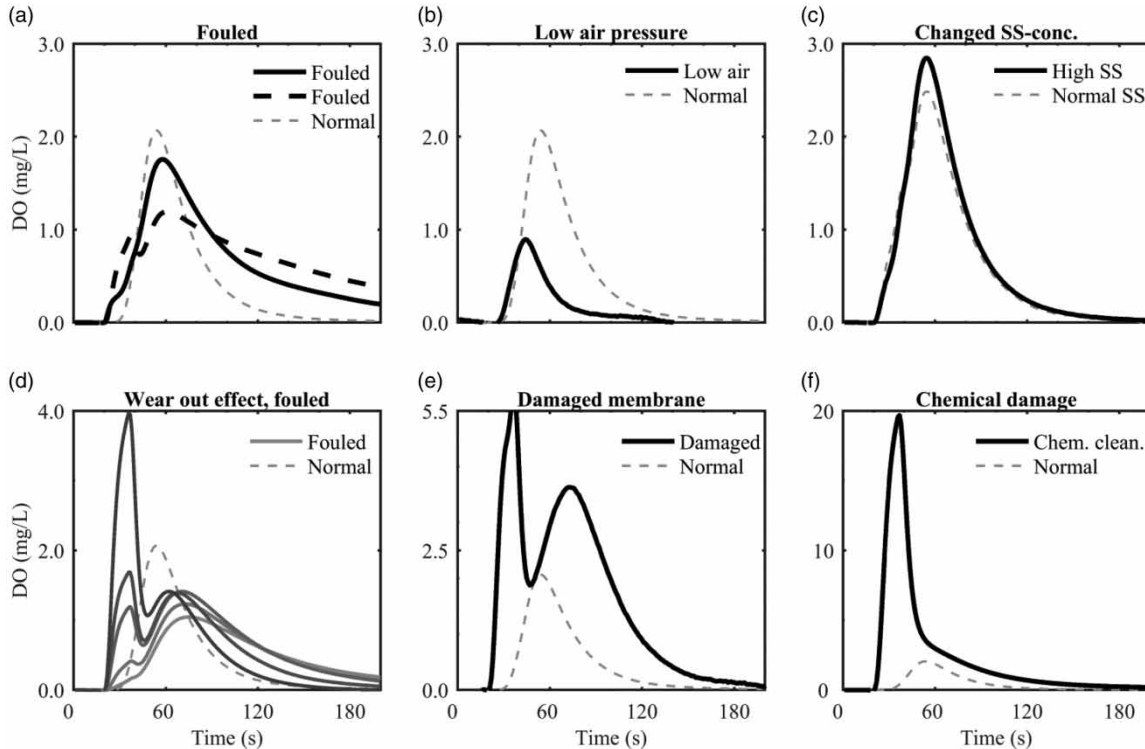


Figure 3 | Mean MEC-sensor IRs for: (a) fouled membrane (grease mixture); mean IR of fouled test data (black solid and dashed lines, $n = 2,628$), (b) low air pressure during the automatic air cleaning procedure ($n = 9$), (c) the effect of increasing the SS from 2,500 mg/L (normal SS, $n = 9$) to 8,500 mg/L (high SS, $n = 10$), (d) a potential gradual wear-out effect by repeated IRs on a fouled MEC-sensor; an increased wear-out of the membrane is indicated by darker grey ($n = 2,180$), (e) a mechanically perforated membrane during manual cleaning ($n = 2$), (f) the effect of using harsh cleaning liquid to remove excess grease ($n = 98$); the air cleaning impulse was between time 20 and 35 s.

cleaning liquid (Figure 3(f)) indicates that the membrane became more sensitive.

Experiment 2 – real biofilm fouling experiments in Bromma WRRF

The results show the impact of biofilm fouling on bias progression and the correlation with IR response time values. Further, variations in the response time values for clean sensors are shown together with the impact on the IRs of damaged sensors. Finally, uncertainties in the results due to sensor maintenance during the experiments are detailed.

