

# Variation in dissolved oxygen concentration and its effect on the activated sludge properties studied at a full scale wastewater treatment plant

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## Abstract

Aeration of activated sludge is very costly and therefore it is desirable to operate the treatment plant at as low DO concentration as possible without risking poor effluent quality. This paper presents a study of the impact of DO concentration on sludge properties at a full scale wastewater treatment plant which utilizes pre-denitrification followed by aeration in activated sludge and with post-nitrification in nitrifying trickling filters. The DO concentration has in the past generally been kept high at the plant (> 5 mg/l) as it has been believed to give better effluent quality. During later years attempts have been made to reduce the DO concentration to 2-3 mg/l. In this study the DO set-point was changed every 3 weeks between 2 and 4 mg/l for a few months. Also short term effects of change in DO concentration was assessed by changing the DO concentration in the three parallel activated sludge tanks to 1, 3 and 5 mg/l for a few hours. The results show that the impact of DO concentration is hard to assess as the process is subjected to constant changes in the environmental conditions. The settling properties were not influenced significantly whereas slight negative effects of reduced DO concentration on effluent quality could be seen. The microscopic investigation showed a tendency towards poorer sludge properties at a DO concentration of 2 mg/l compared to at 4 mg/l.

**Keywords** – dissolved oxygen (DO) concentration, activated sludge, settling properties, flocculation properties, effluent quality

## INTRODUCTION

The activated sludge process is aerated to degrade organic material and to achieve nitrification. Most modern wastewater treatment plants are subject to increasingly strict effluent discharge limits and must continuously be updated and optimized to meet the new requirements. Often, the amount of effluent suspended solids concentration is a critical parameter when low total phosphorus concentrations are required. Conventionally the dissolved oxygen (DO) concentration is kept higher than 2 mg/l to avoid depletion of oxygen. In many plants DO concentration is kept even higher to ensure good effluent quality since it has previously been shown that this has positive influence on the floc formation (Wilén and Balmér, 1999). However, this is very expensive and it is therefore often desired to operate the aeration tank at lower DO concentrations to reduce energy consumption. To exactly determine the optimum DO concentration is difficult since activated sludge systems are subject to constant changes in inflow and wastewater composition as well as in other operational parameters such as dosing of precipitation chemicals and recirculation flows. Most control strategies for DO found in literature focus mainly on the kinetics of the heterotrophic and autotrophic microbial community (Holenda et al. 2008) but less is known about the impact on sludge properties. In the literature contradictory data can be found regarding the influence of DO concentration on sludge solids-liquid separation properties. The occurrence of filaments is connected to low but also to high DO concentrations (e.g. Martins et al. 2003). Repeated oxygen deficiency has been found to enhance the growth of filamentous bacteria (Gaval and Pernelle, 2002). Parameters such as organic loading rate as well as activated sludge floc structure and size are important parameters determining the sensitivity to low DO concentrations; at high organic loading rate the oxygen concentration needs to be sufficient to allow diffusion through the microbial aggregate (Li and Ganczarczyk, 1993). Surprisingly few studies can be found in the literature

concerning the effect of DO concentration on sludge properties. Low DO concentration has in several previous studies been found to lead to poorer flocculated sludge and more turbid effluents (Starkey and Karr, 1984; Wilén and Balmér, 1999). Lower sludge production has been observed at higher DO concentrations (Abassi et al. 1999). Aeration also gives rise to different turbulence conditions in the aeration tank and this might influence the activated sludge flocs; some literature report on floc break-up (Das et al. 1993) whereas others report of the formation of smaller but denser flocs at high homogenous turbulence flow regimes such as in air-lift reactors whereas larger and looser flocs are formed at less homogenous flow regimes such as in stirred tanks (Jin and Lant, 2004).

The aim of this study was to investigate if it is possible to decrease the DO concentration without lowering treatment efficiency at a full scale activated sludge treatment plant which has a history of frequent occurrence of poor flocculation properties leading to high effluent suspended solids concentrations. Historic data were analysed as well as data from a period of 9 months when DO concentration was changed between 2 and 4 mg/l every 3-4 weeks. A short term effects were also assessed by changing the DO concentration in the aeration tanks for a few hours.

