Benchmark Simulation Model No 2 in Matlab-Simulink: towards plant-wide WWTP control strategy evaluation

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Abstract In this paper, implementation of the Benchmark Simulation Model No 2 (BSM2) within Matlab-Simulink is presented. The BSM2 is developed for plant-wide WWTP control strategy evaluation on a long-term basis. It consists of a pre-treatment process, an activated sludge process and sludge treatment processes. Extended evaluation criteria are proposed for plant-wide control strategy assessment. Default open-loop and closed-loop strategies are also proposed to be used as references with which to compare other control strategies. Simulations indicate that the BM2 is an appropriate tool for plant-wide control strategy evaluation.

Keywords Benchmarking; BSM2; control; evaluation criteria; modelling; simulation; wastewater treatment

Introduction

The COST/IWA Benchmark Simulation Model No 1 (BSM1) (Copp, 2002) is widely used all over the world within the research community for testing and evaluating various control strategies for biological nitrogen removal wastewater treatment plants. Although the BSM1 is a valuable tool, it does not allow for evaluation of control strategies on a longer time scale and on a plant-wide basis. Therefore, extensions of the benchmark system for long-term control and monitoring system performance evaluation (Rosen *et al.*, 2004) and for plant-wide control (Jeppsson *et al.*, 2006) have been proposed recently. A model for generating dynamic influent disturbance profiles, which is an essential module for long-term control system evaluation, has also been suggested (Gernaey *et al.*, 2006). The benchmark system is extended with the state-of-the-art anaerobic digestion model No 1 (ADM1) (Batstone *et al.*, 2002). To achieve reasonable simulation times with dynamic influent and with active measurement noise the ADM1 had to be modified with algebraic solvers for the pH and hydrogen (S_{h2}) states (Rosen *et al.*, 2006). Based on these proposals the Benchmark Simulation Model No 2 (BSM2) has been developed within the Matlab-Simulink software. In this paper, a description of the BSM2 implementation is provided, and some simulation results using a proposed default control strategy are presented and evaluated based on a set of extended evaluation criteria.

The paper is organised as follows. In the following section, the Matlab-Simulink implementation of BSM2 is described. Next, simulation results for the open-loop and closed-loop control strategies are shown and are evaluated by the extended BSM2 evaluation criteria. At the end some conclusions are drawn.

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Matlab-Simulink implementation of BSM2

The layout of the BSM2 is shown in Figure 1. All the models used in Simulink are written as C MEX file S-Functions. Such an implementation is elegant and allows for considerably higher simulation speed compared to m-file S-Functions. The BSM2 contains an influent wastewater, the pre-treatment process with a primary clarifier, the activated sludge (AS) process with a secondary clarifier (settler) and the sludge treatment processes with thickener unit, anaerobic digester (AD) and dewatering unit. All these components are connected in Simulink by combiner and splitter model blocks. There are also two extra blocks, the controller block that contains selected controllers and the monitoring block, which is mainly used for representing control results. These two blocks are elegantly connected to the process by using Simulink tags for sending and receiving signals.

State vector

The state vector is extended to 21 components: 13 ASM1 states, total suspended solids (TSS), flow rate, temperature and five dummy states (three soluble and two particulate). The dummy states are added to allow for easy future expansion of the system with additional states, for example to model inhibition of biological processes.

Activated sludge process

The model of the activated sludge (AS) process that is used in BSM2 is the same as the one defined for BSM1 (Copp, 2002). The only difference is that the kinetic parameters of the Activated Sludge Model No 1 (ASM1; Henze *et al.*, 1987) are now temperature dependent.

Secondary clarifier (settler)

