Environment Protection Engineering

Vol. 44 2018 No. 2

DOI: 10.5277/epe180212

KAMIL JANIAK[1, 2], STANISŁAW MIODOŃSKI[1], MATEUSZ MUSZYŃSKI-HUHAJŁO[1]

FAILURE OF THE SIDE-STREAM DEAMMONIFICATION PROCESS. RISK OF VIOLATION OF THE WWTP EFFLUENT QUALITY

Stable and efficient nitrogen removal is one of main goals of wastewater treatment. Applying deammonification, beyond many advantages, results in the risk of the WWTP effluent quality violation in case of the failure of the process. Then nitrogen load to activated sludge is increasing rapidly which could therefore lead to quality violation in activated sludge effluent. Simulation studies have been presented on the effect of deammonification failure on nitrogen removal performance in the case of a typical, medium sized WWTP (ca. 115 000 PE). The studies were based on the calibrated ASM1 model of real WWTP and a fictional scenario of implementing deammonification and subsequent failure. Implementing deammonification enables *SRT* optimization of the sludge retention time (*SRT*) in its main line thanks to lower nitrogen load. Two scenarios have been shown, considering or not optimization of the *SRT* in WWTP. The results show that *SRT* optimization leads to decrease in nitrifier mass and raises difficult issues in appropriate nitrogen concentration in the effluent.

1. INTRODUCTION

Development of wastewater treatment technologies through past decades allowed conscious protection of the aquatic environment from excessive destruction. The control of nitrogen emission through effluents from wastewater treatment plants (WWTPs) is one of the main instruments to prevent eutrophication of rivers and lakes. In the EU, implementation of Urban Waste Water Directive (92/271/EEC) is the legal basis for setting national discharge limits at 10–15 mg N/dm^3 depending on plant's size and area sensitivity. Many of existing WWTPs are reaching their technological capacity limits and only opportunity to meet these standards without

[1]Faculty of Environmental Engineering, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 507-370 Wrocław, Poland, corresponding author K. Janiak, e-mail address kamil.janiak@pwr.edu.pl

[2]Municipal Water and Sewage Company, Wrocław, ul. Na Grobli 14/16, 50-421 Wrocław, Poland.

expensive plant expansion are advanced biological nutrient removal (BNR) technologies for sludge reject water treatment, so called side stream treatment processes [1]. Reject water from sludge dewatering is a high-strength ammonium stream, with nitrogen load equal up to 25% of plant's daily load, low C:N ratio and elevated temperature [2], which makes conventional nitrification-denitrification processes inappropriate for its treatment. Implementing side stream treatment is also an opportunity to improve WWTP energy balance, as some of available technologies (especially deammonification) allows one to remove side stream N-load in more efficient way and might be a vital step towards energy neutrality of such facilities [3, 4]. However, treatment efficiency, especially nutrient removal may not be compromised as the imperative of wastewater treatment and meeting the effluent standards must always has the highest priority for the operators.

Deammonification is a novel solution for nitrogen removal via autotrophic and anaerobic ammonium oxidation using 1.32 mol of nitrite per 1 mol of NH_4-N oxidized in the Anammox reaction. Anammox microorganisms were discovered in the late 90s of 20th century and became an excellent alternative for existing solutions [5]. By 2014, over 100 full-scale implementations of this process were introduced into WWTPs all over the world and their number has rapidly been increasing due to obvious advantages such as lower oxygen demand, no external carbon requirements, low sludge production and high process rates [6]. Despite clear advantages, deammonification has also important drawbacks which cannot be neglected. Robust deammonification requires proper control of the partial nitritation to achieve appropriate nitrite to ammonium ratio and prevent excess nitrate production by inhibitions of selective nitrite oxidizing bacteria (NOB). Anammox biomass is very vulnerable for number of environmental factors such as dissolved oxygen presence, elevated free ammonia and nitrite concentrations, low temperatures, and many others [7]. These facts, combined with very low growth rates of the Anammox bacteria [8] leads to a conclusion that potential disturbances in side stream process operation may affect overall N-removal efficiency for a long time, resulting in significantly higher nitrogen loads returned to the mainstream reactor with reject water stream.

