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Biological nitrogen removal at low water temperatures — long term experience

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ABSTRACT

Many earlier publication presented the lowest temperature of 10°C as feasible for nitrification process. The article evaluates long-term experience with biological nitrogen removal at low temperatures (between 2 and 10°C), studied at four wastewater treatment plants operated with SBR-technology: Holbaek (Denmark), Nowy Targ (Poland), Nynäshamn and Skaulo (Sweden). Influence if nitrogen loads and COD/N ratio on nitrification rate was studied. Despite of operation at low temperatures during 3–4 months of the year good relation between the nitrogen load and the specific nitrification rate has been obtained. Long-term studies regarding nitrification, temperature and SRT demonstrated that the actually needed (aerated) SRT were lower than the normally recommended values. In some cases the nitrification was maintained at a lower efficiency even during non-aerated phases due to remaining free oxygen in the reactor that is used for nitrification.

Keywords: Nitrogen removal; SBR; Low water temperature; Solids retention time

1. Introduction

In many areas, such as Canada, parts of the US, northern Europe and in mountain areas in the northern hemisphere, such as the Carpatíc Mountains and the Alps cold wastewater have to be treated. Now physical, chemical and biochemical reactions are retarded by decreasing water temperature. This fact has been reflected in the design outlines for wastewater treatment by Adams and Eckenfelder [1], who stated that nitrification (oxidation of ammonia nitrogen into nitrate) was not feasible at water temperatures <12°C. Even in a much later publication, such as Eckenfelder et al. [2], the lowest temperature for nitrification of 10°C is presented as feasible. The EU directive on wastewater treatment 91/271 EEC gave clear limitations related to water temperature on nitrogen and phosphorus removal levels, stating that if the water temperature is <12°C, the effluent requirements would be far less stringent with respect to nitrogen and phosphorus. The fact that biological nutrient removal is very temperature dependent is stated by inters alia Eckenfelder et al. [1]. In addition to these biochemical conditions, also physical proprieties of the water are temperature dependent. Fig. 1 demonstrates the dynamic viscosity related to water temperature. The change in viscosity will influence the settling velocity, as an example a temperature drop from 10 to 4°C at an arctic plant in Sweden resulted in a doubling of the needed settling time in a batch reactor operation.

On the other hand a number of modern municipal wastewater treatment plants (WWTPs) have been operated at temperatures <10°C for a number of years [3–7].

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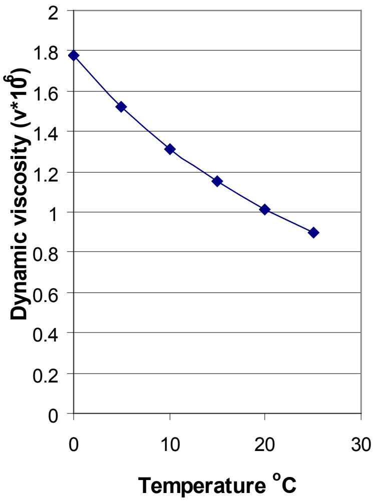

Fig. 1. Dynamic viscosity related to water temperature.

Most of them include a biological treatment step; either based on suspended growth or attached growth. In some cases also biological nutrient removal has been included both in the design outlines and the actual operation.

The objective of this paper is to present and evaluate long-term experience on biological removal at low water temperatures from a number of full-scale WWTP operated with the SBR-technology.

2. Material and methods

Four different plants, with different capacities and treatment objectives have been studied. All plants (save for one) have been in operation for several years, thus providing substantial performance figures. The plants covered in the paper are presented in Table 1.

Operation data from these plants are based on either the internal and external process control, or on specific performance tests. The sampling for external control is based on flow proportional sampling, with the exception for Nowy Targ where a time proportional sampling is used. For internal sampling, such as controlling the suspended solids concentration, the free oxygen level and water levels in the reactors on-lone probes are used. The analysis methods used are in compliance with the EU standard methods.

