WP2: Nitrogen Removal

D2.1 Advanced Control strategy for Nitrogen Removal

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

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Abstract	Discussion on options and performances of advanced control systems for biological nitrogen removal after advanced primary treatment. The process control options are described in details as well as process performance in the demo site was quantified including transition strategy from conventional scheme to process with the advanced carbon extraction.

Dissemination level of this document

X	PU	Public
	PP	Restricted to other programme participants (including the Commission Services)
	RE	Restricted to a group specified by the consortium (including the European Commission Services)
	CO	Confidential, only for members of the consortium (including the European Commission Services)

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Executive Summary

Within POWERSTEP, Work Package 2 addresses new technologies for nitrogen removal. In case Study 1 (Westewitz) an advanced nitrogen control strategy was implemented for treatment of low COD/N wastewater after advanced primary treatment with micro screen. This report presents the functionality of the advanced nitrogen control strategy as well as the operational parameters at different COD/N ratios. Wastewater treatment plant Westewitz (Germany) is designed for 2000 p.e., 390 m³ daily inflow with BOD_5: 308mg/L, COD: 615 mg/L, SS: 359 mg/L, TKN: 56.4 mg/L, TP: 9.23 mg/L.

Effluent threshold values are: BOD_5 < 40 mg/L, COD < 70 mg/, TN < 18 mg/L (for T> 12°C), TP < 8 mg/L.

Advanced primary treatment with a 40 µm microscreen (drum filter) and nitrogen control strategy was implemented successfully, enhancing the COD extraction slowly and evaluating the COD extraction for three different levels (30%, 45% and 68%) with 30%, 42% and 68% load reduction. COD/N ratio dropped from 9.2:1 to minimum 4.4:1 during the trials.

The advanced nitrogen control strategy consisted on the one hand of an optimised standard operation, focussing on SBR feeding, aeration control and process water recycling. On the other hand on special mechanisms coming into action at enhanced nitrate concentrations (reduction of polymer dose, bypass of the filtration, recycling of process water and acetate dosing).

Process water recycling did not have a strong impact on the COD/N ratio only enhancing it by 0.3-0.5 units. VFA content of process water (583 mg/L) is relatively high compared to VFA content in the filtrate (95.3 mg/L, N=32), but the volume of process water withdrawn is not sufficient to have a significant impact on the COD/N ratio.

The denitrification rates were evaluated during three operating phases (30%, 42% and 58% COD extraction). Minimum average denitrification rates in the biological step were observed at 42% COD extraction for SBR 1 (0.581 mg NO_3-N/ (h*g MLVSS))) and at 58% COD extraction for SBR 2 (0.485 mg NO_3-N / (h*g MLVSS)), being in the range of endogenous denitrification.

Glossary

AOB	Ammonium Oxidizing Bacteria
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
DNR	Denitrificationrate
DO	Dissolved Oxygen
DM	Dry Matter
HRT	Hydraulic Retention Time
MBBR	Moving Bed Biofilm Reactor
MLSS	Mixed liquor suspended solids
MLVSS	Mixed liquor volatile suspended solids
N	Nitrogen
NOB	Nitrite Oxidizing Bacteria
NTU	Nephelometric Turbidity Units
TP	Total Phosphorous
PE	People Equivalents
oDM	organic Dry Matter
PCS	Process Control System
Q	Flow
SBR	Sequencing Batch Reactor
SPC	Set Point Concentration
TN	Total Nitrogen
TKN	Total Kjehldahl Nitrogen
TST	Thickening and Storage Tank
VFA	Volatile fatty Acids
SS	Suspended Solids
WP	Work Package
WW	Wastewater
WWTP	Wastewater Treatment Plant

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1. Introduction

Within the European project Powerstep, Work package 1 (WP 1) is dedicated to enhanced carbon extraction in preliminary clarification done via microscreen filtration (production of carbon rich primary sludge) of municipal raw wastewater after the grid.

As the biogas potential of primary sludge is higher than the potential of excess sludge, the idea for energy producing wastewater treatments plants (WWTPs) is to extract as much carbon before the biological step as possible in order to produce more biogas on the one hand and reduce the energy needed for aeration on the other hand.

Pilot trials with microscreen filtration described by Remy et al. (2014) showed that 600 NL/kg oDM Biogas at 56% degradation rate could be produced from primary sludge instead of 430 NL/kg at 50% degradation rate from excess sludge. Mean methane concentration was similar in both sludge types reaching 60%.

But the disadvantage of carbon extraction is that it leads to a change of the influent characteristics, especially the COD/N ratio. This can cause malfunctions of the biological treatment process including deterioration of settleability, of biological phosphorus removal and most important of nitrogen removal.

Nitrogen removal in conventional WWTPs is based on the biological processes of nitrification and denitrification. The nitrification is divided into two steps. In the first step ammonium is oxidized to nitrite.

Step 1 (Nitritation): $NH_{4^+} + 1.5\ O_2 \xrightarrow{Nitrosomonas} NO_{2^-} + H_2O + 2 * H^+ + Energy$

In the second step the nitrite is further oxidized to nitrate.

Step 2 (Nitratation): $NO_{2^-} + 0.5\ O_2 \xrightarrow{Nitrobacter} 2\ NO_{3^-}$

Both steps are performed by chemotrophic bacteria, e.g. Nitrosomonas for the first and Nitrobacter for the second step (Bever at al., 2002).

In denitrification nitrate is reduced to elementary nitrogen under anoxic conditions by heterotrophic bacteria.

Denitrification: $2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O$

The elementary nitrogen degases into the atmosphere, while the carbon is oxidized as well as fixed in the biomass.

As the process is performed by heterotrophic bacteria, organic carbon is the needed energy source or electron donor. According to literature the COD/N ratio in domestic wastewater is about 12.5:1 (Metcalf and Eddy, 1991). Bever at al. (2002) recommend for advanced wastewater treatment a minimum BOD_5/N ratio of 3.3:1, which corresponds to a COD/N ratio of 4.8:1 for a COD/ BOD_5 of 1.4:1 (Metcalf and Eddy, 1991). At low COD/N ratios denitrification rates can decrease down to endogenous denitrification, using the carbon fixated in the biomass for the process. Endogenous denitrification is slower than regular denitrification and can lead to a loss of biomass.

Kujawa and Klapwijk (1999) reported rates for endogenous denitrification between 0.1 - 0.6 mg NO_3-N/(h*g MLVSS), whereas denitrification rates for raw wastewater with sufficient carbon were between 0.6-3 observed by (Henze et Harmoés 1990).

Thus the main task in Work package 2 (WP 2) is to test new technologies and strategies for nitrogen removal in order to guarantee that threshold values in the WWTP effluent are kept.

Aiming at 70% COD extraction in the microscreen COD/N ratio is expected to drop below 5:1, maybe resulting in slow endogenous denitrification and therefore an elongation of denitrification times. To maintain stable operation of the WWTP and keep the effluent threshold values throughout the seasonal variations of influent conditions (quality and quantity) these trials are carried out over at least one year starting in December 2016.

1.) Optimised used of carbon through advanced control:

A non-biological, technical approach for N-removal after enhanced carbon extraction is the implementation of an advanced process control, which is tested in Case Study 1 (WWTP Westewitz). Carbon extraction was implemented and the process control system was equipped with advanced process control for nitrogen removal dealing with low COD/N ratios and consisting of three parts:

1. In standard operation (independent of the nitrate concentration) the remaining carbon must be utilized as efficient as possible with a new feeding regime for the SBRs (providing carbon during denitrification phase, when it is needed) and optimized aeration control. For optimised aeration times are controlled by depletion of dissolved oxygen to avoid loss of COD due to oxidation.
2. Also independent of the nitrate concentration recycling of process water, which is formed while sludge thickening and has high available COD, should be improved by a more regular time based withdrawal regime providing additional carbon.

3. As a backup strategy to prevent high nitrate concentration in the WWTP effluent, the WWTP process control system was equipped with special control mechanisms (s. Figure 1) that are automatically activated by increased nitrogen concentrations in the SBRs to supply carbon for denitrification:

    1. Reduction of COD extraction by reduction of chemical dosing
    2. Bypass of the filtration, meaning direct feeding of the SBRs with carbon rich wastewater
    3. Nitrate concentration triggered supernatant withdrawal during denitrification times
    4. Acetate dosing

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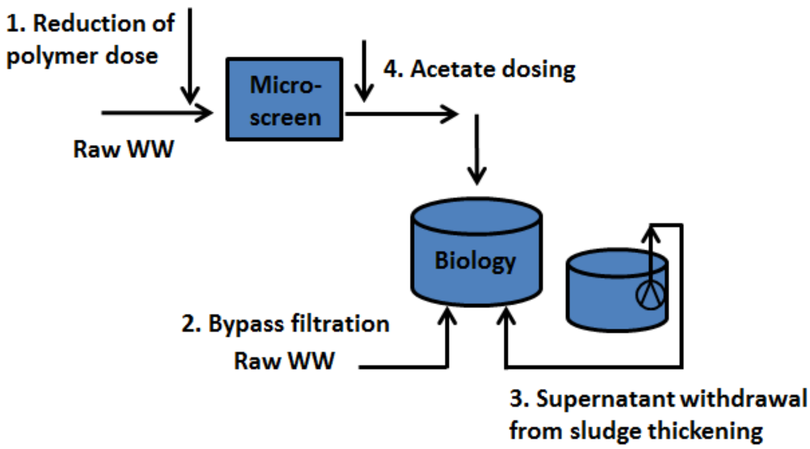

Figure 1: Schematic description of special mechanisms for advanced nitrogen control

2.) Biological nitrogen removal without carbon source:

Another approach of N removal after enhanced carbon extraction is to use the anammox process. In the anammox process bacteria (e.g. planctomyces) transform ammonium and nitrite directly into elementary nitrogen. An advantage over the conventional activated sludge process is a decrease of oxygen demand and organic carbon source demand. Wett and Hell (2007) reported that by implementing the anammox process for process water treatment 25% of the aeration energy and 40% of the external carbon source could be saved.

Biologically it is a two stage process.

First step: Nitritation

$$NH_4^+ + 1.5\,O_2 \xrightarrow{Nitrosomonas} NO_2^- + 2H^+ + H_2O + Energy$$

Optimally approximately half of the ammonia is converted to nitrite in this first step. The produced nitrite can, if conditions for anammox bacteria are not optimal, be reduced by heterotrophic bacteria to elementary nitrogen (denitritation) or further oxidized to nitrate (s. above, second step nitrification).

Both are not favorable for the anammox process (short for anaerobic ammonium oxidation, also called deammonification) as the nitrite is catalyzed for other processes instead of being available for the anammox reaction.

In the anammox step bacteria oxidize the remaining half of the ammonium by using nitrite to produce elementary nitrogen (O'Shaughnessy, 2016). Therefore only half of the ammonium should be oxidized during the first step to guarantee the availability of enough ammonium for the anammox step.

Second step: Anammox

Anammox: $NH_{4^+} + 1.32\ NO_{2^-} \xrightarrow{Planctomycetales} 1.02\ N_2 + 0.26\ NO_{3^-} + 2.2\ H_2O$

Consequently it is important to find ways to avoid nitratation and denitritation by create boundary conditions which reduce the activity of nitrite oxidizing and heterotrophic bacteria and enhance growth of ammonium oxidizing bacteria. Key process parameters are temperature, pH value, dissolved oxygen (DO), ammonium, nitrous acid and anorganic carbon concentrations (Horn et al., 2009)".

The main-stream anammox process is also tested in the within the project. A full scale two stage anammox process was installed at Case Study 2(s. Figure 2) and later converted into a one stage process.

In the two stage configuration both stages were filled with different types of carriers (MBBR) and operated under distinct process conditions to support the growth of aerobic ammonium and suppress the growth of nitrite oxidizing bacteria in the first stage and also enhance the growth of anaerobic ammonium oxidizing bacteria in the second stage (s. Figure 3). The process was later converted into a one stage IFAS process.

More information concerning the setup of the trails as well as the control strategy is given in Deliverable 2.3 "Process description for maintaining stable nitrogen removal using nitritation and anammox with MBBRs in mainstream water".

