The Polish perspective on adopting EU standards for nitrogen removal at large WWTPs – case studies

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Abstract The most challenging issue for existing large WWTPs (>100,000 PE) in Poland will be achievement of the new effluent standards for total nitrogen. Consequently, reliable and accurate information concerning the dimensioning of anoxic compartments is necessary. This study focused on validating to what extent the denitrification rates determined from batch tests were comparable with the rates calculated based on a mass balance over a full-scale activated sludge reactor. The experiments were conducted at two large WWTPs in northern Poland: "Wschod" in Gdansk and "Debogorze" in Gdynia. Two types of batch tests were used to determine the denitrification capability of activated sludge. Lower nitrate utilization rates observed during the full-scale experiments could potentially result from the local disturbances such as nitrate limitation ("Wschod" WWTP) or oxygen penetration to the anoxic zone ("Debogorze" WWTP). These factors should be taken into consideration during the design phase of the anoxic compartments.

Keywords Activated sludge; batch experiments; denitrification; full-scale WWTPs; nitrogen removal

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Introduction

Biological nutrient removal (BNR) wastewater treatment plants (WWTPs) already treat almost 20% of municipal wastewater produced in Poland (CSO, 2001). Among several BNR plants operated in the region of the Bay of Gdansk (northern Poland) two facilities: "Wschod" in the city of Gdansk and "Debogorze" in the city of Gdynia can be classified as the large facilities (>100,000 PE).

One of the primary factors affecting the development of BNR technologies was a regulation of the Ministry of Environment of 1991 demanding nutrient removal. That regulation was introduced concurrently to the EU Urban Wastewater Directive 91/271/EEC. Recently, a new regulation has been proposed aiming to adopt the EU Directive recommendations in the Polish legislation. From comparison of the two regulations it appears that the most challenging issue for existing large WWTPs will be achievement of the effluent concentrations of total nitrogen (Table 1). Consequently, reliable and accurate information concerning the dimensioning of anoxic compartments is necessary. Strategies for adopting the stringent requirements are also worked out at the studied plants. Batch tests with the biomass from the process are considered to be a useful tool in evaluating the kinetics of biochemical processes. This study focused on validating to what extent the denitrification rates obtained from batch tests are comparable with the rates calculated based on a mass balance over a full-scale activated sludge reactor. Such information can be used in two ways: optimizing the denitrification process within the existing capacity ("Wschod" WWTP) or providing guidelines for designing a denitrification zone during the plant upgrade ("Debogorze" WWTP).

Table 1 Regulations concerning nutrient removal at large WWTPs in Poland

Parameter	Unit	Current regulation of 1991	Current limits for Wschod WWTP	Current limits for Debogorze WWTP	Proposed regulation of 2002	EU Directive of 1991
Total N	g N/m^3	30	15	30	10	10
N-NH_4^+	g N/m^3	6	6	6	–	–
N-NO_3^-	g N/m^3	30	15	30	–	–
Total P	g P/m^3	1.5	1.5	1.5	1	1

Materials and methods

Plant description

Wschod WWTP. The "Wschod" WWTP in Gdansk is one of the largest facilities located upon the Baltic Sea. The plant treats wastewater originating from the city of Gdansk and adjusting communities (approximately 500,000 inhabitants). In 2001, the average daily flowrate was 85,000 m^3/d and the total pollutant load to the plant corresponded to approximately 700,000 PE. The treated wastewater is directly discharged to the Bay of Gdansk which is part of the Baltic Sea. The biological step, completed in 1998–1999, consists of six parallel bioreactors and twelve circular secondary clarifiers. The bioreactors run in the MUCT process configuration (Figure 1). A minor modification to the original configuration is a deoxic zone in the internal recirculation line from the aerobic to the anoxic zone. The aerobic zone was designed as a plug flow reactor whereas the other zones were designed as carousel systems. The air is supplied to the aeration zone by means of a diffused aeration system. The set points for dissolved oxygen (DO) concentration are "on-line" controlled in each compartment of the aeration zone (6 points). Redox electrodes are installed both in the anaerobic zone and in the anoxic zones. The deoxic zone is equipped with instruments for "on-line" measurements of DO, N-NO_3^- and MLSS.

