Enhanced nitrogen removal in the combined activated sludge-biofilter system of the Southpest Wastewater Treatment Plant

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Abstract In 1999 the existing activated sludge unit of the Southpest Wastewater Treatment Plant was supplemented by a two-stage biofilter system aiming for nitrification and post-denitrification. In this arrangement excess biomass of the filters is wasted through the activated sludge unit, facilitating backseeding, and recirculation of the nitrate-rich effluent of the N-filter serves for decreasing the methanol demand of the DN-filter and for saving aeration energy at the same time. The paper reports on the development of an ASM1-based mathematical model that proved to be adequate for describing the interactions in the combined system and was used to compare the efficiency of different treatment options. Full-scale results verified that backseeding may considerably improve performance. However, nitrification ability of the activated sludge unit depends on the treatment temperature and, if unexpected, can be limited by insufficient oxygen supply. The upgrading possibilities outlined may serve as a new perspective for implementation of combined activated sludge-biofilter systems.

Keywords Activated sludge; biofilter; denitrification; mathematical modeling; nitrification; seeding

Introduction
Southpest Wastewater Treatment Plant (Southpest WWTP) was established in 1966, with a capacity of 30,000 m³/d, as the first wastewater treatment plant of Budapest, Hungary. The treatment technology was based on a high-load activated sludge unit (with a solids residence time, SRT, of 2–3 days) following preliminary treatment and primary clarification. In the early 1980s the plant was enlarged by the addition of two more, similarly arranged treatment trains. Modifications in the activated sludge bioreactor configuration led to considerable improvement regarding both elimination of carbon source and sludge settling properties (Jobbágy et al., 2000). However, biological nutrient removal proved to be unstable and not efficient for meeting the effluent requirements of the receiving sensitive body. Nitrification occurred just randomly, first of all at high temperatures. Due to unexpected nitrification, considerable amounts of nitrate were detected in the return sludge, leading to the deterioration of biological phosphorus removal.

In order to increase the capacity of Southpest WWTP to 120,000 m³ d⁻¹ as well as to improve its performance, a bidding procedure was carried out in 1998. Regarding the restricted area available for construction, as well as the low total N effluent requirement, implementation of a two-stage biofilter system was decided. The original design idea included a fully aerated, high-load activated sludge unit followed by nitrification (N) and denitrification (DN) filters.

During the discussions with the competitors, a modification was developed for possibly using the carbon source of the wastewater for denitrification through recirculating the nitrate-rich effluent of the N-filters to the head of the activated sludge unit. However, regarding the short capacity of the existing secondary clarifiers, this possibility was assumed to be feasible only until the plant reaches the nominal influent flow-rate. Therefore, in the first four basins of the activated sludge system both aeration devices and
mixers were installed (shaded gray in Figure 1). Both filters are backwashed by the effluent of the N-filter, and the excess biomass is wasted through the activated sludge unit. It could be assumed that this technological solution may provide seeding for the activated sludge unit (Daigger et al., 2000) and may, therefore, enhance and stabilize the randomly occurring nitrification observed earlier (Jobbágy et al., 2000). However, in order to verify or abandon this hypothesis and analyze the different treatment options, a mathematical model had to be developed for the simulation of the interactions in the combined activated sludge-biofilter system.

Development of the simulation model
In the simulation studies the Activated Sludge Model (ASM) No.1 (Henze et al., 1987) was used as a basis. This had to be supplemented with the description of the quality of the unified recirculated stream deriving from the backwash water of the N- and DN-filters as well as from the nitrate-rich effluent of the N-filter. In the course of describing the processes occurring in the biofilters, the following assumptions were made (Jobbágy et al., 1999):

- On the basis of data measured in the Southpest WWTP, NH$_4$-N concentration of the N-filter effluent was regarded to be 1 mg l$^{-1}$ at all temperatures investigated.
- Concentration of NO$_3$-N in the N-filter effluent was calculated regarding the difference of influent and effluent NH$_4$-N concentrations, supplemented by the concentration of eventually occurring NO$_3$-N coming from the activated sludge unit. Incorporation of nitrogen into biomass was assumed to be negligible.
- It was assumed that practically all of the suspended solids leaving the secondary clarifier of the activated sludge unit are retained in the N-filter, which was in accordance with the observations. Estimation of the total effluent suspended solids concentration of the secondary clarifiers was based on measured data, whereas the ratio of the different fractions was adjusted to the results of the ASM1 model applied.
- It was hypothesized that all of the suspended solids having left the secondary clarifiers or having been produced in the filters are fully backwashed and, therefore, end up in the influent of the activated sludge unit.