3. Results

A typical water temperature variation at the studied plants is shown in Fig. 2. The shown figures are all monthly mean values, and the minimum water temperature in February and March are at all three of the plants 6°C. For

Table 1
Summary of the studied plants

Plant name	Holbaek	Nowy Targ	Nynäshamn	Skaulo
Location	West of Copenhagen, Denmark	South of Cracow, Poland	South of Stockholm, Sweden	North of the Arctic Circle, Sweden
Operation start	1991	1994	2003	2007
Wastewater	Municipal + pharmaceutical- leachate	Municipal + tanneries and dairy	Municipal + septic sludge	Municipal
Design capacity, pe	45,000	150,000	25,000	500
Water process train	Pre-treatment+ equalization+ 6 SBR units, including simultaneous precipitation+ equalization + sand filters	Pre-treatment+ 3 SBR units + equalization	Pre-treatment including pre-precipitation + 4 SBR units + post-precipitation and final settling + wetlands	Pre-treatment + 2 SBR units, including simultaneous precipitation
Reactor volumes max, m^3	3×3000 + 2×1500 (1 unit of 3000 m^3 added in 2002)	3×7600	4×1100	2×100
Min. reactor volume, m^3	3×2200 + 2×900	3×4900	4×700	2×65
Sludge process train	Mechanical thickening + thermophilic digestion + dewatering	Mechanical thickening + storage	Thickening + digestion + mechanical dewatering	Thickening
Ruling consent values, ppm	BOD < 15 Total P < 1 Total N < 6 Total N < 4 Summer value	BOD < 15 Total P < 1.0 Total N < 20	BOD < 15 Total P < 0.5 Total N < 15	BOD < 15 Total P < 0.5

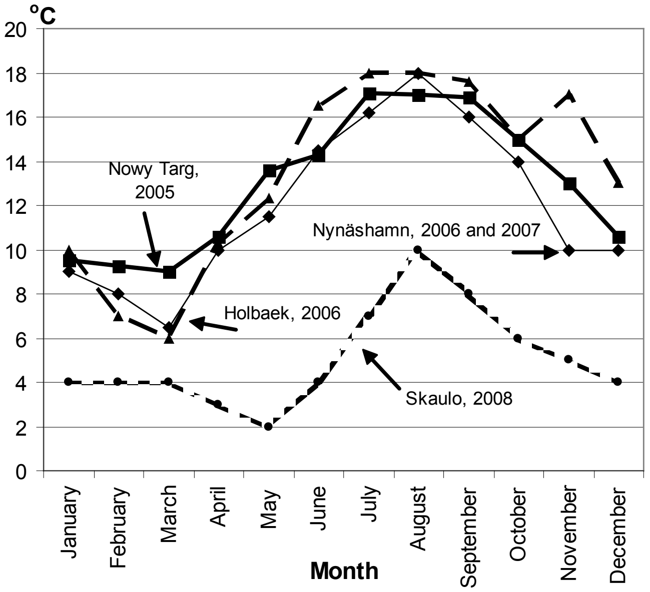

Fig. 2. Annual water temperature variation at four wastewater treatment plants, Holbaek, Nowy Targ, Nynäshamn and Skaulo.

the fourth plant, Skaulo, in the community of Gällivare, no regular temperature control is conducted; however observations done at the plant indicates a temperature span of 2–10°C throughout the year (Fig. 2).

Studies regarding the Nowy Targ WWTP performance were reported earlier by Johansson and Salberg [8], Finnell [9], Kabacinski et al. [10], Sharif [11], Banas et al. [12], Hultman et al. [13], Mikosz et al. [14]. Additional studies based on operation performance data were done later by Morling [7,15]. These studies have covered different aspects of SBR-operation. As underlined in many papers, the Nowy Targ plant has experienced a rapidly growing loading, both with respect to organic compounds as well as nutrients and chromium. The abundance of analysis data has allowed an assessment of both nitrogen removal at low temperatures and the microbiological adaptation of both high concentration of chromium and nitrogen.

