VATTEN 64:121–128. Lund 2008

NITROGEN REMOVAL EFFICIENCY AND NITRIFICATION RATES AT THE SEQUENCING BATCH REACTOR IN NOWY TARG, POLAND

Kvävereduktion och nitrifikationshastigheter vid SBR-anläggningen i Nowy Targ, Polen

by STIG MORLING, Royal Institute of Technology, Stockholm, Sweden and SWECO VIAK AB, P.O. Box 34044, SE 100 26 Stockholm, Sweden
e-mail: stig.morling@sweco.se

Abstract

Biological nitrogen removal by the use of Sequencing Batch Reactors (SBR) is today an accepted and well proven model. The Nowy Targ SBR plant has been in operation for 15 years, and comprehensive performance data are available for assessment. This paper focuses on the 2005 year operation, characterised by high organic and nitrogen loading and also very high chromium loads. The available performance data allows an analysis of both nitrification rates and denitrification rates, along with an assessment of the temperature influence. The results reveal a high nitrification rate even at temperatures in the range 6–10°C, close to 2 g N/kg VSS/h, a clear relation between nitrogen loading and nitrification as well as denitrification. Furthermore a relation between the COD/N- ratio and the nitrification rate is found: the rate increases with decreasing COD/N-ratio.

Key words – Nitrogen, Nitrogen removal, Nitrification rate, Denitrification rate, SBR

Sammanfattning

SBR-tekniken har använts sedan början av 1980-talet som en pålitlig modell för att åstadkomma biologisk kvävereduktion. I denna studie presenteras resultat från en av de större SBR-anläggningarna i Europa, Nowy Targ i södra Polen. Anläggningen har varit i drift sedan mitten av 1990-talet och behandlar förutom kommunalt spillvatten stora mängder avloppsvatten från kromgarverier i staden. Driftsresultaten från år 2005 har använts i denna studie för att belysa kvävereduktionen. Resultaten visar på hög nitrifikationshastighet även vid låga temperaturer; vid 6–10°C har nitrifikationshastigheten varit nära 2 g N/kg VSS/h. Materialet möjliggör också att studera nitrifikations- och denitrifikationshastigheten relaterade till kvävebelastningen. Det kan också konstateras, att nitrifikationshastigheten är omvänt proportionell mot kvoten COD/N i inkommande vatten.

Introduction

The wastewater treatment plant in Nowy Targ in southern Poland is one of a large number of modern plants built during the last decade in Eastern Europe to improve the water environment. The majority of Poland's water bodies belong to rivers connected to the Baltic Sea. This is one reason why a number of these wastewater treatment plants were built with Swedish financial support. This was also the case with the Nowy Targ plant. As it was built as a Sequencing Batch Reactor it draws considerable attention from the scientific world. A number of studies resulting in master theses were performed during the first five years of operation; see for instance Johansson Å. and Salberg H. (1996) and Sharif A. (1998). Also other studies were performed to understand the performance; see for instance Hultman B. et al. (1999) and Mikoz, J. et al. (2001). A special condition at the plant was soon found, being rather "unique": an unforeseen heavy loading of wastewater from chromium based tanneries occurred after only about two years of operation. This load has since then increased through-

Table 1 *Summary of the original Nowy Targ SBR plant design loadings and the actual load figures for first 3 quarters of 2005.*

Variable	Design values	2005 year values, 1st quarter	2005 year values, 2nd quarter	2005 year values, 3rd quarter
Number of observations	n.a.	29	30	25
Daily flow, m^3/d	21,000	15,646	17,700	16,086
Design flow per hour, m^3/h	1,210	910	960	920
COD, kg/d	11,050	15,501	19,033	24,610
BOD_5, kg/d	6,975	7,345	7,657	9,012
SS, kg/d	2,230	7,848	11,496	14,093
Total N, kg/d	567	1,986	2,309	2,167
Total P, kg/d	181	145	184	222
Cr, kg/d l	11	69	89	166

out the years. Some of the studies performed focused on the possible inhibition of nitrogen removal due to the chromium impact. However, after some "acclimatisation" time (about one year) no inhibition effect was identified. The chromium may even act as a precipitant for phosphorus; see Morling (2007).

Objectives

This paper focuses on the nitrogen removal performance, especially as found in year 2005 when the plant operated at full or substantially above design load capacity. These influent conditions allow an assessment of the actual nitrification and denitrification rates related to varying loads and temperatures.

