# Modelling dissolved air flotation as pre-treatment for reaching low P effluent with activated sludge

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## Abstract

In view of optimizing the WWTP of Eindhoven (The Netherlands) to meet the requirements set forth by the European Water Framework Directive, a model-based assessment was performed to quantify the effect of dissolved air flotation on the subsequent activated sludge process for the WWTP. Within this assessment, different control strategies were evaluated to come up with a satisfying solution. The optimal scenario proves to perform well for the averages of the effluent quality parameters and is able to reach the target discharge limits for nitrogen and phosphorus. The need for further investigation in order to improve the confidence in the model outcome under low phosphate concentrations is explained.

**Keywords:** model-based assessment; enhanced biological phosphorus removal; activated sludge models; wastewater treatment plant

## Introduction

In the European Union, the Water Framework Directive (WFD) enforces a good ecological and chemical status of all surface waters, which is to be accomplished by 2015. Many surface waters throughout Europe still do not meet the WFD requirements due to discharges of combined sewer overflows (CSO) and effluents of wastewater treatment plants (WWTP). Mathematical models provide a valuable tool for guiding the decisions towards meeting the requirements set forth by the WFD.

The Dommel is a relatively small and sensitive river flowing through the city of Eindhoven (The Netherlands) from the Belgian border (South) into the river Meuse (North), receiving discharges from the 750,000 PE wastewater treatment plant (WWTP) of Eindhoven and from over 200 combined sewer overflows (CSOs) in 10 municipalities. In summer time, the WWTP effluent equals the base flow of 1.5 $m^3/s$ of the Dommel River just upstream the WWTP. The Dommel River does not yet meet the requirements of the European Union WFD. The water quality issues to be addressed are DO depletion, ammonia peaks and seasonal average nutrient concentration levels (Weijers et al., 2012).

In order to deal with the water quality issues mentioned above, replacing the primary sedimentation tanks (PST) by dissolved air flotation (DAF) units was investigated. The DAF units proved successful in getting a higher performance in removing particles, and consequently chemical oxygen demand (COD), compared to the conventional primary sedimentation tanks. But in conjunction with the higher COD removal also a higher removal of phosphorus (both particulate organic phosphorus and soluble ortho-phosphate) is observed. The impact of this reduced inflow of phosphorus on the succeeding biological treatment needs to be investigated before a final decision can be taken. For this investigation a model-based approach is chosen, applying an existing model of the WWTP of Eindhoven (Amerlinck et al., 2013).

Modelling of biological phosphorus removal and in particular enhanced biological phosphorus removal (EBPR) received a lot of attention during the 1990s resulting in the publication of the ASM2d (Henze et al., 1999). In the same period metabolic models (Lopez-Vazquez et al., 2009; Schuler and Jenkins, 2003; Smolders et al., 1995) also have shown to be promising for modelling EBPR. More recently, a lot of criticism arose about ASM2d concerning the inability to account for several processes and many extensions have been published (García-Usach et al., 2010; Larrea et al., 2002; Makinia et al., 2006; Manga et al., 2001). This large choice of models leads, although the model predictions have improved significantly over the course of time, to a large uncertainty in the model outcome and reduces the confidence in its predictions. So, there is still the need to take decisions under uncertainty as models are simplifications of reality and by definition contain a certain degree of uncertainty (Belia et al., 2009).

In this work, a model-based evaluation was performed to quantify the effect of the DAF on the downstream activated sludge process. The approach chosen to reduce the uncertainty and to increase the confidence in the model predictions is based on a detailed discussion with the technologists of Waterboard De Dommel. As such, this entailed increasing the level of understanding both for the wastewater technologists and the modellers. This resulted in a greater confidence in the modelling results. During the discussions focus was given to trends rather than absolute numbers, as such taking into account the limitations of the models (Amerlinck et al., 2013).

This paper reports on the results of this model-based evaluation, the issues encountered and the need for further research.