The Holbaek plant in Denmark is operated with very stringent effluent requirements (Table 1) and was earlier studied by Morling and Nyhuis [5] and Morling [7]. For both plants it has been possible to establish good relations between the nitrogen load and the specific nitrification rate (Figs. 3 and 4). High value of correlation coefficient has been obtained in both cases. Nitrogen load varied between 4,673 kg N/d and 1000 kg N/d for Nowy Targ WWTP during the first quarter of 2005, giving the nitrification rate in the range between 4 and 0.7 g N_{ox}/kg VSS/h. The figures for Holbaek WWTP in 2006 were between 545 kg N/d and 261 kg N/d for giving the nitrification rate in the range between 1.73 and 0.83 g N_{ox}/kg VSS/h.

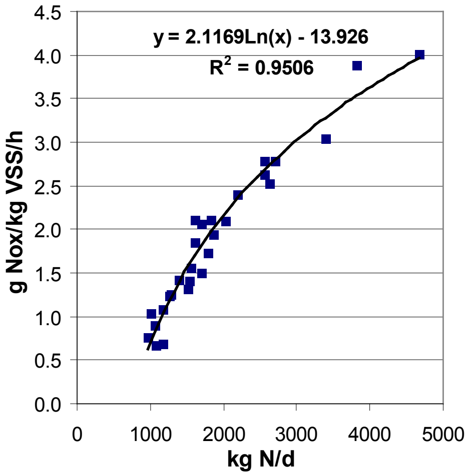

Fig. 3. Nowy Targ SBR plant nitrogen load and specific nitrification rate, 1st quarter 2005, log-normal relation (29 observations).

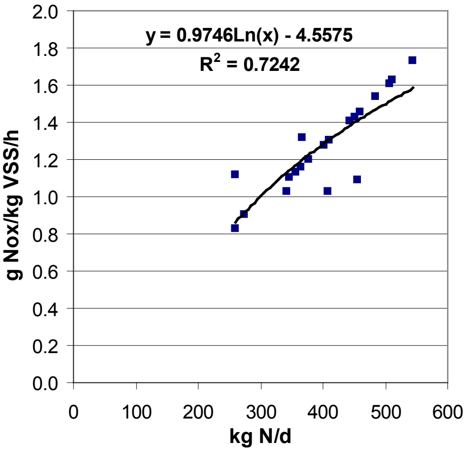

Fig. 4. Holbaek SBR plant nitrogen load and specific nitrification rate, year 2006 (20 observations).

Evaluation of denitrification process resulted also in high correlation coefficient between nitrogen load and denitification rate (Figs. 5 and 6). The denitrification rates varied between 9.12 g Nred/kg VSS/h and 0.34 g N_{red}/kg VSS/h at Nowy Targ WWTP during the first quarter of 2005. The corresponding denitrification rates for Holbaek were between 1.83 g N_{red}/kg VSS/h and 0.83 g N_{red}/kg VSS/h during year 2006.Also for the Nynäshamn SBR plant similar results were obtained (Figs. 7–9).

The Nynäshamn SBR plant was built with special objectives:

- To improve the treatment performance especially on nitrogen removal that was found insufficient using only constructed wetlands as the biological treatment stage;

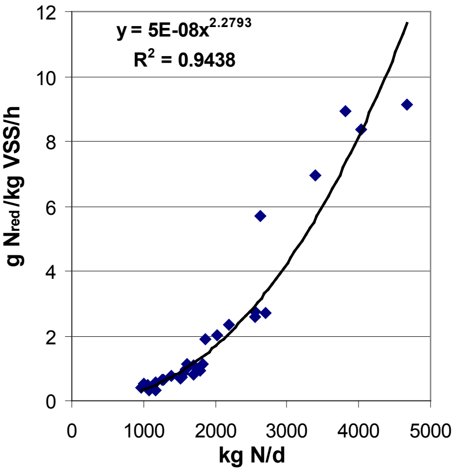

Fig. 5. Nowy Targ SBR plant relation nitrogen load and specific denitrification rate 2005, 1st quarter, 29 observations.

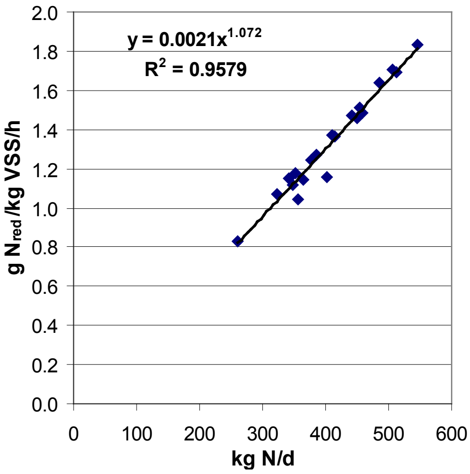

Fig. 6. Holbaek SBR plant relation nitrogen load and specific denitrification rate, 2006, 20 observations.