Materials and Methods

Design data

The plant was designed for about 120 000 pe. A simplified flow sheet of the plant is shown in Figure 1.

The main (original) design data for the plant are summarized in Table 1. Along with these figures are presented the load figures 2005, from the first through to the third quarters.

The plant was initially operated with a 6 hour cycle as illustrated in Figure 2. However, as the peak loading from the industries occurred at about 09.00 hours in a regular pattern, one of the reactors was overloaded, while the others received a lower load. This situation was mitigated by changing the cycle time to 5.5 hours; as shown in Figure 3.

Sampling and analysis

The presented pollution data has been analysed in accordance with the Polish Standards (PN) that generally comply with the corresponding Standard Methods. All sampling and some of the analyses have been performed on site by the plant staff. Sampling of inlet wastewater has been done by automatic sampler, based on a flow proportional operation for the early years of operation. Later, the sampling mode has been altered to a time based composite sampling. Effluent sampling has been

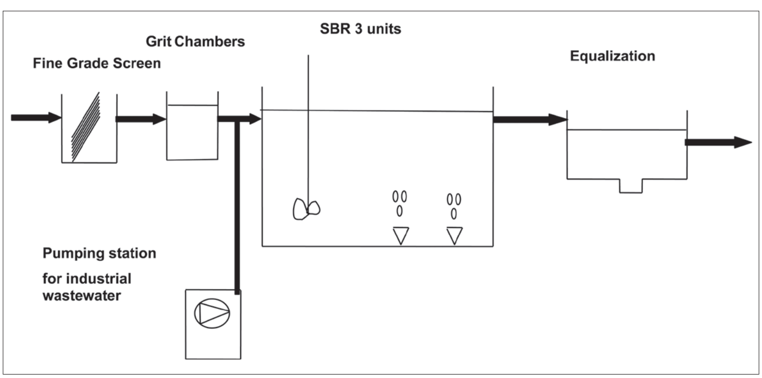

Figure 1. *Simplified flow sheet of Nowy Targ SBR plant.*

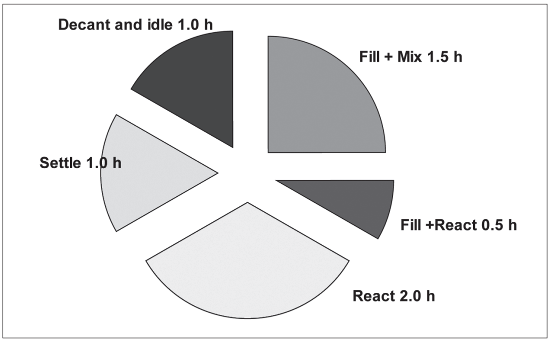

Figure 2. *Nowy Targ SBR plant operation cycle 1996–1999.*

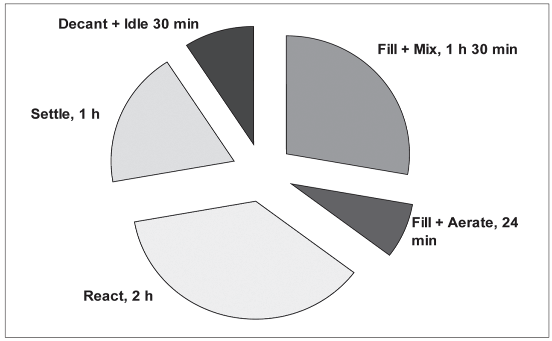

Figure 3. *Nowy Targ SBR plant operation cycle from 2000.*

based on automatic, flow proportional sampling. All data are based on the normal sampling and operation control at the plant (Unpublished performance data from Nowy Targ WWTP, year 2005).

Results and discussion

Nitrification

The documentation from the Nowy Targ SBR plant is very comprehensive and includes information of the plant operation at different loadings. This makes it possible to analyse and calculate the loading and the specific nitrification rate with an acceptable accuracy.

The specific nitrification rate does not seem to be deteriorated by low water temperature at the Nowy Targ plant. A substantial nitrification has taken place throughout the year. Another way to address the nitrification capacity is to relate the nitrification rate to the nitrogen loading. In Figures 4 to 6 the relationships are evaluated for the three quarter year periods. The most suitable way to express the relation is expressed by a logarithmic function; see Equation (1).

$$\text{g } N_{ox}/\text{kg VSS/h} = a^* \text{ Ln(N load)} - b \qquad (1)$$

This model is used for the results for the first three quarters from Nowy Targ in 2005.