## Material and Methods

With a treatment capacity of 750,000 population equivalents (PE), the WWTP of Eindhoven (The Netherlands) is the largest treatment plant of Waterboard De Dommel and the third largest in The Netherlands. The incoming wastewater is treated in three parallel lanes with a total plant maximum hydraulic load of 26,250 $m^3$/h. Each lane contains a primary settler, a biological tank and four secondary clarifiers. An extra 8,750 $m^3$/h can be treated mechanically and passes a pre-settling tank before it is discharged in the river Dommel or treated in the biology when the hydraulic load again drops below 26,250 $m^3$/h. The WWTP has a modified UCT configuration (Tchobanoglous et al., 2004) and has 7 metres deep biological tanks (Figure 1).

Over the years, several gradually more complex versions of a process model of the plant have been set up and calibrated using WEST (http://www.mikebydhi.com, Denmark). The model that served as the basis for the model-based evaluation in the current study was thoroughly calibrated for describing carbon and nitrogen removal under dry weather flow (Amerlinck et al., 2013). Prior to the scenario analysis a calibration with special focus on phosphorus removal was performed. This calibration, a calibration level 1 according to WERF classification (Melcer, 2003), was based on default values, assumptions and engineering experience. For further processing mass balances, calculation of the sludge phosphorus content and effluent phosphate concentration ranges were compared with the practical experience of the plant staff and data available from measurement campaigns.

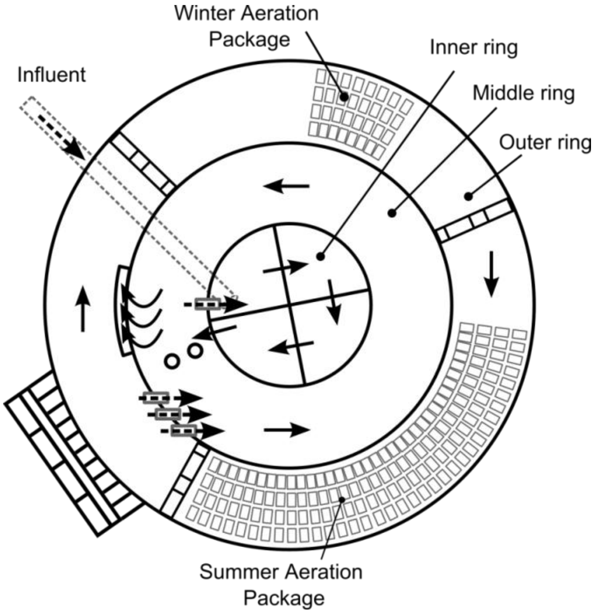

**Figure 1** The circular modified UCT configuration of the activated sludge tanks at the WWTP of Eindhoven.

In order to support the calibration, the lab “Gemeenschappelijk Waterschapslaboratorium” at Boxtel performed phosphate release and uptake tests, according to STOWA guidelines (STOWA, 1991). The tests were executed in a 2 litres beaker placed in a water bath to control the temperature. The beaker was equipped with a pH and a combined oxygen-temperature probe. pH was corrected using 0.1M solutions of either $H_2SO_4$ or NaOH. Aeration was provided through an air stone with associated tubing. Before starting the test, the pH, dry solid content and ash rest of the activated sludge was determined. At the start of the test the activated sludge was first aerated for at least 15 minutes. After this initial period, the aeration was stopped and once anaerobic conditions were reached, i.e. oxygen concentrations lower than 0.2 mg $O_2$/l, sodium acetate was dosed in abundance. The release of ortho-phosphate (o-$PO_4$) under anaerobic conditions was followed taking and analysing samples for o-$PO_4$ every 10 minutes for the next hour. To follow up the uptake of o-$PO_4$ under aerobic conditions, the aeration was turned on after 1 hour and again every 10 minutes for the next hour, samples were taken and analysed for o-$PO_4$.

The results of the test were further analysed using a model set up in WEST (http://www.mikebydhi.com, Denmark). The model (Figure 2) mimicked the set-up and included a beaker, the acetate dosage and a timer to control the dosing and the aeration. The beaker is modelled as a completely mixed tank reactor with biological reactions, according to the modified version of ASM2d as used in the model of Eindhoven (Amerlinck et al., 2013). The ASM2d model is adapted (i) to make the lysis of biomass dependent on the environmental factors (anaerobic, anoxic or aerobic) (Gernaey and Jørgensen, 2004) and (ii) to allow for the inclusion of a particulate inorganic fraction (Wentzel et al., 2002).