1.1. IMPACT OF SIDE STREAM PROCESS PERFORMANCE ON MAINSTREAM TREATMENT

As side stream treatment deammonification technologies are continuously developing, number of papers have been published related to various aspects of the matter. Main attention was usually paid to recognize biochemical issues and pathways of Anammox process itself and impact of potential inhibiting factors. Recently, as side stream deammonification topic became more and more explored, authors turned their attention to mainstream deammonification as the potential heir of conventional activated sludge (CAS) technology used for over 100 years [9]. Full-scale implementations of side stream deammonification facilities at many WWTPs were also followed by numerous papers on their operation results, technical aspects and potential advantages, especially considering improvement in N-removal efficiency, energy balance and other environmental impact such as greenhouse gases emission [10–14].

Unfortunately, association between implementing deammonification and operation of a mainstream CAS reactor is poorly described and not many detailed information is provided. Significant reduction of nitrogen load directed into mainstream treatment releases some optimization potential in CAS reactor operation, i.e., *SRT* reduction [15]. However, if the mainstream reactor is adopted to lower loads, disturbances in deammonification performance will result in the increase in returned N-load and may cause potential violation of the WWTP discharge limits for nitrogen.

An example of such situation can be found in report describing Strass WWTP after implementing deammonification. As presented in Fig. 1, side stream reactor operation problems resulted in higher load directed to main treatment line and, in effect, a rapid drop in plant's overall treatment efficiency by about 15% and 30% for NH_4-N and total N, respectively [16].

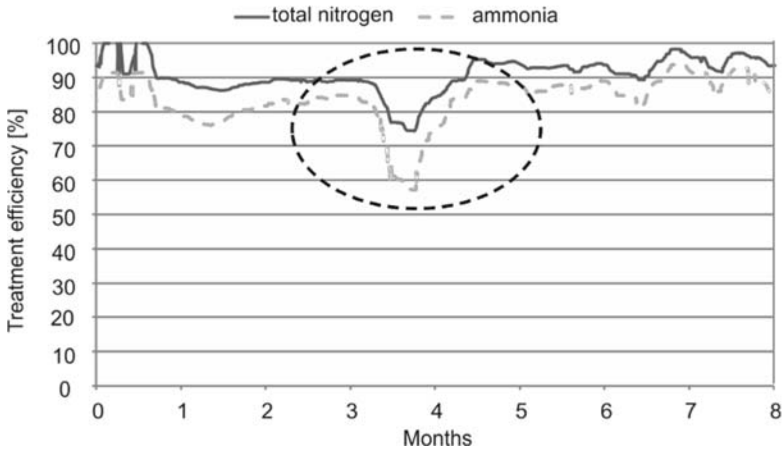

Fig. 1. STRASS WWTP N removal efficiency
after side stream deammonification (DEMON® technology) implementation;
the period of failure of the side stream process is marked with a dashed ellipse

As other authors report occurrence of sudden Anammox activity loss in full-scale systems due to various reasons [17, 18], such phenomenon may be a real threat for the WWTP effluent quality. Another confirmation of the importance of highlighted problem may be found in a detailed survey of 14 full-scale deammonification facilities performed by Lackner et al. [6]. As it turned out, 20–30% of total disturbances experienced in these plants had significant impact on the process performance, mostly considering incidents connected with pH-shock and high influent solids' concentrations [6].

1.2. INFLUENT N-LOAD IMPACT ON NITRIFIER MASS IN A MAINSTREAM TREATMENT LINE

According to the activated sludge model (ASM) [19], the net growth of nitrifiers (M_{nit}, g COD/day) in activated sludge is proportional to nitrogen load (L_N, g N/day) and can be estimated by the following equation:

$$M_{\text{nit}} = Y_A \frac{1}{1 + b_A SRT} L_N \tag{1}$$

where SRT is the sludge retention time (day), Y_A is the yield coefficient (g COD/g N), b_A is the decay rate (1/day).

Total mass of nitrifiers ($M_{\text{nit, total}}$, g COD) in activated sludge depends on SRT and, in long term (T close to SRT) on the average nitrogen load ($L_{N,\text{av}}$) and is given by:

$$M_{\text{nit, total}} = Y_A \frac{1}{1 + b_A SRT} L_{N,\text{av}} SRT \tag{2}$$

As SRT in BNR systems should be longer for proper treatment effects, diurnal and short-term variations in nitrogen load have limited consequences on the overall ammonium removal. The mass of nitrifiers is fluctuating very slightly because the average long-term load is practically constant (Fig. 2).