In 2001, the "Wschod" WWTP operated at temperatures varying within the range of 12.7°C (February) – 21.0°C (August). Mixed Liquor Suspended Solids (MLSS) concentrations were maintained at 2.64–3.79 kg/m^3 and the corresponding Sludge Retention Times (SRTs) were equal to 14.1–28.5 d. The average concentrations of conventional parameters for the settled wastewater were as follows: COD = 531 g COD/m^3, BOD_5 = 251 g BOD_5/m^3, TSS = 241 g/m^3, $P_{tot.}$ = 14.4 g P/m^3, P-PO_4^- = 9.7 g P/m^3, $N_{tot.}$ = 68.5 g N/m^3 and N-NH_4^+ = 47 g N/m^3. Variations in the effluent total N concentrations and N removal efficiency between July, 2000 and June, 2002 are presented in Figure 2.

Debogorze WWTP. The "Debogorze" WWTP treats wastewater originating from the city of Gdynia and four surrounding smaller towns (approximately 330,000 inhabitants). In 2001,

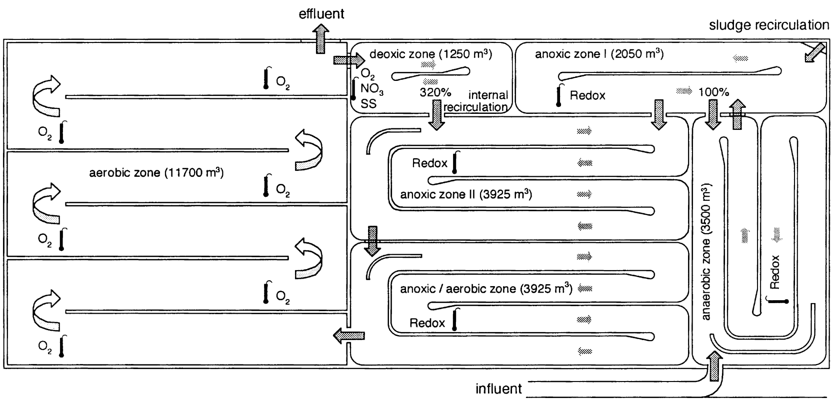

Figure 1 Layout of the activated sludge reactor at the "Wschod" WWTP

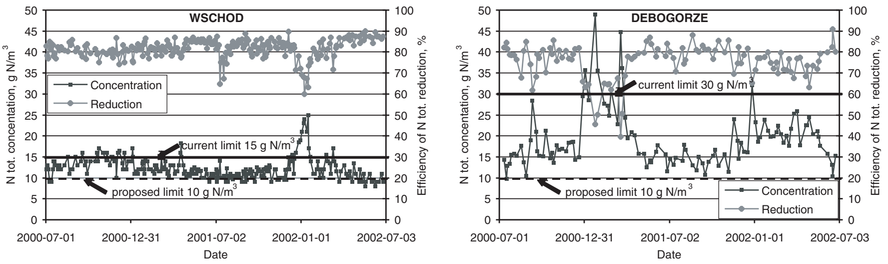

Figure 2 Efficiency of nitrogen removal at the "Wschod" and "Debogorze" WWTPs

the average daily flowrate was 56,700 m^3/d and the total pollutant load to the plant corresponded to approximately 500,000 PE. A recipient of the treated wastewater is the Bay of Gdansk. The existing biological step, retrofitted in 1994–1997, consists of four parallel bioreactors and six secondary clarifiers. The bioreactors run in the Johannesburg process configuration (Figure 3). The anaerobic zone and the sludge denitrification zone were designed as completely mixed reactors. A reactor designed as plug flow consists of the following compartments: anoxic, intermediate (anoxic/aerobic) and four aerobic. There are no internal baffles between the compartments which causes oxygen penetration to the anoxic zones due to dispersion. The air is supplied to the aerobic zone by means of a diffused aeration system. The set point of 4 g O_2/m^3 is "on-line" controlled in the third compartment of the aerobic zone. The DO concentration is also measured "on-line" in the first compartment. A redox electrode is installed in the anoxic zone.