The chosen functional model fits well for both the 1st and 2nd quarter results, with high regression factors, while for the 3rd quarter the regression factor is substantially lower; see Table 2.

It is found in these results that the nitrification rate is proportional to the nitrogen loading. The relation seems to be clear throughout the studied period. A similar pattern with respect to the nitrification rate is found at the other SBR plants working below the design conditions; see Morling (2008). Now is this entirely true? The matter is not easily resolved to due to a basic reason: As long as the nitrification is complete the potential nitrification rate is probably higher than the one found by analysing the figures. The main reason for this situation is most likely that the potential nitrification capacity in the system is not fully used. By studying the nitrification rate versus the nitrogen loading a relation is accordingly found. It is clear that the nitrification rate is increasing with an increase of the nitrogen load. This statement is also in accordance with the findings presented by Choubert et al. (2005).

Another way to analyse the nitrification rate variation is to compare it with the variation of the ratio COD/TKN in the untreated wastewater. Choubert et al. (2005) present results on low COD/TKN ratios (6:1) and simulations made with the ASM1 model for "normal" COD/TKN ratio (11.5:1). They also propose a

Table 2. *Nitrification rates, temperature ranges and regression factors. Three quarters, 2005, see also figures 4–6.*

Period	Temperature range, °C	Nitrogen load range, kg N/d	Nitrification rate range, g N_{ox}/kg VSS/h	R^2
1st quarter 2005	6–10	1000–4600	0.6–4.0	0.956
2nd quarter 2005	10–18	1000–5200	0.9–4.6*	0.8566
3rd quarter 2005	15–20	1000–3400	0.7–3.1	0.496

* One extreme value Nr > 6.5 g Nox/kg VSS/h is excluded in the presentation

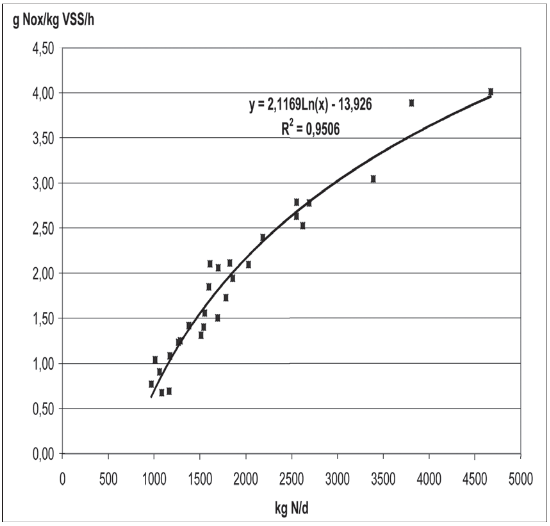

Figure 4. *Nowy Targ SBR plant Nitrogen load and specific nitrification rate, 1st quarter 2005. Data fitted to a logarithmic function, (29 observations).*

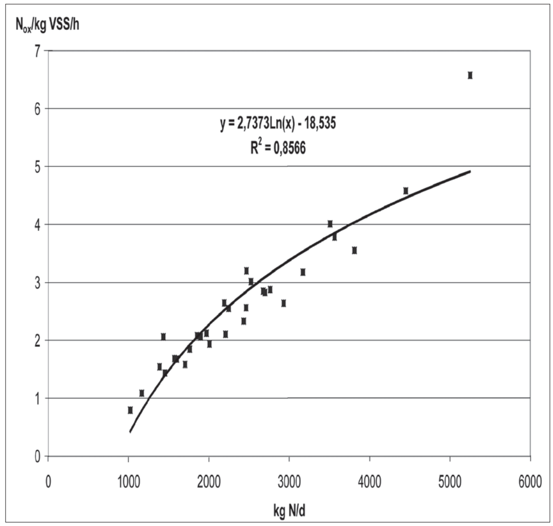

Figure 5. *Nowy Targ SBR plant Nitrogen load and specific nitrification rate, 2nd quarter 2005. Data fitted to a logarithmic function, (30 observations).*

relation for the mass of nitrifying bacteria with the added amounts of nitrogen per day; see Equation (2). This equation is valid for a steady state situation, and not for any dynamic situation, such as the SBR cyclic operation may represent (The symbols used by Choubert 2005 are found in the equation):