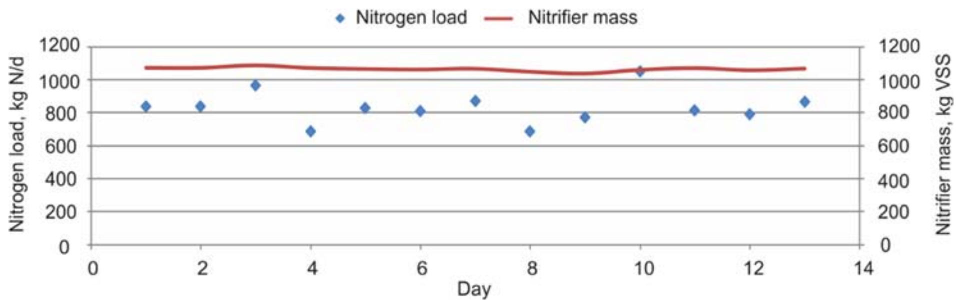

Fig. 2. Time dependences of the nitrogen load and nitrifier mass in the reactor (simulations based on the WWTP model, $T = 15$ °C, $SRT = 15$ days)

As mentioned before, in the case of implementation of deammonification, long-term average nitrogen load is lowered substantially and permanently and, in consequence, the mass of nitrifiers in the mainstream reactor decreases permanently within few weeks (Fig. 3). The nitrification potential adjusts then to current N-load and may be too low in case of the increase of nitrogen load due to deammonification failure. As nitrifiers belong to slowly growing bacteria, build-up of sufficient nitrifier mass may take weeks and during this time risk of the violation of discharge limits exists.

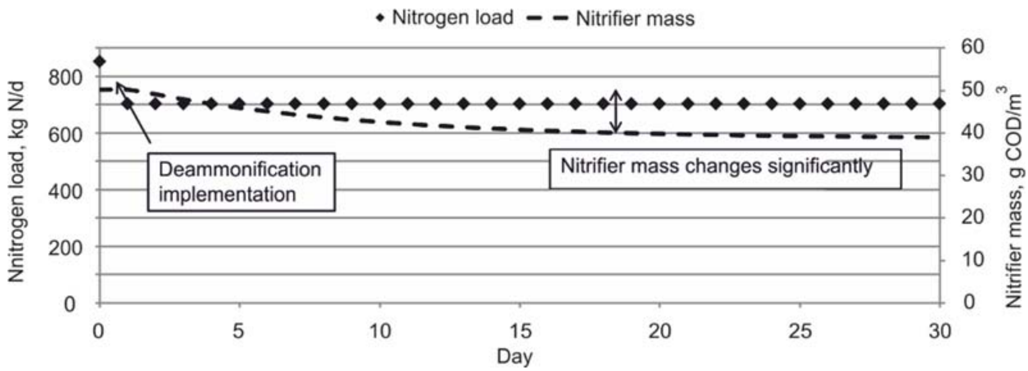

Fig. 3. Time dependences of the nitrogen load and nitrifier mass in the reactor (simulations based on the WWTP model, T = 15 °C, SRT = 15 days, 20% of nitrogen load removed in the side-stream deammonification reactor)

2. MODEL AND PLANT DESCRIPTION PRIOR TO DEAMMONIFICATION IMPLEMENTATION

A calibrated ASM1 model, representing one of Polish municipal WWTPs (115 000PE) was used in the study. This tool allowed one to model autotrophic and heterotrophic reactions, with a facultative consumption of oxygen or nitrate as an electron acceptor, without phosphorus removal. The model was calibrated based on collected operational data and intensive measuring campaign (two weeks) under steady-state operating conditions. Model accuracy was satisfactory, despite quite poor results for nitrate concentrations, and could be used in this study.

The plant is composed of two parallel anoxic-oxic reactors. The model does not include primary sedimentation. Wastewater characteristics after primary treatment are presented in Table 1. Plant is operated at the *SRT* ranging from 15 to 25 days depending on the wastewater temperature.

Table 1

Raw wastewater characteristics without deammonification implementation

Parameter	Flow [m^3/day]	TN [g N/m^3]	TN [kg N/day]	COD [kg O_2/day]	BOD_5 [kg O_2/day]	Alkalinity [eq/m^3]
Value	14 000	61	854	7434	4269	not limited

Main plant parameters are presented in Table 2. Raw wastewater composition and WWTP parameters used in this study are real data from existing Polish WWTP.

Table 2

Plant characteristics

Parameter	*SRT* [day]	Aeration volume [m^3]	Anoxic volume [m^3]	Nitrate recirculation flow [m^3/day]	Oxygen concentration [g O_2/m^3]
Value	15–25	13 811 (HRT ≈ 1day)	7 944 (HRT ≈ 0.57day)	69 120	1.5

HRT – hydraulic retention time.