In 2001, the "Debogorze" WWTP operated at temperatures varying within the range of 13.5°C (February) – 20.7°C (July). MLSS concentrations were maintained at 4.46–5.93 kg/m^3 and the corresponding SRTs were equal to 17.4–28.5 d. The average concentrations of conventional parameters for the settled wastewater were as follows: COD = 573 g COD/m^3, BOD_5 = 292 g BOD_5/m^3, TSS = 249 g/m^3, $P_{tot.}$ = 14.9 g P/m^3, P-PO_4^- = 10.6 g P/m^3, $N_{tot.}$ = 78.5 g N/m^3 and N-NH_4^+ = 48.5 g N/m^3. Variations in the effluent total N concentrations and N removal efficiency between July, 2000 and June, 2002 are presented in Figure 2.

More information about the "Wschod" and "Debogorze" WWTPs, characteristics of the settled wastewater and operational parameters can be found elsewhere (Makinia *et al.*, 2002).

Batch experiments

A batch reactor with the maximum volume 3.7 dm^3 and an automated control and monitoring was designed and built to carry out lab experiments. The reactor was equipped with pH, redox, temperature and oxygen electrodes. Moreover, a temperature control system allowed to maintain a constant temperature in a water coat of the batch reactor. Within the

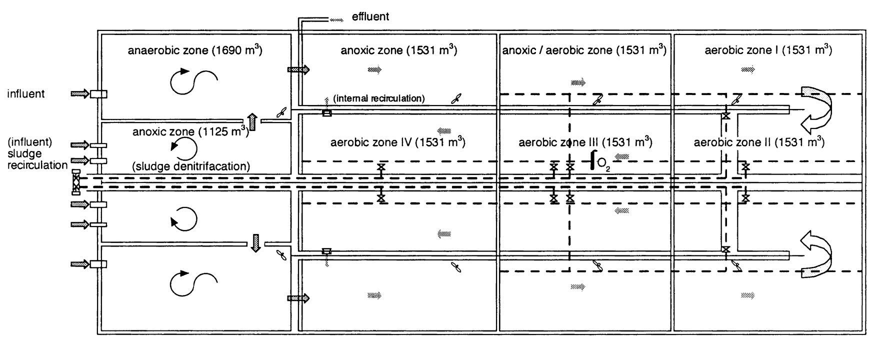

Figure 3 Layout of the activated sludge reactor at the "Debogorze" WWTP

period of November, 2001–September, 2002 three series of various batch tests were carried out at the "Wschod" and "Debogorze" WWTPs. Experimental procedures were prepared based on the literature data (Brdjanovic *et al.*, 2000). Below are described two types of the tests which were used to determine the denitrification capability of activated sludge.

Nitrate utilization rate (NUR). Fresh returned activated sludge was diluted with settled wastewater. The dilution rate was adjusted to maintain MLSS at approximately 3 kg/m^3. The actual MLSS concentration in the reactor was measured at the beginning of the test. In order to raise the concentration of the readily biodegradable organic matter by 50 g COD/m^3 sodium acetate was also added. The samples were withdrawn with the frequency of 10–30 min., filtered under vacuum pressure on the Whatman GF/C filter and analyzed for N-NO_3^- and COD.

Phosphorus release in the anaerobic conditions and phosphorus uptake in the anoxic conditions. Fresh returned activated sludge was diluted with settled wastewater or wastewater after secondary treatment. In the latter case, sodium acetate was added to raise the concentration of the readily biodegradable organic matter by 200 g COD/m^3. The dilution rate was adjusted to maintain MLSS at approximately 3 kg/m^3. At the beginning of the anoxic phase, potassium nitrate was added to raise the N-NO_3^- concentration by 30 g N/m^3. Before the principal phase of the experiment started the present nitrates had been denitrified using sodium acetate in the approx. ratio of 4 g CH_3COONa/g N-NO_3^-. The samples were withdrawn with the frequency of 10–30 min., filtered under vacuum pressure on the Whatman GF/C filter and analyzed for P-PO_4^- and COD (anaerobic phase) and P-PO_4^-, N-NO_3^- and COD (anoxic phase). The actual MLSS concentration in the reactor was measured at the beginning and at the end of the test.

