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Membrane bioreactor (MBR) sludge inoculation in a hybrid process scheme concept to assist overloaded conventional activated sludge (CAS) process operations

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ABSTRACT

This study analyzes the effect of inoculating membrane bioreactor (MBR) sludge in a parallel-operated overloaded conventional activated sludge (CAS) system. Modelling studies that showed the beneficial effect of this inoculation were confirmed though full scale tests. Total nitrogen (TN) removal in the CAS increased and higher nitrate formation rates were achieved. During MBR sludge inoculation, the TN removal in the CAS was proven to be dependent on MBR sludge loading. Special attention was given to the effect of inoculation on sludge quality. The MBR flocs, grown without selection pressure, were clearly distinct from the more compact flocs in the CAS system and also contained more filamentous bacteria. After inoculation the MBR flocs did not evolve into good-settling compact flocs, resulting in a decreasing sludge quality. During high flow conditions the effluent CAS contained more suspended solids. Sludge volume index, however, did not increase. Laboratory tests were held to determine the threshold volume of MBR sludge to be seeded into the CAS reactor. Above 16–30%, supernatant turbidity and scum formation increased markedly.
Key words | bio-augmentation, full-scale membrane bioreactor, hybrid system

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INTRODUCTION

Membrane bioreactors (MBR) for municipal wastewater treatment can be considered as an established technology. The design of hybrid systems – how to integrate a MBR with an existing conventional activated sludge (CAS) plant – is less straightforward. Single sludge systems in which sludge is continuously recirculated between CAS and MBR lanes (e.g. Heenvliet wastewater treatment plant (WWTP) (Mulder 2009)) as well as parallel operated plants (e.g. Ootmarsum WWTP (Futselaar *et al.* 2007)), are in operation.

There is no scientific consensus on which of the scenarios is optimal. The MBR lane is generally designed on the dry weather flow (DWF). The remaining flow is diverted into the CAS system, avoiding unused membrane filtration capacity during DWF. On the other hand, during dry periods, the MBR will handle all the influent, and the load to the CAS lane may be too low to support biomass maintenance.

It has been shown in the past that higher specific nitrification rates can be achieved in MBRs than in conventional plants (Manser *et al.* 2005; Parco *et al.* 2006; Jiang *et al.* 2009; Fenu *et al.* 2010a, b).

This study analyzes the option of using MBR sludge to inoculate a parallel-operated overloaded CAS system. Can inoculation of MBR sludge into the CAS contribute to a significant nutrient removal advantage? The second issue the paper addresses is the settleability of the mixed sludge. What is the fate of the MBR sludge flocs in the CAS system? What will happen to sludge quality and sludge settling characteristics?

MATERIALS AND METHOD

The full-scale hybrid WWTP

The Schilde WWTP is composed of two independent treatment lanes (Figure 1): the MBR lane treats a nominal average flow of 270 m^3/h, and a maximum peak flow of

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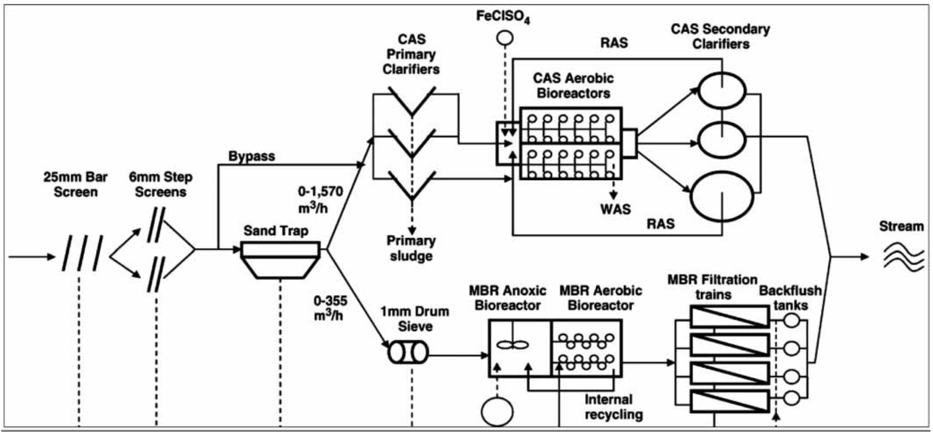

Figure 1 | Layout of the Schilde WWTP (CAS and the MBR lanes are parallel).