## **METHODS**

### *WWTP*

The Rya WWTP, serving about 825 000 pe, is designed for biological nitrogen removal utilizing pre-denitrification and post-nitrification in a trickling filter (Figure 1). Phosphorus is removed by chemical precipitation using ferrous sulphate. The flow varies between 2 and 16.5 m<sup>3</sup>/s with an average daily flow of 4 m<sup>3</sup>/s. Up to 6 m<sup>3</sup>/s of the secondary settler effluent can be recirculated to nitrifying trickling filters. This nitrified stream is then mixed with the recycled activated sludge stream ( $Q_{rs}$ ) for deoxygenation after which it is mixed with the primary settled wastewater and led into the anoxic part of the activated sludge reactors for denitrification, thus utilizing the carbon available in the influent. Approximately 40-60% of the activated sludge tank volume is kept anoxic and the rest oxic to ensure degradation of excess carbon source and to improve effluent quality. Due to fluctuations in the wastewater composition, carbon source (ethanol) is added to reach full denitrification. The dose is adjusted according to the nitrate concentration in a feed-back mode plus feed-forward of nitrate production. When the flow of primary settled water changes ( $Q_{ps}$ ), the recycling over the trickling filter ( $Q_{tf}$ ) is adjusted so that the flow to the secondary settler ( $Q_{sed}=Q_{ps} + Q_{tf}$ ) is kept as close as possible to their maximum capacity. The recycle activated sludge flow ( $Q_{rs}$ ) is quite constant due to pumping capacity limitations. The estimated maximum settling capacity is set manually by the operators by stressing the settlers until a minor overload is reached and then a minor flow reduction is made. Unlike most WWTPs where the hydraulic loading rate of the secondary settlers varies significantly due to variations in water flow, the variation at the Rya WWTP is small due to the recycling stream. Since the plant is operated at a short solids retention time (SRT), 2-4 days, the floc characteristics change quickly resulting in a direct response in maximal settling capacity. The plant experiences periods with poor clarification and/or poor settling properties.

### *Acquisition of process data*

On-line historical process data (hourly averages) were processed for the period 2005-2009. Daily analyses of effluent suspended solids (SS) concentration, non-settleable solids (NSS) concentration (after 1 h settling), stirred sludge volume index (SSVI) and stirred initial settling velocity (SISV) (standard procedure using a 3 litre cylinder with slow stirring, Triton), mixed liquor suspended solids concentration (MLSS) and volatile suspended solids concentration (VSS) were carried out according to (APHA 1998). The primary settled and effluent wastewater was analysed daily (24

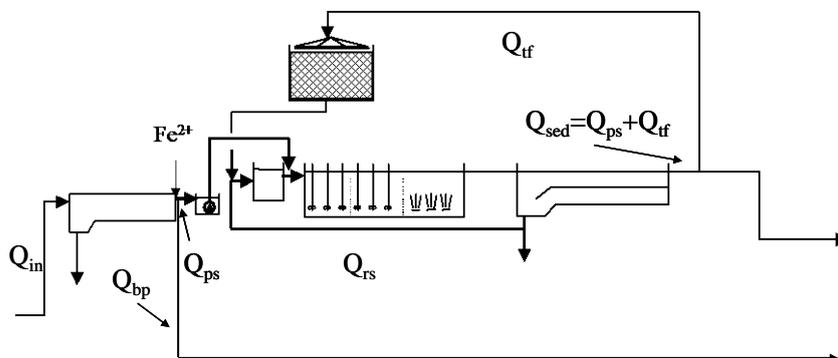
hour composite flow proportional samples) for chemical compounds chemical oxygen demand (COD), phosphate, suspended solids and total phosphorus. BOD<sub>7</sub> was only measured in the short term experiment.

#### *Long term effects of DO concentration*

Before 2005 the DO concentration at the end of the aeration tank was generally kept at 5-6 mg/l to ensure good treatment efficiency and good settling properties. From 2006 attempts have been made to reduce the aeration intensity to save energy. However, no clear correlation between DO concentration and sludge properties has been observed. During the spring 2009 the DO concentration was changed between 2 and 4 mg/l approximately every 3 weeks to assess whether this would have any impact on the activated sludge properties. This period would be suitable to study more long term effects of DO concentration as the SRT is only 2-4 days at the same time as other process parameters are relatively constant.