Full-scale measurements

Each series of the lab experiments was accompanied by an additional 48-hour "continuous" measurement campaign conducted in the full-scale reactors. Wastewater samples were grabbed every two hours at the selected locations (reactor inlet, effluent from the anaerobic zone, effluent from the anoxic zone, middle of the aerobic zone, reactor effluent). Apart from the reactor inlet, the samples were filtered under the gravity pressure using paper filters. Several parameters were analyzed in the filtered samples including the N-NO_3^- concentrations in the following locations: effluent from the anoxic zone, middle of the aerobic zone, reactor effluent. All necessary "on-line" recordings (flowrates) were also collected for the calculations. After averaging the data for one day (two results per campaign) an approximate mass balance was carried out over the anoxic compartment of the activated sludge reactor.

Results and discussion

Selected results of the NUR tests performed at the "Wschod" and "Debogorze" WWTPs during three experiment series are presented in Figure 4 and Figure 5, respectively. Based on these experimental data the corresponding specific nitrate utilization rates were calculated as shown in Table 2 ("Wschod" WWTP) and Table 3 ("Debogorze" WWTP). In the first case, the rates associated with the utilization of readily biodegradable substrate (RBCOD) varied within the range of 4.95–6.82 g N/(kg VSS·h), whereas the rates associated with the utilization of slowly biodegradable substrate (SBCOD) remained very stable during all experiments (2.82–2.98 g N/(kg VSS·h)). The obtained results revealed that in the lab conditions denitrification was independent of temperature within the measured range, i.e. 13.6–20.0°C.

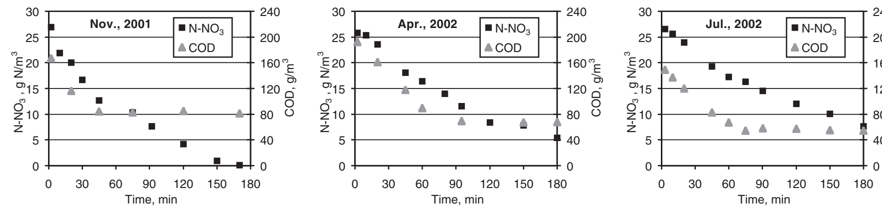

Figure 4 N-NO_3^- and COD concentrations in the NUR batch tests ("Wschod" WWTP)

Table 2 NURs and ΔCOD:ΔN ratios determined from the batch tests ("Wschod" WWTP)

Experiment series	Process temp. °C	I phase (RBCOD) ΔCOD:ΔN ratio g COD/g N	I phase (RBCOD) NUR 1 (RB) g N/(kg VSS·h)	II phase (SBCOD) NUR 2 (SB) g N/(kg VSS·h)
November, 2001	14.6	8.5	6.82	2.82
March–April, 2002	13.6	9.7	5.88	2.98
June–July, 2002	20.0	10.7	4.95	2.87

Significant variations in the nitrate utilization rates were observed at the "Debogorze" WWTP (Figure 5 and Table 3), especially with respect to the second experiment series conducted in May–June, 2002. It should be emphasized that the process of N removal remained unstable at that time after the winter nitrification loss. The intermediate zone was still aerated to increase the aerobic SRT in the system. Consequently, the volume of the anoxic zone was reduced by 50% compared to the normal operating conditions. This would have resulted in a reduced growth rate (or reduced fraction) of the population of denitrifiers.

Apart from the spring series (March–April, 2002 at the "Wschod" WWTP vs. May–June, 2002 at the "Debogorze" WWTP), the results obtained at both plants are comparable in terms of the nitrate utilization rates (both on RBCOD and SBCOD) as well as COD:N requirement.

