Model-based evaluation of a new upgrading concept for N-removal

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Abstract Mathematical modelling is considered a time and cost-saving tool for evaluation of new wastewater treatment concepts. Modelling can help to bridge the gap between lab and full-scale application. Bio-augmentation can be used to obtain nitrification in activated sludge systems with a limited aerobic sludge retention time. In the present study the potential for augmenting the endogenous nitrifying population is evaluated. Implementing a nitrification reactor in the sludge return line fed with sludge liquor with a high ammonia concentration leads to augmentation of the native nitrifying population. Since the behaviour of nitrifiers is relatively well known, a choice was made to evaluate this new concept mainly based on mathematical modelling. As an example an existing treatment plant (WWTP Walcheren, The Netherlands) that needed to be upgraded was used. A mathematical model, based on the TUDP model and implemented in AQUASIM was developed and used to evaluate the potential of this bioaugmentation in the return sludge line. A comparison was made between bio-augmentation and extending the existing aeration basins and anoxic tanks. The results of both modified systems were compared to give a quantitative basis for evaluation of benefits gained from such a system. If the plant is upgraded by conventional extension it needs an increase in volume of about 225%; using a bioaugmentation in the return sludge line the total volume of the tanks needs to be expanded by only 75% (including the side stream tanks). Based on the modelling results a decision was made to implement the bioaugmentation concept at full scale without further pilot scale testing, thereby strongly decreasing the scale-up period for this process.

Keywords BABE concept; bio-augmentation; modelling; nitrification; upgrading of a treatment plant

Abbreviations

DO = dissolved oxygen (g/m³)
SRT = cell residence time (day)
BABE = Bio-Augmentation Batch Enhanced
T = temperature (°C)
TSS = total suspended solids (g/m³)
SO₂ = oxygen concentration (g/m³)
S_F = fermentable organic substrate (g/m³)
S_A = fermentation products, acetate (g/m³)
S_I = soluble inert organic matter (g/m³)
S_NH₄ = the soluble ammonia nitrogen (g/m³)
S_NO₃ = the soluble nitrate nitrogen (g/m³)
S_N₂ = dinitrogen produced (g/m³)
kj-N = Kjeldahl nitrogen (g/m³)
S_alk = alkalinity (mol/m³)
X_aut = nitrifying biomass (g/m³)
X_S = slowly biodegradable COD (g/m³)
X_H = active heterotrophic biomass (g/m³)
X_I = particulate inert organic matter (g/m³)
Introduction

Activated sludge is the most widespread wastewater treatment process today. For almost a century, it has been successfully utilised as a system for carbon removal. For the last few decades its potential to remove nutrients has been explored and used. The growing public concern for environmental protection and stricter regulations directed research to improve the removal efficiency of the treatment systems. The main difficulty with activated sludge systems is their limited potential to nitrify at low temperatures (<15°C), making large volumes of aeration tanks needed. The large volume is due to the low growth rate of nitrifiers requiring long aerobic SRTs. Besides nitrification, denitrification needs often to be achieved too. In large aerobic tanks also a significant heterotrophic COD-oxidation occurs limiting denitrification potential.

Increasing nitrification in the mainstream aerobic reactor can be obtained by several approaches. One approach is adding nitrification capacity in the aerobic compartment by addition of immobilised nitrifiers (e.g. the Pegasus process; Tanaka et al., 1996) or by adding a carrier material on which a biofilm can grow (e.g. Chen et al., 1995). Adding immobilised nitrifiers is however a relatively expensive process. A second alternative is to augment the sludge with extra nitrifiers grown in separate fermentation equipment leading to a lower minimal SRT requirement (e.g. Rittmann et al., 1996).

Inoculation of external grown nitrifiers is expensive and might lead to introduction of a strain that is not active at the prevailing process conditions. Using the sludge treatment flow with a high N-content to boost the nitrifying bacteria in a side stream tank has been proposed by DHV-Water under the name BABE process (Zilverentant et al., 1999). BABE is an acronym for Bioaugmentation Batch reactor Enhanced. By maintaining a short solid retention time in this side stream process predominantly the endogenous nitrifying population will be enhanced. The potential of this process has been extensively evaluated by Salem et al., 2001.