Production of autotrophic bacteria ($P_{aut}$) in the N-filters was calculated by using Eq. (1).

$$Y_{NH4-N} \text{[g COD biomass g}^{-1} \text{NH}_4\text{-N]}$$

represents the growth yield, $\Delta \text{NH}_4\text{-N} \text{[g m}^{-3} \text{]}$ stands for the difference between the influent and effluent ammonia concentration of the N-filters, whereas $Q_N \text{[m}^3 \text{d}^{-1}]$ indicates the total flow rate through the N-filters. Having reviewed the relevant data published (Henze et al., 1987; Copp and Murphy, 1995; Vayenas et al., 1997), the value of $Y_{NH4-N}$ was set to 0.32 g COD biomass g$^{-1}$ NH$_4$-N.
\[ P_{\text{aut}} = Y_{\text{NH4-N}} \cdot \Delta NH_4-N \cdot Q_N \text{ [g COD biomass d}^{-1}] \] (1)

In the DN-filters of the Southpest WWTP methanol is used as external carbon source. The production of the relevant heterotrophic bacteria can be described by Eq. (2).

\[ P_{\text{het}} = Y_{\text{X/MeOH}} \cdot R_{\text{MeOH/NO3-N}} \cdot \Delta NO_3-N \cdot Q_{DN} \text{ [g COD biomass d}^{-1}] \] (2)

where \( Y_{\text{X/MeOH}} \) [g COD biomass g\(^{-1}\) COD MeOH] is the heterotrophic yield on methanol as carbon source, \( R_{\text{MeOH/NO3-N}} \) is expressed by Eq. (3) and represents the amount of methanol in COD necessary for reducing 1 g NO\(_3\)-N as electron acceptor (Purtschert and Gujer, 1999). \( Y_{\text{X/MeOH}} \) was set to 0.4 g COD biomass g\(^{-1}\) COD MeOH on the basis of the data available in the literature (Koch and Siegrist, 1997; Lemmer et al., 1997; Aesoy et al., 1998; Purchert and Gujer, 1999). \( Q_{DN} \) [m\(^3\) d\(^{-1}\)] is the flow rate through the DN-filter.

\[ R_{\text{MeOH/NO3-N}} = \frac{2.86}{1 - Y_{\text{X/MeOH}}} = 4.8 \text{ g COD MeOH g}^{-1} \text{ NO}_3-N \] (3)

The value of \( R_{\text{MeOH/NO3-N}} \) was also used for calculating the methanol demand of the post-denitrification. Since the recirculated effluent of the N-filter as well as the backwash water of the biofilm reactors may considerably change the quality of the influent of the activated sludge system, and its effluent quality influences the quality of the recycled streams, the calculations necessarily involved an iteration routine.

**Design evaluation**

In order to illustrate the impact of different design and operational options on the performance of coupled activated sludge-biofilter systems, simulation studies were carried out. A typical set of data deriving from the Southpest WWTP was used for the calculations (see Table 1). In this period only two trains giving a total volume of 6,600 m\(^3\) were in operation with regard to the low influent flow. The organic fraction of the biomass was 65\%. TSS concentration of the secondary clarifier effluent was assumed to be 32 mg l\(^{-1}\), and NO\(_3\)-N concentration of the DN-filter effluent to be 4 mg l\(^{-1}\). During the simulations oxygen concentration was uniformly set to 2 mg l\(^{-1}\) in the aerated basins, and to 0 mg l\(^{-1}\) in the anoxic basins. Values of kinetic and stoichiometric parameters were taken from the literature (Grady et al., 1999). The results obtained are illustrated in Figures 2a–c.