Figure 2: Case Study 2 (WWTP Sjölunda, Sweden), detailed picture of the 2-stage anammox reactor

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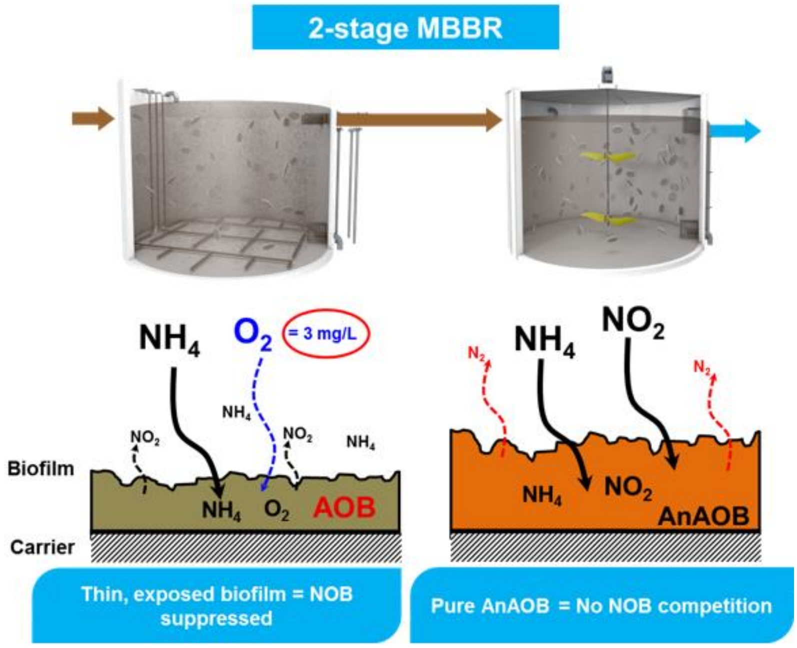

Figure 3: Schematic description of the two stages of the anammox process and the corresponding biofilm characteristics. Left: First step: Nitritation under aerobic conditions (NOB: Nitrite oxidizing bacteria; AOB: Ammonium oxidizing bacteria); right: Second step: anammox reaction under anoxic conditions

3.) Alternative processes e.g. wastewater treatment with duckweed

Duckweed can be found in various habitats all over the world due to their wide range of tolerable living conditions. They mainly grow in shallow waterbodies, converting the nutrients and minerals into biomass. Under optimal growth conditions the fastest of the duckweed species can double its biomass within 29.8 hours which corresponds with a relative growth rate of 0.56 d^{-1} (Sree, Sudakaran et al., 2015).

Cheng et al. (2002) observed for Lemna Punctata thriving on synthetic swine lagoon water a maximum ammonium uptake rate of 0.96 mg/(L*h), which corresponds under consideration of applied tank geometry to uptake rates per surface area of 1.33 g /(m^2*d) under the assumption of a constant uptake rate over the whole day (24 hours).

Taking the nitrogen uptake rate of 1.33 g/ (m^2*d), the theoretically required hydraulic retention time (HRT) for an 80% nitrogen removal can be estimated for the following conditions:

- Treated volume:150 L
- Surface area of 2 m^2 with a water depth of 7.5 cm
- Total nitrogen influent concentration: 70 mg/L

For these conditions the required retention is more than three days. Together with the high surface demand the long retention time is one of the main obstacles for nitrogen removal with duckweed in practice.

The realization of duckweed-based wastewater treatment is comparable to conventional lagoon systems. Both commonly consist of a facultative pond or tank for solid removal followed by one or more duckweed ponds (ORON et al., 1988). However, the increased efficiency of duckweed-based wastewater treatment over conventional lagoons results in less land area occupation due to enhanced biomass growth and uptakes rates (Skillicorn et al., 1993).

In the project Powerstep a full scale pilot plant is built (s. Figure 4) in order to treat the nitrogen rich effluent of the drum filter and shift the probably unfavorable COD/N ratio after carbon extraction. For more information see Deliverabel D2.4 "Feasibility of mainstream nitrogen removal and biomass production with duckweed bioreactor".

Figure 4: left: Aerial image of the full scale duckweed pilot plant on Case study 1 (WWTP Westwitz, Germany); right: Measurement of the pH value in the duckweed trays within the plant

As this report focusses on advanced nitrogen control a short outlook on the following chapters should be given at this point:

- Chapter 2: Setup of the WWTP with and without advanced primary treatment
- Chapter 3: Sampling and Analysis
- Chapter 4: Operation and control of the WWTP including advanced primary treatment and nitrogen control
- Chapter 5: Results of WWTP in- and effluent analysis, the microscreen and biological performance
- Chapter 6: Summary and Outlook (recommendations for other WWTPs)

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2. WWTP Westewitz

WWTP Westewitz (belonging to the Abwasserzweckverband Döblen-Jahnatal) is located in a rural area approx. 70 km south-west of Leipzig (Germany), was built in 2009 and is operated by the "OEWA Wasser und Abwasser GmbH" ("OEWA Water and Wastewater Ltd."). The catchment area mainly consists of domestic wastewater as well as wastewater from the local a hospital. The catchment area is connected to the WWTP via a separate sewer system (OEWA, 2012) which means rainwater is separated from the municipal wastewater and therefore influent concentrations are higher than in combined sewer systems.

2.1. Design criteria and effluent requirements

Dimensioned for 2000 PE and a BOD_5 influent load of 120 kg/d (s. Table 1), it comes under the class 2 WWTPs according to the German federal regulation (Wastewater ordinance). But OEWA as an operator has imposed itself partly stricter requirements (s. Table 2) for the effluent quality than given by law in order to lower the discharge fees.

Table 1: Design parameters WWTP Westewitz (OEWA, 2012)

Inflow volume	Peak inflow volume	Water quality parameter	Influent Concentrations	Influent Loads
[m³/d]	[m³/h]		[mg/L]	[kg/d]
390	38	BOD_5	308	120
		COD	615	240
		SS	359	140
		TKN	56.4	22
		TP	9.23	3.6

Table 2: Requirements for the effluent quality of WWTP Westewitz (OEWA, 2012) for qualified grab sample or two hour composite sample, 4 of 5 consecutive samples must by below the limit value to fulfil the requirements

Parameter	Threshold values for effluent quality for the OEWA	Threshold values for effluent quality according the law (AbwVO)
BOD_5 [mg/l]	<40	<25
COD [mg/l]	<70	<110
TN [mg/l]	<18 (for T >= 12°C)	-
TP [mg/l]	<8	-

2.2. Technical setup plus dimensioning

2.2.1. Treatment steps at the WWTP

The original WWTP Westewitz (s. Figure 5) consists of a mechanical and a biological step as well as sludge thickening by gravity.

The raw wastewater is pumped from the inlet pumping station via a compact mechanical pre-treatment system (consisting of a 6mm grid and a classifier) into the sump shaft to feed the two SBRs (sequencing batch reactors). In the SBRs the wastewater is purified by activated sludge process with biological phosphorous removal, intermittent nitrification and denitrification (controlled by online measurement of dissolved oxygen), followed by settling and decanting (output of biomass prevented by turbidity control of the discharged water).

After passing the SBRs the treated wastewater of both reactors is discharged via one drainage shaft. An adjustable amount of excess sludge is withdrawn from the SBRs during sedimentation to keep a constant DS concentration in the reactors as well as a stable sludge age. The withdrawn excess sludge is pumped to a thickening and storage tank.

The function of the thickening and storage tank is to dewater the sludge as much as possible before transport and disposal. The bigger particles settle down to the bottom of the tank, leaving a supernatant at the top, which is manually pumped into a pipe leading to the sump shaft again as return load to the biological process.

As the thickened sludge is transported to a larger routing WWTP and is disposed, the solid content should be as high as possible (at least > 10 g/L) for efficient transport of the sludge.

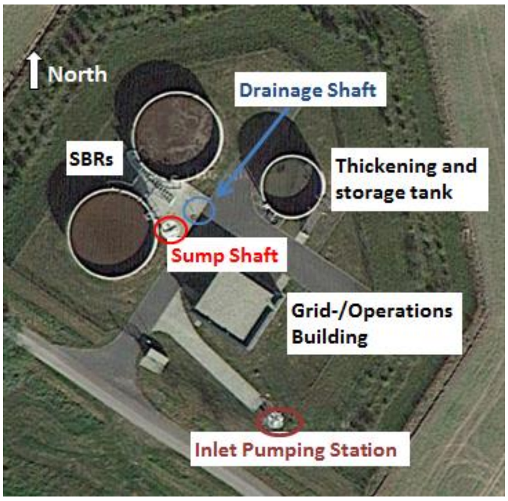

Figure 5: Aerial image of the original WWTP Westewitz with naming of the facilities

2.2.2. Dimensioning of the WWTP

The WWTP is dimensioned according to DWA-M210 as specification of the ATV A131 based on loads shown in Table 1, which are characteristic for domestic wastewater.

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The dimensioning result in the following parameters for each SBR:

- SBR Volume: 597 m³
- Discontinuous SBR discharge: 78 - 94 m³/ h.
- Maximum filling level: 4.35 m
- Min HRT: 4.9 h
- TS SBR: 4.5 g/L referred to maximum filling level
- Sludge age: 25 d
- Theoretical excess sludge production: 125.5 kg DM /d.

2.2.3. Upgrade with microscreen for enhanced carbon extraction

In the scope of WP 1 the primary treatment process was expanded by:

- **Microscreen:** A filtration plant including a drum filter with a 40 µm mesh designed for maximum inflow of 40m³/h was installed after the mechanical pre-treatment (s. Figure 6) to extract the COD prior to the biological treatment. 150 mm level difference between feed tank and filtrate tank will start the automatic back-wash (7 bar backwash pressure) to clean the filter media. The drum filter was operated continuously (24h/d) preventing dry out of the mesh.

  Upstream of the drum filter coagulant and polymer can be dosed in the two separate tanks to enhance the COD extraction and TP removal as well as the capacity of the filter (depending on the combination of the chemicals used). In case of too high COD extraction causes operational issues in the SBRs acetate can be dosed. Facilities for storage and preparation of the chemicals as well as dosing pumps and internal piping were supplied by the microscreen supplier (Hydrotech). The filtrate (COD reduced wastewater) flows by gravity into the SBRs, and the sludge produced during backwash of the drum filter is discharged into the same thickening and storage tank (TST) as the excess sludge. For precise dosing of chemicals, inflow to the drum filter should also be as stable as possible, avoiding any peak flow events or stops of operation. As the inflow of the WWTP varies considerably (day and night hydrograph) different flows to the drum filter had to be realized by frequency controlled pumps. Further information on the microscreen technology and operation is given in Deliverable 1.1 ("Optimized design of microscreen and periphery for primary filtration").
- **Frequency controlled pumps:** Water is pumped to the drum filter by the pumps in the sump shaft, which also feed the SBRs. As the original pumps were not frequency controlled, they were replaced and frequency converters were retrofitted in the electrical cabinet of the WWTP.
- **Piping / Flow meters:** To allow several operating modes in feeding the SBRs and the drum filter, a change in the WWTP pipeline construction including the assembly of automatic valves was necessary. The plant was also upgraded with flow meters (Proline Promag W 400 from Endress and Hauser) to obtain the volumes of the SBR and drum filter inflow.

- **Nitrate probes:** For online monitoring of the nitrate concentration probes were installed in both SBRs (Nitratax Sc, Hach Lange)
- **Turbidity probes / transmitter:** Continuous measurement of turbidity (Solitax Sc, Hach Lange) in the WWTP influent (probe located in the sump shaft) for water quality depended dosing of chemicals was installed as well as in the drum filter effluent for control of filtration performance transmitted by an SC 1000 (Hach Lange)
- **TSS controlled process water pump:** For optimized supernatant withdrawal the manually operated process water pump was replaced by an automatic pump controlled by TSS level in the supernatant. Having an adjustable TSS sensor attached to the top of the pump, a search cycle is started at given times or triggered by an external signal. During the search cycle the pump is moved vertically through the TST and sensor detects the TSS concentration at the actual position. If the concentration is lower than a predefined values the pump starts and the found supernatant is pumped to the sump shaft.