- To establish a treatment capacity for septic sludge from the surrounding areas.

The plant performance was evaluated by Berg and Biderheim [16] pointing out a sufficient nitrogen removal capacity even at low water temperatures. The long-term improvement of nitrogen discharges is shown in Fig. 7. The most striking results obtained with the SBR introduction at the plant was that the wetlands have been kept open throughout the year, in contrast to earlier operation when an annual closing in wintertime was found necessary. In addition to this effect both BOD and total Phosphorus discharge levels have been lowered substantially [6,7]. The number of observations at the Nynäshamn SBR plant has also made it possible to elaborate mass balances with respect to BOD and nitrogen (Figs. 8 and 9). The specific nitrification rates calculated for two quarters, 1st quarter 2004 and 4th quarter 2005 would be regarded as high (3.2 and 4.3 g N_{ox}/kg VSS/h respectively), especially with respect to the prevailing water temperature, ranging from 7 to 12°C.

Additional results on nitrogen conversion at low water temperatures have been recorded at an arctic small facility, called Skaulo SBR plant. During a performance test period, in May 2008 nitrogen compounds were analysed and evaluated during one week. A partial nitrification of incoming nitrogen was observed at a prevailing temperature of 2.5°C. Organic nitrogen was almost completely hydrolysed or assimilated by the biomass (Fig. 10). The prevailing total solids retention time (SRT) during the test period was about 25 days, and the aerated SRT about 16 days. The effluent demands are limited to BOD and phosphorus thus no regular analysis is performed on

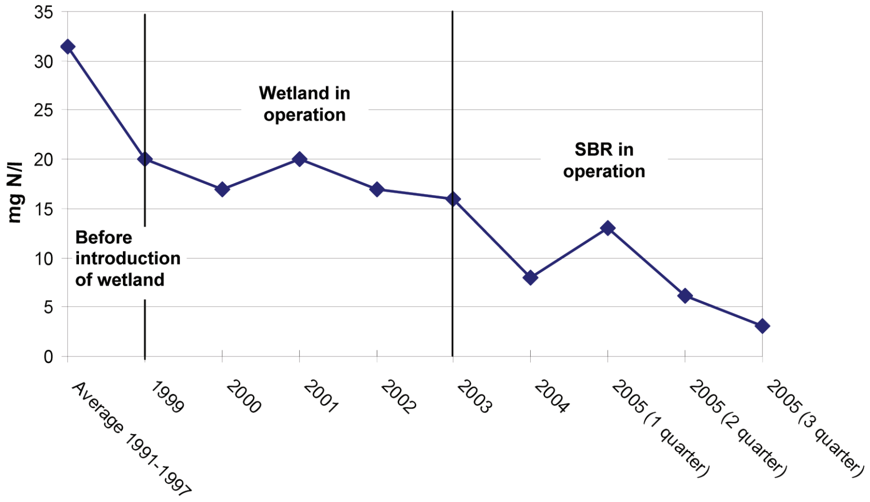

Fig. 7. Discharge levels of total N from the Nynäshamn WWTP, including observations during periods with by-pass of wetland, from 1991 to third quarter of 2005.

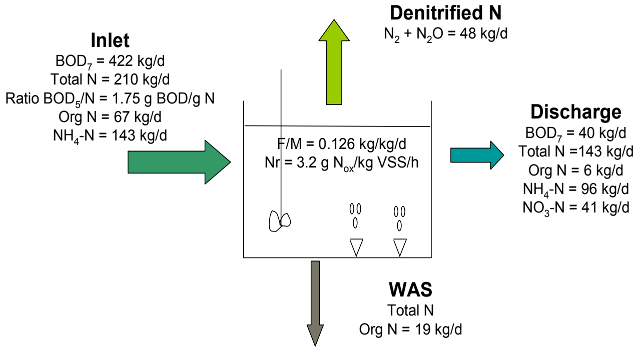

Fig. 8. Nitrogen balances and specific nitrification at the Nynäshamn SBR plant, 1st quarter of 2004, 13 observations, water temperature 7–10°C.