It is obvious that the original design idea having fully aerated basins (option “No N-rec. all aerob”) would have facilitated partial nitrification already from 18\(^\circ\)C under the conditions investigated. Moreover, effluent NO\(_3\)-N concentration would have even approached 20 mg l\(^{-1}\) at temperatures exceeding 21\(^\circ\)C. It is therefore very likely that this design would have led to sludge floating in the secondary clarifiers in summer. This problem could have been quite dramatic, and extended down to temperatures as low as 15\(^\circ\)C, in a system wasting excess sludge of the N-filter through the fully aerated activated sludge unit (option “Seed in rec. all aerob”). Application of two anoxic reactors out of eight (option “No N-rec. all aerob”) would have given a much more balanced nitritation process.
Figure 2 Calculated activated sludge effluent concentration values (a. NH$_4^+$-N, b. NO$_3^-$-N) and methanol demand for post-denitrification (c.) at MLSS = 3 g l$^{-1}$
1,2 anox”) could have considerably decreased the effluent nitrate concentration partly by repressing the nitrification and partly by denitrifying the nitrate produced. In the options where the activated sludge and biofilter units are combined through a recycled flow (options “No seed in rec. 1,2 anox” and “Seed in rec. 1,2 anox”) the drastic decrease in the effluent ammonia concentration can partly be attributed to the dilution. However, it is obvious that backseeding may enhance nitrification in the activated sludge unit to a great extent, first of all in the range of 15–21°C. Since ammonia is almost fully converted to nitrate in the N-filter and Q_DN is independent of the recycled flow rate, the methanol demand is directly proportional to the Total Inorganic Nitrogen (TIN) concentration of the activated sludge effluent. In Figure 2c the methanol demands of the different design and operational options are compared. It is obvious that huge amounts of methanol and related aeration energy costs can be saved by choosing the appropriate variant even at fixed internal recirculation rates within the activated sludge system.

**Evaluation of full-scale results**

Startup of the new treatment system using 2 anoxic basins was begun in July 1999. Since the influent flow-rate in this period proved to be considerably lower than the nominal value, just two out of the three activated sludge systems were used and the number of the filter units was also appropriately decreased. Backwashing of the N-filters was started at the end of July. A stable operation of the combined system was achieved by the last week of September. Changes of the ammonia concentration throughout the treatment stages, as well as the effluent nitrate concentration of the secondary clarifiers for the period of September 8th–October 30th are presented in Figure 4. It can be observed that from September 27th the influent ammonia was almost fully eliminated in the upgraded treatment plant, leading to effluent concentrations < 1 mg l⁻¹ NH₄-N. In this period the effluent NO₃-N concentration was stabilized below 5 mg l⁻¹ and the effluent total N concentration below the required level of 10 mg l⁻¹ (data not shown in this paper). This has been a great improvement in nitrogen removal that had just randomly occurred earlier with a poor efficiency.

A unique aspect of the evaluation has been the nitrogen removal in the activated sludge system. As it is pointed out above, the current design is much safer than the original version of a fully aerated activated sludge unit could have been, and facilitates consumption of the influent carbon source for denitrification. This leads to considerable savings in the cost of methanol as well as in the cost of aeration. The optimal utilization of the possibilities offered by the combined treatment system seems to be the enhanced nitrification in the

**Table 2** Parameter values used in the simulation studies of the full-scale plant

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Simulation Period</th>
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<tbody>
<tr>
<td>Flow rates (m³ d⁻¹)</td>
<td>A</td>
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<tr>
<td>Primary clarifier effluent</td>
<td>48,000</td>
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<tr>
<td>N-Recirculation including backwash water</td>
<td>14,800</td>
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<tr>
<td>Return activated sludge</td>
<td>57,600</td>
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<tr>
<td>MLSS (g l⁻¹)</td>
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<tr>
<td>Temperature (°C)</td>
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<tr>
<td>Concentrations (mg l⁻¹)</td>
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</tr>
<tr>
<td>Preclarified COD</td>
<td>317</td>
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<tr>
<td>Preclarified TSS</td>
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</tr>
<tr>
<td>Preclarified NH₄-N</td>
<td>30</td>
</tr>
<tr>
<td>Secondary effluent NO₃-N</td>
<td>1.3</td>
</tr>
<tr>
<td>Secondary effluent NH₄-N</td>
<td>16.7</td>
</tr>
</tbody>
</table>
activated sludge unit. The reality of this option was investigated through analyzing the full-scale data by using the mathematical model developed.