The calculations for estimating the denitrification efficiency of BNR systems with enhanced biological P removal (EBPR) differ from that for a purely denitrifying activated sludge plant for two reasons: virtually all the readily degradable influent COD is used in the anaerobic reactor and a substantial fraction of the Phosphorus Accumulating Organisms (PAO) can denitrify on their stored substrate (Koch *et al.*, 2001; Ekama and Wentzel,

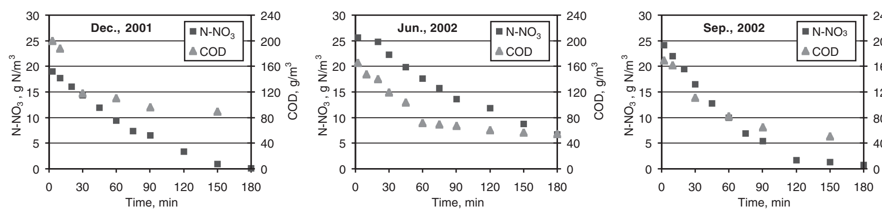

Figure 5 N-NO_3^- and COD concentrations in the NUR batch tests ("Debogorze" WWTP)

Table 3 NURs and ΔCOD:ΔN ratios determined from the batch tests ("Debogorze" WWTP)

Experiment series	Process temp. °C	I phase (RBCOD) ΔCOD:ΔN ratio g COD/g N	I phase (RBCOD) NUR 1 (RB) g N/(kg VSS·h)	II phase (SBCOD) NUR 2 (SB) g N/(kg VSS·h)
December, 2001	14.5	9.8	3.96	2.31
May–June, 2002	18.8	9.5	2.80	1.42
September, 2002	21.0	7.4	6.14	3.08

1999). In order to evaluate the impact of the anaerobic zone on denitrification, P release/anoxic uptake batch tests were carried out. Results of the tests with two different sources of volatile fatty acids (VFAs) for P release (sodium acetate and settled wastewater) are presented in Figure 6 ("Wschod" WWTP) and Figure 7 ("Debogorze" WWTP). The experimental data revealed that two different rates, called NUR1 and NUR2, were observed in terms of the available substrate. The NUR1, accompanied by decrease in the COD concentration, was associated with the utilization of RBCOD, whereas the NUR2 was associated with the utilization of SBCOD (without decrease in the measured COD concentration). However, the first rate only occurred during the tests with sodium acetate which was added in access to the demand for P release in the anaerobic phase. The calculated specific nitrate utilization rates are listed in Table 4 and Table 5 for the "Wschod" WWTP and "Debogorze" WWTP, respectively.

At the "Wschod" WWTP, the rates associated with the utilization of sodium acetate (NUR1) were relatively constant, i.e. 4.03–4.44 g N/(kg VSS·h). However, these rates were substantially lower (by approximately 20%) than the rates associated with the utilization of RBCOD during the NUR batch tests (Table 4), which may indicate that sodium acetate is not representative for RBCOD of the actual wastewater. When settled wastewater was used as a source of VFA the nitrate utilization rates (NUR 2) were comparable with those observed during the second phase of the NUR batch tests (associated with the utilization of SBCOD). The corresponding values were respectively equal to 3.11 vs. 2.98 g N/(kg VSS·h) in March–April, 2002 and 2.53 vs. 2.87 g N/(kg VSS·h) in June–July, 2002. These results may indicate a poor contribution of denitryfing PAO to the utilization of nitrates,

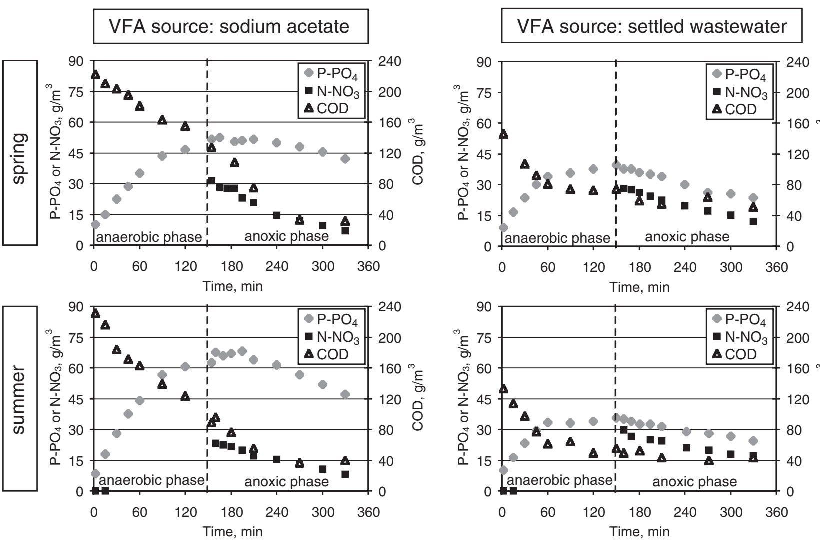

Figure 6 Concentrations of $P\text{-}PO_4^-$, $N\text{-}NO_3^-$ and COD in the P release/anoxic uptake batch tests ("Wschod" WWTP)