Mathematical modelling has become an operational tool for the design and operational procedures of activated sludge systems. Operational difficulties together with nutrient removal greatly increased the demand for process modelling. Considering the design, modelling has led to the identification of procedures to estimate the optimal or near optimal design configuration, reactor sizes and operational parameters (e.g. sludge age) and an estimation of the expected response (Henze et al., 1987). With regard to the application of new treatment concepts, models can also be used to decrease the time and costs of scaling-up these new processes.

Traditionally a new application is tested extensively on lab scale, then a pilot scale test period is used after which finally a full-scale application will be constructed. Usually it takes long and expensive periods especially for pilot plant phases. Mathematical models can help to bridge this gap between lab and full-scale application. Microbial conversions can be well studied at lab-scale, as they are scale independent. Based on laboratory experiments a proper model for the description of microbial processes as influenced by the microenvironment can be made. By modelling the well-known mass transport and transfer processes in a large reactor the micro-scale biological model can be coupled to a macro-scale model. This can give adequate prediction of the full-scale behaviour and sensitive process parameters can be rapidly evaluated and eventually further tested at lab-scale. This approach has been successfully applied in the scale-up of the SHARON process (a 2 litre lab-scale was scaled up to a 1,500 m³ full-scale reactor, Hellinga et al., 1998) and is used here for the BABE process.

We used the WWTP Walcheren, The Netherlands as an example. Application of the BABE concept and traditional upgrading by expansion to meet a total N-content in the effluent of 10 mg/l were compared.
**Methods**

**The WWTP Walcheren**

The WWTP Walcheren was designed for 140,000 PE and treats a total flow of 43,215 m$^3$/d. Wastewater is treated in 2 parallel lanes. First, the water goes through 2 pre-sedimentation tanks followed by 2 selectors (anoxic tanks) each of volume 340 m$^3$. In the presedimentation chemical P-precipitation occurs, this is maintained in the upgrading. The presettled water is treated in 2 aeration tanks each of capacity 2,660 m$^3$ followed by 4 final clarifiers. The treatment plant operates at an average temperature of 14.5°C and a sludge age of 4.8 days. The treatment plant has an influent Kj-N of 46 mg/l and influent COD of 236 mg/l. The TSS is maintained at 2.8 g TSS/l in the aeration tanks and is 4.2 g TSS/l in the return sludge. The DO in the aeration tanks is controlled at 0.8 mgO$_2$/l. The return sludge flow is two times the influent flow and no internal recirculation of mixed liquor was present. The return water coming from digested sludge filtration (the so-called reject water) has the following characteristics: a total flow of 324 m$^3$/d, an average temperature of 26°C and an NH$_4$-N concentration of 636 mg N/l. This reject water is pumped back upstream of the treatment plant.

The AQUASIM 2.0 software with model TU-Delft (Hao et al., 2001) was used to simulate the treatment plant. This simulation environment allowed simulation of the new BABE concept and to evaluate its effect on the performance of the treatment plant. Only the activated sludge tanks and the settlers were considered in the simulation model. The settler was modelled with no processes inside but in the return sludge line a non-aerated tank of 1,650 m$^3$ was used to simulate the sludge blanket in the settler (Figure 1). This volume was based on the observed denitrification in the settler during summer periods as evaluated from measurement of nitrate in the effluent and in the return sludge. The model was calibrated to obtain correct effluent parameters according to the measured data reported from the treatment plant. The daily variations in influent composition were small therefore only the daily flow variations needed to be taken into account.

The influent composition was evaluated (Table 1) according to STOWA method (Roeleveeld and Kruit, 1998). The model was calibrated according to a procedure described by Meijer et al., 2001. In the calibrated model, all model parameters remained at
their default values (Hao et al., 2001) except for the half saturation/inhibition coefficient for oxygen for growth of autotrophic biomass ($K_{NO}$). It was changed from 0.5 to 0.3 to obtain a correct effluent prediction for ammonium and nitrate.