The model of the secondary clarifier is the same as in BSM1. It consists of a 10-layer one-dimensional non-reactive settler model using the Takács double-exponential settling function (Takács *et al.*, 1991). The settling properties of the sludge in the secondary clarifier are not temperature dependent.
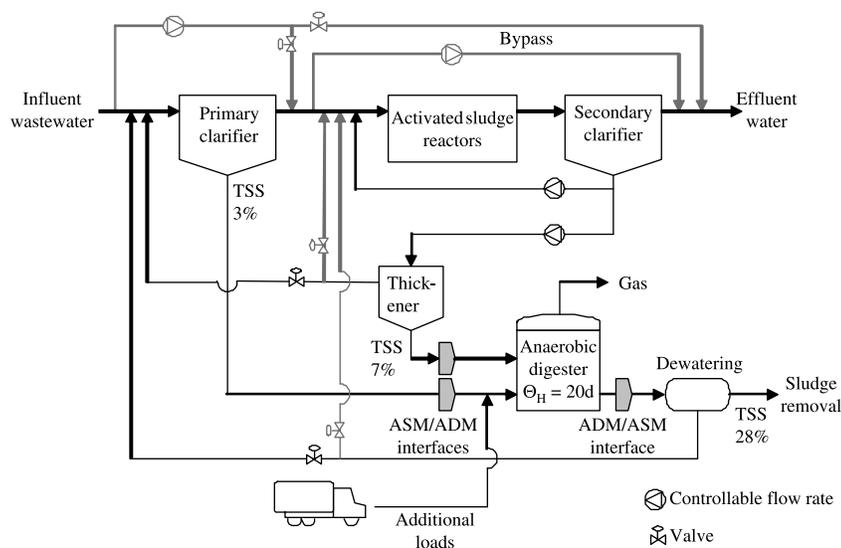

Figure 1 Layout of the BSM2

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Primary clarifier

The input to the primary clarifier combines the influent to the treatment plant, the reject water stream resulting from the sludge dewatering and the recycle from the thickener overflow. The underflow rate of the primary clarifier is controlled proportionally to the incoming flow. The primary clarifier is implemented using the model proposed by Otterpohl and Freund (1992). The volume of the primary clarifier and the parameters of the clarifier are set so as to obtain a TSS concentration in the sludge stream of about 30,000 g/m^3 and a TSS removal efficiency of about 50% (Jeppsson *et al.*, 2006).

Thickener and dewatering unit

Ideal thickener and dewatering units are used, where 98% of all particulate matter entering the units concentrates in the sludge stream. The TSS concentration in the sludge stream of the thickener unit is set to 70,000 g SS/m^3, and for the dewatering unit to 280,000 g SS/m^3. In order to achieve the defined TSS concentration in the sludge stream the underflow flow rate is changing instantaneously.

Anaerobic digester

The anaerobic digester model No. 1 (ADM1) (Batstone *et al.*, 2002) is used for modelling the anaerobic digester process. The model has been implemented within Matlab-Simulink aimed at obtaining fast simulation speed (see next subsection). The input of the anaerobic digester combines the sludge output from the thickener unit, the sludge output from the primary clarifier and additional loads with concentrated waste reaching the plant sporadically.

ADM1 model implementation

Applicability of the BSM2 largely depends on simulation speed. To implement the ADM1 model to obtain reasonable simulation times of the BSM2 even with dynamic influent and measurement noise, the stiffness of the ADM1 model has to be reduced. This is done by approximating the differential equations of the pH and liquid hydrogen S_{h2} states of the ADM1 by algebraic equations, and solving them with an iterative numerical method (Rosen *et al.*, 2006). The differences that are introduced by applying these solvers can be neglected.

ASM1–ADM1 interfaces

Since the state variables of the ADM1 are not the same as in the ASM1, interfaces are needed to connect these two processes. The interfaces proposed by Copp *et al.* (2003) are applied. As the sludge generated in the primary clarifier (primary sludge) and the thickener unit (secondary sludge) differs in composition and characteristics, two interfaces having somewhat different parameters are used.

Temperature dependence

Only temperature dependence of the AS kinetic model parameters is considered. The temperature dependence of these parameters is modelled using an Arrhenius function. At 15 °C BSM2 AS parameters have exactly the same values as in BSM1 for reasons of compatibility. Temperature dynamics in the processes are described by simple temperature mass balance equations.

Hydraulic delays

At the input of the primary clarifier and AS process, hydraulic delays have been added to prevent algebraic loops (a result of wastewater recycling). The hydraulic delays are

modelled in the same way as in BSM1 (Copp, 2002), simply by filtering the model states with a fast first-order filter.

Combiners and splitters
The combiners and splitters that are applied are the same as those used in BSM1. Combiners calculate the output concentrations by summing up the influx of each input stream for each pollutant, and subsequently dividing the resulting total flux by the total flow rate to obtain the output concentrations. On the other hand the splitters divide the input stream into two streams with identical concentrations but different flow rates.