Table 4 Determined COD requirements for P release in the anaerobic phase, P uptake rates and NURs in the anoxic phase of the batch tests ("Wschod" WWTP)

Experiment series	Source of VFA	Process temp. °C	Anaerobic phase ΔP rel./ΔCOD g P/g COD	Anoxic phase P uptake rate g P/(kg VSS·h)	NUR 1 (RB) g N/(kg VSS·h)	NUR 2 (SB) g N/(kg VSS·h)
March–April, 2002	Sodium acetate	13.2	0.72	1.39	4.44	2.05
March–April, 2002	Settled w-water	13.9	0.38	3.01		3.11
June–July, 2002	Sodium acetate	19.7	0.46	4.09	4.03	2.61
June–July, 2002	Settled w-water	19.2	0.35	2.16		2.53

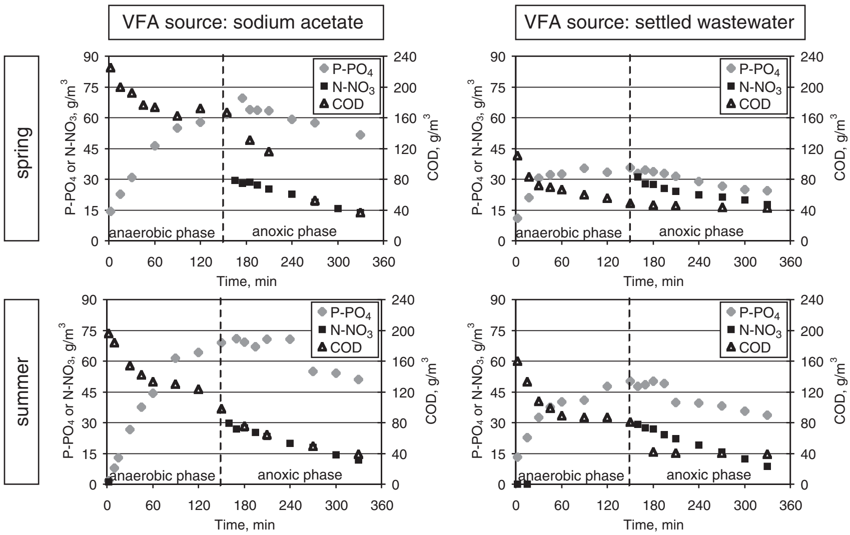

Figure 7 Concentrations of P-PO_4^-, N-NO_3^- and COD in the P release/anoxic uptake batch tests ("Debogorze" WWTP)

Table 5 Determined COD requirements for P release in the anaerobic phase, P uptake rates and NURs in the anoxic phase of the batch tests ("Debogorze" WWTP)

Experiment series	Source of VFA	Process temp. °C	Anaerobic phase ΔP rel./ΔCOD g P/g COD	Anoxic phase P uptake rate g P/(kg VSS·h)	Anoxic phase NUR 1 (RB) g N/(kg VSS·h)	Anoxic phase NUR 2 (SB) g N/(kg VSS·h)
May–June, 2002	Sodium acetate	18.7	0.56	3.39	3.36	
May–June, 2002	Settled w-water	19.1	0.50	1.90		2.05
September, 2002	Sodium acetate	22.0	0.61	4.23	3.26	
September, 2002	Settled w-water	21.9	0.37	3.09		3.72

even though the anoxic P uptake was occurring (2.16–3.01 g P/(kg VSS·h)). The literature data provide no conclusive judgment concerning the issue of anoxic activity of PAO in the BNR systems (Wenzel and Ekama, 1997).