Bias progression due to biofilm fouling

Different stages of biofilm-growth fouled sensors can be seen in Figure 2 with resulting bias progression in Figure 4.

The bias progression differed between the MEC- and OPT-sensors in several aspects (top graphs in Figure 4(a) and 4(b)). Firstly, the OPT-sensor had an increasing bias in all six periods in contrast to the MEC-sensor, which

mainly had a decreasing bias (period 1, 2, and 5). Secondly, the bias magnitude was larger for the OPT-sensor compared to the MEC-sensor. Lastly, the OPT-sensor showed a transition in bias progression from linear to exponential increasing after 10–14 days during period 1–3 and after 28 days during period 4–5. The MEC-sensor showed a linear bias trend throughout all periods. Note also that the bias in the OPT-sensor temporarily decreased after reaching a large value (above 2–3 mg/L) in period 2–5.

Bias detection with the response time estimation method

The changes in response times due to bias (bottom graphs in Figure 4(a) and 4(b)) were not as evident as expected. For the OPT-sensor, there was a clear change in period 2–5 for bias larger than 1 mg/L and a correlation between bias and the response time values was identified (see details in the Supplementary materials). For the MEC-sensor, there was no obvious change in response time that correlated to the bias magnitude in any of the periods (Figure 4(b)). Only a slight increase in the variance for the response