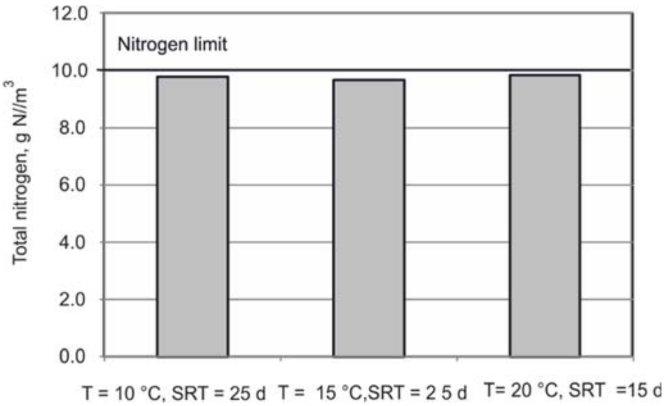

Fig. 4. Average total nitrogen concentrations in the WWTP effluent at various temperatures (simulation results)

The parameters presented in Tables 1 and 2 were used to simulate the effluent quality prior to the implementation of side-stream deammonification. In this configuration, WWTP struggles to obtain proper effluent quality standards. Average total nitrogen concentration in WWTP effluent was always above 9.5 g N/m^3 despite temperature and process parameters (Fig. 4), where the total nitrogen limit in the effluent is 10 g N/m^3 without ammonium limitation. When temperature is lower (i.e., 10 °C or 15 °C), the required *SRT* is 25 days, at 20 °C the plant is operated with a lower *SRT*. The concentration of dissolved oxygen is kept at 1.5 g O_2/m^3. Below this value, ammonium concentration in the effluent increases, while above this value, the nitrate concentration in effluent increases. For the *SRT* equal of 15 days, the mass of nitrifiers is 830–1360 kg COD depending on temperature.

The total nitrogen effluent concentration nearly exceeds the limits set by Polish and the EU legislation for WWTPs of similar size and may suggest that this facility has reached its nitrogen removal capacity or needs deep optimization. No matter the reason, such situation is unfavorable and requires remedial actions. Any potential disturbance in nitrogen removal may cause violation of discharge limits. In this case, implementing a side stream deammonification process is natural alternative for plant extension and way to improve the overall treatment efficiency.

3. DEAMMONIFICATION IMPLEMENTATION SCENARIO

The simulation failure is based on fictional assumptions that nitrogen load in reject water from sludge dewatering constitutes 20% of daily WWTP N-load being fully removed in the deammonification reactor with nitrate production according to the process stoichiometry. Wastewater characteristics after implementing deammonification is shown in Table 3.

Table 3

Wastewater characteristics after implementing deammonification

Parameter	Flow [m^3/day]	TN [g N/m^3]	TN [kg N/day]	$N\text{-}NO_3$ [kg N/day]	COD [kg O_2/day]	BOD_5 [kg O_2/day]	Alkalinity [eq/m^3]
Value	14 000	49	683	18	7379	4234	not limited