355 m^3/h; the CAS lane treats the remaining flows, resulting in a variable flow pattern ranging between 0 and 1,450 m^3/h, or 21,000 PE.

The primary treatment consists of preliminary screens with a 6 mm mesh and a rectangular primary clarifier. Secondary treatment is achieved by a single-stage stirred tank (2×600 m^3), intermittently aerated (continuously in winter), with an O_2 set point (Osp) of 2.5 mg/l. Phosphorus is removed by simultaneous chemical precipitation. Mixed liquor suspended solids (MLSS) concentration is controlled at 3.5 g/l. Sludge–effluent separation is achieved by three round clarifiers (total surface area of 1,017 m^2).

The MBR lane was built with the aim of meeting more stringent water quality norms (including the requirement for nutrient removal), and increasing the WWTP biological capacity to 28,000 people equivalents (PE) and the hydraulic capacity to $6 \times Q_{14}$, i.e. $Q_{14} = (150 * \text{liter})/(14 * \text{PE} * \text{hour})$.

The wastewater is pretreated by a sand trap, followed by a 1 mm mesh drum-sieve. The plant layout is composed of a pre-denitrification tank (500 m^3), an aeration basin (500 m^3) and an aerated filtration unit (240 m^3) with total membrane surface of 10,500 m^2. The MBR lane aerates the biomass by means of fine and coarse bubble aeration. The fine bubble aeration operates in the bioreactor tank with an on–off system control on a fixed Osp of 2.5 mg O_2/l. MLSS concentration is controlled at 10 g/l.

The installation has undergone the necessary adaptations to realize this study in full scale: (i) the excess MBR sludge, previously wasted from the recycle channel directly to the sludge buffer, is now pumped at a rate of 0–15 m^3/h into the CAS basin. On average, 60 m^3/day of MBR sludge can be evacuated while maintaining an average mixed liquor concentration of 10 g/l in the bioreactor; and (ii) the CAS lane was equipped with an extra sludge waste pump.

Samples and analysis

The effect of the MBR sludge seeding (MSS) is evaluated by:

(i) An ASM model. The model was calibrated on 2006 data and validated on 2009 data. The model has been described in Fenu *et al.* (2010b). The Schilde WWTP model was implemented in MATLAB SIMULINK using a model library developed by Aquafin. The ASM2d model variant that incorporates the inorganic fraction was used.

(ii) An analysis of the plant performance before and after the start of the inoculation. Composite samples were collected at the WWTP influent and effluent (in both cases summing up CAS and MBR) with two-weeks frequency in 2006–2011. The samples were analyzed according to the Standard Methods (APHA 1998) for biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), suspended solids (SS), ammonia, nitrate and nitrite, organic nitrogen, orthophosphate and total phosphorus.

(iii) Maximum nitrification rates of MBR and CAS sludges. These were occasionally assessed in controlled batches (pH 7.2–7.5 at 20 °C, stirring at 500 round per minute, Osp of 3 mg/l).

(iv) Calculations to evaluate the autotrophic biomass (Xaut) in static conditions by use of the Equation (1) below:

$$X_{\text{AutBM}} = \frac{M_{\text{NO3}}}{(1 + b_{\text{aut}} \cdot \text{SRT})} . Y_{\text{a}} \cdot \text{SRT} \quad (1)$$

where M_{NO3} is the nitrate formed, Y_a is the autotrophic sludge yield SRT is the sludge retention time, and b_{aut} is the autotrophic decay rate.