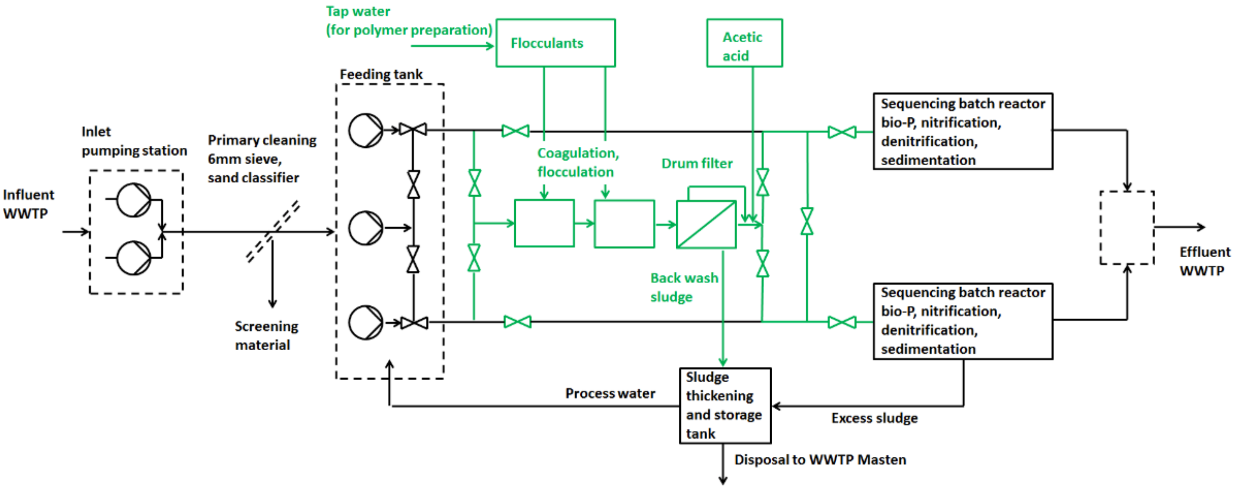

Figure 6: Process flow diagram of the WWTP Westewitz with advanced primary treatment

Figure 7: left: Aerial image of the WWTP Westewitz after installation of the filtration plant (encircled in red); right: Front view of the containers of the filtrations plant located between the SBRs.

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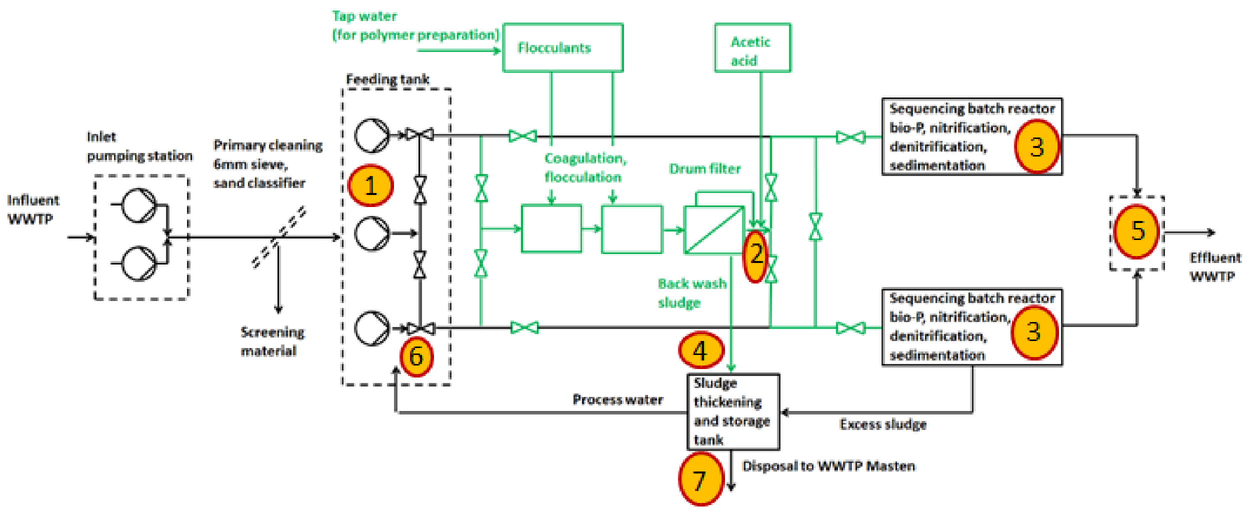
3. Methods: Sampling Strategy and Analytics

To determine the COD extraction and the biological performance of the SBRs laboratory analyses as well as online monitoring have been used.

3.1. Laboratory Analysis

Grab samples were taken at the sampling points shown in Figure 8 one to five times a week.

Activated sludge samples were taken from the SBRs at the end of the aerated phase (highest homogenization of the reactor assumed at that time). From Table 3 parameters measured in the laboratory and the number of measurements per week for each sampling point can be purported.



1 Influent WWTP/ Influent filtration*

2 Effluent filtration = Influent SBRs (filtrated)

3 Biology SBR 1 und 2

4 Primary sludge

5 Effluent WWTP from SBR 1 und 2

6 Recycled process water (supernatant)

7 Thickened sludge

*Same Sampling Point

Figure 8: Process flow diagram of the WWTP (grey) and the filtration plant (green) with sampling points (modified graphic, originally from Herrmann (2016))

Table 3: Overview parameters and the number of weekly measurements at the sampling points

Sampling point	Measured Parameters (laboratory analysis)	Measurements per week
1 (Influent WWTP/ filtration)	**COD, TP** (TN, NH_4^+-N, NO_3^--N, NO_2^--N)	**3** (1)[1]
2 Effluent filtration	**COD, TP** (TN, NH_4^+-N, NO_3^--N, NO_2^--N, VFA)	**3** (1)[2]
3 SBR 1 and 2	Mixed liquor suspended solids, sludge volume[3]	2-5
4 Primary sludge[4]	Dry matter (DM)	2-5
5 Effluent WWTP	**COD, TN, NH_4^+-N** (TP, NO_3^--N, NO_2^--N)	**3** (1)[5]
6 Recycled process water	NH_4^+-N, VFA	1
7 Thickened sludge[6]	pH, COD, COD_{fil}, oP, NH_4^+-N, VFA, DM, organic DM	Only during sludge disposal

Standard parameters:

Standard parameters (COD, TP, TN, NH_4^+-N, NO_3^--N, NO_2^--N, VFA) were measured photometrical in the in- and effluent of the WWTP (sampling point 1 and 5, s. Figure 8) and in the in- and effluent of the filtration (sampling point 1 and 2, s. Figure 8) using Hach Lange Cuvette Test Kits (photometer: DR 2800 Hach Lange). 0.45µm filtration was performed for measurement of the nitrogen fractions (NH_4^+-N, NO_3^--N, NO_2^--N) and VFA's.

Mixed liquor suspended solids (MLSS):

Mixed liquor suspended solids in the activated sludge from the SBRs (sampling point 3) was determined from homogenized and filtrated samples, dried at 105°C with a moisture determination scale (MA35 from Sartorius) till a constant weight was reached.

Due to the varying water level in the SBRs the DS was normalized to the maximum filling level (4.35 m, s. Chapter 2.1).

[1] Number of COD and TP measurements are higher in periods with coagulant dosing (up to five measurements per week)

[2] During start-up phase of the first SBR (Dec. 2016 - March 2017) COD, TP TN, NH_4^+-N, NO_3^--N, NO_2^--N and pH were measured five times per week (regulatory obligation from the water authority)

[3] Analytical methods and results for sludge volume are not part of this report

[4] Analytical methods and results for primary sludge are not part of this report

[5] Number of measurements vary due to operational issues (in case closer monitoring is necessary)

[6] Analytical methods and results for primary sludge are not part of this report

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$$MLSSnorm = MLSS * \frac{level_{sampling}}{level_{max}}$$

Mixed liquor volatile suspended solids (MLVSS):

Mixed liquor volatile suspended solids were estimated via the mixed liquor suspended solids content.

In previous studies (Franke, 2016) it was found out, that the MLVSS / MLSS ratio is constant in both SBRs. In SBR 1 MLVSS / MLSS = 0.8 (+/- 5%), in SBR 1 MLVSS / MLSS = 0.79 (+/- 2%).

3.2. Online Monitoring

Table 4 shows the online measurements at the different sampling points. The water quality parameters were measured with Hach Lange probes and transmitted via a SC 1000 from Hach Lange to the process control system (PCS).

Table 4: Overview online measured parameters

Sampling point	Online measured parameters
1 (Influent WWTP/ filtration)	Q, NTU
2 Effluent filtration	Q, NTU
3 SBR 1 and 2	DO, NO_3^- -N, NTU

a) Online monitoring of SBRs:

- DO concentration and temperature (LDO probe)
- Nitrate concentration (Nitratax Sc probe, +/- 3% measurement accuracy)
- Turbidity (NTU, Solitax Sc probe)
- Inflow (Q, Proline Promag W 400 from Endress and Hauser)

Nitrate online probes are maintained twice a year in the frame of a maintenance agreement with Hach Lange. Laboratory results for nitrate in the effluent of the WWTP are randomly compared with the online values of the nitrate probe.

b) Online monitoring drum filter in- and effluent:

- Turbidity (Solitax Sc probe)
- Q (Proline Promag W 400 from Endress and Hauser)

4. Process control system for existing SBR, drum filter and nitrogen control strategies

4.1. SBR Operation

The SBR configuration is a variation of the activated sludge process from continuously operated plants to discontinuously operated reactors. During this discontinuous operation the reactor passes through different phases, which are not locally separated like in a continuously operated plant , but separated by controlling the different process conditions (according to DWA-M 210). A complete iteration of the process conditions is called a cycle.

Figure 9 shows a complete SBR cycle with the different phases. The beginning and end of each phase is either controlled by time, measured concentrations in the reactor or via the inflow.

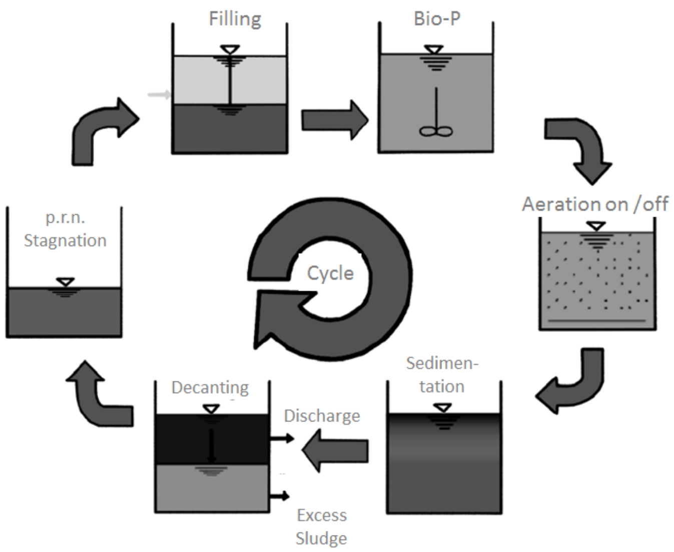

Figure 9: Scheme of the phases within a cycle of SBR operation (modified graphic from DWA-M 210 (2009)

1. **Filling:**

   During the filling phase mechanically treated wastewater is fed into the stirred reactor. At the beginning of the filling phase (s. Figure 10) the reactor is operated under anaerobic conditions to enable biological phosphorous removal (Bio-P[7]), followed by an alternation of aerobic (nitrification) and anoxic (denitrification) conditions for nitrogen removal. Phosphorous and nitrogen removal form the inner cycle in contrast to the full cycle, which is also called outer cycle (s. Figure 10).

   The filling phase ends when a remaining water uptake capacity (volume reserve) is undershot and a certain filling level is reached.

[7] Biological phosphorous removal via microorganisms by uptake in the biomass

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2. After aeration:

After the filling phase the aeration is switched on once again to convert the remaining ammonium to nitrate, which is the end of the reaction phase.

3. / 4. Sedimentation / decanting and excess sludge withdrawal:

After the reaction phase the reactor is no longer stirred, sludge settling (sedimentation phase) starts and the purified water is discharged (decanting phase), until a certain minimum filling level of the SBR is reached.

