Control of an activated sludge process with nitrogen removal – a benchmark study

B. Carlsson and A. Rehnström

Department of Systems and Control, Uppsala University, PO Box 27, SE-751 03 Uppsala, Sweden. (E-mail: *Bengt.Carlsson@syscon.uu.se*)

Water Science and Technology **Vol 45 No 4–5 pp 135–142** © 2002 IWA Publishing and the authors

Abstract In this paper, a simulation benchmark of a predenitrifying activated sludge process is used to evaluate a number of control strategies. A main procedure has been to use feedforward terms that are based on simplified physical models. Important mass balance relations may then be incorporated in the control law. The nitrate level in the last anoxic zone is controlled by the dosage of an external carbon source and the nitrate level in the last aerobic zone is controlled by the internal recirculation flow rate. The ammonia level is controlled by a DO set-point controller. In order to be able to have as high a sludge level as possible without sludge escape, the sludge blanket height in the settler is controlled by the excess sludge flow rate. Compared to the default set up of the benchmark, the controllers could reduce the effluent nitrate significantly whereas the effluent ammonia was only marginally decreased. The main problem is that the aeration capacity defined in the benchmark is too low.

Keywords Activated sludge process; automation; benchmark; control; feedforward control; nutrient removal; wastewater treatment

Introduction

Wastewater treatment plants (WWTPs) are non-linear systems consisting of a great number of complex processes. The influent water varies both in amount and composition and the variations are difficult to predict. Still WWTPs have to be operated consistently while meeting stricter and stricter regulations. Many different control strategies have therefore been proposed for WWTPs, but it has been troublesome or even impossible to evaluate and compare the strategies, either practically or by simulation. One problem is the large variation in plant configurations and influent characteristics. An additional factor complicating the evaluation is the lack of standard evaluation criteria. This follows from the fact that regulations regarding effluent water quality and labour costs are often location specific. The complexity of the process makes it difficult to put new control strategies into practise, which in turn means that different strategies rarely are compared in a fair way and some ideas are never realised at all.

To enhance the development and acceptance of new control strategies the evaluation procedure must be made easier and in some way uniform. Therefore, a simulation benchmark of an activated sludge process (ASP) has been developed within the COST Action 624 and 682. The benchmark is a simulation protocol defining a plant layout, a process model, influent loads, test procedures and evaluation criteria. Demand for realism, simplicity and accepted standards were taken into consideration when developing these different parts. For more information see the Benchmark homepage http://www.ensic.inplnancy.fr/COSTWWTP/ and Alex *et al*. (1999).

In this paper, we will describe and evaluate a number of control strategies that have been implemented in the benchmark. A more detailed description of the work is given in Rehnström (2000). See also Singman (1999) and Vrecko *et al*. (2001) for some related work on the benchmark. A key procedure in the work presented here has been to use simplified physical models to derive feedforward control strategies. By using physical models in the feedforward controller design, important mass balance relations can be incorporated in the control law. This is in contrast to when a black box model is used for controller design. In order to compensate for model approximations, etc, feedback control is also needed. However, by having a good feedforward controller, the feedback part can be made slow which is advantageous since problems with instability and oscillations are reduced. The goal at this stage is not primarily to optimise the benchmark performance; it is rather to evaluate some SISO controllers in a fairly realistic environment. The following strategies will be presented and evaluated. The nitrate level in the last anoxic zone is controlled by the dosage of an external carbon source. A combined feedforward–feedback strategy, suggested by Samuelsson and Carlsson (2001), is used where the feedforward part is obtained from a steady state analysis of a simplified ASM1. The ammonia level in the last aerobic zone is controlled by a cascade controller similar to the one presented in Lindberg and Carlsson (1996) but in order to compensate for process nonlinearities a gain scheduling PI controller was designed. The nitrate level in the last aerobic zone is controlled by the internal recirculation flow rate. A feedforward control strategy based on a simplified mass balance model is used together with a standard PI feedback controller.

The benchmark

We here give a short description of the benchmark. We refer to the benchmark homepage cited in the introduction for details.

Plant layout and process model

The layout of the plant is a standard activated sludge process consisting of a bioreactor and a secondary settler. The bioreactor has five compartments and predenitrification is applied. The first two compartments are anoxic while the last three are aerated using a maximum KLa of 10 hr^{-1}. All five compartments are fully mixed. The process has two internal recycles: nitrate internal recycle Q_a from the fifth to the first tank and RAS recycle Q_r from the underflow of the secondary settler to the front end of the plant. Excess sludge Q_w is pumped continuously from the secondary settler underflow.