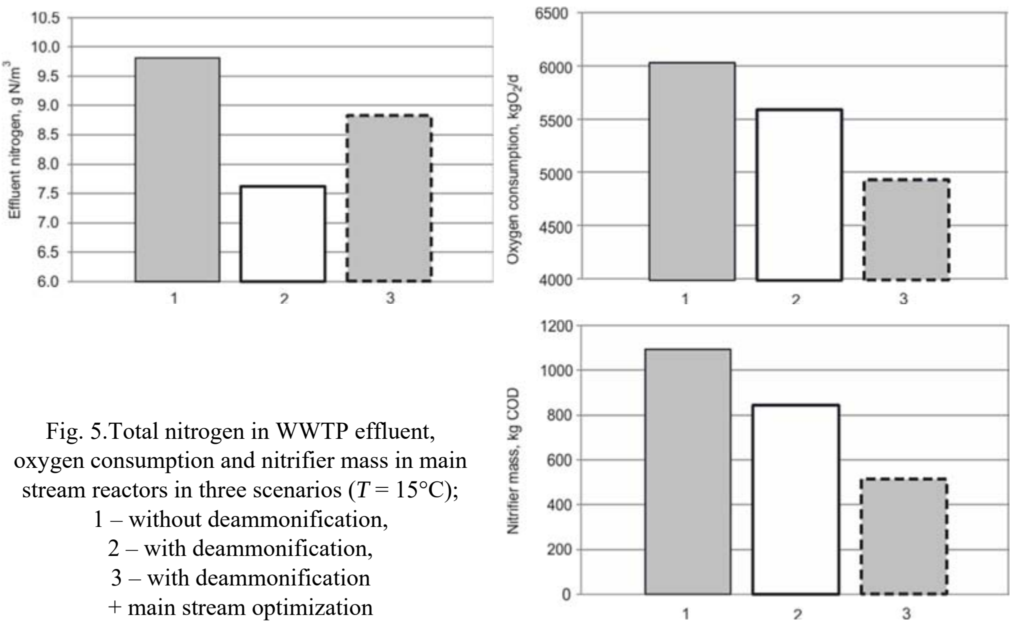

Fig. 5.Total nitrogen in WWTP effluent, oxygen consumption and nitrifier mass in main stream reactors in three scenarios (T = 15°C);
1 – without deammonification,
2 – with deammonification,
3 – with deammonification + main stream optimization

Before implementation, nitrogen removal was not efficient (Fig. 5). Side stream deammonification resulted in significant decrease in the concentration of total nitrogen in the effluent (from 9.7 to 7.6 g N/m^3), lower overall plant oxygen consumption (by 7%) and lower nitrifier mass in the CAS reactor (by 23%). Low nitrogen concentration in effluent created possibility of optimization of the mainstream reactor energy use by lowering sludge retention time to 15 days at 10 °C and 8 days at 15 °C. In both situations, the total N concentration in the effluent was 8.3 g N/m^3 in the coldest season, and 8.8 g N/m^3 at moderate temperatures. Due to the *SRT* change, at all temperature ranges the oxygen consumption was reduced by 18% (100% – base scenario without deammonification), but at the cost of the overall nitrifier mass decrease by 53% (Fig. 5).

Implementing side stream deammonification leads to significant improvement of WWTP effluent quality but has limited influence on overall plant oxygen consumption. Potential energy saving can be achieved by further optimization, i.e., *SRT* reduction, but at the cost of nitrifying biomass present in mainstream reactors.

4. SCENARIOS OF DEAMMONIFICATION FAILURE

Two different failure scenarios have been presented in the paper:

Scenario 1. Deammonification failure in the plant after *SRT* optimization (T = 10 °C, *SRT* before failure 15 days, *SRT* after failure 25 days).

Scenario 2. Deammonification failure in a plant without *SRT* optimization (T = 10 °C, *SRT* before failure 25 days, *SRT* after failure 25 days).

Both scenarios assume that deammonification failure is a long-term process (period of one month). In this paper, only low temperature (10 °C) cases were studied as those at higher temperatures have similar consequences with shorter recovery times and faster WWTP effluent quality violation.

Figure 6 presents the course of total nitrogen in the effluent after deammonification failure for scenario 1. Before failure, total nitrogen is kept at very low level (8.3 g N/m^3) despite low temperature and low *SRT* and no problems occur with the fulfilment of the effluent standards. As the deammonification fails, the nitrogen load to mainstream reactor increases immediately and the total nitrogen in WWTP effluent increases to 12.7 g N/m^3 within less than 3 days. Due to deammonification failure, WWTP operators change the *SRT* from 15 to 25 days to preserve more nitrifiers in reactors. The simulation studies revealed that higher *SRT* did not have much better effect on recovery time, furthermore excessive increase in the concentration of suspended solids above some level have negative impact on the process of biomass separation in secondary clarifiers. An increase in the oxygen concentration also had no impact on the recovery time. Upon the increasing oxygen concentration, nitrates concentration in the effluent increased and no important effect on the growth rate of nitrifiers was observed.

Despite the *SRT* change to 25 days after failure, the nitrifier mass is insufficient to nitrify all ammonium which leads to violation of the quality standard for 30 days. As mentioned, long recovery time relates to low nitrifier growth rate.