During sludge settling and water discharge the excess sludge is withdrawn from the bottom of the SBR. The starting time is controlled by a set countdown (e.g. 180 min), which starts after at the beginning of the sedimentation phase. The duration of the withdrawal is set by a given running time for the excess sludge pump (e.g. 600 sec).

After the excess sludge withdrawal, the full SBR outer cycle starts again.

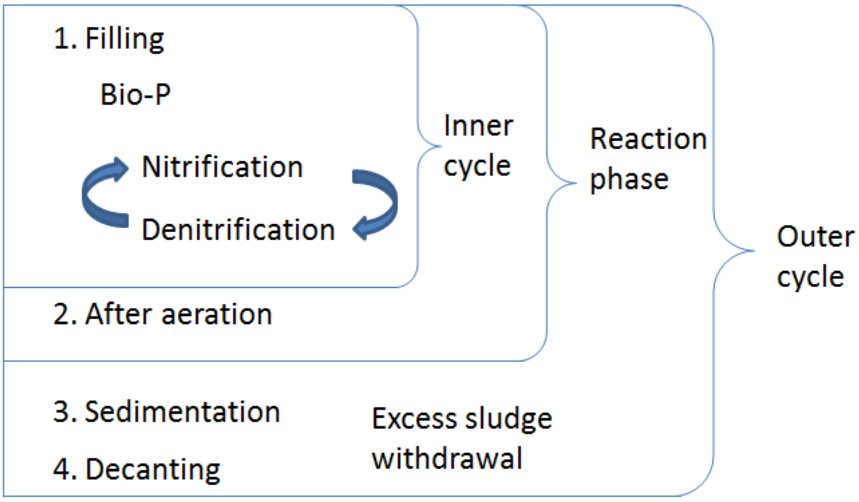

Figure 10: Classification of the different phases within a cycle of SBR operation

To extend the treatment capacity, several SBRs can be operated in parallel (DWA, 2009), taking the incoming wastewater at the same time. As both SBRs cannot go into sedimentation/decanting phase at the same time (no receptive SBR) there is an extra control that times the filling and settling/decanting phases.

At some point both SBRs are in filling phase. When a minimum volume reserve in one of the SBRs is undershot it goes into sedimentation, leaving enough volume in the other SBR to take the inflow that reaches the WWTP in the time of sedimentation and decanting phase of the first SBR.

4.1.1. Aeration Control

A way to avoid losing carbon on the one hand and gaining more time for denitrification on the other hand is the optimization of the aeration control.

In the original process control system of the WWTP (PCS) the duration of the aerated phase while filling of the SBRs was time controlled, meaning the blowers keep up a stable oxygen concentration (control input) for a defined period of time (aeration time), operating as soon as the DO is below this set point (s. Figure 11, left). Within the advanced nitrogen control strategy the oxygen depletion based control of the aeration time was implemented.

For the depletion control an upper and a lower set point has to be defined, whereby the control input (1.5 mg/L) should be the same value as the upper set point. For the lower set point a concentration of 1 mg/L is recommended (s. Figure 11, right)

At the beginning of the aerated phase the blowers run with maximum frequency till the upper set point (1.5 mg/L) is reached. Then the blowers stop and the time for the oxygen concentration to go down to the lower set point is measured. From the difference in concentration and the time to reach the lower set point oxygen depletion is calculated. As the difference in concentration is fixed by the upper and lower set point, the depletion depends on the time needed to reach the lower set point. If the depletion is smaller than a previously defined limit value, the aerated phase is stopped as it can be assumed there is no ammonium left to be oxidized. Shorter aerated phases imply less oxidation of COD and a higher proportion of none aerated phases in the filling phase. Consequently denitrification times are longer.

To guarantee sufficient nitrification time, a minimum value (in practise 40-60 min) that is kept independently from the depletion can be set in the PCS.

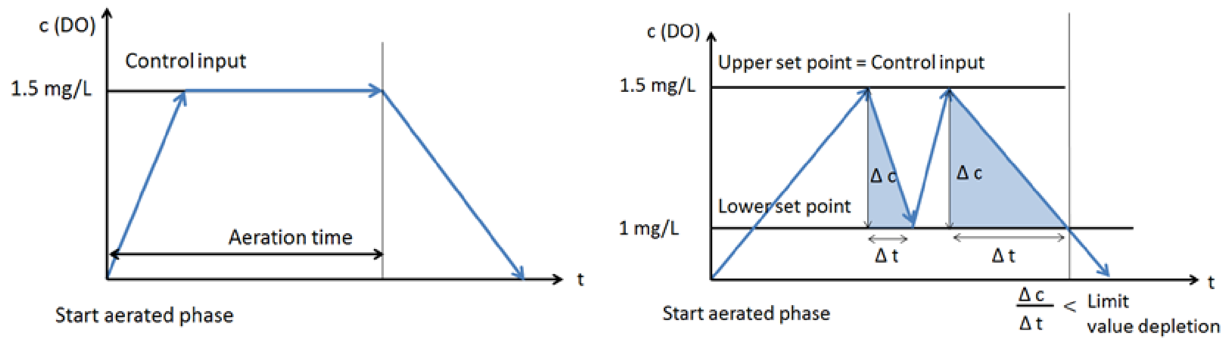

Figure 11: left: Scheme explaining the functionality of the time based oxygen control; right: Scheme explaining the functionality of the depletion based oxygen control

4.2. Combined SBR and Drum Filter Operation

4.2.1. Feeding Regime

Originally the pumps in the sump shaft were operated in parallel, which guaranteed an equal distribution of the wastewater between the SBRs.

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The installation of the filtration plant together with the implementation of the advanced nitrogen control strategy required an adapted feeding regime.

Additional valves and piping was installed to realize the different feeding variants for drum filter and SBRs and to be suitable for varying inflow conditions.

Figure 12 displays a screenshot of the process control system (PCS) showing the connection of the sump shaft with the SBRs and the filtration plant.

Wastewater passes the primary treatment (grid) and flows in to the sump shaft. From there it can be pumped to the filtration plant and/or to the SBRs in different combinations:

- **Filtration only:** Water is pumped to the filtration plant and flows gravity driven into one of the SBRs (indicated by the blue arrows, all valve settings are also implemented the other way around, feeding SBR 1 with filtrated wastewater.
- **Filtration plus bypass:** Water is pumped simultaneously, directly into one of the SBRs (indicated by the red arrows) e.g. in case that the inflow quantity exceeds the capacity of the drum filter
- **Bypass only:** Pump directly to both SBRs (indicated by the black arrows) without filtration

Which SBRs is fed priority with filtrated / none filtrated wastewater is determined by the inner cycle (s. Chapter 4.1). Carbon and therefore feeding is needed mostly during biological phosphorous removal and denitrification phase. In nitrification phase there is no carbon demand and feeding is avoided in this phase.

The filtrate cannot be parted between the SBRs. Therefore is has to be set, which SBR should obtain the water.

The inner cycles of the SBRs are totally independent, having a set of blowers for each SBR. Which SBRs is fed with filtrated wastewater is set be inner cycles. The different constellations and feeding scenarios are

- One SBR in Bio-P the other in nitrification or denitrification (both SBRs in Bio-P is not possible as they are not allowed to have a parallel outer cycle): Filtration plus bypass to the in the SBR in Bio-P
- One SBR in nitrification, one in denitrification: Filtration plus bypass to the SBR in denitrification
- Both SBRs in denitrification: Filtration only to the SBR that entered denitrification phase second, bypass to the SBR that entered denitrification phase first,
- Both SBRs in nitrification: Filtration only to the SBR that entered nitrification phase first, bypass to the SBR that entered nitrification phase second

With these feeding priorities an optimal utilization of the organic carbon as well as an evenly filling of the SBRs is assured.

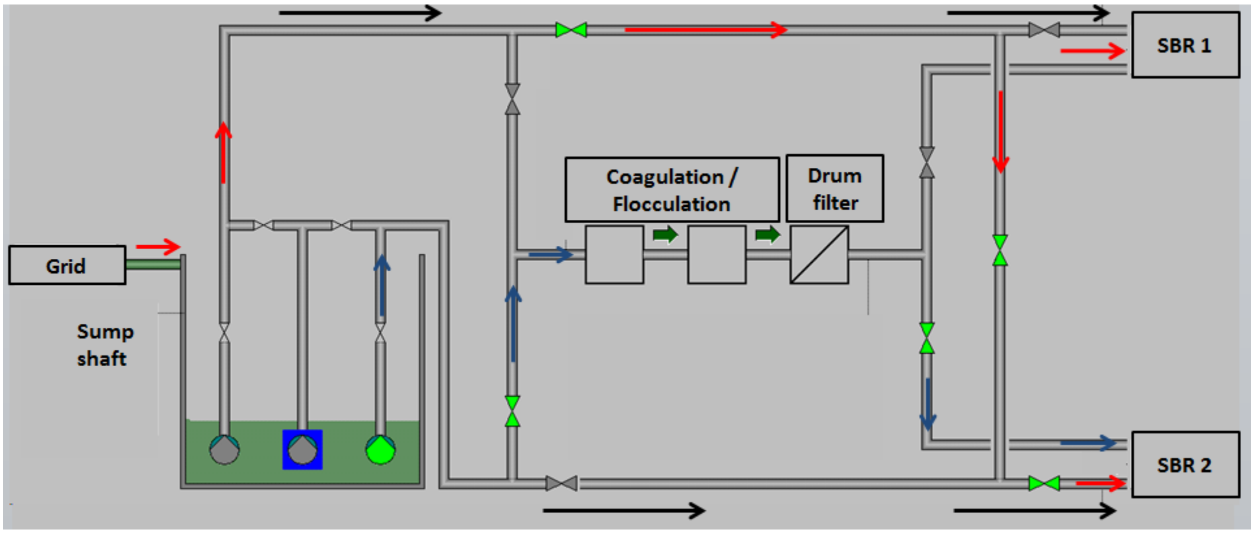

Figure 12: Screenshot from the PCS: Grid and sump shaft with drum filter and SBRs. Blue arrows: Pumping to the drum filter and SBR fed with filtrated water; red arrows: direct feeding of the SBRs with 2nd pump parallel to the drum filter operation; black arrows: direct feeding of both SBRs, no filtration

4.2.2. Dosing of Coagulant and Polymer

As it can be seen in Figure 12 and also described in Chapter 2.2.2 part of the filtration plant is the dosing of coagulant and polymer.

Two parameters are relevant for the dosing of these chemicals:

1. **Concentration in the stock solution:**

   The dosed amount of coagulant solution has to be referred to the metal content in the stock solution (product: VTA 69 with **5.2 g/L Aluminium**) and the dosed amount of polymer has to be referred to the active substance concentration in the stock solution (product: 1 g/L active polymer solution prepared from Hydrex 6454 polymer powder).

2. **Set point concentration (SPC):**

   This is the concentration of chemical aimed for in the drum filter influent. There are again two options for the dosing strategy either volume or turbidity proportional:

   - Quantity of chemical per liter drum filter influent (mg /L)
   - Quantity of chemical per turbidity unit in the drum filter influent[8] (mg /NTU)

   For the dosing of the polymer the turbidity based dosing (s. Figure 14) for the set point concentrations are:

[8] Maximum dose can be limited to buffer turbidity peaks in the influent

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1. Quantity of chemical per turbidity unit in the drum filter influent (mg /NTU) (see above)
2. Quantity of chemical per turbidity unit in the drum filter influent (mg /NTU) correlated with COD extraction[9]
3. Quantity of chemical per turbidity unit in the drum filter influent (mg /NTU) correlated with COD extraction and limited by increasing nitrate concentrations in the SBRs (further explanation in Chapter 4.3.1)

4.3. Special control mechanisms within the nitrogen removal strategy

The implementation of the PCS with an advanced control strategy for nitrogen removal has not only changed the aeration control and the feeding regime of the SBRs as described above, but has also added special control mechanisms (s. Figure 13).