#### *Short term effects of DO concentration*

During one day, short term effects of DO concentration on sludge properties were investigated by changing the DO set-point in the three parallel activated sludge lines for 4 hours to 1 mg/l in line 1, to 5 mg/l in line 2 and to 3 mg/l in line 3. Prior to the change in DO set-point as well as after 4.5 hours with the new DO set-point, samples for SSVI, SISV, and supernatant SS, NSS, COD(tot) and BOD<sub>7</sub> were analysed in line 1 and 2.



**Figure 1** Schematic of the Rya WWTP.

#### *Microscopic investigation*

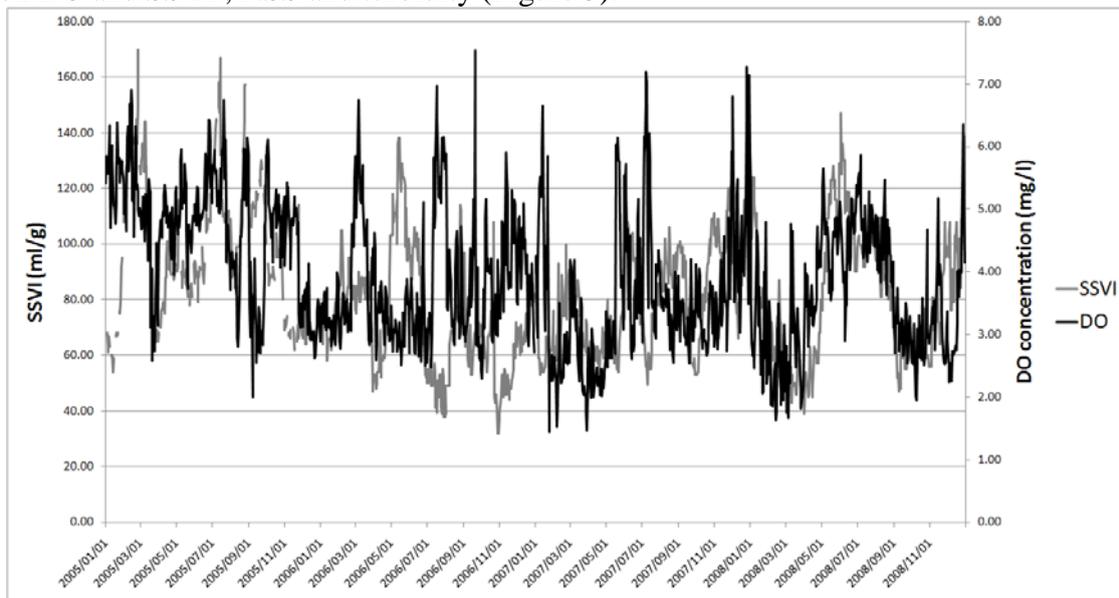
Floc morphology was judged by light microscopy (Olympus N547) examination according to a classification scheme. During the period 09/03/2009 to 12/06/2009 sludge samples were investigated 2-3 times per week as compared to the normal frequency of twice per month. The filaments index (FI), number and type of protozoa, flagellates, metazoan, zoogloea-like bacteria and free bacteria were classified on a scale from 0 = no filaments to 5 = excessive numbers. Floc shape was classified on a scale from 0 = very branched to 5 = very round. Floc structure was judged in a similar way as varying from 0 = very open to 5 = very dense. Digital images were recorded at different magnifications.