With regard to essential operational changes three distinct periods were designated for the investigations (see Figures 3 and 4 and Table 2). In the first period, due to technical reasons, backwashed biomass was mainly introduced into Train I, which just received a negligible part of the influent. At the same time, dissolved oxygen (DO) concentration in the activated sludge system was very low, partly due to the higher biomass concentration. The simulation results achieved by applying a DO profile of 0, 0.2, 0.3, 0.3, 0.4, 0.5, 1.2, 3 mg l\(^{-1}\) for both of the versions investigated, clearly support that the activated sludge system was not efficiently backseeded in this period.

From September 18th even distribution of the streams recycled from the filters was assured between Trains II and III receiving the bulk of the wastewater during the trial operation. Both the increased rate of anoxic substrate removal and the decreased biomass concentration helped to increase the DO level in the aerated basins. As a result, increasing
efficiency of nitrification could be observed in the activated sludge unit (see Figure 3). Simulation studies carried out for Period B by using the oxygen concentration values of 0, 0.2, 0.4, 0.9, 1.6, 2.3, 3.4, 5 mg l$^{-1}$ support that efficient backseeding enhanced the nitrification ability of the activated sludge unit of the combined system. All results shown in Figure 4 were achieved by introducing a so called “viability factor” into the calculations (regarding also the remarks of Parker and Richards, 1994) and setting its value to 0.9.

During the third period of the simulation, repeatedly decreased DO concentration was observed in the activated sludge unit. In order to illustrate the impact of the DO level, the simulation studies were carried out for four different cases. In the first two options the DO level was set to 0, 0.1, 0.2, 0.3, 0.4, 0.5, 1, 2.5 mg l$^{-1}$, whereas in the second two options the DO concentration was set to 0 mg l$^{-1}$ in the two non-aerated basins and to 2 mg l$^{-1}$ in the aerated basins. The measured NH$_4$-N concentration of the secondary clarifier effluent proved to be closest to the result of the option calculated with the actual DO concentrations and efficient backseeding. It is also obvious that at this low DO level, without backseeding, much higher NH$_4$-N concentration could have occurred in the effluent of the secondary clarifier. The results also support that activated sludge nitrification efficiency could have been increased by increased air supply. However, due to the reasons mentioned by Daigger et al. (1993), this was not a treatment aim. Moreover, nitrification in the activated sludge system was not just unexpected with regard to the short SRT but even opposed in order to test the efficiency of the N-filters. The fourth simulated option refers to the fact that in the lack of backseeding growth of nitrifiers could have been enhanced by elevated DO levels. However, as it is shown in Figure 2 and supported by a separate pilot-scale experiment carried out on-site, both backseeding and appropriate air supply are crucial at decreased temperatures in order to maintain an efficient nitrification in the activated sludge system.

Conclusions
The ASM1-based mathematical model developed for the simulation studies has proven to be adequate for describing the interactions between the activated sludge unit and the coupled nitrification and denitrification filters. Full-scale results verified that backseeding may considerably enhance nitrification in the high-load activated sludge unit. Denitrification of nitrate produced in the activated sludge system is advantageous because the recycled amount is not limited by the secondary clarifier capacity. Thus, enhanced nitrification in the activated sludge unit facilitates a better usage of the carbon source of the wastewater for denitrification and, besides aeration energy savings, may result in a considerably decreased demand on external carbon source.

On the other hand, wasting excess sludge of the nitrification filter through a fully aerated activated sludge unit may threaten the safe operation due to undesired nitrate production and consequently occurring floating sludge in the secondary clarifier. Under the conditions simulated with regard to Southpest WWTP, nitrification ability of the activated sludge system proved to be dependent on the treatment temperature and on the biomass concentration applied. Since nitrification in the activated sludge unit was rather unexpected, beyond the design scope and unnecessary for meeting the effluent criteria, it was limited by the oxygen supply. It is believed that the upgrading possibilities outlined can serve as a new perspective for implementation of combined activated sludge-biofilter systems.

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