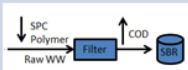
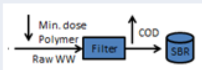
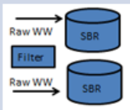
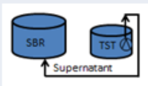
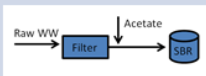
Steps of nitrogen control mechanisms	Schematic description of the mechanism	Set point: NO_3^- -N concentration [mg/L]	Set point is based on
1. Reduction polymer dose		2* – 7	Mean value over the measurements in both SBRs at the end of the last three denitrification phases
Polymer dose on minimum level		7 - 9	s. above
2. Bypass filtration (can be triggered for one or both SBRs)		9 /10*	Actual measured value in the SBR monitored during nitrification and denitrification phase
3. Process water recycling		10 /11*	Mean value over the measurement both SBRs at the beginning of the nitrification phase
4. Acetate Dosing		12 /14*	Actual value measured in the SBR at the end of the filling phase

Figure 13: Nitrogen control mechanisms in the order of occurrence during the operation, *set point was changed during the trials

4.3.1. The nitrate dependent dosing of polymer

The first control mechanism that happens when a certain nitrate concentration is exceeded is the reduction of the polymer dose (Figure 13, Figure 14), leaving higher COD concentrations in the filtrate going to the SBRs.

[9] In previous trials the correlation between turbidity proportional dosing and the achieved COD extraction in the drum filter was estimated. The resulting concentrations for the different extraction levels (50%, 65%, 75%) can be put into the PCS and the requested COD extraction can be chosen directly

A maximal tolerable nitrate concentration can be defined for the COD extraction levels (s. Figure 14, "SPC polymer nitrate limit COD extraction").

At the end of each denitrification phase the mean value over the two preceding and the current denitrification phases of both SBRs (six values in total) is calculated and compared with the nitrate set point concentrations (2,4 and 7 mg/L for 50%, 65% and 70% COD extraction).

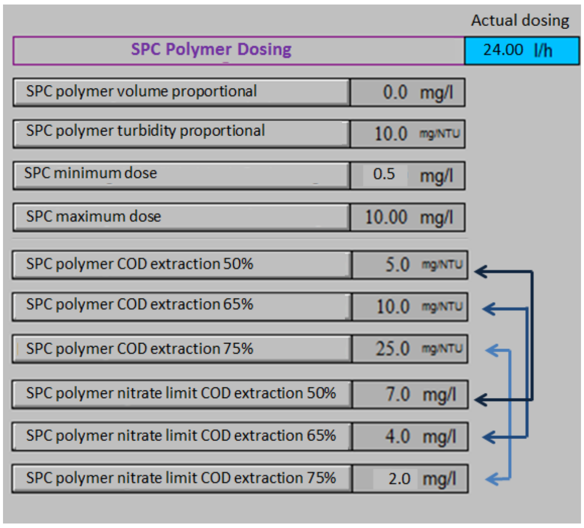


Figure 14: Screenshot from the PCS with nitrate limit set point concentrations for the polymer dosing

For the set points, shown in Figure 14 the following quantities are dosed depending on the actual nitrate value:

- 0 - 2 mg NO3--N/L: 75% COD extraction, with 25 mg/NTU dosed
- 2 - 4 mg NO3--N/L: 65% COD extraction, with 10 mg/NTU dosed
- 4 - 7 mg NO3--N/L: 50% COD extraction, with 5 mg/NTU dosed
- NO_3^--N > 7 mg/L: reduction to minimum dose[10] (s. Figure 14, "SPC minimum dose")

4.3.2. **Bypass of the filtration plant**

When the polymer dose is already reduced to a minimum and no supernatant is found another mechanism to feed more COD to the SBRs is to fully bypass the filtration. A set point nitrate concentration can be individually defined for each SBR, at which it is no longer fed with drum filter effluent, but with carbon rich raw wastewater from sump

[10] Dosing of polymer enhances the filter capacity. Minimum dosing can be necessary at high (> 500 NTU) inflow turbidity to guarantee a stable filtration process

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shaft. The nitrate concentration is continuously monitored (nitrification and denitrification phase) and triggers the bypass mechanism instantly when it exceeds the set point.

In the event of an exceedance the respective SBR is not fed with filtrated, but with raw wastewater for next two hours to allow for a stabilization of the denitrification process.

4.3.3. **Activation of process water recycling**

The supernatant in the thickening and storage tank for primary and excess sludge is a high loaded (average COD: 1056 mg/L, N=3) carbon source. As the supernatant needs to be separated from the sludge in order transport as less water with the sludge as possible, the idea is to use it as an easily accessible, cheap source of mainly soluble carbon.

Applied in the process control it means, that at start of each denitrification phase the mean nitrate value of both SBRs is compared to the set point nitrate concentration that triggers the mechanism (10/11 mg/L, s. Figure 13) If the actual value is higher than the set point a search cycle of the automatic process water pump is triggered and supernatant (if detected by the TSS sensor on the pump, s. Chapter 2.2.2) is pumped to the sump shaft to provide additional soluble COD, which passes the rum filter unaltered and reaches the SBRs.

4.3.4. **Acetate Dosing**

If all the other steps will not work out to achieve sufficient denitrification to keep the threshold values, acetate dosing in the filtrate is started as a last step to provide an external carbon source to stabilize denitrification.

To ensure enough reaction time with the external carbon source, an “after denitrification phase” phase was added to the SBR cycle at the end of the filling phase (s. Figure 15) in this case.

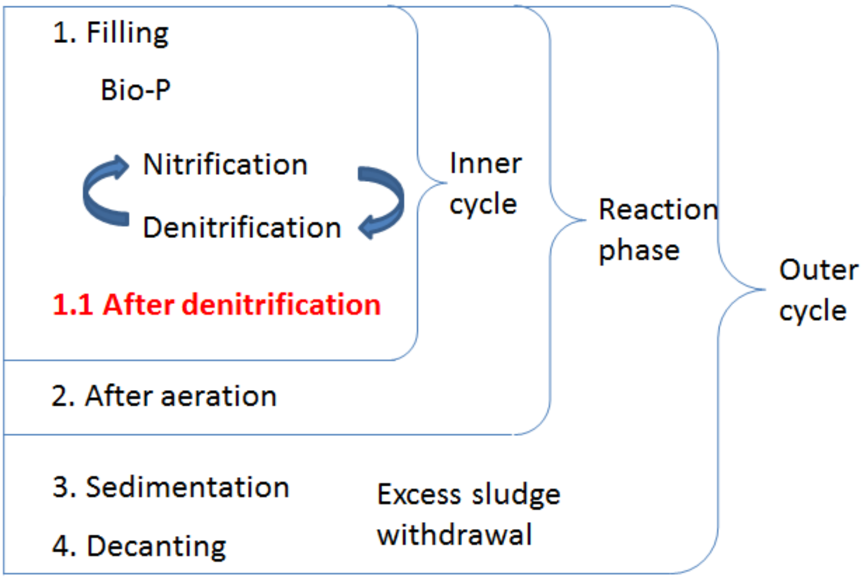

Figure 15: Classification of the different phases within a cycle of SBR operation with added "After denitrification" phase (red)

Therefore at the end of the "regular" filling phase the nitrate concentration in the SBR is checked. If the current value is higher than the set point the SBR goes into after denitrification phase, in which the acetate dosing is started and the polymer and coagulant dosing is automatically reduced to minimum. After denitrification phase continues as long as acetate is dosed[11].

If the current value is lower than the set point the after denitrification phase is skipped and sedimentation/decanting is started.

[11] Dosing time is calculated from the concentration of the stock solution, volume of dosed solution (determined by the maximum capacity of the pump), the difference of the allowed and the measured nitrate concentration and a safety factor

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5. Results

5.1. Characterization of WWTP / drum filter influent and effluent from WWTP and drum filter

During the trials the influent to the WWTP/ drum filter (same sampling point) has been characterized in terms of standard parameters (s. Table 5) and compared to the design values (s. Table 1). The concentrations during the trials were between min 19 % (COD) and 125% (TKN) higher than the design values. The COD/N ratio was still in an optimal range of 9.2:1.

Table 5: Statistic of influent concentrations from WWTP Westewitz (Jan 2017- Nov 2017) and design concentrations, measured in the OEWA laboratory in Masten (located near Westewitz)

Influent WWTP/drum filter	COD	BOD_5	NH_4^+-N	NO_3^--N	NO_2^--N	TN	TP
	[mg/L]						
Number of samples	46	45	46	9	9	46	46
Average	734	419	46.9	1.36	0.41	79.8	11.5
Minimum	420	230	22.5	0.13	0.02	38.3	3.43
Maximum	1186	827	78.6	2.54	0.98	133	25.6
Design Concentration	615	308	-	-	-	56.4[12]	9.23

For the nitrogen removal in the SBRs the COD/N ratio in the effluent of the filtration is the critical parameter, having the biggest impact on denitrification apart from temperature. A minimum COD/N ratio of 4.8:1 (s. Chapter 1) is vital for the denitrification process and therefore for keeping the total nitrogen effluent threshold values of the WWTP.

Table 6: Statistic of effluent drum filter concentrations, measured on site in Westewitz

Effluent drum filter		Jan-Nov 2017	30% COD Reduction	45% COD Reduction	60% COD Reduction
Number of samples		153 (COD)/ 100(TN)	6 (COD)/ 5 (TN)	9 (COD)/ 3 (TN)	7
COD [mg/L]	Average	347	389	321	245
	Minimum	121	263	161	121
	Maximum	1791	504	417	418
TN [mg/L]	Average	73.9	68.2	75.1	Not determined
	Minimum	37.4	50.7	69	
	Maximum	170	92.1	77.2	

[12] For domestic raw wastewater: according to Metcalf and Eddy (1991) NO_3^- - N: 0 mg/L, NO_2^- -N: 0 mg/L, consequently no difference between TN and TKN

With only 5.3 % TN removal in the drum filter (measurements from Jan 2017- Aug 2017: mean concentration influent WWTP (N=28)/drum filter: 78.0 mg/L (N= 125), mean concentration effluent drum filter: 72.9 mg/L (N=125) the nitrogen content is not changed by filtration. For further calculation of COD/N ratio a 5.3% TN reduction in the drum filter was assumed.

Drum filter effluent mean concentrations from May (both SBRs fed with filtrated wastewater, s. Table 8) till November 2017 were COD 318 mg/L and TN 78.4 mg/L (COD/N ratio: 4.05:1)

Looking at the COD and TN influent loads of the SBRs (filtrated and none filtrated wastewater) the ratio is shifted to 4.8:1.

This ratio is close to the minimum ratio of 5:1 (s. Chapter 1). Table 7 shows the concentrations in the effluent of the WWTP. It can be seen, that the average values are far below the threshold values. Even maximum nitrate concentration is below 10 mg/L (9.55 mg/L), showing that there was no major issues due to inhibited denitrification. The main operational issues were caused be insufficient nitrification due to wearout of the diffusors and irregularities at the installation of the new process control (maximum ammonium concentration: 25.5 mg/L).

Table 7: Statistic on effluent concentrations from WWTP Westewitz (Jan 2017- Nov 2017) and threshold values for discharge quality

Effluent WWTP	COD	BOD_5	NH_4^+-N	NO_3^--N	NO_2^--N	TN	TP
	in mg/L						
Number of samples	110	60	115	58	64	114	N=68
Average	18.6	6.39	1.84	2.88	0.04	6.07	3.78
Minimum	5.6	3	0.01	0.22	0.01	0.01	0.61
Maximum	41	13	25.5	9.55	0.2	26.8	8.95
Threshold value	70	40	-	-	-	18	8

In Figure 16 effluent values for each SBR are presented. In April/ May an increase in the ammonium effluent concentration of SBR 1 can be seen. This increase was caused by an insufficient aeration due to wear out of the diffusors. They had to be changed during the trials, which happened at the beginning of July. Another operational issue affecting the nitrification occurred in October also resulting in increased ammonium effluent concentrations (s. Chapter 5.3.2), but could be eliminated promptly.