## **RESULTS AND DISCUSSION**

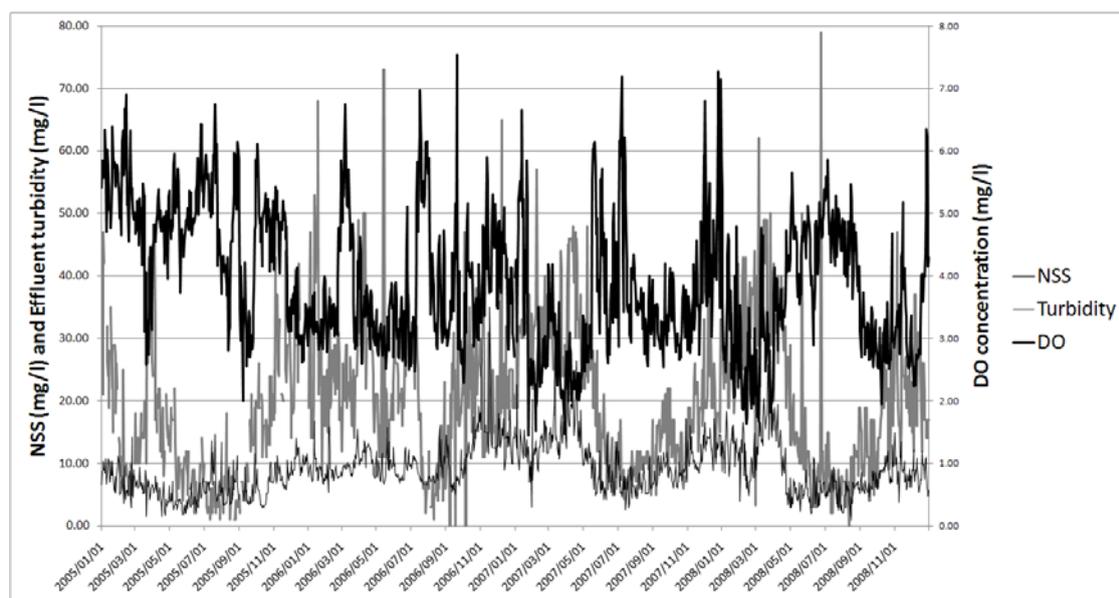
#### *Historic data*

Historic data show that there is no clear correlation between DO and SSVI. Surprisingly, for some periods slight positive correlation can be seen whereas for others, an increased DO concentration appears to lead to decreased SSVI (Figure 2a). This is an interesting observation. When looking at the other process parameters it can often be seen that high SSVI coincide with high concentration of

COD(tot) in the primary settled wastewater and also an increase in required iron sulphate dosage (data not shown). This indicates that the positive trend between DO concentration and SSVI could be a consequence of trying to combat the poor settling properties by increasing the DO concentration. If looking at the time line it can be observed that increased DO concentrations has positive impact on the settling properties during some periods. For the effluent quality in terms of NSS, SS and turbidity a clear seasonal variation can be seen with generally lower values during the warmer summer months which have been reported in earlier studies of the plant (Wilén et al. 2008, 2009) (Figure 2b). Mainly the NSS concentration seems to decrease with increased DO concentrations. It can also be observed that the DO concentration is often kept higher during the summer months. The time line also shows that it appears as increased DO concentration reduces the effluent suspended solids concentration under certain conditions. There were weak correlations between DO and SSVI, NSS and turbidity (Figure 3).



(a)



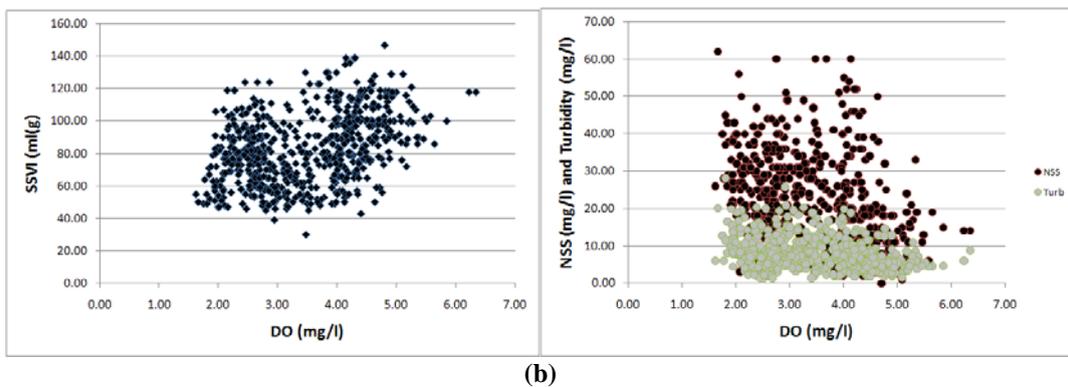
(b)