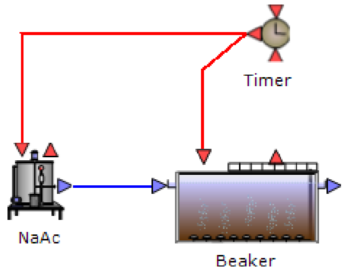

**Figure 2** The set-up of the phosphate release and uptake tests as modelled in WEST. The detailed model (left) and the simplified model (right).

In order to quantify the effect of the DAF on the downstream activated sludge process, the DAF was modelled based on data from a measurement campaign performed on a 50 m³/h pilot installation. Constant removal efficiencies for biological oxygen demand (BOD), COD and total suspended solids (TSS), as deduced from the data, were implemented in the model. On the other hand, as observed in the measurement campaign data, o-$PO_4$ concentration in the DAF effluent could be controlled on a constant value as they mainly depended on the dosing of chemicals and as such the o-$PO_4$ concentration in the DAF effluent were modelled to be constant.

For the reference situation (scenario 0 in Table 1), the model describing the actual, current plant was adapted by (i) replacing the primary sedimentation tank by DAF and (ii) switching off alum dosing before the activated sludge tanks. A set of scenarios (Table 1) based on experience from previous studies (Amerlinck et al., 2013) was proposed to improve the plant performance and the best options were explored in detail.

**Table 1** The set of possible measures evaluated in the scenario analysis to optimize the WWTP after replacing the PST with a DAF.

| Scenario | Measure |
|---|---|
| **0** | DAF as replacement for PST |
| **1.1.1.** | Scenario 0 with increased MLSS concentrations |
| **1.2.1.** | Scenario 0 with relocation recycle B |
| **1.2.2.** | Scenario 0 with relocation recycle B and increased MLSS concentrations |
| **1.3.1.** | Scenario 1.2.1. with COD dosing in the anoxic tank |
| **1.3.1.bis** | Scenario 1.3.1. with relocation of the NO3 sensor |
| **1.3.1.tris** | Scenario 1.3.1.bis with relocation of COD dosing to the anaerobic tank |
| **1.3.1.quater** | Scenario 1.3.1.bis combined with COD dosing in the anaerobic tank |

## Results and Discussion

*Calibration of the actual, current situation*

A first evaluation of the actual, current situation in the model showed the absence of enhanced biological phosphorus removal (EBPR) which is not in line with observations at the plant. Two factors likely to impact the model prediction of the EBPR were investigated, i.e. the effects of temperature and the anaerobic storage of polyhydroxyalkanoates (PHA).

Baetens (2001) states that temperature moderately affects EBPR. García-Usach et al. (2006) reflected that the temperature influences on the biological phosphorus removal subprocesses in a different way. The maximum rate for polyhydroxyalkanoates storage is more influenced by the temperature than the maximum rate for phosphorus release. Temperature correction factors proposed by Mamais and Jenkins (1992), Brdjanovic et al. (1998) and Baetens et al. (1999) were compared with the ones of ASM2d (Henze et al., 2000) as used in the model of the Eindhoven WWTP. Comparing the sets of factors used by Baetens et al. (1999) required the transformation of the exponential based temperature correction function (Equation 1) into the power based temperature correction function (Equation 2) as used in ASM2d (Henze et al., 2000) .

$$\boldsymbol{r_T = r_{20} \cdot e^{\left(\theta\cdot\left(T-T_{Ref}\right)\right)}} \qquad \textbf{Equation 1}$$

$$\boldsymbol{r_T = r_{20} \cdot \theta^{\left(T-T_{Ref}\right)}} \qquad \textbf{Equation 2}$$

Figure 3 left demonstrates the difference in temperature corrections for the maximum specific phosphorus uptake rate ($Q_{PP}$) and Figure 3 right for the rate constant for storage of polyhydroxyalkanoates ($Q_{PHA}$). For $Q_{PP}$, the temperature correction for the parameter set determined by Mamais and Jenkins (1992) and Baetens et al. (1999) are more pronounced (steeper slopes) than for ASM2d. On the other hand the temperature correction for $Q_{PP}$, determined by Brdjanovic et al. (1998) is less important. For the temperature correction factor of $Q_{PHA}$ ASM2d is clearly the less pronounced. Taking into account that the wastewater temperature most of the time is below 20°C, changing the parameters in the Eindhoven model would result in even lower values for $Q_{PP}$ and $Q_{PHA}$ and as a consequence the already low or non-existing EBPR activity in the model would decrease even more.