The BABE reactor

The sludge line nitrification was introduced as a nitrification/denitrification system. Denitrification is implemented to control the alkalinity of the side stream process. The design was based on a general model-based evaluation of the process (Salem et al., 2001). The anoxic compartment has a volume of 350 m$^3$ for denitrification and the aerated compartment has a volume of 500 m$^3$. Internal recirculation between the two tanks was at a ratio of about 15 times the total flow to the BABE reactor. The source of ammonia to be treated in the BABE reactor was the warm reject water (636 mg N/l) resulting from filtration of the digested sludge. The load of ammonia sent to the side-stream reactor was subtracted from the influent ammonia composition of the WWTP. Alkalinity in the sludge liquor flow was based on the assumption that the molar ratio between NH$_4$ and HCO$_3$ is 1:1, (636 mg NH$_4$/l or 46 mmol/l alkalinity). Alkalinity inside the BABE reactor was controlled by means of de-nitrification. The DO in the aerated compartment was set at 2 mg O$_2$/l. The sludge liquor is mixed with a portion of the return sludge of the main line of the treatment plant. The effluent from the BABE reactor, return sludge enriched with nitrifiers, is mixed with the remainder of the return sludge and then introduced in the selector compartment of the treatment plant. For comparison, two ratios of reject water flow to return sludge flow (1:1 and 5:1) were used. Thereby two different operating temperatures occur, 22°C and 28°C respectively.

Results and discussion

The treatment plant operates at a relatively low DO level (0.8 mg/l). Consequently, the effect of increasing the DO in the aeration tanks in improving the effluent quality was first evaluated. Then the effect of applying the BABE concept on the existing treatment plant effluent was estimated. Finally the system (with or without the BABE concept) was upgraded to meet the effluent requirements.

Increasing the DO in the aeration tank

The effect of increasing the DO level in the aeration tanks of the treatment plant was evaluated at average (14.5°C) and winter temperatures (9°C) Figure 2. The DO was increased from 0.8 mg/l to 1.5 mg/l and the corresponding changes in the effluent N parameters were calculated with the calibrated model.

### Table 1  Influent composition of the WWTP Walcheren, The Netherlands

<table>
<thead>
<tr>
<th>Measured composition (mg/l)</th>
<th>Model fractions (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total influent COD = 236</td>
<td>$S_{OO} = 0$</td>
</tr>
<tr>
<td>Soluble influent COD = 160</td>
<td>$S_F = 100$</td>
</tr>
<tr>
<td>($S_F + S_A + S_i$)</td>
<td>$S_i = 60$</td>
</tr>
<tr>
<td>Particulate influent COD = 76</td>
<td>$X_i = 24$</td>
</tr>
<tr>
<td>($X_i + X_o + X_H$)</td>
<td>$X_o = 52$</td>
</tr>
<tr>
<td>Influent kj-N = 46</td>
<td>$X_H = 0$</td>
</tr>
<tr>
<td>Alkalinity (mmol/l)</td>
<td>$S_{NH4} = 34.7$</td>
</tr>
<tr>
<td></td>
<td>$S_{NO3} = 0$</td>
</tr>
<tr>
<td></td>
<td>$S_{NO2} = 0$</td>
</tr>
<tr>
<td></td>
<td>$S_{ALK} = 8$</td>
</tr>
</tbody>
</table>

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Increasing the DO at winter temperature has no effect on the effluent N parameters of the treatment plant, as the system is still unable to nitrify. At the yearly average temperature (14.5°C), increasing the DO level has a beneficial effect on the performance of the treatment plant but this is only to a certain extent and then it levels off. Increasing the DO from 0.8 to 1 mgO2/l could decrease the effluent NH4-N by about 60% from its original value. The effluent NO3-N was increased concomitantly. Under summer conditions full nitrification occurs.