Influent
The influent data are obtained from the influent model proposed by Gernaey et al. (2006), although the nitrogen load is reduced by 15% in order to obtain a plant, which is not significantly overloaded in nitrogen during the winter. The data represent a dynamic influent including diurnal, weekend, seasonal and holiday effects as well as rainfall, sludge settling in the sewer system, first-flush events etc. The temperature trajectory in the influent is composed of a sinusoidal function with a period of one year to model seasonal temperature variations, with a second sinusoidal function superimposed on it (period of one day) to model small variations of the temperature between day and night.

Additional loads
Additional loads from outside sources are also considered in the BSM2. These loads are considered to be added directly into the AD. However, they are not used in this study.

Simulation results
Simulation procedure
The BSM2 is first simulated with a constant influent for 200 days to reach its steady-state. The values of the influent soluble components and the flow rate are the same as those used in BSM1, whereas the values of the influent particulate components are doubled. The temperature, which is also included in the constant influent, is 15 °C. The steady-state values obtained in this first simulation are subsequently used as initial values for simulation with the dynamic influent. The BSM2 is then simulated with the dynamic influent for 63 days (9 weeks, from $t = 0$ d to $t = 63$ d) so that a quasi steady state is reached. These 63 days are followed by 182 days of dynamic simulation (26 weeks, from $t = 63$ d to $t = 245$ d) in order to get dynamic data, which are intended to be used for training monitoring and control strategies. The start date for this period of 26 weeks corresponds to January 1st. Finally, the BSM2 is simulated for an additional 364 days (52 weeks, starting at $t = 245$ d, ending at $t = 609$ d) and the data obtained during this period are used for plant performance and monitoring strategy performance evaluation. The dynamic influent data for plant performance evaluation start on July 1st, and finish on June 30th the next year.

Default open-loop case
In the proposed open-loop case, constant control variables are used to obtain a reasonable behaviour of the plant for the whole year. The oxygen transfer rates for the last three tanks of the AS (K_La_3, K_La_4, K_La_5) are set to 240 d^{-1}, values of the internal (Q_{intr}) and external (Q_r) recycle flow rates of the AS are the same as defined for BSM1, the waste sludge flow rate (Q_w) is set to 300 m^3/d and the external carbon flow rate (Q_{carb}) is set to 2 m^3/d (800 kg COD/d). The possibility to bypass the influent wastewater was not used. Similarly, a recycle stream to the AS from the thickener and dewatering unit has not

been used. Selected daily averaged values of open-loop results for the evaluation period of one year are shown in Figure 2.

The ammonia removal efficiency in the AS process is highly correlated with the influent temperature. During the winter period, when the wastewater temperature values are at their lowest, the nitrification process is not as efficient compared to the summer period, and as a consequence higher effluent ammonia values are obtained during the winter period. Because of this, effluent total nitrogen values increase during the winter as well. The primary clarifier output concentration of the TSS represents around 50% of the TSS concentration at the influent (400 g SS/m^3). This means that approximately 50% of the TSS is removed in the primary clarifier, as was defined in the design phase. The whole plant, including the secondary clarifier, efficiently removes the TSS. The digester effluent ammonia concentration is high. Since the ammonia is recycled back to the primary clarifier it contributes significantly to the nitrogen load of the AS plant, even though the supernatant flow rate from the dewatering unit is small in comparison with the influent flow rate. This implies that special treatment of the supernatant from the dewatering may be a valid operational strategy. Such an approach is evaluated in Volcke et al. (2006).