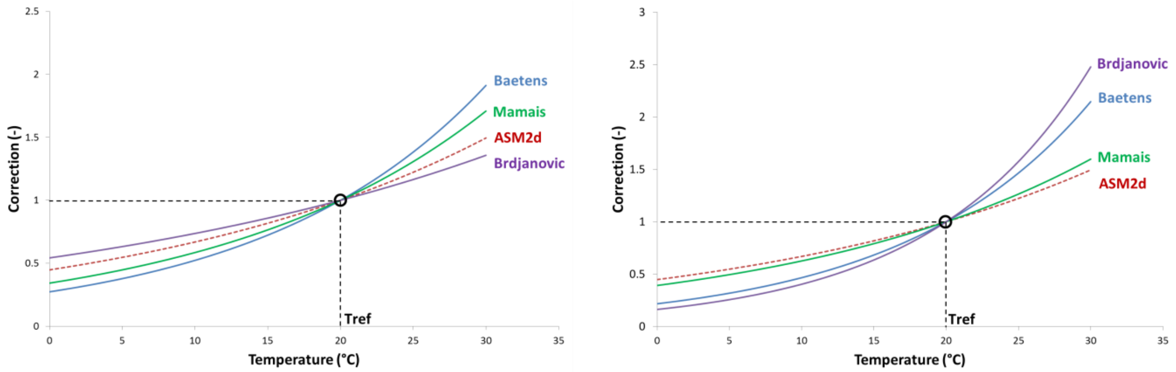

**Figure 3** The difference in temperature corrections for $Q_{PP}$ (left) and $Q_{PHA}$ (right) according to Mamais and Jenkins (1992) (green line), Brdjanovic et al. (1998) (purple line) and Baetens et al. (1999) (blue line) compared to ASM2d (Henze et al., 2000) (red dashed line).

The second factor that was investigated is the anaerobic storage of PHA, which is the first step and one of the prime drivers of EBPR. As expected, the rate constant for storage of PHA ($Q_{\mathbf{PHA}}$), significantly impacted EBPR. Increasing the rate constant for storage of PHA ($Q_{\mathbf{PHA}}$) allowed the model to predict the occurrence of EBPR and as a consequence acceptable phosphate effluent concentrations were reached. The better results caused by increasing $Q_{\mathbf{PHA}}$ can be explained by the rate limiting effect of the presence of oxygen or nitrate. This increase balances out the rate limiting effect. In the model implementation for Eindhoven, similar to for example the metabolic model of TU Delft (Lopez-Vazquez et al., 2009), a direct inhibition by nitrate or oxygen is assumed. This in contrast to the original ASM2d model (Henze et al., 2000), where the effect is the result of the competition for carbon sources. As this direct inhibition has the same effect as reducing the rate constant, further tests are needed to determine the correct mechanism.

An attempt was undertaken to estimate the $Q_{PHA}$ from the phosphate uptake and release tests. However the test did not contain sufficient information to reliably estimate the $Q_{PHA}$ and resulted in multiple estimates, ranging from 3.8 up to 8.9 gCOD/(gCOD.d), depending on the chosen algorithms and initial estimates. Zhang et al. (2010) demonstrated that the parameters $Q_{PHA}$, $K_{PP}$ and the initial concentration of $X_{PAO}$ are correlated, i.e. these parameters or not uniquely identifiable, for tests with an excess of volatile fatty acids (VFA) as is the case in the phosphate release and uptake tests. As such $Q_{PHA}$ can only be estimated when either $K_{PP}$ or the initial concentration of $X_{PAO}$ is known.

### *Scenario analysis*

After thorough evaluation of the results of the reference (with DAF), a set of scenarios, extending the reference, was proposed to improve the performance. The most promising scenario extends the reference scenario with controlled carbon dosing in both the anaerobic (stimulating EBPR) and denitrification tank (stimulating denitrification). The carbon source used for dosing is assumed to have a COD content of 1061 g COD/l.