**Figure 2.** Development in DO concentration and (a) SSVI; and (b) effluent turbidity and NSS.

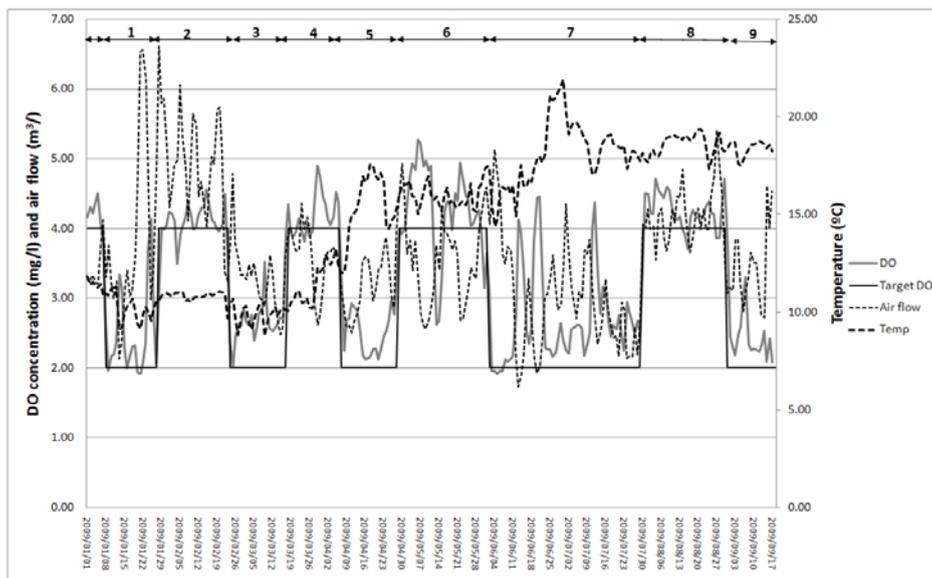
*Data from systematic change in DO concentration*

During the spring 2009 the DO concentration was changed according to Figure 4a. The required air