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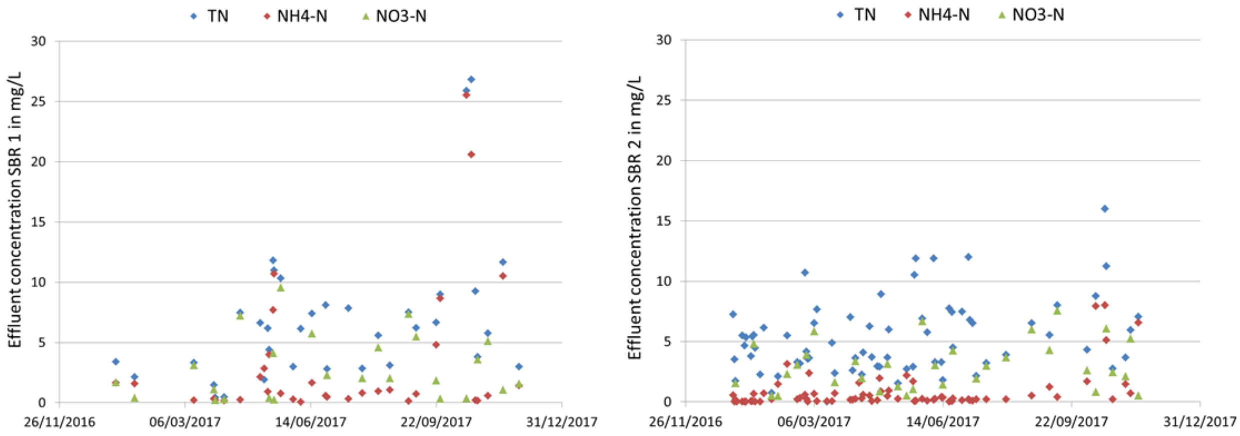

Figure 16: Effluent quality SBR 1(left) and SBR 2 (right) for different nitrogen fractions from Jan 2017 - Nov 2017

5.2. Reference phase and periods with different COD load reductions

In the months after commissioning the filtrated wastewater was only fed into SBR 2 (regulatory obligation from the water authority) and the COD load reduction was slowly increased (s. Table 8). Thus it should be ensured, that negative consequences for the biocenosis could have been identified before causing violations of the effluent quality requirements. In May 2017 the filtrated wastewater was fed to both SBRs, and load reduction was increased to 60% in September 2017.

Table 8: Increase of COD load reduction during the trials

	COD load reduction referred to		
	WWTP	SBR 1	SBR 2
	[%]		
Nov-16	commissioning phase		
Dec-16	5	0	6
Jan-17	7	0	13
Feb-17	11	0	17
Mar-17	9	0	16
Apr-17	23	0	37
May-17	30	29	31
Jun-17	35	33	37
Jul-17	36	40	33
Aug-17	56	55	58
Sep-17	60	60	59

5.2.1. Selection of periods and calculation of denitrification rates

To assess the denitrification performance of the SBRs three time periods with different COD extractions were chosen and compared to a reference phase without COD extraction. COD extraction in the drum filter over these periods should be close to 30%, 50% and 70% (s. Figure 17).

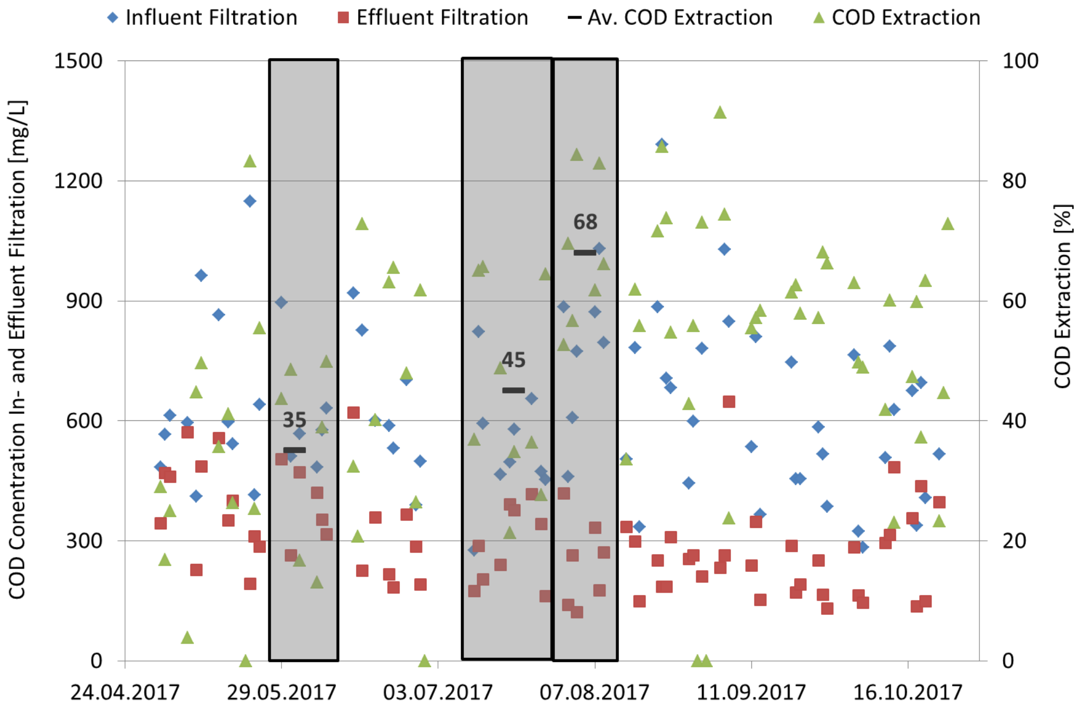

Figure 17: COD concentrations of in- and effluent to filtration and time periods chosen for evaluation of denitrification rates (grey) with average COD extraction

The mass balances for these periods were also calculated including bypasses of the drum filter, resulting in lower load reductions for the SBRs than the direct COD extraction in the filter (s. Table 9).

Table 9: Target COD extraction, actual COD extraction in the filter and corresponding load reduction for the SBR for different time periods

Time	Target COD Extraction	Actual COD Extraction in the filter	Overall load reduction in the SBR
	[%]		
22.05.-08.06.2017	30	35	30
11.07.-27.07.2017	50	45	42
31.07.-09.08.2017	70	68	58

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Denitrification rates were calculated by the following equation:

$$DNR = \left(\frac{\Delta c \, (NO_3^- - N)}{c \left(MLVSS^{13} \right) * \, \Delta t} \right)$$

Including the last two days of each period applying the following criteria:

- Starting point for calculation: highest nitrate value during or after aeration (> 2 mg NO_3-N/ L as homogenization of reactor as a limiting factor)
- Endpoint for calculation: Lowest nitrate value before next aeration period
- Minimum denitrification time: 45 min
- Temperature correction according to literature, standardized to 20°C

$$DNR_{20} = \frac{DNR_T}{1.09^{(T-20°C)}}$$

The denitrification rates and operational data for the different phases are compared with a reference phase shortly before commissioning of the filtration plant.

5.2.2. Operational data and denitrification rates in reference phase

Figure 18 gives an overview of the relevant operational parameters (water level, nitrate and dissolved oxygen concentration) in SBR 1 and 2 in the reference phase, i.e. without primary filtration. The nitrate concentration rises in nitrification phases (DO > 0.5 mg/L) over the course of one cycle and drops close to zero during the settling phase (indicated by the sinking of the water level). This pattern can be observed for each cycle in both SBRs, if there are no disturbances in operation. Daily temperature variations in the SBRs are < 1°C and can be neglected.

[13] Referred to mean water level in the SBRs during denitrification phase

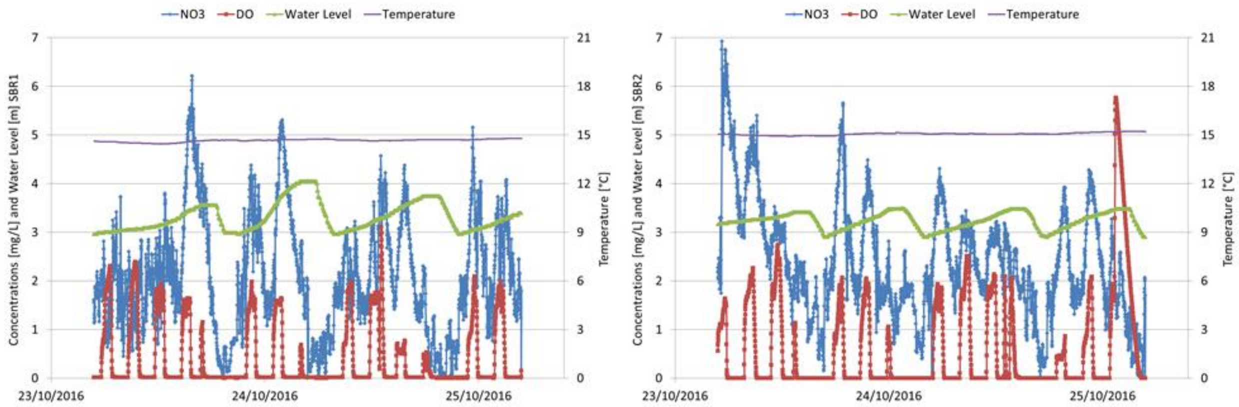

Figure 18: Operational Data for reference Phase in SBR 1 and 2

Temperature corrected denitrification rates (DNR) for the reference phase range between 1.30 and 1.60 mg NO_3-N/(h*g MLVSS) for SBR 1 and between 0.351 and 1.63 mg NO_3-N/(h*g MLVSS) (s. Table 10). Henze and Harmoés (1990) give denitrification rates from 0.6 - 3 mg NO_3-N/(h*g MLVSS) for domestic wastewater. The minimum DNR in SBR 2 was observed during the late evening hours (03:52-06:02), indicating lower COD influent loads at night time and therefore being lower than literature values.

Table 10: Statistics for temperature-corrected denitrification rates (DNR) and SBR temperature for reference phase

Reference Phase	DNR SBR 1	Temp. SBR1	DNR SBR 2	Temp. SBR2
	mg NO_3-N/ (h*g MLVSS)	[°C]	mg NO_3-N/ (h*g MLVSS)	[°C]
Number of samples	9	online	9	online
Average (DNR and T)	1.30	14.7	0.876	15.1
Minimum (DNR and T)	0.993	14.4	0.351	14.9
Maximum (DNR and T)	1.60	14.8	1.63	15.2

5.2.3. Operational data and denitrification rates for COD load reductions

Operational data and denitrification rates for 30% COD load reduction

COD/N ratio in the raw wastewater during this period was at 8.5:1. Ratio in the SBR influent loads (mixture of filtrated and none filtrated wastewater) was 6.0:1. There was no recycling of supernatant from TST during that period.

The operational data show the same pattern as during the reference phase. But looking at the DNRs an influence of the reduced COD load can be seen in SBR 1 resulting in generally lower rates between 0.462 and 1.18 mg NO_3-N/(h*g MLVSS), s. Table 12. This reactor was not fed with filtered water before, so the reduced COD load led to a slower denitrification.

DNRs for SBR 2 show lower variation in minimum and maximum range than in the reference phase as well as a lower mean value (0.749 mg NO_3-N/(h*g MLVSS)). But the decrease of the DNR in SBR 2 (14.4%) was not as strong as in SBR 1 (47.6%). It can be as-

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sumed that as SBR 2 was already fed with filtrated, low COD/N wastewater before this period, the biocenosis was already adapted in this reactor to lower COD load.

For both SBRs the maximum DNRs are reduced by approx. 30% - 40% due to a COD load reduction of 30% compared to the reference scenario.