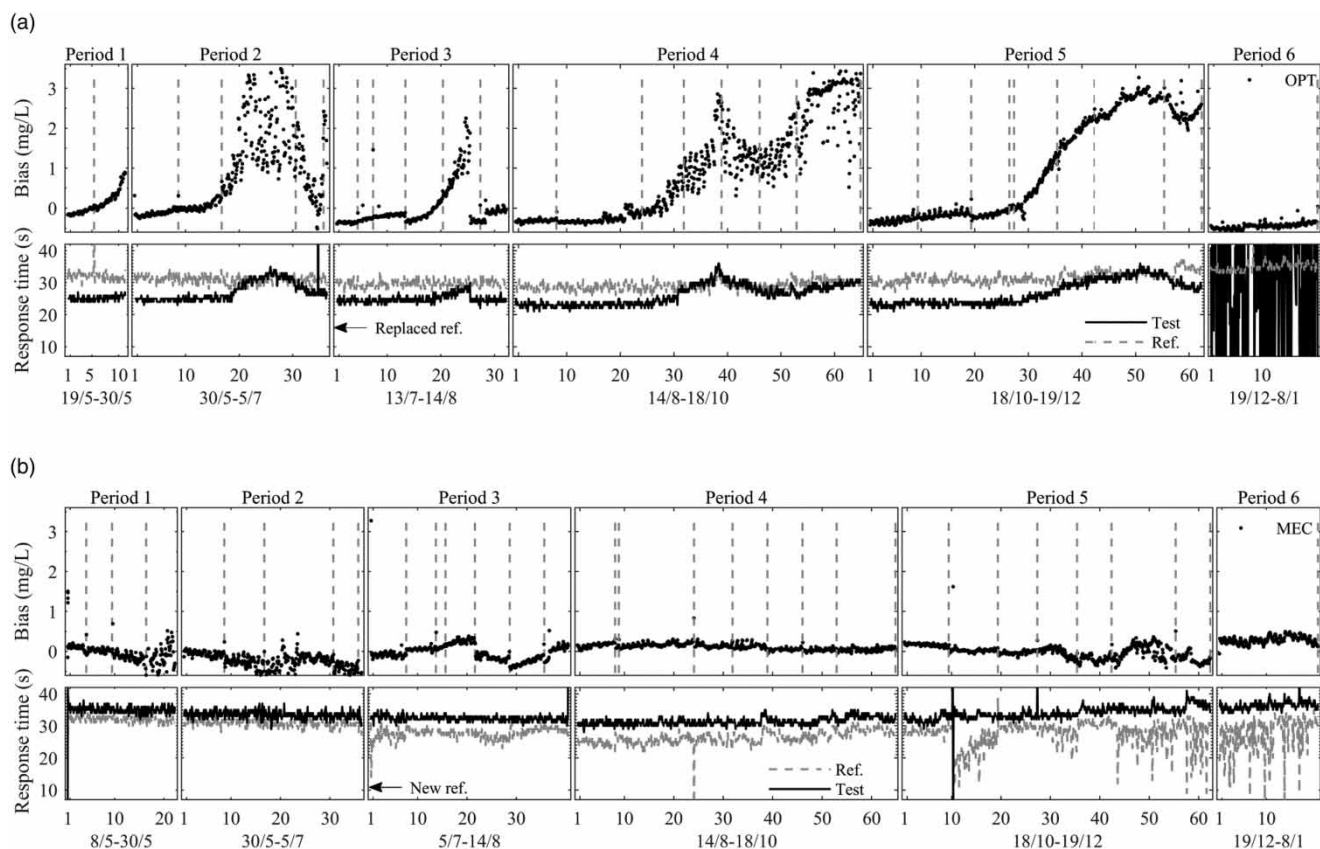


Figure 4 | Bias and response time values during experimental periods 1–6 in Bromma WRRF for (a) optical sensor (OPT) and (b) membrane sensor (MEC). Manual cleaning of reference sensor is indicated with dashed vertical lines.

time values in period 2 (days 15–20) and period 5 (days 35–60) was indicated.

Variations in response time values

Surprisingly, the response times also changed for the reference sensors during the experiments. Firstly, a small trend of decreasing response times with about 1 s per 30 days can be seen for the OPT-sensor's reference (period 1–3) and for the MEC-sensor's reference (period 1–2). This is similar to the artificial biofilm fouling experiments where the MEC-sensor had a decreasing response time during the wearing-out experiment (Figure 3(d)). A similar decrease can also be noted for the OPT test sensor by comparing the response times during the first days in each test period (period 1–5). Note that there is an opposite trend with increasing response time values for the OPT-sensor's reference and for the MEC test sensor (period 4–6). Secondly, the new MEC-sensor's reference had larger variations in its response time values, with a large increase in variation during period 5–6.

The OPT-sensor had in general a smaller response time than the MEC-sensors (recall that all reference sensors were MEC-sensors). Note also that the MEC sensors had different response times at clean conditions with new membranes.

The response time values for the OPT test sensor in period 6 deviated considerably from previous periods. The reason was an accidental kink in the air supply hose that blocked the air supply to the sensor's air cleaning system, disabling all IRs after period 5. The estimated response time values were therefore randomly obtained. At the same time, its reference sensor was instead given a surplus of air resulting in an increase in IR peak value (see the Supplementary materials). Surprisingly, there was no large change in the response time for the reference sensor (Figure 4(a), period 6) despite the increased air flow and pressure.

Damaged sensors

After the final experimental period, both test sensors were deliberately damaged to study mechanically worn-out sensors. The MEC-sensor's membrane was perforated with a needle and later with a screw driver and the OPT-sensor's fluorophore coating was scratched with an iron brush. Photos of the damaged sensors together with corresponding IRs are provided in the Supplementary materials.

For the MEC-sensor, both the needle and screwdriver perforation resulted in a double peak behavior as was seen

in Figure 3(d), although with a smaller initial peak than previously observed. About half of the IRs with needle perforation showed a dip instead of a double peak. There was only a minor change in bias due to the perforation events (before perforation 0.37 mg/L, after needle perforation 0.49 mg/L, and after screwdriver perforation 0.42 mg/L).

For the OPT-sensor, the IRs maintained a one-peak shape characterised by decreasing response time values with increasing amount of scratches. The first scratches did not result in any bias change although the following scratches, which removed >50% of the fluorophore coating, resulted in a large negative bias (before scratching –0.54 mg/L, after first scratching –0.51 mg/L, and after second scratching –1.54 mg/L).

Sensor maintenance

After period 2, a new membrane was installed in the MEC reference sensor. The existing membrane was moved to the OPT-sensor reference sensor. The reason for replacing the membrane already after 2 months was to assure that the observed small bias was an effect of biofilm fouling and drift in the test sensor, and not of a drift in the reference sensor.