The most promising or optimal scenario proves to perform well for the averages of the effluent quality parameters (Table 2) and is able to reach the target discharge limits for nitrogen and phosphorus. COD and TSS (results not shown) do not change, where $NH_4$ (+0.1 mg/l) increase slightly. On the other hand $NO_3$ (-11.8 mg/l) and consequently TN (-11.7 mg/l) are reduced significantly. Also $PO_4$ (-1.1 mg/l) and TP (-1.1 mg/l) decrease significantly on average. Unfortunately, this strategy results in higher maximum values (Table 2) for $NH_4$ (+1.5 mg/l). These high values for NH4, significantly higher than the controller set point occur despite the higher input of oxygen, i.e. the airflow rate is about 30% higher than in the reference case. These observations can be explained by the stimulated EBPR, which results in very low concentrations of $PO_4$. The very low concentrations of $PO_4$ become limiting for the nitrification according to the model (in the range of phosphate half saturation constant $K_P$). The latter poses new research questions that need to be investigated further: i.e. how low can $PO_4$ concentrations really go when using EBPR and as of which level does $PO_4$ become limiting for nitrification (how reliable is the $K_P$ value when pushing the system to extreme conditions).

**Table 2** The optimal scenario shows good average performance for effluent quality parameters ($NH_4$, $NO_3$, TN, $PO_4$, TP) but also shows some high maximum values compared to the reference situation (both for a DAF effluent concentration of 1 mg $PO_4$/l). The operational costs calculated from the sludge production (SP), flow rate for carbon dosing ($Q_{carbon}$) and airflow rate ($Q_{air}$) are significantly higher than in the reference situation.

| | **Parameter** | **$NH_4$** | **$NO_3$** | **TN** | **PO4** | **TP** | **SP** | **$Q_{carbon}$** | **$Q_{air}$** |
|---|---|---|---|---|---|---|---|---|---|
| | **Unit** | mg/l | mg/l | mg/l | mg/l | mg/l | ton/d | $m^3/d$ | $m^3/d$ |
| **Reference** | **Min** | 0.002 | 7.636 | 9.372 | 1.015 | 1.046 | 3.985 | 0.000 | 164360 |
| | **Average** | 0.162 | 13.658 | 15.063 | 1.258 | 1.284 | 7.253 | 0.000 | 312948 |
| | **Median** | 0.012 | 14.414 | 15.710 | 1.259 | 1.286 | 7.302 | 0.000 | 300229 |
| | **Max** | 1.114 | 18.178 | 19.446 | 1.471 | 1.491 | 10.972 | 0.000 | 679156 |
| **Optimal scenario** | **Min** | 0.003 | 0.259 | 1.596 | 0.002 | 0.030 | 0.000 | 0.987 | 209525 |
| | **Average** | 0.261 | 1.814 | 3.329 | 0.123 | 0.152 | 12.728 | 10.951 | 398206 |
| | **Median** | 0.040 | 1.368 | 3.080 | 0.102 | 0.132 | 12.606 | 9.688 | 353134 |
| | **Max** | 2.600 | 5.436 | 6.704 | 0.467 | 0.504 | 14.873 | 22.693 | 876343 |

For the optimal scenario, operational costs were significantly higher compared to the reference scenario. The carbon dosing (+11 $m^3/d$) increased and largely contributed to the increased sludge production (+5.5 ton/d). Considerably higher aeration flow rates were applied by the aeration control to overcome the limitation of the nitrification caused by the very low concentrations of $PO_4$.

## Conclusions

A model-based assessment was performed to quantify the effect of dissolved air flotation on the subsequent activated sludge process for the WWTP of Eindhoven. Within this assessment, different control strategies were evaluated to come up with a satisfying solution. The optimal scenario proves to perform well for the averages of the effluent quality parameters and is able to reach the target discharge limits for nitrogen and phosphorus. The need for further investigation is demonstrated both during the calibration and the scenario analysis. I.e. (1) the need for a procedure to estimate the most important parameters, (2) the need for a discrimination in the way inhibition of PHA storage by oxygen and nitrate are described and (3) the need for a better understanding on the effect of low phosphate concentrations on nitrification and heterotrophic growth.

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