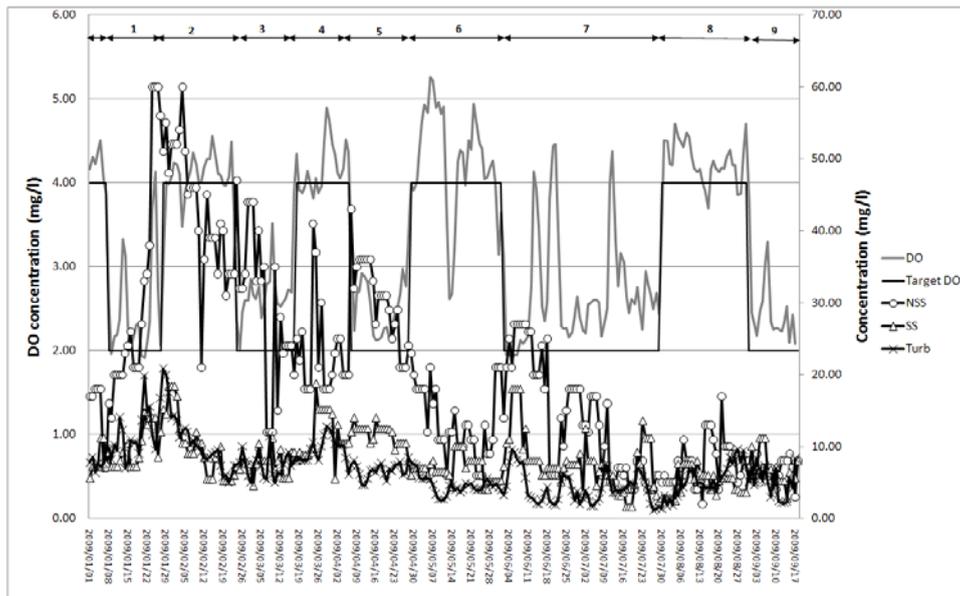
flow to reach the targeted DO concentration varied significantly due to variations in wastewater composition. There were some disturbances to the process during this experimental period. Between 20<sup>th</sup> of January and 10<sup>th</sup> of February something in the wastewater caused growth of what was believed to be yeast cells which gave high effluent turbidity at the same time as the oxygen uptake rate was exceptionally high which can be seen in the high required air flow to reach a DO concentration of 4 mg/l (Figure 4a). During this period (period 1-2), sudden decreases in DO concentration gave higher effluent turbidity and suspended solids concentration (Figure 4b). As the DO concentration was increased to 4 mg/l, both effluent SS and turbidity decreased gradually. An interesting observation is that the high air flow during this period also coincided with the poorer effluent quality. It can be hypothesized that when the sludge flocs are very open with weak structure, sudden changes in turbulence can disperse them, especially during the winter when the flocs are generally more open (Wilén et al. 2009). During the period 23<sup>rd</sup> of March – 1<sup>st</sup> of July, a temporary effluent tunnel was installed due to an extension work at the plant which allowed a maximum inflow of 3 m<sup>3</sup>/s. This gave lower hydraulic loading of the secondary settlers. During this period (4-8) the effluent NSS and effluent SS decreased with increased DO concentration. During period 8 and 9 no effect of DO concentration on effluent quality could be observed. One reason could be that the flocs at this plant are generally more compact during the warmest months (July to September, Figure 4a) and are probably less sensitive to DO fluctuations. The SSVI was not influenced by the DO concentration; during period 7 and 9 with 4 mg O<sub>2</sub>/l the SSVI appeared to increase in a similar way as was observed in the historical data. The change in SSVI was found to follow the concentration of total COD in the incoming wastewater (data not shown).



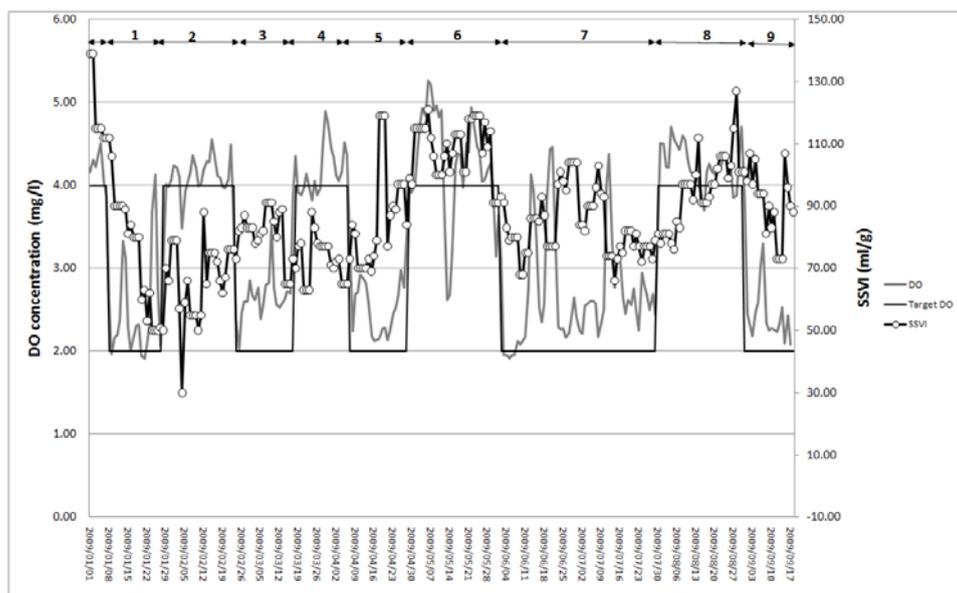
**Figure 3.** Correlation between DO and (a) SSVI; and (b) NSS and turbidity (years 2008 and 2009).