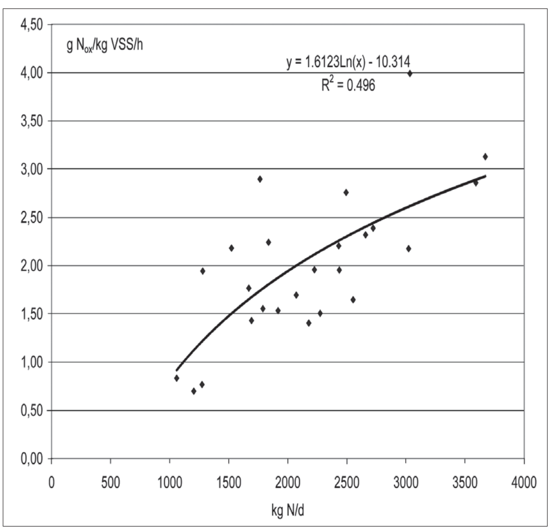

Figure 6. *Nowy Targ SBR plant Nitrogen load and specific nitrification rate, 3rd quarter 2005. Data fitted to a logarithmic function, (25 observations).*

$$MX_{B,A} = Y_A * \Phi N_{nit} / (b_A + 1/SRT) \qquad (2)$$

where

$MX_{B,A}$ = mass of nitrifying bacteria in the reactor, in g COD
Y_A = yield of nitrifying bacteria, in g $COD_{produced}$/g $N_{nitrified}$
ΦN_{nit} = nitrified nitrogen mass per day, in g N/d
b_A = decay rate of nitrifiers, in d^{-1}
SRT = solids retention time, in days.

The equation is logical and describes theoretically the build up of nitrifiers. Some remarks may be given: The equation implies that the water temperature is constant (possibly included in the steady state conditions) and that the relation between autotrophic and heterotrophic mass in the system.

Eckenfelder (1989) presents an equation to estimate the fractions of nitrifiers in the biomass; see Equation (3):

$$f_N = Y_a * N_r / (Y_a * N_r + Y_H * C_{ox}) \qquad (3)$$

where

f_N = fraction of nitrifying bacteria in the reactor, in g COD
Y_a = yield of nitrifying bacteria, in g $COD_{produced}$/g $N_{nitrified}$
N_r = nitrified nitrogen mass per day, in g N/d
Y_H= yield of heterotrophic bacteria, in d^{-1}
C_{ox} = oxidised substrate.

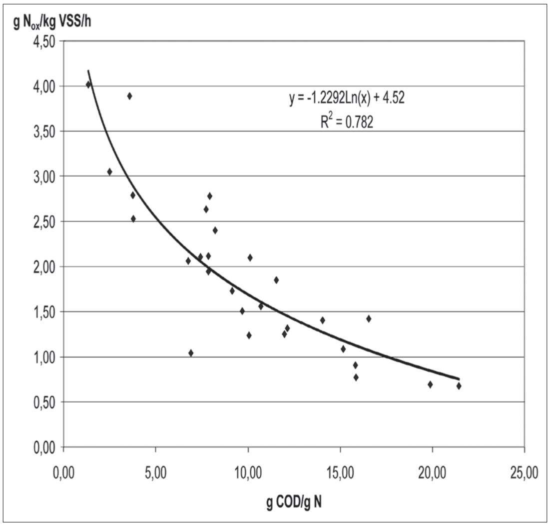

Figure 7. *Nowy Targ SBR plant COD/N ratio and specific nitrification rate, 1st quarter 2005. Data fitted to a logarithmic function, (29 observations).*

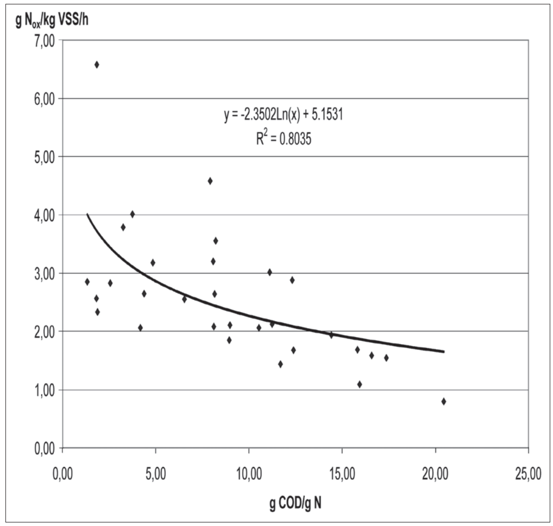

Figure 8. *Nowy Targ SBR plant COD/N ratio and specific nitrification rate, 2nd quarter 2005. Data fitted to a logarithmic function, (30 observations).*