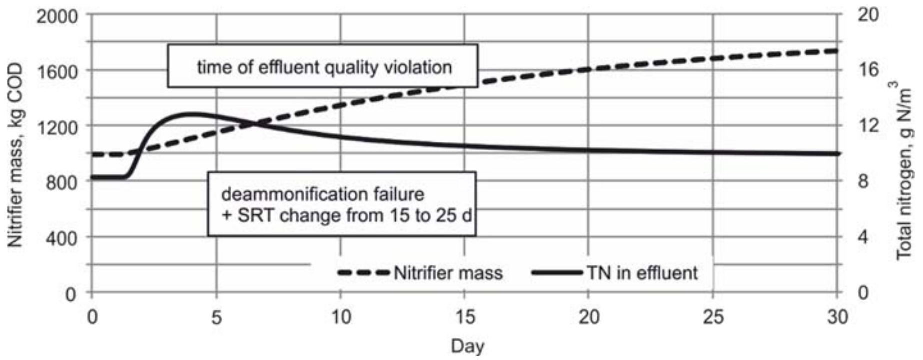

Fig. 6. Total nitrogen in the WWTP effluent
and failure of the nitrifier mass after deammonification (scenario 1)

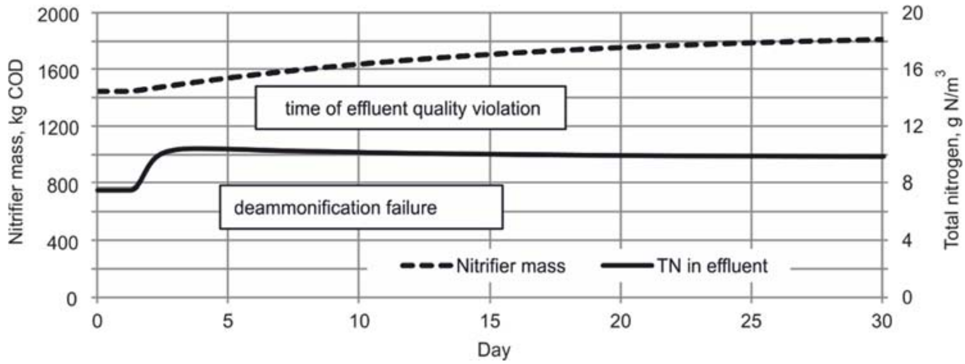

Fig. 7. Total nitrogen in the WWTP effluent and failure
of the nitrifier mass after deammonification (scenario 2)

In scenario 2, where *SRT* after implementing deammonification does not change, the total nitrogen concentration increases, however the observed peak is much lower, reaching 10.4 g N/m^3 (Fig. 7). Violation of the effluent quality standards still can be noticed, but for a shorter time due to much higher mass of nitrifiers in the mainstream reactors. When the *SRT* is kept 25 days, the mass of nitrifiers is by ca. 40% higher than that in the same plant operated at *SRT* of 15 days.

5. CONCLUSIONS

Number of full-scale implementations, emerging new patented technologies and wide scope of research projects connected with deammonification process has proven its usefulness as an appropriate method for side stream treatment and great alternative for traditional methods. Nevertheless, interactions between side stream deammonification and mainstream CAS reactor have not been sufficiently investigated. It seems that this the impact of the deammonification failure on the overall WWTP efficiency has been examined probably for the first time.

Simulations studies performed using the calibrated ASM1 model of a medium-size Polish WWTPs reveal that potential implementing side stream deammonification will result in a decrease of the effluent total nitrogen concentration from 9.7 to 7.6 g N/m^3 and lower the overall plant oxygen consumption by 7%. Lower N-load directed to main stream reactor releases also some optimization potential for further improvements in the energy balance. After potential *SRT* optimization the total nitrogen concentration in the effluent did not exceed 9 g N/m^3 and oxygen consumption was reduced by 18%. As the nitrifier mass in CAS reactor is strictly connected with the influent N load and *SRT*, implementing a side stream treatment reactor resulted in a 23% decrease of nitrifying biomass while further optimization led to a 53% decrease with respect to that before deammonification.

Scale of violation of effluent quality standards can be lower if plant operators keep conservative *SRT* and other parameters in activated sludge reactors (scenario 2 – no plant optimization after side stream implementation). However, it is operator's decision to choose if energy savings or lower process stability is more important. Despite potential risks, advantages of such optimizing action may be very rewarding. Nevertheless, proper assessment of risk is especially important when nitrogen limit must be fulfilled in every sample, so even violation limited in time may lead to financial penalties.

Above all, robust side stream deammonification process plays a key role in safe WWTP optimization which guarantees huge savings in operation costs of the whole plant without any potential threats for treatment efficiency and all operators should be aware of consequences of a potential failure .

ACKNOWLEDGEMENTS

The authors gratefully acknowledge co-funding from the National Centre for Research and Development (grant No. PBS2/B9/25/2014) and Municipal Water and Sewage Company in Wrocław.

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