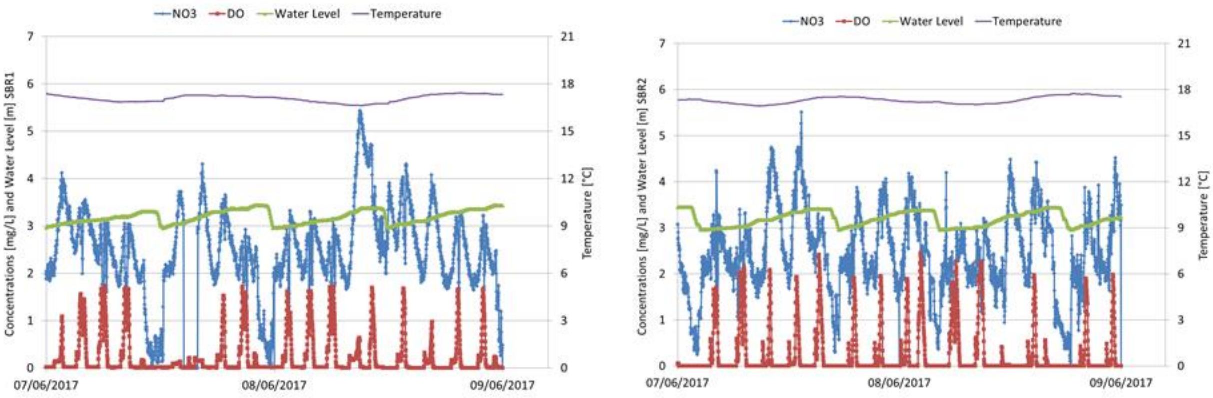

Figure 19: Operational data for SBR 1 and 2 at 30% COD load reduction

Table 11: Statistics for temperature-corrected denitrification rates at 30% COD load reduction

30% COD load Reduction	DNR SBR 1	Temp. SBR1	DNR SBR 2	Temp. SBR2
	mg NO_3-N/ (h*g MLVSS)	[°C]	mg NO_3-N/ (h*g MLVSS)	[°C]
Number of samples	11	online	9	online
Average	0.681	17.1	0.749	17.3
Minimum	0.462	16.6	0.568	16.9
Maximum	1.18	17.4	1.017	17.7

Operational data and denitrification rates for 42% COD load reduction

In this period, COD/N ratio in raw wastewater was 7.0:1, so already lower than during the previous period of load reduction (8.5:1 for 30% COD load reduction). Looking at the SBR influent loads from filtration and direct feeding, COD/N was 4.1:1. Adding carbon from regular process water recycling (VFA/N ratio of 7.8:1 and mean VFA concentration of 583 mg/L (N=10)) increased the ratio to 4.4:1.

No difference in the operational data was apparent (s. Figure 20), but DNRs showed again a decreasing trend in both SBRs compared to reference and previous phase with 30% load reduction (s. Table 12, mean value SBR 1: 0.581 mg NO_3-N/(h*g MLVSS), mean value SBR 2: 0.531 mg NO_3-N/(h*g MLVSS)) to the level of endogenous denitrification (> 0.6 NO_3-N/(h*g MLVSS) despite supernatant withdrawal during this period.

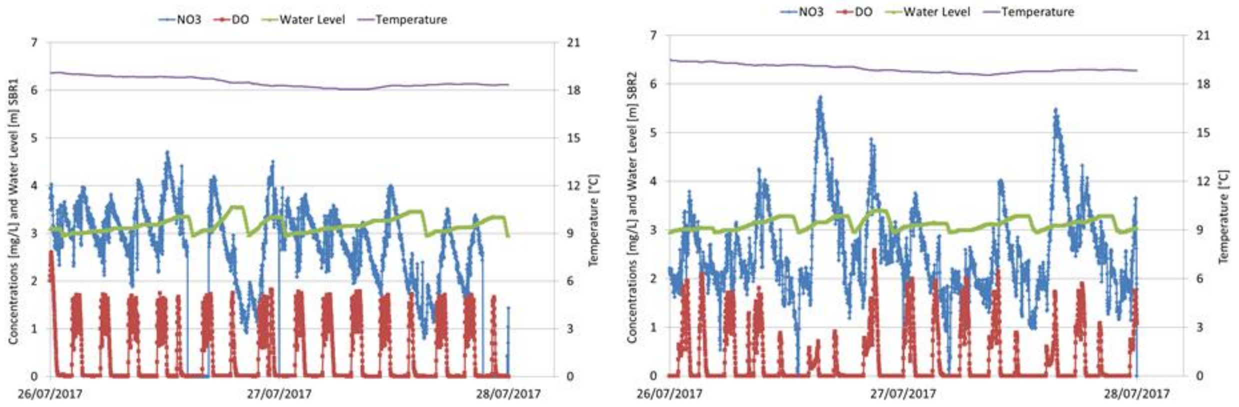

Figure 20: Operational data for SBR 1 and 2 at 42% COD load reduction

Table 12: Statistics for temperature-corrected denitrification rates at 42% COD load reduction

42% COD load Reduction	DNR SBR 1	Temp. SBR1	DNR SBR 2	Temp. SBR2
	mg NO_3-N/ (h*g MLVSS)	[°C]	mg NO_3-N/ (h*g MLVSS)	[°C]
Number of samples	14	online	15	online
Average	0.581	18.5	0.531	18.9
Minimum	0.390	18.1	0.260	18.5
Maximum	0.846	19.1	1.059	19.4

Operational data and denitrification rates for 58% COD load reduction

For this period, the COD/N ratio in the raw wastewater was 9.4:1. The higher COD reduction did therefore the COD/N ratio in the influent load to the SBRs was similar to the period with 42% load reduction. Including supernatant withdrawal the COD/n ratio 58% load reduction was 4.4:1 (for 42% COD load reduction 4.1:1). Nevertheless DNRs in SBR2 decreased, whereas DNRs in SBR 1 increased (maximum DNR: 1.887 mg NO_3-N /(h*g MLVSS)). Looking at the SBRs separately it becomes clear that SBR 1 gets 168% more (SBR1: 26.3 m³/d; SBR 1: 15.7 m³/d SBR 2) non filtrated wastewater than SBR 2 (COD/N ration SBR1 for this period: 4.3:1, COD/N ration SBR2 for this period: 4.0:1). This can be a reason for the higher DNRs in SBR 1 as well as differences in the biocenose.

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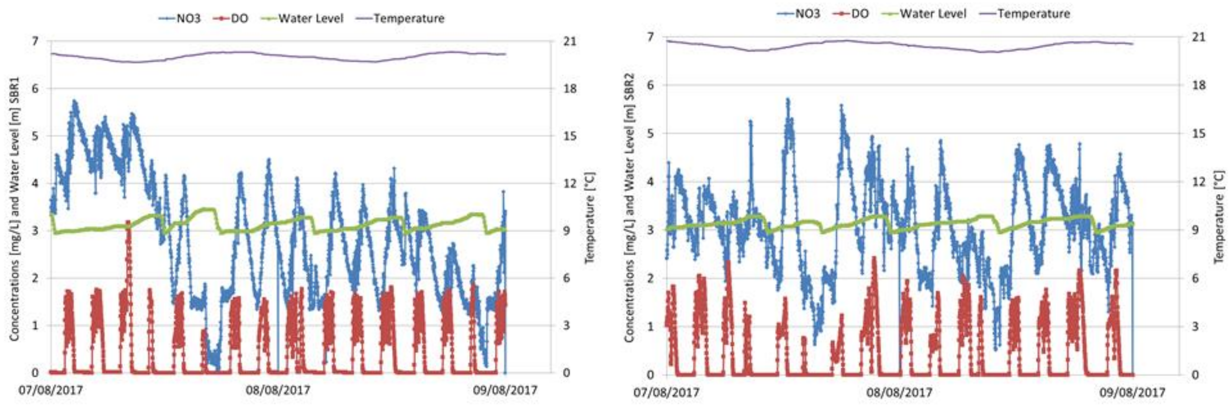

Figure 21: Operational data for SBR 1 and 2 at 58% COD load reduction

Table 13: Statistics for temperature-corrected denitrification rates at 58% COD load reduction

58% COD load Reduction	DNR SBR 1	Temp. SBR1	DNR SBR 2	Temp. SBR2
	mg NO_3-N/ (h*g MLVSS)	[°C]	mg NO_3-N/ (h*g MLVSS)	[°C]
Number of samples	14	online	14	online
Average	0.712	20.0	0.485	20.5
Minimum	0.363	19.7	0.299	20.1
Maximum	1.887	20.3	0.830	20.8

Despite the low DNRs (close to endogenous level), it can be stated, that none of the mechanisms for advanced nitrogen control was activated during the trials. During all extraction levels denitrification rates could be kept high enough for stable SBR operation mainly by means of the special feeding regime (feed only during denitrification phase) supported by the time based process water withdrawal. Table 14 summarized again the COD/N ratios for the load reduction different periods.

Table 14: COD/N ratio for the different periods of load reduction

Period	Influent before filtration	WWTP COD/N ratio	SBR 1 COD/N ratio	SBR 1 Av. DNR	SBR2 COD/N ratio	SBR 2 Av. DNR
				mg NO_3-N/ (h*g MLVSS)		mg NO_3-N/ (h*g MLVSS)
30	8.5	6.0	6.3	0.681	6.1	0.749
42	7.0	4.2	4.2	0.581	4.2	0.531
58	9.4	4.0	4.3	0.712	4.0	0.485

5.3. Exceptional situations with enhanced nitrate concentrations

Nevertheless exceptional situations occurred during the trials in which nitrate levels in the effluent increased, so that the backup strategies for advanced control could be tested.

5.3.1. Permanent aeration

In one of these exceptional situations the aeration was manually switched on for regular sampling (samples were taken during the aerated phase, s. Chapter 3) and accidentally not turned off afterwards, resulting in a four hour permanent aeration. This effect can be clearly seen in Figure 22 with very high DO levels, and a related increase of NO3 effluent concentration due to "missing" denitrification phase.

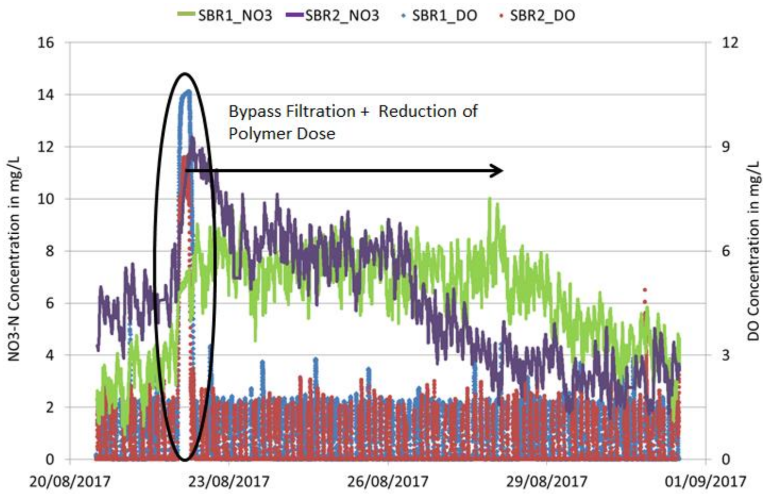

Figure 22: Operational data SBR 1 and 2 during and after permanent aeration. Time of permanent aeration encircled in black

Permanent aeration is paralleled by continuous nitrification which leads to nitrate concentrations above 12 mg/L in SBR 2 (having the lower DNRs), and an activation of the backup strategies in the following order:

1. **Reduction of polymer dose** (actual nitrate limit concentrations of 0, 4, 7 mg NO_3-N/ L corresponding to 35, 25, 10 mg/NTU, minimum dose: 1 mg/L) to minimum dose due to the fast increase in nitrogen concentration. In the following days the dose increased again, varying between 2.5 - 25 mg/ NTU, which correspond to 1 – 6.25 mg/L[14].

   Although the polymer dose was reduced to 1 mg/L, the COD extraction in the drum filter was still higher than expected (average extraction during 22.-31.08.2017: 64% minimum: 43%, maximum 85%, N = 6) showing that the extraction also strongly depends on the actual influent characteristics (average COD inflow concentration during 22.-31.08.2017: 750 mg/L, minimum: 444 mg/L, maximum: 1291 mg/L). Finally, this measure is not suitable as a quick solution for rising nitrate

[14] Calculated for an average influent turbidity of 250 NTU

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concentration in the effluent, but rather to prevent a gradual deterioration of the denitrification process over some days.

2. **The bypass of the filtration** (set point 10 mg/L NO_3-N) was activated for SBR 2 on 22.08.2017.

   COD influent concentration and COD extraction were very high (drum filter influent: 1291 mg/L; effluent: 185 mg/L) making the bypass of the filtration even more effective. Thus the COD/N ratio with filtration was 3.6:1 for SBR 1 and for SBR 2, which was fed with none filtrated wastewater in when the bypass of the filtration was active 6.0:1 for SBR 2. DNRs on the 22./23.08.2017 were 0.653 NO3-N/(h*g MLVSS) (N=13) in SBR 1 and 0.500 NO_3-N/(h*g MLVSS) (N=9) in SBR2.