Default closed-loop case

In the proposed default closed-loop case, simple proportional-integral (PI) and proportional (P) controllers are applied. Oxygen in the last aerobic tank (S_{O5}) is controlled with a PI controller by manipulating the K_La_5, whereas K_La_3 and K_La_4 are kept constant as in BSM1. Nitrate in the second anoxic tank (S_{NO2}) is controlled with a PI controller that uses the internal recycle flow (Q_{intr}) as the manipulated variable. The daily averaged total suspended solids concentration in the last aerobic tank (TSS_5) is controlled by a P controller that uses waste sludge flow rate (Q_w) as the manipulated variable. Parameters for the PI and P controllers were tuned from step response experiments using the internal model control (IMC) tuning rules (Olsson and Newell, 1999). Controller parameter values are given in Table 1. The set-point for the total suspended solids in the last aerobic tank (TSS_{5set}) is changing according to the weekly averaged wastewater temperature (T). The TSS set-point is set to 3,500 g SS/m^3 for temperatures above 15 °C and to 4,500 g SS/m^3 below 15 °C. Averaged values of TSS and T are approximately obtained by using
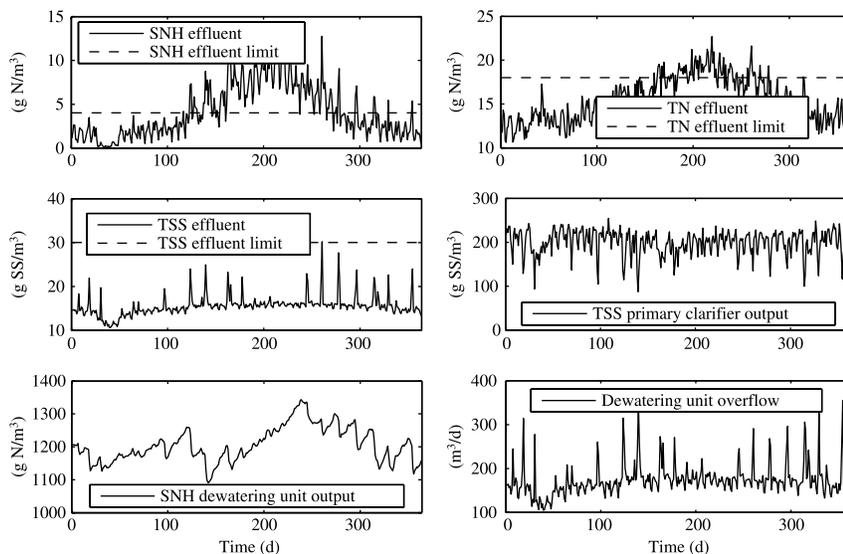

Figure 2 Daily averaged values obtained in open-loop simulation for the evaluation period

Table 1 Parameters used for controllers

	S_{O5}	S_{NO2}	TSS_5
K_P	$100\,\text{d}^{-1}\,(\text{g(O}_2)\text{m}^{-3})^{-1}$	$10{,}000\,\text{m}^3\,\text{d}^{-1}\,(\text{gNm}^{-3})^{-1}$	$-1\,\text{m}^3\,\text{d}^{-1}\,(\text{gSSm}^{-3})^{-1}$
T_i	$0.01\,\text{d}$	$0.04\,\text{d}$	–
T_t	$0.01\,\text{d}$	$0.04\,\text{d}$	–
Set-point	$2\,\text{g O}_2\,\text{m}^{-3}$	$1\,\text{g N m}^{-3}$	Variable

first-order filters with a time constant of one and seven days, respectively. Both external carbon flow (Q_{carb}) and external recycle flow (Q_r) are controlled proportional to the influent flow rate. Proportional constants were tuned manually to obtain a reasonable behaviour of the AS system (for Q_{carb} 0.00008 and for Q_r 1.5). The waste sludge flow rate (Q_w) is kept constant as in the open-loop case. Bypassing of the influent and recycling of the reject water to the AS is not used. In Figure 3, daily averaged values of effluent ammonia and total nitrogen, controlled and manipulated variables obtained in closed-loop simulation for the evaluation period are shown.

Effluent limit violations of ammonia and total nitrogen are much lower than in the open-loop case. Oxygen and nitrate PI controllers follow defined set-points so tightly that the difference between the set-points and true values cannot be distinguished in the graphs. This is not the case for the P control of *TSS*, where a noticeable but approximately constant offset from the set-point is obtained. It can be also noticed that the average external carbon flow rate is lower than the constant external carbon flow rate used in the open-loop case.