In period 3, the MEC test sensor showed a segmented line with both increasing and decreasing bias trends within the segments. The cause of the segmentation was the manual cleaning of the reference sensor (vertical dashed lines), which coincides with the line segments (Figure 4(b), period 3). Since the bias changed when the reference sensor was cleaned, this indicates that the reference was also affected by biofilm fouling. This was not seen in the remaining periods where a weekly cleaning interval seemed to be sufficient.

For period 3, it is therefore hard to draw conclusions about the bias direction since we are not certain whether it was the reference or test sensor (both of MEC type) that was actually drifting. In addition, the last three manual cleanings were conducted during the vacation period by personnel unfamiliar with the experiments. This resulted in an uncertainty as to whether only the reference sensor or both the test and reference sensors were manually cleaned. The third last cleaning (day 21 for MEC-sensor and day 12 for OPT-sensor) introduced a change in bias, similar to what would be expected after cleaning the test sensor. In addition, the exact time locations for the last three manual cleaning events were not obtained, but only the actual date. Therefore, these cleanings were marked at 12:00 and should be interpreted with a \pm 4 hours' uncertainty.

DISCUSSION

The outcomes of Experiment 1 (artificial biofilm fouling) and Experiment 2 (biofilm fouling) are discussed and compared with existing results. Further, implications of the findings are discussed with the perspective of using IRs for fault detection on a full-scale application. This includes the aspects of bias progression linked to sensor maintenance, DO process control, and factors with an impact on the IRs and their potential limitations on a full-scale fault detection and diagnosis application.

Bias progression in oxygen sensors due to biofilm fouling

The purpose of using grease in the artificial biofilm fouling experiments was to resemble organic biofilm growth. The results showed that the MEC-sensor received a negative bias for both artificial and real biofilm foulings. However, the effect on the IRs was larger for small bias with grease compared to the real biofilm. It is hard to find a good explanation for the difference. Although we can intuitively expect that grease resulted in a denser film compared to a water-permeable biofilm, which may have contributed to the difference.

For the OPT-sensor, all real experiments resulted in a positive bias, which is in contrast to the results by [Andersson & Hallgren \(2015\)](#). Despite the difference in bias direction, the detection sensitivities were in the same range (1.0 mg/L compared to 0.6–0.8 mg/L in the previous study). The OPT-sensor had in addition a faster increase in bias than the MEC-sensor. No results for the MEC-sensor were reported by [Andersson & Hallgren \(2015\)](#), but their unpublished data suggest that the bias was small for the MEC, in contrast to the OPT-sensor, which is in agreement with this study. A potential explanation for the large impact on OPT-sensor is that the small fluorophore area was more easily covered by biofilm, compared to the larger membrane area in the MEC sensor (compare [Figure 2\(g\)](#) with [Figure 2\(f\)](#)). Additional studies are needed to verify whether this is valid in general or only for the specific sensor brand in this study. Future studies should compare parallel treatment lines and different WRRFs as this may contribute to variations in a biofilm growth.

As expected, both sensor types had a faster bias increase during summer conditions compared to winter conditions. However the magnitude of this seasonal effect was larger than expected. The time to reach a bias of 0.3 mg/L was

less than 1 week for the OPT-sensor during summer conditions, and beyond 60 days for the MEC-sensor during winter time. The large span shows the importance of designing an adaptive sensor cleaning schedule when compared to a fixed interval of 1 or 2 weeks, which is common practice today.

Oxygen sensor bias implications for process control

As seen from a process control perspective, knowledge about the bias progression is important. That is, does a fouled sensor result in a positive or negative bias, or even alternate between the two? When a DO sensor is used in a feedback control loop (which is de facto standard), a bias in the sensor will lead to different consequences depending on the bias direction, the controller structure, and the controlled process.