This equation is another way to express that the ratio COD/N influences the nitrification rate.
For the evaluated three quarters in 2005 at the Nowy Targ plant the relation between COD/TKN ratio and the specific nitrification rate are presented in Figures 7 to 9. The "best" relation is found to be a logarithmic function, even though the relation is not as "strong" as found in the previous model – nitrification rate versus nitrogen loading.

Some important operation conditions would be kept in mind when addressing these results:

1. The composition of the raw wastewater in Nowy Targ changes over time – both in a short and an extended perspective, due to the variations in the tanneries activities within the catchments area. This is reflected in both the variations in the wastewater strength and the variation in pollution ratios. The latter statement is not limited to the COD/TKN ratio; similar variations are found for all pollution variables that are measured regularly;
2. The presented periods 1st, 2nd and 3rd quarters in 2005 cover a temperature span, as presented in Table 2;
3. The SBR facility is operated with a change of the phases in the SBR-cycle, principally following the actual loading of the plant. The main change is the aerated part of the cycle varying from 10.9 h/day/reactor to 15.1 h/day/reactor. The shortest aeration time represents a "low load" situation when the plant is operated below the original design level; and the longest aeration time represents "peak load situations".
4. The typical total solids retention time (SRT) has been in the range 15 – 20 days, and the "aerated" SRT has been less than 10 days in all cases.

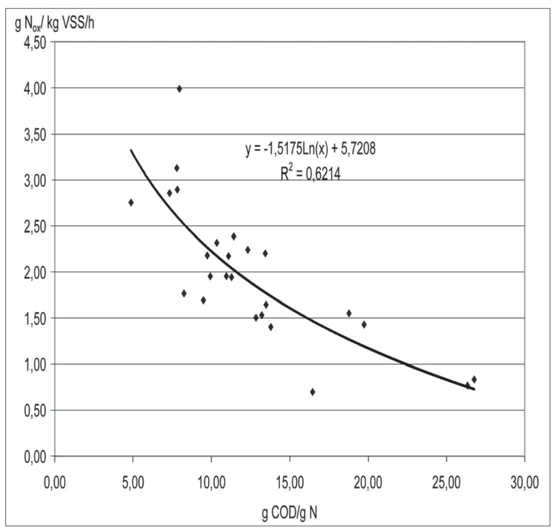

Figure 9. *Nowy Targ SBR plant COD/N ratio and specific nitrification rate, 3rd quarter 2005. Data fitted to a logarithmic function, (25 observations).*

Table 3. *Nitrification rates and regression factors at different COD/TKN ratios and temperature ranges for the three quarters at Nowy Targ plant in year 2005. See also figures 7–9.*

Period	Temp. range (°C)	Nitrification rate (g N_{ox}/kg VSS/h)			R^2
		COD/TKN=5 g/g	COD/TKN=10 g/g	COD/TKN= 15g/g	
1st quarter 2005	6–10	2.5	1.6	1.1	0.782
2nd quarter 2005	10–18	3.0	2.2	1.5	0.8035
3rd quarter 2005	15–20	3.3	2.2	1.5	0.6214

Now, would this way to address the Nowy Targ results provide a better indication of a temperature dependent nitrification rate? Table 3 summarises the results from the three quarters compared with the prevailing temperature intervals.

This way to address the nitrification rate shows an influence of water temperature. While the second and third quarters show rates with high degrees of similarities the rates found during the first quarter are substantially lower. For all ratios COD/TKN the nitrification rate is 25 to 27 % lower than for the other two quarters. Another way to illustrate the simultaneous nitrification/denitrification is shown in Figure 10. The figure is based on a full scale test plant operation in Rock Falls, Illinois, operated by Aqua Aerobics Systems Inc, Rockford, Illinois. The pilot operation was running in 1986 and 1987 (unpublished data provided by Aqua Aerobic). The figure demonstrates the operation cycle modes – Filling, Mixing, Aeration and React, as well as the ammonia nitrogen and nitrate nitrogen concentrations versus process time. The key to understanding the simultaneous nitrification/denitrification is to observe the variations of the nitrate nitrogen concentrations versus time: Regardless of the ambient conditions in the reactor – aerobic or anoxic the nitrate nitrogen level is kept below 2 mg N/l.