The sludge quality after inoculation was monitored both in lab and full-scale conditions. The following methods were employed:

(i) Sludge floc size monitoring by microscopy.
(ii) Filamentous bacteria assessment. Phase contrast (wet preparation) and bright field (stained preparation) microscopy were used at different magnifications (100×, 200×, 400× and 1,000×). The qualitative and quantitative assessment was based on a defined reference. This reference consists of detailed descriptions (for a qualitative assessment) of the determinants, or a scoring system (for a quantitative assessment). The amount of the filamentous bacteria is also based on reference photographs. The filaments were identified by using the Eikelboom scheme (Eikelboom 1999) and staining methods, referring to morphological and color characteristics of the filaments.
(iii) Monitoring of the CAS supernatant turbidity by use of a turbidity analyzer (Nephla – Dr Lange).
(iv) Daily monitoring of the full scale diluted sludge volume index (DSVI) (according to Jenkins *et al.* 2003).
(v) Daily measurement of MLSS and mixed liquor volatile suspended solids (MLVSS) in both lanes.

RESULTS AND DISCUSSION

Model and feasibility study

The MBR lanes achieve complete nitrification as well as solids retention all through the year. The performance of the CAS lane instead is very poor in winter. In winter, the CAS is overloaded and the SRT, estimated as 5–9 days, cannot be increased due to the high surface load of the clarifiers, which prevents an increase of the MLSS. Severe flow peaks and sustained low water temperatures challenge regularly the nitrifiers' retention, and consequently the biological reactor is often continuously aerated. The average ammonia concentration (measured on-line in the CAS aeration outlet) in winter was 13.5 mg/l in 2009, 8.43 mg/l in 2010, and 9.49 mg/l in 2011. Nitrification batch tests, repeated in winter and summer 2010, confirmed in fact that the specific nitrification rate is 5–10% higher in the MBR sludge.

The effect of MSS was studied by means of static and dynamic assessments. Static calculations (using Equation (1)), based on seasonal averages, demonstrated that in winter the MBR autotrophic biomass concentration is higher than in the CAS. The MBR has a higher SRT (21 days compared with 6 days of the CAS); shows complete nitrification (versus partial nitrification in the CAS) and has a lower b_{aut} due to the larger MBR anoxic volume (the b_{aut} is halved in anoxic conditions, as in Nowak *et al.* 1994; Siegrist *et al.* 1999; Salem *et al.* 2006; Fenu *et al.* 2010b). In summer, instead, the total influent flow decreases from, on average, 700–350 m^3/h. As influent is preferentially sent to the MBR, the influent flow to the CAS is on average below 100 m^3/h. This results in a markedly higher amount of nitrifiers in the MBR system.

The impact of the MSS was also evaluated by means of a dynamic ASM model. In 2009, the MBR was shut down from day 6 to 20 (Figure 2), and all the influent was sent to the CAS. This led to a complete washout of the nitrifiers (ammonia reaches 25 mg/l in day 12). This event occurred in real life and no MSS took place at that time. Recovery from nitrifier washout without MSS was compared with recovery with MSS using the ASM model. Figure 2 shows that during days 25–90 the modeled MSS scenario recovers faster from the washout compared to the real-life situation without inoculation.

After day 300, persistent high influent flow in combination with low temperatures, typical of the Flanders region, caused a reduction of nitrification activity. In this period, the MSS scenario shows a markedly lower effluent ammonia concentration.

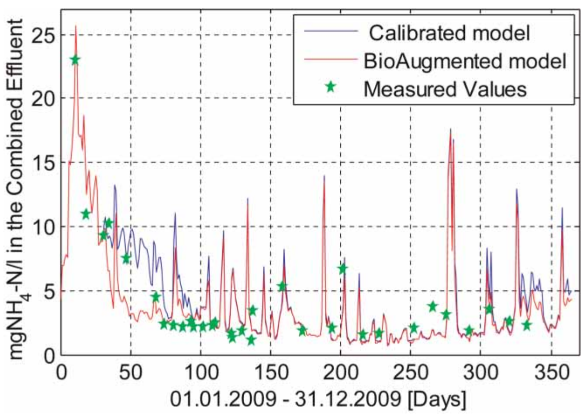

Figure 2 | Modelled versus measured soluble ammonia in the combined effluent. The effluent ammonia was measured in a year (2009) when no MSS operations were applied. Read '0' as 01.01.2009 and '365' as 31.12.2009.

Plant performance

In January–April 2010 MSS was in operation. The MSS flow to the CAS was 1.25–7.5 m^3/h, with daily flows between 30 and 90 m^3/day. During MSS an ammonia and total nitrogen (TN) removal of respectively 72% and 47% was recorded at an average water temperature of 8.9 °C. This is the best result ever achieved for WWTP Schilde in that period. The best ammonia and TN removal that was achieved without MSS was recorded in 2007 (respectively 67 and 45%) at an average water temperature of 10.4 °C.