**(a)**



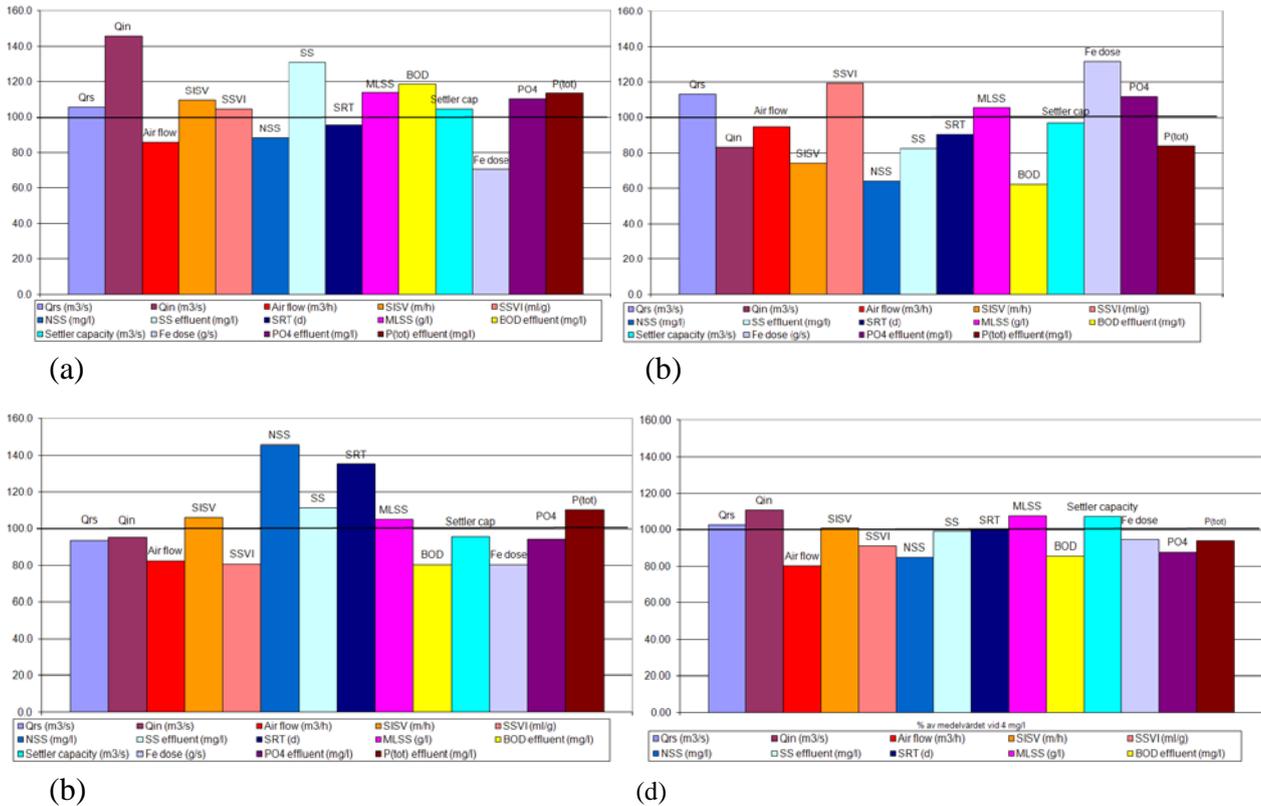
(b)



(c)

**Figure 4.** Development in DO concentration during 2009 and (a) air flow and activated sludge temperature; (b) NSS and effluent SS and turbidity; and (c) SSVI.