Evaluation criteria

Evaluation criteria are proposed for simple evaluation and comparison of control strategies for the BSM2. The evaluation criteria represent an extension of the criteria for BSM1 and consider the features of the new processes that are included in BSM2. The evaluation period has been extended from one week to one year. The effluent quality (*EQ*) is calculated the same as in the BSM1. However, for the operational cost index
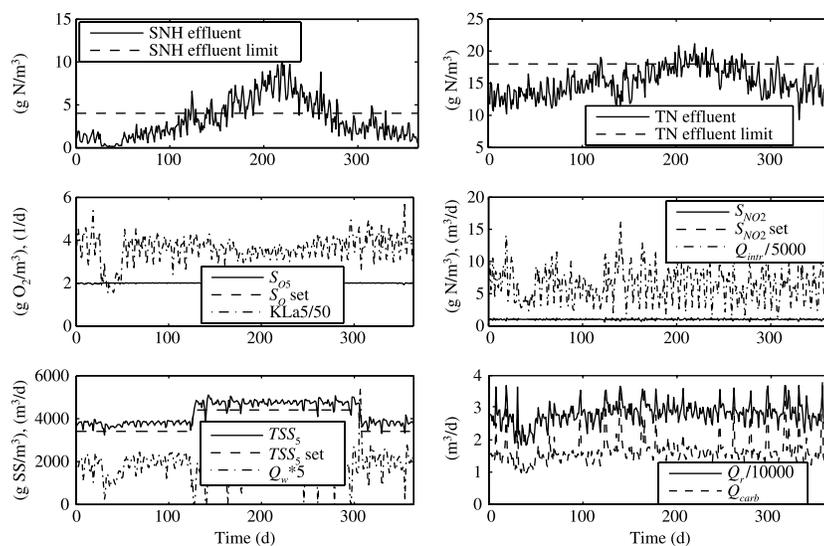
Figure 3 Daily averaged values obtained in closed-loop simulation for the evaluation period

Table 2 Values of evaluation criteria for default open-loop and closed-loop cases

Evaluation criteria	EQ (kg/d)	OCI (1/d)	AE (kWh/d)	PE (kWh/d)	SP (kgSS/d)	EC (kgCOD/d)	ME (kWh/d)	MP (kgCH$_4$/d)
Open-loop	8,847	18,967	8,548	2,978	3,216	800	648	876
Closed-loop	8,727	17,268	7,771	2,453	3,205	661	648	867

Evaluation criteria	HE^{net} (kWh/d)	TN$_{e95}$ (g/m^3)	S$_{NH,e95}$ (g/m^3)	TSS$_{e95}$ (g/m^3)	T_{viol}TN$_e$ (%)	T_{viol}S$_{NH,e}$ (%)	T_{viol}TSS$_e$ (%)
Open-loop	0	21.4	11.9	20.7	23.9	40.9	0.7
Closed-loop	0	20.5	10.1	21.7	19.5	33	0.7

(*OCI*), a modified version of the weighted sum of different costs is proposed:

$$OCI = AE + PE + 3 \cdot SP + 3 \cdot EC + ME - 6 \cdot MP + HE^{net}, \qquad (1)$$

where *AE* is aeration energy, *PE* is pumping energy, *SP* is sludge production for disposal, *EC* is external carbon addition, *ME* is mixing energy, *MP* represents methane production in the AD and *HE*^{net} is a net heating energy for the AD. Aeration energy (*AE*) is calculated in a similar way as in the BSM1. External carbon addition (*EC*) is calculated the same as in BSM1. For the pumping energy calculation (*PE*) also the primary clarifier underflow, thickener underflow and dewatering overflow are included. Sludge production for disposal (SP) is calculated based on the amount of solids that are accumulated in the plant and from the solids that are removed from the plant as dewatered sludge. The weight for the *SP* has been reduced from the value 5, which was used in BSM1 (no sludge treatment explicitly included in BSM1 but the cost was still included in the *OCI*), to the value 3. Mixing energy (*ME*) combines energy used for mixing the AS anoxic tanks and energy used for mixing the AD. Methane production (*ME*) represents an economic benefit, and can be included in the cost index as a negative cost. The weight for the *MP* is set to 6 and it defines that around 50% of the energy content of the methane is converted into electricity using a gas motor. Net heating energy (*HE*^{net}) represents energy that is needed for heating the sludge of the AD in case the assumed heat exchange system together with the heat provided by the gas motor is not sufficient. Other criteria, such as time of effluent limit violations (T_{viol}) and 95 percentile of effluent variables, are calculated as in the BSM1. Values for the proposed evaluation criteria for the open-loop and closed-loop cases are given in Table 2.