Consider a MEC sensor with a strictly negative bias that is operating in a feedback loop with a fixed DO set-point. The true DO concentration will be underestimated resulting in excess air supply with a higher DO concentration than desired. Consider instead the same MEC-sensor but in an ammonium cascade controller where the effluent ammonium adjusts the DO set-point. In such a situation, the exact DO concentration will be less important since the bias will be partly compensated for by the DO set-point given by the ammonium master controller. The opposite argumentation applies for a strictly positive bias as was indicated for the OPT-sensor. Whether a positive or negative drift direction is bad or worse depend on the process configuration. This raises the question whether the most likely bias direction for a specific sensor should be included in the early process design.

Factors affecting the impulse responses and response time values

One of the questions in this study was to investigate the impact of changed process conditions on the IRs and the corresponding response time values. This was mainly conducted for the MEC-sensor due to the damaged OPT-sensor in Experiment 1. Some of the factors, such as varied SS or initial DO concentration, were well studied during the artificial biofilm fouling experiments, but the interpretation of normal variations in response time values remains uncertain. The main problem was that the response time values differed between the clean MEC-sensors. The variation in response time values for the new membrane in the MEC-sensor's reference sensor in period 3 was larger than for the other

MEC-sensors. In addition, it was not possible to define the cause of the long-term small change in response time values with both decreasing and increasing values. As seen in the artificial experiments, decreasing response time values could be a consequence of wearing out the membrane, but the results in Experiment 2 indicate that the decrease could equally well be related to a temperature, seasonal, or unknown effects. Only a few sensor individuals were used in the study, which raises the question whether some of the noted changes are effects of variation among sensor individuals. Note that it is not clear from the results whether variations in the IR and its related response time are due to factors that are independent of sensor bias or, for example, seasonal effects that only affect the dynamics of the IR.

Future studies should therefore study potential seasonal effects in the response time as well as multiple parallel sensors to distinguish variations in sensor individuals from general effects. In future studies it is also important to avoid ambiguities in bias estimation about whether it is the reference sensor, test sensor or both that are affected by biofilm fouling. Regular checks of the sensor reading in known zero-valued and saturated oxygen conditions should be used as supplement to the reference measurements.

Fault detection and diagnosis based on impulse responses

The lowest detectable bias with the response time method was larger than the desired 0.3 mg/L. It is therefore interesting to further study if other fault detection algorithms can improve the detection sensitivity. Based on the bias progression, biofilm fouling detection would be most valuable during summer condition when the biofilm growth is fast with a high likelihood of obtaining a bias. Summer is also the time of year when personal resources may be restricted due to vacations; furthermore, ammonium effluent permits can be stricter in summer than during winter time (in Sweden). Therefore, automatic biofilm fouling detection in DO sensors has the largest potential to improve process treatment during summer time.

The results also showed that the IRs contained information about different faults including: reduced air supply in the air cleaning system of the sensors and damaged sensor membrane. These faults gave rise to distinct pattern changes in the IRs, fault signatures, extending the possibility of fault detection to diagnosis. Most importantly, double peaks were evident in both Experiment 1 and 2. By studying unpublished data in the study by [Andersson & Hallgren \(2015\)](#), we noted that both the double peak behaviour

([Figure 3\(d\)](#)) and the extreme peaks ([Figure 3\(f\)](#)) were present in that dataset. The results suggest that a double peak indicates a damaged membrane, although the size of the first peak differed for different wearing or perforation causes. We have no physical explanation for the double peaks, although it seems like the first peak is aligned with the 20 s long air cleaning phase. As repeated perforation experiments are costly, the existence and occurrence of double peaks should be evaluated on a full scale, studying a more natural occurrence of double peaks. An important question to answer is how early before complete sensor failure a double peak arises.

CONCLUSIONS

The results have improved our knowledge of how biofilm fouling impacts the data quality of DO sensors. The bias progression speed due to biofilm fouling differed between sensor types, which needs to be considered in fall-back strategies for process control. In addition, the bias progression was faster during summer conditions compared to winter conditions. The results could be used to design effective sensor maintenance routines and to detect and diagnose sensor faults. This is a step towards an increased robust wastewater treatment with decreased environmental impact.