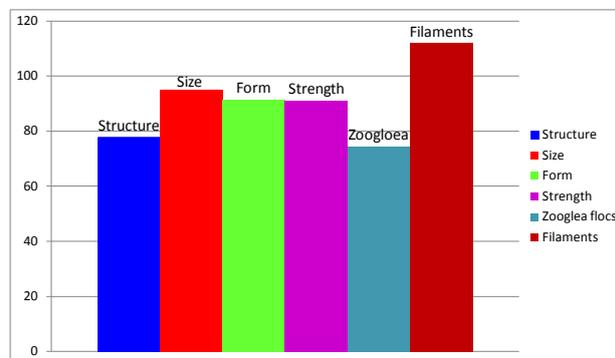
Since activated sludge plants are very dynamic systems where many parameters change simultaneously, it is very hard to assess effects of a certain parameters such as the DO concentration on sludge properties. The average values of the different process parameters for two consecutive periods with DO concentrations 2 and 4 mg/l were compared and expressed as the percentage (%) at 2 mg/l compare at 4 mg/l (Figure 5a-d). For the period 14-01-2009 to 22-03-2009 (Figure 5a), slightly higher effluent SS,  $PO_4$  and P(tot) could be observed for a DO of 2 mg/l compared to at 4 mg/l whereas the settling parameters were only slightly higher. For the period 23-03-2009 to 28-04-2009 (Figure 5b) the effluent SS, NSS and total P were lower at a DO of 2 mg/l with slightly higher SSVI and lower SISV. For the period 05-05-2009 to 01-07-2009 (Figure 5c) the effluent NSS, SS and P(tot) were higher at 2 mg/l whereas the SSVI was lower. When all data at 2 mg/l are compared with the data at 4 mg/l only very small differences can be seen (Figure 5d).



**Figure 5.** Percentage at 2 mg/l compare to at 4 mg/l for different process parameters for the periods (a) 14 Jan – to 22 Mar; (b) 23 Mar – 28 Apr; (c) 5 May – to 1 Jul; (d) average over the entire period 1 Jan – 1 Sep.

### Microscopic examination

The microscopic investigation showed the flocs were generally relatively small, open and contained low to moderate numbers of filamentous bacteria (FI=0 to 2, occasionally 3). From the frequent observation of the floc morphology it was observed that they became more compact, slightly larger and appeared stronger at the floc edge at a DO of 4 mg/l (Figure 6). There were generally few protozoa present in the sludge and correct estimation of the number is therefore hard but a trend towards lower numbers at 2 mg O<sub>2</sub>/ was observed.



**Figure 6.** Summary of the microscopic investigation given as percentage of the classification index at 2 mg/l compared to at 4 mg/l. High values for the morphology parameters indicate good floc properties.

### Short term experiment

The DO concentration was changed for 4.5 hours, equal to one hydraulic retention time, during one day when all other process parameters were relatively constant and it is therefore likely that this would not influence the activated sludge floc morphology. However, colloidal and floc stability could potentially be affected. In Table 1 the results are summarized. The results show that by

decreasing the DO concentration to 1 mg/l no significant effects on the properties on either the supernatant or the activated sludge. The only parameter that significantly increased at low DO concentrations was the BOD<sub>7</sub>. During the settling of the sludges in the standardized cylinders an interesting observation was made; probably the sudden increase in aeration intensity caused disintegration of some flocs and the supernatant after settling looked more turbid in sludge from line 2 (DO = 5 mg/l) compared to in line 1. This was also seen in the somewhat higher NSS concentration.

**Table 1.** Summary of short term experiment.

<b>Part I: 9:00 a.m.</b>		
<b>Tested parameters</b>	<b>Line 1</b>	<b>Line 2</b>
DO (mg/l)	2	2
SS (mg/l)	1.75	1.79
NSS (mg/l)	10	11
SISV (m/h)	3.4	3.1
SSVI (ml/g)	91	95
COD (total)	1660	1770
COD(filtered)	37	37
BOD <sub>7</sub> (mg/l)	3.8	3.9
<b>Part II: 1:30 p.m.</b>		
<b>Tested parameters</b>	<b>Line 1</b>	<b>Line 2</b>
DO (mg/l)	1	5
SS (mg/l)	1.7	1.8
NSS (mg/l)	11	13
SISV (m/h)	3.24	3.0
SSVI (ml/g)	92	96
COD (total)	1610	1770
COD(filtered)	30	33
BOD <sub>7</sub> (mg/l)	5.7	3.5

## CONCLUSIONS

The main conclusions that can be drawn from this study is that:

- DO concentration has no or limited effect on SSVI at this plant.
- DO concentration has some, but not statistically significant, influence on the effluent quality in terms of suspended solids concentration, non-settleable suspended solids and turbidity.
- Investigations over longer periods of different maintained DO concentrations have to be performed (at least one year) to better assess the impact of DO on sludge properties.

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