In winter 2011, instead, foaming problems caused the MBR sludge to be completely wasted on two different occasions. The membrane permeability was low, necessitating a low influent flow to the MBR (i.e. the system was in winter 2011 operated at 160 m^3/h, the design flow being 270 m^3/h). MSS could only be occasionally done in 2011, and therefore only the effect of occasional MSS on CAS sludge quality could be evaluated.

The on-line nitrate sensor data help explain the effect of MSS on nitrification in the CAS. First flush events lead to a higher sludge production in the MBR. This sludge can subsequently be wasted into the CAS, leading to higher nitrification rates. In Figure 3, it is shown how a MSS rate to the CAS basin in 2010 increased the measured specific nitrate formation rate (Figure 3).

The MLVSS content of the CAS and the MBR without MSS was roughly the same (70%, winter 2010–2011). This was not expected as the higher SRT in the MBR would normally lead to a lower MLVSS content. We think that the finer MBR pre-treatment (i.e. the MBR system is sieved down to 1 mm) filters out part of the inert particulate material in the influent. This could then allow a higher concentration of active biomass in the MBR sludge.

The MSS was performed whenever excess sludge was present. During periods of low organic load (coinciding with periods of low influent flow, leading to sedimentation of particles in the sewers), MBR excess sludge production was too low, leading to a decreasing nitrification capacity in the CAS. Therefore it was investigated through modelling how MBR sludge production could be increased. The MBR lane produces an average 60 m^3/day of sludge to maintain 10 g/l MLSS in the bioreactor. It is thus a question of how to produce enough MBR sludge. The lowering of the SRT_{MBR} was found to increase the sludge production but at the cost of the X_{aut} concentration reduction (as in Equation (1)) and thus this solution is not optimal. Moreover, lowering of the SRT necessitates an MLSS concentration lower than the optimal one for filtration of 10 g/l.

The only possibility to boost the MBR sludge production is by sending more influent to it. The model was very useful in investigating this scenario as in reality the amount of influent that can be sent to the MBR is dependent on membrane area and permeate extraction flow. Figure 4 demonstrates that TN removal increases when more flow is sent to the MBR lane. The difference in

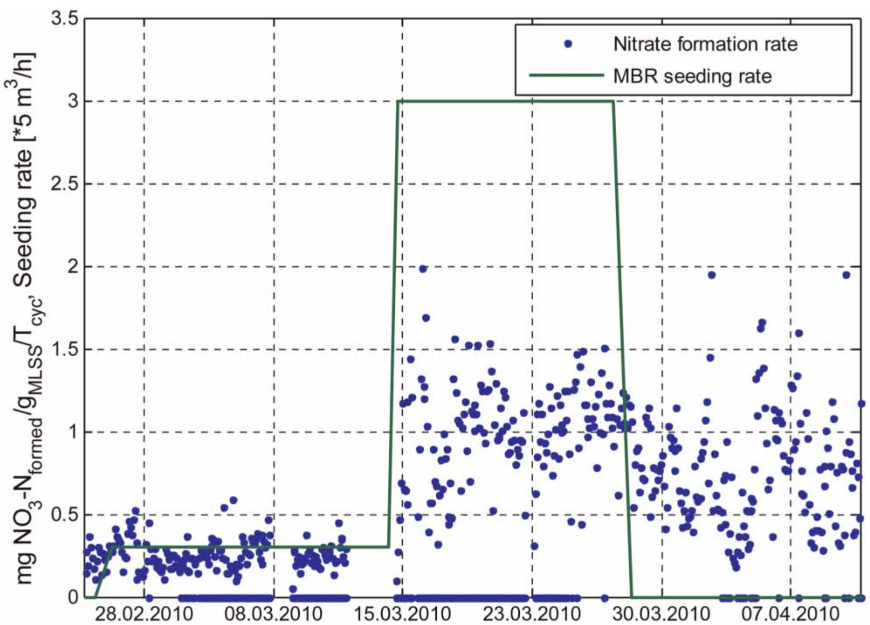

Figure 3 | Measured specific nitrate formation rate in the CAS aeration tank during MSS operations. The MBR seeding rate is also reported.