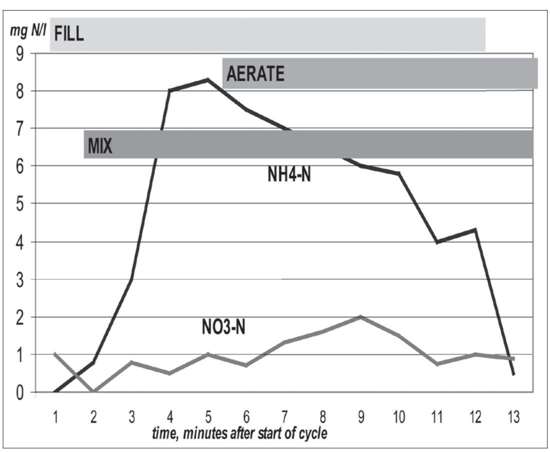

Figure 10. *Nitrogen compound levels during an SBR-cycle (with courtesy of Aqua-Aerobic Systems Inc.).*

Denitrification

The denitrification has not been found to be a limiting factor for the total nitrogen removal at the Nowy Targ plant. However, the situation, at this plant during the first years of operation with mainly municipal wastewater and later on changing into a heavy load from the tanneries revealed some specific conditions: the change includes effects of a change of the COD/total N ratio (as a mean value) from lower to higher figures; and a substantially higher concentration of both P and Cr in the raw wastewater. As discussed by Sharif A. (1998) and Morling (2007) these changes have not affected the performance in a detrimental way. The amounts of easily degradable organic material, expressed as BOD_5 are found "normal" or even lower than "normal" related to the total N load, as seen in Table 4.

However, no significant limitation on the denitrification may be derived from this ratio. At the Nowy Targ plant the cycle time for a "true" denitrification is rather short, and would indicate a very high denitrification rate. In Table 5 calculated denitrification rates at the plant during three quarters in 2005 are presented; thus the same time as the nitrification rates have been examined. The calculations of the denitrification rates are

Table 4 *Ratio BOD_5: Total N in raw wastewater at the Nowy Targ SBR plant, three quarters 2005 (kg/kg).*

	2005, 1st quarter	2005, 2nd quarter	2005, 3rd quarter
Nos of observations	26	27	25
Max value	9.41	7.5	9.86
Mean value	4.54	3.8	4.66
Median value	4.35	3.01	4.07
Min. value	0.98	0.92	2.25
Standard deviation	2.13	1.43	2.03

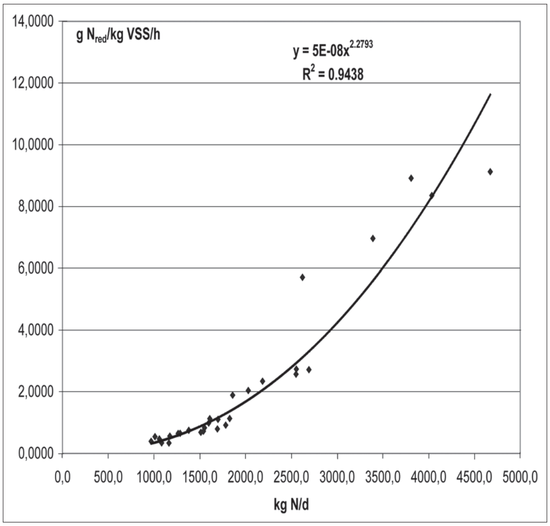

Figure 11. *Nowy Targ SBR plant relation Nitrogen load and specific denitrification rate, 1st quarter 2005. Data fitted to a power function, (29 observations).*