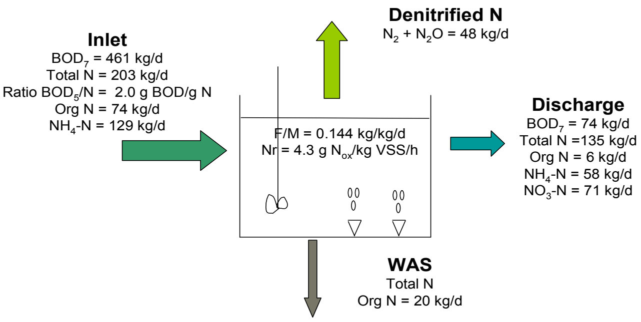

Fig. 9. Nitrogen balances and specific nitrification over the Nynäshamn SBR plant, 4th quarter of 2005, 12 observations, water temperature 10–12°C.

nitrogen. Nevertheless it has been stated that after the test period the discharge levels of BOD and phosphorus have been substantially lower than before the test period. It is likely that the partial nitrification has remained at the plant during the rest of year 2008.

4. Discussion

One of the key conditions for nitrification is the solids retention time, and more specifically the aerated SRT. Long-term observations regarding nitrification, temperature and SRT at a number of plants operated with cold wastewater are presented in Table 1 and Fig. 2. The results reveal that the actually needed (aerated) SRT are substantially lower than the recommended design values (including safety factors) [17]. Another important result especially demonstrated at Nowy Targ (Fig. 4) is the strikingly high nitrification rate, even at the low prevailing water temperature (6–10°C) up to 4 g N$_{ox}$/kg VSS/h. The results from Nynäshamn resemble with the Nowy Targ results (Figs. 9 and 10). This may be compared with the results obtained at Holbaek where the nitrification rate is less than 1.8 N$_{ox}$/kg VSS/h. The latter value resembles more with what is often observed at plants working in the range 12–20°C. This difference may be attributed to a number of circumstances:

- The nitrification is maintained at a lower intensity even during non-aerated phases, due to remaining free oxygen in the reactor that is used for nitrification;
- The actual aerated SRT compared with recommended values provides a better resemblance;

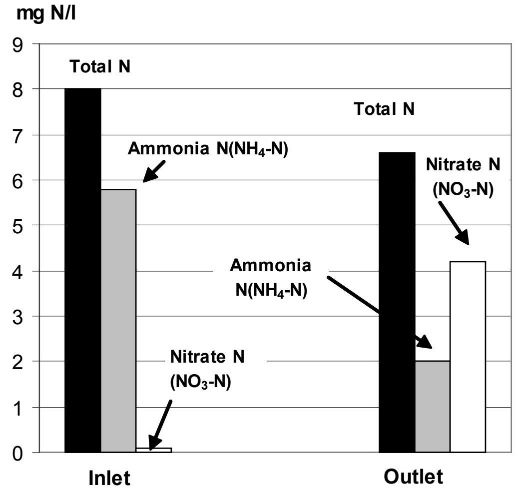

Fig. 10. Nitrogen transformation at the Skaulo SBR plant, operating temperature 2.5°C, May 2008, sampling test period in all four observations.