At the "Debogorze" WWTP, interpretation of the results obtained during the P release/anoxic uptake batch tests is not straightforward. When sodium acetate was added as a VFA source the nitrate utilization rates remained relatively constant, i.e. 3.26–3.36 g N/(kg VSS·h), as opposed to the high variations which occurred in the NUR tests. During the tests with settled wastewater the observed rates were higher by 44% and 21%, respectively, than the corresponding rates (NUR2) in the NUR tests. The anoxic P uptake rates (1.90–3.09 g P/(kg VSS·h)) were similar to those observed at the "Wschod" WWTP. Consequently, a minor contribution of denitrifying PAO to the utilization of nitrates can be also assumed. In such a case, the mentioned discrepancies in the NUR values can be potentially explained by a more complex composition of the wastewater, e.g. due to the presence of readily hydrolysable substrate which was not used for P release in the anaerobic phase of the batch test.

The data used for the mass balance over the anoxic compartment of the full-scale reactors are presented in Table 6 and Table 7 for the "Wschod" WWTP and "Debogorze" WWTP, respectively. Apart from the first measurement at the "Debogorze" WWTP, the calculated nitrate utilization rates were lower than the rates determined from the batch tests. This exception can be explained by the fact that the measurement was conducted at the end of the stabilization period when the denitrification process was reaching its optimal

Table 6 NUR measurements in the full-scale reactor at the "Wschod" WWTP

Date	$N\text{-}NO_3^-{}_{eff,DN}$ g N/m³	$N\text{-}NO_3^-{}_{eff,N}$ g N/m³	Q m³/d	Q_{RAS} m³/d	Q_{MLR1} m³/d	Q_{MLR2} m³/d	MLVSS g/m³	NUR g N/(kg·h)
22/23.04.02	0.15	7.9	20,425	23,045	30,240	92,534	2,830	**1.33**
23/24.04.02	0.12	7.2	21,380	21,369	30,240	92,534	2,870	**1.20**
18/19.06.02	1.0	8.4	19,808	23,045	30,240	92,534	2,380	**1.48**
19/20.06.02	0.22	7.5	19,340	20,112	30,240	92,534	2,290	**1.50**

eff,DN – effluent from the anoxic zone, eff,N – effluent from the aerobic zone

Table 7 NUR measurements in the full-scale reactor at the "Debogorze" WWTP

Date	$N\text{-}NO_3^-{}_{eff,DN}$ g N/m³	$N\text{-}NO_3^-{}_{eff,N}$ g N/m³	Q m³/d	Q_{RAS} m³/d	Q_{MLR} –	MLVSS g/m³	NUR g N/(kg·h)
11/12.06.02	2.4	10.8	23,247	32,363	300% Q	4,305	**2.53**
12/13.06.02	1.5	9.0	16,085	24,273	300% Q	4,121	**1.72**
24/25.09.02	2.8	12.0	13,075	24,872	300% Q	3,750	**2.01**
25/26.09.02	3.4	11.5	13,630	24,828	300% Q	4,127	**1.60**

capacity at this plant (see: Figure 2). A relatively high variation of the NUR values during that test was caused by changeable operational conditions, i.e. heavy rain on the first day. Among several potential reasons that could contribute to the reduced rates there were also factors specific for each facility, such as nitrate limitation ("Wschod" WWTP) and oxygen penetration to the anoxic zone ("Debogorze" WWTP).

Conclusions

Batch tests provide useful information about the denitrification kinetics in the continuous EBPR systems. However, the conventional procedure for NUR measurements should be modified to reflect the impact of the anaerobic zone. This can be done by determining the NUR in parallel to the anoxic P uptake during the P release/anoxic P uptake batch test. Lower nitrate utilization rates observed during the full-scale experiments could potentially result from the local disturbances such as nitrate limitation ("Wschod" WWTP) or oxygen penetration to the anoxic zone ("Debogorze" WWTP). Correction factors due to these disturbances have to be taken into consideration during the dimensioning of anoxic compartments. The results of this study will be subjected to a further model-based evaluation (e.g. using ASM2d).

Acknowledgements

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