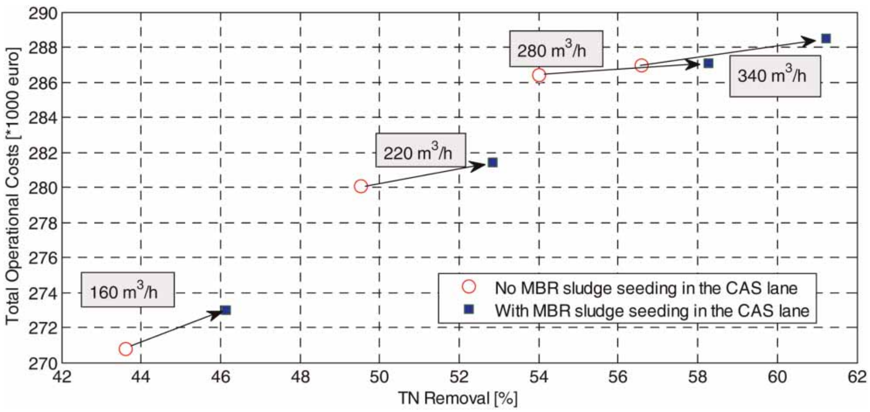

Figure 4 | Costs and TN removal while varying the influent flow to the MBR system. Scenarios with MSS and without MSS operations have been compared.

TN performance of the MSS scenarios versus no MSS progressively increases with increasing flow to the MBR lane. Costs slightly increase with higher flows to the MBR.

Finally it is relevant to note that the MSS scenarios only corresponded to a 1% increase in yearly aeration demand of the CAS lane, thus being almost energy neutral.

Sludge settleability and flocs morphology

A microscopic evaluation of the sludge from CAS and MBR was carried out to assess the basic morphological differences between the two sludges. While the CAS sludge (before any seeding) appears more compact, the MBR flocs were characterized by a very open form and were composed of many sub-compartments, including compact cores, cell clusters, and filamentous bacteria. In the former sludge the filamentous bacteria presence is very high, with a co-domination of *Nocardia* and *Microthrix parvicella*, and a high presence of Type 0041/Type 0675. The particle size distribution of both sludges was measured (Fenu *et al.* 2010b), yielding an average floc size of 40–50 μm for the MBR and 200 μm for the CAS, as in Masse *et al.* (2006).

The fate of the MBR sludge in the CAS sludge matrix during full-scale seeding was followed up through microscopy analysis. It was observed that the CAS flocs evolved into a more open and irregular form, including often small compact clusters (Figure 5). As in the MBR sludge, frequent *Nocardia* are found loose in the CAS sludge water. The MBR flocs, grown without settling selection pressure, are incorporated in the CAS flocs structure. However the CAS settling process appears unable to transform them in to regular settleable CAS flocs. It is possible that the marked presence of *Nocardia*, by growing loose out of the flocs, does not allow floc compactness.

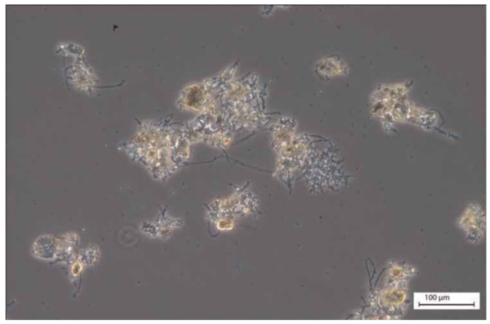

Figure 5 | CAS sludge during MSS operations (2010).

Consistent with the microscopic results, the continuous seeding in 2010 led to a persistent increase of *Nocardia* and dispersed material in the CAS. During one of the occasional MSS periods in 2011, i.e. between 28.02.2011 and 07.03.2011, a sudden increase of dispersed material as well as of *Nocardia* filaments was observed in the CAS supernatant.