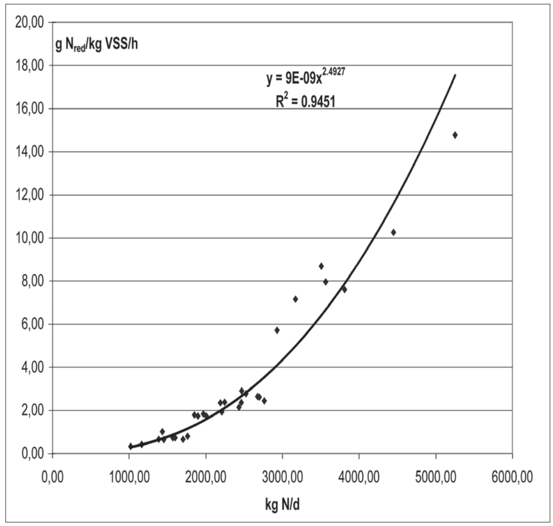

Figure 12. *Nowy Targ SBR plant relation Nitrogen load and specific denitrification rate, 2nd quarter 2005. Data fitted to a power function, (30 observations).*

based on the actually removed amounts of nitrogen through denitrification as presented in the following:

$$N + N_2O\text{-}N = \text{Total } N_{discharge} - NO_3\text{-}N; \qquad (4)$$

The "anoxic time" used to calculate the specific denitrification rate is based on the "modified" anoxic SRT (Solids Retention Time): The non aerated fill and react times in the cycle + 50 % of the time for settling. As discussed above this assumption is deemed more realistic than using only the non aerated react times. Another question to be raised is to what extent even this assumption is too "conservative". The very complex environment in the reactor promotes most likely a "simultaneous" nitrification/denitrification to occur. This phenomenon seems to occur in most full scale SBR plants; whereas the same pattern is not found in a bench-scale test operation. This matter would explain the very high maximum denitrification rates found in the Nowy Targ plant; see Table 5 and Figures 11 to 13. Subsequently, the actual denitrification time in the Nowy Targ plant may be longer than the theoretically calculated ones, and as a

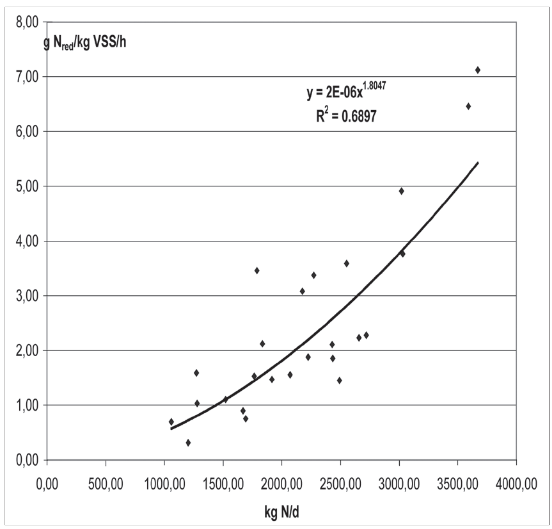

Figure 13 *Nowy Targ SBR plant relation Nitrogen load and specific denitrification rate, 3rd quarter 2005. Data fitted to a power function, (25 observations).*

Table 5 *Denitrification rates, temperature ranges and regression factors potency-normal functions at Nowy Targ SBR plant.*

Period	Temperature range, °C	Nitrogen load range, kg N/d	Denitrification rate range, $g\ N_{ox}/kg\ VSS/h$	R^2
1st quarter 2005, 29 obs.	6–10	1000–4600	0.34–9.12	0.9438
2nd quarter 2005, 30 obs.	10–18	1000–5200	0.32–14.7	0.9451
3rd quarter 2005, 25 obs.	15–20	1000–3400	0.32–7.12	0.6897

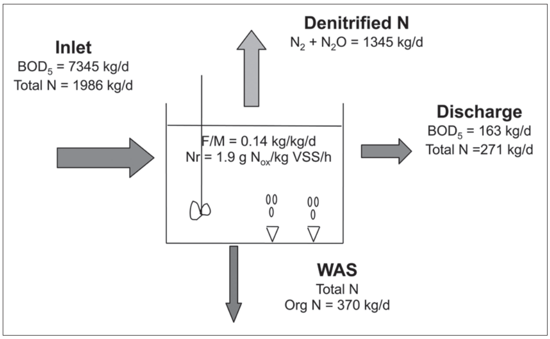

Figure 14. *Nitrogen balances and specific nitrification over the Nowy Targ SBR plant, 1st quarter 2005, 29 observations, water temperature 6 – 10°C.*

consequence the indicated maximum denitrification rates may be too high. For other SBR plants the evaluated denitrification rates are more "normal" and comparable with general findings, see Morling (2008). A Nitrogen balance is possible to present for the operation of the Nowy Targ plant. In Figure 14 such a balance is shown for the first quarter of 2005, based on 29 observations.