The IAWQ Activated Sludge Model No 1 (ASM1) was selected to model the biological processes in the bioreactor. The ASM1 model is probably the most widely used for describing wastewater treatment and can be considered as a “state of the art” model. A further description of ASM1 can be found in Henze *et al.* (1986). The secondary settler is modelled as a series of ten layers and the double exponential settling velocity model proposed by Takács *et al.* (1991) is chosen to resemble the behaviour of the settler.

We have used a Matlab/Simulink implementation of the benchmark, see the acknowledgments.

Influent files

There are three influent files, representing three different weather conditions over 14 days. The sampling interval is 15 minutes. The data files aim to mimic real operating conditions. The first file, denoted *dry weather influent*, is constructed to resemble a dry weather period with decrease in flow and load during weekends. The other two files are designed with the dry weather file as a starting point with an added rain event during the second week. The first of the two rain files, *rain weather influent*, simulates a period of steady downpour during the second week, which results in a constant increase in influent for two days. Compared to the dry weather file this file has a constant hydraulic load increase without any increase in carbon oxygen demand (COD) or nitrogen. The second rain file, *storm weather influent*, has two storm events during the second week that are shorter in time compared to the rain events, but more intense. The storm events give rise not only to an increase

Table 1 Effluent constraints for the violation variables

Variable	Effluent constraint
Ammonia ($S_{NH,e}$)	4 gN m^{-3}
Total nitrogen ($N_{tot,e}$)	18 gN m^{-3}
BOD5 (BOD,e)	10 gBOD m^{-3}
Total COD (COD,e)	100 gCOD m^{-3}
Suspended Solids (TSS,e)	30 gSS m^{-3}

in the hydraulic load, but also an increase in particulate load. The increase in particulate load illustrates a first flush event in the sewer system.

Effluent constraints

The assessment is based on data generated during the last seven days when the weather files are used as input. A number of constraints with respect to the effluent water quality that should not be violated are presented in Table 1. In the benchmark a number of performance and water quality measures are also defined.

A feedforward–feedback external carbon flow rate controller

Dentrifying bacteria need readily metabolised carbon in order to convert nitrate to nitrogen. An external carbon source can improve the denitrification rate and hence decrease the nitrate level when the carbon/nitrogen ratio is too low. The aim with an external carbon controller is to adjust the carbon flow so that the nitrate concentration in the last anoxic zone is close to a pre-specified value (the set point). We will use the control strategy suggested in Samuelsson and Carlsson (2001). By considering a completely mixed reactor and making some simplified assumption in the ASM1 model it was shown that the following mass flow rate of external carbon gives a nitrate concentration of S_{NO} during steady state in the reactor:

$$u = Q\left[\frac{1}{\beta}\left(S_{NO,in} - S_{NO}\right) - \left(S_{S,in} - S_S\right)\right]$$

where Q is the influent flow rate, $S_{NO,in}$ is the influent concentration of nitrate, $S_{S,in}$ is the influent concentration of readily biodegradable substrate. Using ASM1 default values, the conversion factor $b = (1 - 0.67)/2.86$. The mass flow rate of external carbon is defined as: $u = Q_{car}COD_{car}$ where Q_{car} [m^3/d] is the flow rate of the external carbon source and COD_{car} [g COD/m^3] is its COD content. Ethanol was chosen as an external carbon source with $COD_{car} = 1.2 \times 10^6$ [g COD/m^3].

The above expression for the flow rate of external carbon was derived for an ASP with one anoxic compartment. It can be shown that the same control law is also applicable for the multi-compartment case. A "mass balance" feedforward controller is obtained by replacing S_{NO} with a set point (reference value) $S_{NO,ref}$. To compensate for model simplifications and unmeasurable disturbances the feedforward strategy is combined with a feedback PI-part including anti-windup. With the benchmark notations, the final control law (excluding discretization and anti-windup design) becomes:

$$u(t) = Q_t\left[\frac{1}{\beta}\left(S_{NO,0}(t) - S_{NO,ref}(t)\right) - \left(S_{S,0}(t) - S_{S,2}(t)\right)\right] + K_p\left(S_{NO,2}(t) - S_{NO,ref}(t)\right)$$
$$+K_1\int_0\left(S_{NO,2}(\tau) - S_{NO,ref}(\tau)\right)d\tau$$

where Q_t is the total (including recirculated flows) incoming flow rate, $S_{NO,0}$ and $S_{S,0}$ is the nitrate and soluble substrate concentration in the total flow. The subscript 2 denotes concentrations in the second zone. Since the feedforward part attenuates disturbances relatively fast the feedback part can be made slow. We have followed the choice by Singman (1999), and selected the PI parameters as $K_I = 7 \times 10^6$ and $K_P = 0$. The choice of set point for the nitrate is closely related to how much carbon one can accept to add. After some trial and errors we chose $S_{NO,ref} = 1.0$ [g/m^3].