The full-scale operations analysis offers the possibility of further considerations. With regards to the reliability of operations, the DSVI and the effluent SS were followed up over time. The DSVI did not show significant variations that could be related to MSS, even after massive seeding. SS effluent concentration however seems to be affected by MSS during peak flows. This is demonstrated by Figure 6 in which the online effluent SS concentration is plotted versus the influent flow, between January and March of 2009–2011 (Figure 6), i.e. only in 2010 was there continuous MSS.

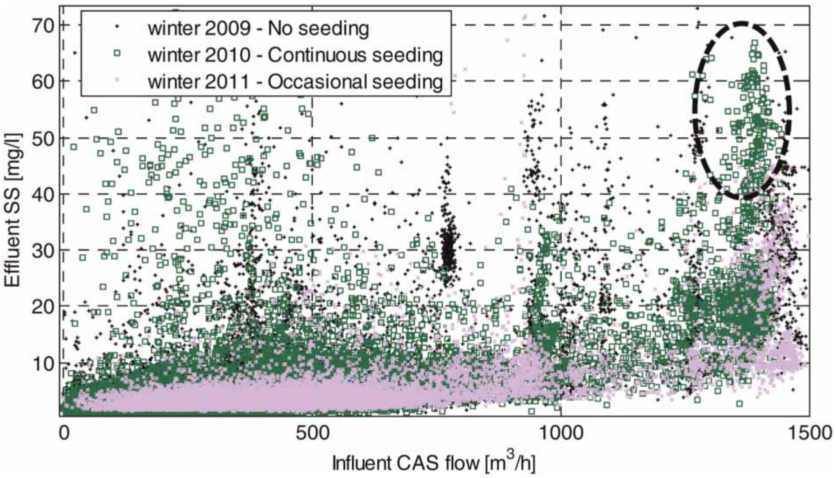

Figure 6 | Effluent SS on-line versus CAS influent flow (2009–2010–2011).

The effect of mixing CAS and MBR sludges was studied also via lab batches. Different mixtures of fresh MBR sludge and CAS sludge were prepared. Evidently, the more MBR sludge was added, the higher the sludge concentration. As expected, the settling rate was found to be proportional to the MLSS concentration.

Following the DSVI protocol, the batches were rediluted with permeate water up to a proper sludge volume (Jenkins *et al.* 2003). A similar DSVI was found at different MBR sludge percentages, confirming the full-scale observation that SVI also did not increase during MSS. However above 16% MBR sludge (V/V), sudden changes were observed and a thick layer of scum was formed at the top of the batch (Figure 7). The turbidity of the supernatant increased as well. The undiluted MBR sludge performed better in terms of scum formation, SVI, and supernatant turbidity than the above 16% MBR mixtures. This shows that the MSS has its limits. In this case, exceeding the 16–30% V_{MBR}/V_{CAS} (water volumes) should be avoided, i.e. in full scale a maximum of 15% was reached.

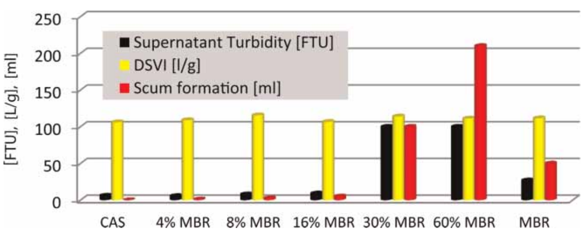

Figure 7 | CAS supernatant turbidity, DSVI and scum formation as a function of Volume MBR water/Volume CAS water.

CONCLUSIONS

This study analyzes the option of using MBR sludge to boost nitrification in a parallel-operated CAS system. The beneficial effect of MSS on nitrogen removal was first examined using static and dynamic models and later demonstrated on full scale. The TN removal gain was proven to be dependent on MBR sludge loading.

The MBR flocs, grown without settling selection pressure and characterized in this specific case by a high amount of filamentous bacteria, are not embedded in the CAS flocs after seeding. MSS coincided with an increase in supernatant turbidity, filamentous bacteria and dispersed material in the CAS sludge. SVI did not increase. During high flow conditions more SS left the CAS.

This study also suggests not to surpass a certain inoculation rate. Above 16–30% v_{MBR}/v_{CAS}, supernatant turbidity and scum formation increased to problematic levels.

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