Conclusions

The nitrogen removal at the Nowy Targ SBR plant has been stable and reached consistently high levels throughout its years of operation. The current nitrogen load, to a large extent caused by the tannery wastewater is beyond the design load levels. Nevertheless the performance even at low water temperature has been good, and the specific nitrification rates have been high, close to 2.0 g N/kg VSS/h, during the first quarter of 2005. The performance has also revealed a clear relation between the nitrogen loading and the nitrification rate. The nitrification rate is accordingly found to be related to the COD/N ratio, with increasing rate at lower ratio. The denitrification rate has been high whenever the load has been high, and no limitations have been identified with respect to the peak load conditions.

Acknowledgements

A number of persons have made this paper possible by various contributions. The present plant operator Mr Maciej Podpłomyk and his staff have maintained the operation with very good results, even at situations of excessive loading. They have also provided all relevant information on plant performance figures. Mr Guy Taylor has scrutinized the text and corrected lingual mistakes. Prof. Elzbieta Plaza at the Royal Institute of Technology (KTH) in Stockholm has followed the plant ever since the start by initiating and supporting studies for M.Sc. degrees at the plant. She has also given constructive criticism and encouragement during the work with this paper. Finally I would like to address all former students at Swedish universities performing M. Sc thesis at the Nowy Targ plant (see reference list below), thus providing substantial information that has contributed to this paper.

References

Choubert, Jean-Marie, Racault, Y., Grasmick, A. and Beck, C. (2005) "*Maximum nitrification rate in activated sludge processes at low temperature: key parameters, optimal value*" Official Publication of the European Water Association, pp 1–13.

Eckenfelder, W. W. Jr (1989) *Industrial Water Pollution Control, Second Edition*, McGraw-Hill Book Company.

Hultman B., Levlin E., Plaza E. and Trela, J. (1999) "*Sludge handling at Nowy Targ Wastewater Treatment Plant, Poland – Evaluation and recommendations for improvements*" Joint Polish-Swedish Reports, No 6, TRITA-AMI REPORT 3064, Royal Institute of Technology, Sweden.

Johansson Å. and Salberg H. (1996) "*Full Scale Study of Sequencing Batch Reactor in Nowy Targ*" MSc Thesis, 1996:067 E, Division of Sanitary Engineering, Luleå University of Technology, Sweden.

Kabacinski M., Hultman B., Plaza E. and Trela J. (1998) "*Strategies for improvement of sludge quality and process performance of SBR plant treating municipal and tannery wastewater" Water Science and Technology,* **38**(4–5), pp 69–77.

Sharif A. (1998) *Efficiency and Process Performance of Sequencing Batch Reactor With Respect to Wastewater Characteristics, Wastewater Treatment Plant in Nowy Targ, Poland* MSc Thesis, AVAT-EX-1998-07, Department of Civil and Environmental Engineering, Royal Institute of Technology, Sweden.

Mikoz, J., Plaza, E. and Kurbiel, J. (2001). *"Use of computer simulation for cycle length adjustment in sequencing batch reactor"* Water Science and Technology 43, No 3 2001, pp 61–68.

Morling, S. (2001) *"Performance of an SBR-plant for advanced nutrient removal, using septic sludge as a carbon source"* Water, Science and Technology Volume 43 No 3 pp 131–138.

Morling, S. (2007) *"Plant performance of an Sequencing Batch Reactor in Poland, operated with high Chromium load, reaching advanced nutrient removal"* presented at the conference on design and operation of large wastewater treatment plants, in Vienna September 2007, published in Conference Proceedings.

Morling, S. (2008) *"Long time experiences from four SBR-plants operated with cold wastewater, comparisons and synthesis"* presented at the 4th SBR-conference in Rome 2008, Proceedings.

Unpublished material

Operation data from the Nowy Targ WWTP, year 2005.

Operation data and elaboration work from Rock Falls SBR test facility, with courtesy of Aqua Aerobic Systems Inc., Rockford, Illinois.