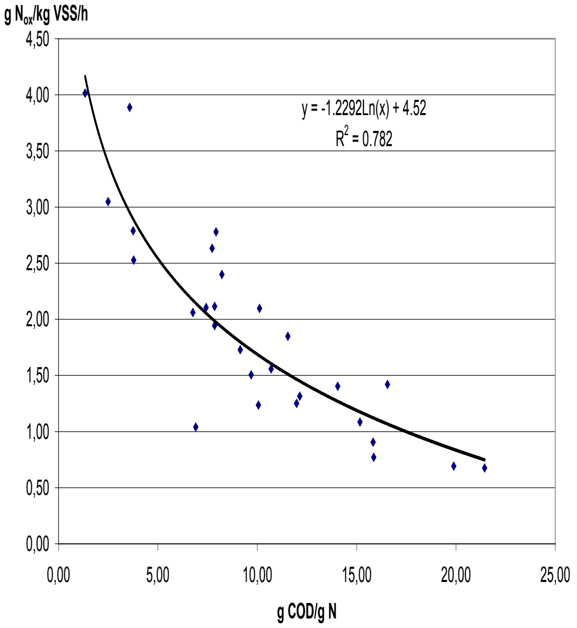

Fig. 11. Relation between COD/N ratio in crude wastewater and nitrification rate at Nowy Targ SBR-plant,1st quarter of 2005, 29 observations, prevailing temperature 6–10°C.

- The SBR operation has been defined as a "controlled, unsteady state activated sludge process" [18]. This in turn suggests that the risks for a wash out of nitrifiers may be controlled (and limited) thanks to the batch mode. This function is possibly enhanced by a short fill time in relation to the total cycle time.
- Most of the plants shown in Fig. 12 are operated with a limited amount of organic compounds in the crude wastewater — in relation to nitrogen. The abundance of observations at some of the plants allows for a study of the relation between nitrification rate and the COD/N-ratio (Fig. 11). These results are in accordance with findings by Choubert et al. [19]. This circumstance also accordingly supports the high nitrification rates observed at Nowy Targ and Nynäshamn.

5. Conclusions

- Operation of biological nitrogen removal has been demonstrated feasible even at low water temperatures at four different plants.
- The nitrification and denitrification rates at Nowy Targ plant were found to be substantially higher than literature indications. Accordingly has the nitrification rate at Nynäshamn WWTP been found to be high even at low water temperature. In both cases ratio COD/total N in the untreated wastewater to be lower than what may be expected at municipal plants.
- The observed short SRT at the different plants needed for nitrification may be related to a number of reasons: the theoretically needed SRT include safety factors, taking into consideration of the risk for a washout.
- The conditions to obtain and maintain nitrification are favoured by the controlled operation mode, and thus resulting in stable conditions even at SRT close to a true theoretic time (excluding the safety factor).
- Another circumstance that adds to the result is the fact that a simultaneous nitrification/denitrification takes place, resulting in an ongoing, but slower nitrification as the reactor mode moves from aerated into anoxic situation.
- Actually found aerated SRT may represent a shorter SRT than the actually efficient one.
- The partial nitrification at the Skaulo plant demonstrates that it is possible to both establish and maintain oxidation of nitrogen even at water temperatures = 2–4°C.

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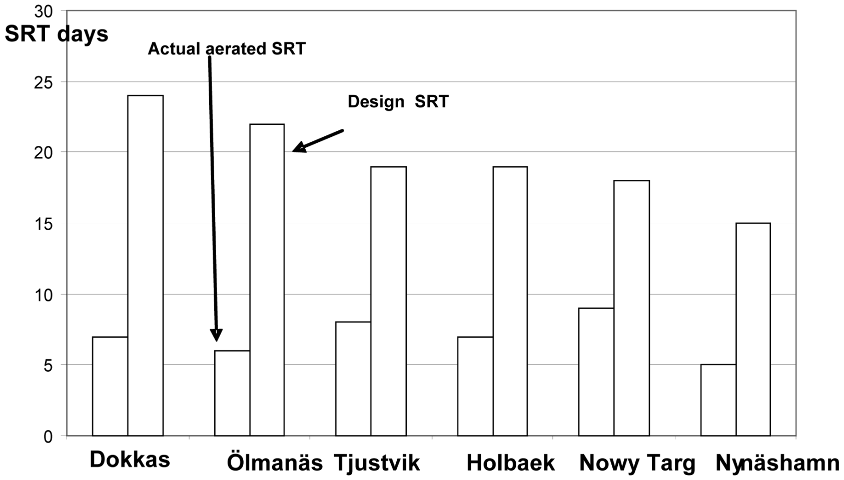

Fig. 12. Actually found aerated SRT: s at some plant operated with prevailing temperature 6–10°C, compared with the normally recommended design SRT (including a safety factor).

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