The results showed that IRs and related response time values contained information about the status of both MEC- and OPT-sensors. Bias due to biofilm fouling was detected for bias above 1 mg/L in OPT-sensor but not for values up to 0.8 mg/L in the MEC-sensor. Surprisingly, changes in the pattern of IRs were matched to common sensor faults in the MEC-sensor, suggesting that such fault signatures can be used for fault diagnosis.

The OPT-sensor was affected by biofilm growth to a greater extent than the MEC-sensor, with a positive bias compared to the MEC-sensor with mainly a negative bias. Without manual cleaning or fault detection, it is likely that a DO-controlled process will be operated at a different (unknown) DO concentration than desired, especially when an OPT-sensor is used. Whether this is a general draw-back for the OPT-sensor compared to the MEC-sensor or not should be studied in future studies. Future studies should also consider the following questions.

- Can other fault detection methods be applied to the IRs and improve the bias detection sensitivity?
- Which type of faults can be diagnosed based on IR data, and which fault diagnosis methods are suitable for this task?

- What is the normal variation in response time values and shapes of IRs with respect to seasonal variations, among multiple sensor individuals of the same brand, and in relation to sensor bias?

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REFERENCES

- Andersson, S. & Hallgren, F. 2015 Sensor fault detection methods applied on dissolved oxygen sensors at a full scale WWTP. In: *9th Watermatex Congress, Gold Coast, Australia*.
- Carlsson, B. & Zambrano, J. 2016 [Fault detection and isolation of sensors in aeration control systems](#). *Water Science and Technology* **73** (3), 648–653.
- Clark, L. C. 1959 Electrochemical device for chemical analysis. US patent No. 2,913,386A.
- Demas, J. N., DeGraff, B. A. & Coleman, P. B. 1999 [Oxygen sensors based on luminescence quenching](#). *Analytical Chemistry* **71** (23), 793A–800A.
- Hsu, L. H. H. & Selvaganapathy, P. R. 2013 Development of a low cost Hemin based dissolved oxygen sensor with anti-biofouling coating for water monitoring. In: *Proceedings of IEEE Sensors*.
- International Organization for Standardization. 2012 *Water Quality – Determination of Dissolved Oxygen – Electrochemical Probe Method (ISO 5814:2012)*. International Organization for Standardization, Geneva, Switzerland.
- Janzen, C., Murphy, D. & Larson, N. 2007 Getting more mileage out of dissolved oxygen sensors in long-term moored applications. In: *Oceans Conference Record (IEEE)*.
- Kay, S. M. 1993 *Fundamentals of Statistical Signal Processing: Estimation Theory*. Prentice-Hall, Upper Saddle River, NJ, USA.
- Li, T., Winnel, M., Lin, H., Panther, J., Liu, C., O'Halloran, R., Wang, K., An, T., Wong, P. K., Zhang, S. & Zhao, H. 2017 [A reliable sewage quality abnormal event monitoring system](#). *Water Research* **121**, 248–257.
- Olsson, G., Nielsen, M., Yuan, Z., Lynggaard-Jensen, A. & Steyer, J. P. 2005 *Instrumentation, Control and Automation in Wastewater Systems*. IWA Publishing, London.
- Spanjers, H. & Olsson, G. 1992 [Modelling of the dissolved oxygen probe response in the improvement of the performance of a continuous respiration meter](#). *Water Research* **26** (7), 945–954.
- Thürlimann, C. M., Dürrenmatt, D. J. & Villez, K. 2018 [Soft-sensing with qualitative trend analysis for wastewater treatment plant control](#). *Control Engineering Practice* **70**, 121–133.
- WEF 2013 *Automation of Water Resource Recovery Facilities: WEF Manual of Practice No. 21*, 4th edn. Water Environment Federation, Alexandria, VA, USA.
- Yoo, C. K., Villez, K., Van Hulle, S. W. H. & Vanrolleghem, P. A. 2008 [Enhanced process monitoring for wastewater treatment systems](#). *Environmetrics* **19** (6), 602–617.

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