Upgrading of the WWTP by the BABE concept

The treatment plant was in simulation upgraded by applying the BABE concept (Figure 1). The approach was introduced as a nitrification/de-nitrification system. Two tanks were implemented in the return sludge line. The first is anoxic where denitrification takes place and the second is aerated for converting all the ammonia coming with the reject water. The results are presented in terms of the model fractions obtained in the aeration tanks of the main stream (with and without the BABE process) and the side-stream process. This was done for two ratios of reject water flow and return sludge flow. The results are illustrated in Table 2. In order to prevent a limiting alkalinity (too low pH) extra COD was added to the process. To allow full nitrification this amounted to 1,166.4 kg/day (11.4% of the input COD load to the treatment plant). In principle it would be possible to enlarge the denitrification zone to allow more endogenous denitrification in the side stream reactor. The choice of larger tanks or adding extra COD will depend on the specific site and costs.

The results illustrate the positive effect of bioaugmentation on improving the effluent N-parameters. The total N concentration in the effluent was reduced by around 40%. Part of this improvement is due to the reduction in the load of ammonia to the main stream of the

Table 2  The effect of applying the BABE concept on the performance of the treatment plant (in terms of the model fractions)

<table>
<thead>
<tr>
<th>Fractions (mg/l)</th>
<th>Without BABE Process</th>
<th>With BABE Process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reject water: return sludge</td>
<td>Reject water: return sludge</td>
</tr>
<tr>
<td></td>
<td>T_BABE = 22°C</td>
<td>T_BABE = 28°C</td>
</tr>
<tr>
<td></td>
<td>Concentration in the main aeration tank</td>
<td>Concentration in the BABE Reactor</td>
</tr>
<tr>
<td>SO2</td>
<td>0.8</td>
<td>2</td>
</tr>
<tr>
<td>SNH</td>
<td>25.4</td>
<td>7.7</td>
</tr>
<tr>
<td>SNH</td>
<td>2.2</td>
<td>18.8</td>
</tr>
<tr>
<td>Xaut</td>
<td>80</td>
<td>155</td>
</tr>
<tr>
<td>% (X_aut / X_total)</td>
<td>2.5%</td>
<td>4.7%</td>
</tr>
<tr>
<td>MLSS</td>
<td>2800</td>
<td>3000</td>
</tr>
</tbody>
</table>
WWTP (about 40%) and the rest (60%) is due to the inoculation of nitrifiers cultivated in the side-stream process and introduced into the main stream. The amount of nitrifiers present in the main stream process has been approximately doubled.

By applying bio-augmentation the effluent parameters were improved but still the system was not able to fully nitrify or to meet the required effluent standards.

Using different ratios of return sludge to sludge liquor has a small effect on the overall performance of the treatment plant. Higher amounts of return sludge decrease the temperature and thereby the sludge activity, this is compensated by a higher sludge content in the reactor.

The relation between the percentage of ammonia removal in the BABE reactor and the amount of COD (kg/day) needed to keep, by denitrification, a neutral pH in the reactor is illustrated in Figure 3. An almost linear relation exists between NH₄ removal in the BABE reactor and COD addition, resulting in about 40% removal without COD addition. This gives an effluent of the treatment plant containing N-total of 19 mg N/l. The effect of the ammonia conversion efficiency on the effluent N-total of the treatment plant is relatively small. It should be remembered that this is without any change in the main WWTP. It is clear that the side stream process should not be optimised on maximal N-conversion in the side stream, but on the effluent N of the upgraded WWTP and the costs of extra COD addition. Such complex evaluations can only be performed by dynamic simulation models.

Modification of the WWTP Walcheren to meet the effluent requirements

Only implementing a side stream nitrification and augmentation of the Walcheren WWTP was not sufficient to reach the required effluent standard of 10 mg N/l. We evaluated the needed increase of the main stream treatment plant with and without the BABE process to obtain a N-total in the effluent of 10 mg N/l at the average operating temperature. The volumes of the aeration tank and the anoxic tank in the main stream were increased, also an internal recirculation was introduced. The following modifications were needed in the case of applying the BABE process (for the option 1:1 rejectwater: return sludge flow):

- The volume of the aeration tanks needs to be increased by 22% of the original value.
- The volume of the anoxic tanks needs to be increased with 370% of the original value.
- Internal recirculation between anoxic and aerated tanks in the main stream at a ratio of 4 times the influent flow rate was introduced.
- The SRT in the system was modified to adjust the total suspended solids in the system (from 4.8 days to 7.8 days).