   It can be clearly seen, that the bypass of the filtration delivers high COD loads to SBR2 in a short time, leading to a slight increase in the DNRs in this reactor (mean DNR at 58% COD extraction: 0.485 NO_3-N /(h*g MLVSS), with bypass: 0.500 NO_3-N /(h*g MLVSS). The bypass led to an immediate drop of the nitrate effluent concentration in SBR 2, which makes it a suitable measure to react to unexpected changes in the process.

3. **The process water recycling** (set point 11 mg/L) was triggered, but no supernatant was found as the TST was emptied shortly before the incident.

4. **Acetate dosing** (set point: 14 mg/L) was not triggered as there was no exceedance of the set point at the end of the filling phase of SBR 2.

As the denitrification performance of the SBRs was not permanently affected in this event, the accumulated nitrate was gradually degraded in the course of the next days.

5.3.2. Degradation of accumulated ammonium

In order to oxidise as less COD as possible minimum nitrification time and depletion based oxygen control (s. Chapter 4.1.1) were adopted for both SBRs in the course of the trials, allowing up to 5 mg/L NH_4^+-N in the effluent of the WWTP.

But it was not taken into consideration that the reduced COD influent load to the SBRs had a negative effect on the aeration control: Since there were less readily oxidisable compounds in the SBR influent the upper DO set point value was quickly exceeded at the beginning of each nitrification phase, leading to a longer period without aeration. This effect was especially affecting SBR 1, which was equipped with new diffusors during the trials.

These “artificially created” denitrification phases lead to an accumulation of ammonium in the SBRs (maximum concentration in SBR 1: 25.5 mg/L NH_4^+-N). When the issue was identified and the upper DO set point increased, the ammonium was fully converted to nitrate (s. Figure 22) which activated the advanced control as explained in Chapter 4.3.

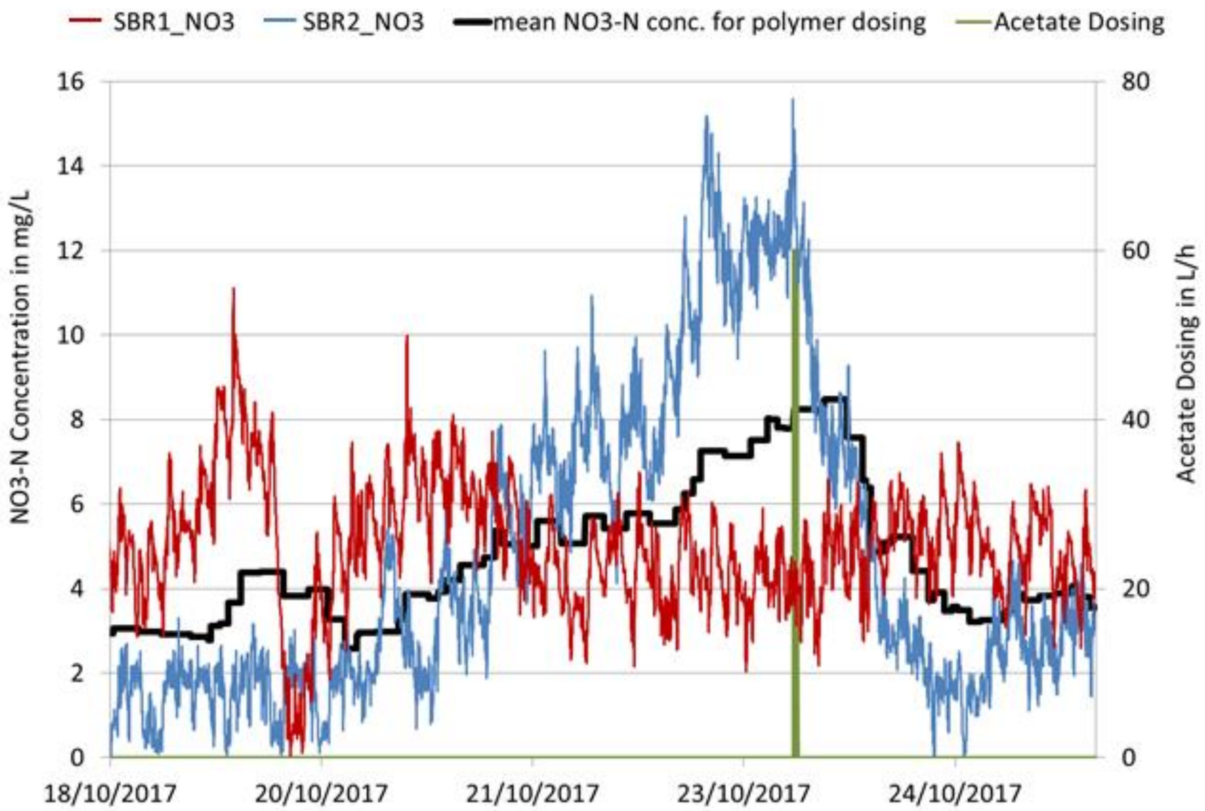

Figure 23: Operational data during and after ammonium accumulation, for SBR1 and 2 mean nitrate concentration as a moving average of five values shown, monitored values of mean nitrate concentrations in both SBRs relevant for nitrate based polymer dosing indicated by the black line

All mechanisms were triggered and apart from the process water recycling, functioned well:

1. **Reduction of polymer dose** (in steps of 0, 4, 7 mg NO_3-N /L corresponding to 25, 10, 5 mg/NTU, minimum dose: 1 mg/L) down to minimum value. COD extraction was lowered by the reduction of the polymer dose from 63% to 23% (20.10.2017 – 23.10.2017).

2. **Bypass of the filtration** (set point 10 mg NO_3-N/L) during the increase of the nitrogen concentrations (22./23.10.2017). The direct influent to SBR 1 on the 22.10.2017 is 15.2 times, on the 23.10.2017 5.2 times higher than average (s. Table 15) due to the bypass. SBR 2 shows the same trend, but the division of flows it not changed to the same extent as in SBR1, because of the lower nitrate concentrations in the effluent of SBR2 (s. Figure 23). Consequently the bypass of the filtrations worked as a mechanism and changed the COD/N ratio to 6:1 for the SBR 1 influent loads and to 4.7:1 for the SBR 2 influent loads. Nevertheless, no immediate decrease in the nitrate concentration could be seen from the bypass as the extremely high ammonium load had to be oxidized first, even increasing the nitrate concentration.

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Table 15: Division of flows for period of enhanced nitrate values compared to a weekly average of operation without enhanced nitrogen concentrations

	Influent WWTP [m³/d]	SBR 1 filtrated influent [m³/d]	SBR 1 direct influent [m³/d]	SBR 2 filtrated influent [m³/d]	SBR 2 direct influent [m³/d]
22.10.17	256	23	107	123	3
23.10.17	243	52	37	144	10
Average value 02.-09.10.2017	270	123	7	133	7

3. **Process water recycling** (set point 11 mg NO_3-N/L) was triggered, but not did work due to too high sensitivity adjustment, meaning that the TSS sensor was too sensitive, so no process water was found.

4. **Acetate Dosing** (set point changed in this period from 14 mg/L to 12 mg/L NO_3-N) [15] of 22.7 kg acetate in 38 minutes (s. Figure 23) during the "after denitrification" phase with an average flow of 16 m³/h coming to a concentration of approx. 2.25 g/L Acetate in the SBR. The denitrification rate during acetate dosing increased to 1.92 g NO_3-N/ (h*g MLVSS). Denitrification rates for acetate or other easily degradable carbon sources in literature range from 2-10 g NO_3-N/(h*g MLVSS) (Kujawa and Klapwijk 1999, Henze and Harmoés 1990), meaning the DNR measured during acetate dosing in this trial is below literature values. Optimizations in the dosing should be taken into consideration (s. Chapter 6)

   In the following hours DNRs were constantly high (1.19 NO_3-N/(h*g MLVSS)) on average (mean value, N=6)), achieving a prompt decrease of nitrate concentration down to 0 mg/L.

[15] As the set point of 14 mg /L was exceeded during filling phase on the 22.10.2017, but not at the end of the same filling phase, the set point was changed to 12 mg/L.

6. Summary and conclusions

Advanced primary treatment with a 40 µm microscreen (drum filter) and nitrogen control strategy was implemented successfully, enhancing the COD extraction in the drum filter over several months up to 68% leading to 58% COD load reduction for the biological treatment. Consequently, COD/N ratio dropped from 9.2:1 to minimum 4.4:1.

Process water recycling did not have a strong impact on the COD/N ratio only enhancing it by 0.3-0.5 units. VFA content of process water (583 mg/L) is relatively high compared to VFA content in the filtrate (95.3 mg/L, N=32), but the volume of process water withdrawn is not sufficient to have a significant impact on the COD/N ratio.

The denitrification rates were evaluated during operating phases with 30%, 42% and 58% COD extraction. Minimum average denitrification rates in the biological step were observed at 42% COD extraction for SBR 1 (0.581 mg NO_3-N/ (h*g MLVSS))) and at 58% COD extraction for SBR 2 (0.485 mg NO_3-N / (h*g MLVSS)), being in the range of endogenous denitrification.
Nevertheless **none of the backup strategies was activated during the trials** (except few exceptional situations, see below) and **no violation of the WWTP's TN effluent threshold values was caused by enhanced COD extraction**.

Therefore it can be assumed that sufficient denitrification was on the one hand achieved by the optimization of the standard SBR operation with the new feeding regime and aeration, minimizing carbon loss due to oxidation and providing most COD for denitrification. On the other hand over dimensioning of the WWTP has to be considered, securing sufficient denitrification by high reaction volume.

The effectiveness of the backup strategies could be studied during selected exceptional situations. The direct feeding of the SBRs with carbon rich wastewater by bypassing of the filtration seems the most suitable measure to quickly mitigate rising NO3 effluent levels, immediately changing the available COD/N ratio and enabling higher DNRs, followed by the reduction of polymer dose to achieve a long-term stabilizing effect of denitrification.

If enhanced carbon extraction should be implemented in an SBR plant, the following strategies for advanced control are recommended:

In terms of improvement three main points can be addressed:

1. **Aeration control:**

   To guarantee sufficient nitrification online monitoring of ammonium is recommended and ammonium probes should be installed.

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2. **Nitrate dependant polymer dosing of polymer:**

   The turbidity proportional dosing of polymer in the drum filter influent for achieving different COD extraction levels cannot be recommended as the actual extraction strongly depends on the influent quality. Therefore COD extraction for specific polymer dose shows high variations. In addition the operation is not intuitive and only serves as a link to the nitrate depend polymer dosing. The idea is to remove the extraction based dosing and directly use the nitrate dependant polymer dosing.

3. **Backup strategies for advanced control to mitigate high NO_3-N effluent levels:**

   - Nitrate dependant polymer dosing: Taking the nitrate concentration at the end of the denitrification phase as a set point for dosing of polymer turned out to be a good solution. Therefore the idea is to directly link a limit nitrate concertation to certain turbidity proportional polymer dosing
   - Process water recycling: Supernatant with a low TSS content was pumped to the sump shaft and via the drum filter into the SBRs. But as it does not contain solids it is a waste of energy to pump it via the drum filter. Depending on the WWTP a direct pumping to the SBRs should be considered.

     Furthermore the volume of withdrawn supernatant is not enough to increase the COD/N ratio significantly during day time. But in the night hours with reduced inflow to the WWTP and thereby to the drum filter, it can enhance the VFA concentration by more than 10 folds. Consequently a time based withdrawal between 0:00 and 06:00 is recommended
   - Bypass of influent wastewater
   - Acetate dosing: Acetate dosing increases the DNRs, but the denitrification phase, in which the acetate is dosed, is followed by after aeration, meaning an oxidation of the acetate. A possible idea is to set a delay after the end of the acetate dosing to guarantee full utilization of the carbon for denitrification. The disadvantage of a delay is that it will elongate the SBRs cycle, lowering the treatment capacity.

To summarize; the optimal strategy concluded from the experiences in Case Study 1 is to keep the tested feeding regime and aeration control, add ammonium probes for monitoring the nitrification and simplify the nitrate depended polymer dosing.

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