In both cases approximately the same effluent quality (*EQ*) is obtained. However, in the closed-loop case the operating cost index (*OCI*) is about 10% lower. Moreover, also effluent limit violations of ammonia and total nitrogen are much lower. The net heating energy (*HE*^{net}) is in both cases zero, which means that the energy from the heat exchange system together with the heat generated by the gas motor is sufficient to heat the sludge of the AD.

Conclusions

A first version of the BSM2 has been implemented and tested within the Matlab-Simulink software. It consists of a pre-treatment process, an activated sludge process and the sludge treatment processes. For objective evaluation and comparison of plant-wide control strategies on a long-term basis, a set of extended evaluation criteria are proposed for BSM2. Assessment of simulation results in terms of evaluation criteria has shown that in the closed-loop example considerably lower operational costs and lower effluent nitrogen violations are achieved in comparison with the open-loop case. Simulations indicate that the BSM2 can be successfully used for plant-wide control strategy evaluation. It should

be noted that the BSM2 is still in its development phase by the IWA Task Group on Benchmarking of Control Strategies for WWTPs. Consequently, some details regarding the ADM1 model implementation, ASM1–ADM1 interfaces and evaluation criteria presented in this paper are likely to change in the future. The finalised version of the BSM2 will be presented in 2008.

References
Batstone, D.J., Keller, J., Angelidaki, I., Kalyuzhnyi, S.V., Pavlostathis, S.G., Rozzi, A., Sanders, W.T.M., Siegrist, H. and Vavilin, V.A. (2002). *Anaerobic Digestion Model No. 1*, IWA Scientific and Technical Report No. 13. IWA Publishing, London, UK.

Copp, J.B. (ed.) (2002). *The COST Simulation Benchmark – Description and Simulator Manual*, ISBN 92-894-1658-0. Office for Official Publications of the European Communities, Luxembourg.

Copp, J.B., Jeppsson, U. and Rosen, C. (2003). Towards an ASM1-ADM1 state variable interface for plant-wide wastewater treatment modelling. *Proc. Water Environment Federation Conference WEFTEC 2003*, 11–15 October, Los Angeles, California, USA.

Gernaey, K.V., Rosen, C. and Jeppsson, U. (2006). WWTP dynamic disturbance modelling – an essential module for long-term benchmarking development. *Wat. Sci. Tech.*, **53**(4–5), 225–234.

Henze, H., Grady, C.P.L., Jr, Gujer, W., Marais, G.v.R. and Matsuo, T. (1987). *Activated Sludge Model No. 1*, IWA Scientific and Technical Report No. 1. IWA Publishing, London, UK.

Jeppsson, U., Rosen, C., Alex, J., Copp, J., Gernaey, K.V., Pons, M.-N. and Vanrolleghem, P.A. (2006). Towards a benchmark simulation model for plant-wide control strategy performance evaluation of WWTPs. *Wat. Sci. Tech.*, **53**(1), 287–295.

Olsson, G. and Newell, B. (1999). *Wastewater Treatment Systems. Modelling, Diagnosis and Control*, IWA Publishing, London, UK.

Otterpohl, R. and Freund, M. (1992). Dynamic models for clarifiers of activated sludge plants with dry and wet weather flows. *Wat. Sci. Tech.*, **26**(5–6), 1391–1400.

Rosen, C., Jeppsson, U. and Vanrolleghem, P.A. (2004). A common benchmark for long-time control evaluation and monitoring methodology testing. *Wat. Sci. Tech.*, **50**(11), 41–49.

Rosen, C., Vrecko, D., Gernaey, K.V. and Jeppsson, U. (2006). Implementing ADM1 for plant wide benchmark simulations in Matlab/Simulink. *Wat. Sci. Tech.*, **54** (in press).

Takács, I., Patry, G.G. and Nolasco, D. (1991). A dynamic model of the clarification thickening process. *Wat. Res.*, **25**, 1263–1271.

Volcke, E.I.P., Gernaey, K.V., Vrecko, D., Jeppsson, U., van Loosdrecht, M.C.M. and Vanrolleghem, P.A. (2006) Plant-wide (BSM2) evaluation of reject water treatment with a SHARON-Anammox process. *Wat. Sci. Tech.*, **54**(8), 93–100 (this issue).

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