When the Walcheren WWTP needs to be upgraded by traditionally extending the
aeration basins and the anoxic tanks to have an N-total in the effluent of 10 mg N/l, the following modifications were needed:
• The volume of the aeration tanks needs to be increased by 88% of the original value.
• The volume of the anoxic tanks needs to be increased by 1,300% of the original value.
• Internal recirculation between anoxic and aerated tanks in the main stream at a ratio of 4 times the influent flow rate was introduced.
• The SRT in the system was modified to adjust the total suspended solids in the system (from 4.8 days to 20 days).

Comparison of the upgrading strategies for the Walcheren WWTP
A comparison between upgrading the treatment plant by the conventional method (only extending the aeration and anoxic basins) and by applying the BABE concept is illustrated in Table 3. It is clear that a large saving in area requirement for the treatment reactors (approximately 50%) can be obtained by the bioaugmentation concept. The aerobic volume can be reduced because of the reduced minimal aerobic SRT needed. The anoxic volume can be reduced because less denitrification needs to occur in the main stream of the treatment plant, and aerobic COD removal is less because of a lower aerobic SRT.

The cost effectiveness can be roughly compared, keeping in mind that site specific aspects might give a large change in these calculations. Here we compare the costs based on the standard cost analysis as used by DHV-Water. Using the BABE concept reduces the construction costs, for upgrading of the WWTP Walcheren for N-total effluent of 10 mg N/l, by approx. 750,000 Euro because of the much smaller tank volumes required. The costs of land use are neglected. The smaller total aerated volume leads to a saving in aeration energy of 25,000 Euro/year. The addition of external COD in the form of methanol in the BABE concept costs approximately 35,000 Euro/year. This addition of methanol and the lower SRT lead to a higher sludge production before digestion. This higher sludge production generates extra energy in the methane digestion process leading to a saving in energy costs of 70,000 Euro/year. The slightly higher amount of sludge after digestion costs 30,000 Euro/year for treatment and disposal. The difference in net yearly costs can be calculated based on an interest rate of 6% and 30 years depreciation for the civil engineering works. The net savings per year amount to 11,500 Euro.

Use of computer modelling
In most modelling studies at Dutch WWTPs it was shown that the default parameter set did not need to be calibrated in order to describe the process performance adequately. Since the concept proposed here is not strongly different we expect that the results will match future practical results. Modelling studies compared with pilot scale tests are relatively cheap and give the opportunity to evaluate all kinds of process aspects in a systematic manner. This can strongly shorten the scale-up time of new treatment concepts. Based on the model results it has been decided to construct a BABE process at the WWTP Garmerwolde, The

<table>
<thead>
<tr>
<th>Item</th>
<th>Upgrading the treatment plant by conventional method</th>
<th>Upgrading the treatment plant by applying the BABE concept</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Increase (additional volume required/old volume) (%)</td>
<td></td>
</tr>
<tr>
<td>Aeration volume</td>
<td>88</td>
<td>22</td>
</tr>
<tr>
<td>Anoxic volume</td>
<td>1,300</td>
<td>370</td>
</tr>
<tr>
<td>Side stream reactor</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>Total increase</td>
<td>225</td>
<td>75</td>
</tr>
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</table>
Netherlands, a treatment plant handling 300,000 PE. The planning of the upgrading of the Walcheren WWTP was already in a too far stadium to allow changes in the project planning.

Conclusions
The BABE concept could be considered as a cost-effective method for upgrading the activated sludge systems, which do not meet the effluent requirements. It allows treatment plants to work at shorter aerobic SRTs which is compensated for by the nitrifiers grown in the return sludge tank and digester effluent or other ammonium waste sources. Mathematical modelling can efficiently bridge the gap between lab-scale tests and full-scale application of new technologies saving time and money.

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References