The maximum flow rate of external carbon significantly influences the nitrate removal (and the costs). Figure 1 shows the control performance for three different values on the upper bound on the external carbon flow rate. From the figure it can be seen that an upper bound on the external carbon flow rate of 2.6×10^6 [gCOD/d] gives a very good control performance. Note also the performance improvement compared to not using an external carbon source (right column in Figure 1). The middle column in Figure 1 shows that the performance deteriorates when too low a bound is chosen.

The controller was evaluated using steps in the set point and step disturbances. The result was very good, see Rehnström (2000). Also the performance when the weather data files were used was very good. A typical example is shown in Figure 2. The heavy rain period of the rain weather influent file (around days eight to ten) can clearly be noticed in the figure; the control signal then decreases significantly.

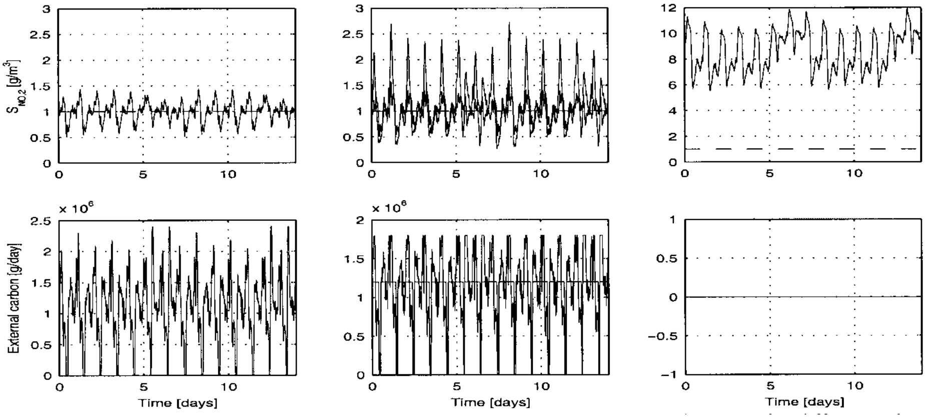

Figure 1 Nitrate concentration in zone two (upper plots) and external carbon flow rate for different values on the upper bound of the external carbon flow rate (lower plots). From left to right, the upper bound on the external carbon flow rate is 2.4×10^6, 1.8×10^6, and 0 [g COD/d], respectively. The file dry weather influent is used

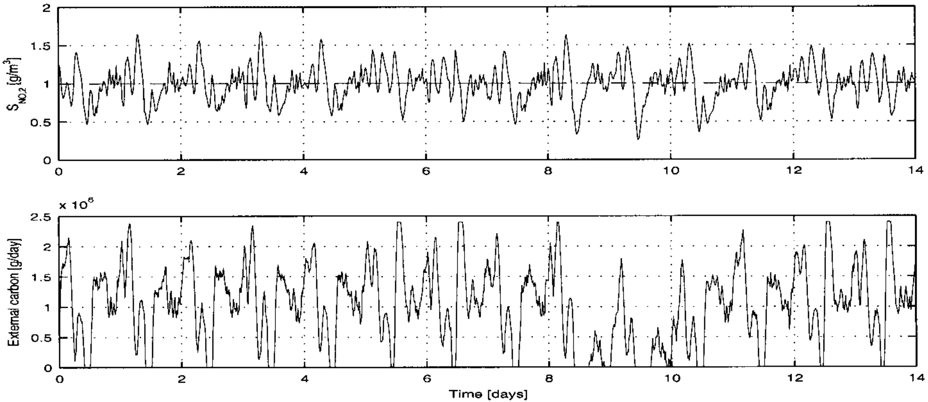

Figure 2 Nitrate concentration in zone two (upper plot) and external carbon flow rate (lower plot). The file rain weather influent is used. The used sensors are simulated with noise and delays

An internal recycle flow rate controller

In order to decrease the effluent nitrate in a pre-denitrifying ASP, a nitrate recycle is needed. The nitrate concentration in the last zone may be controlled by the internal recycling flow rate Q_a. By using a simplified mass balance model of ammonia and nitrate the following control strategy can be derived (see Rehnström (2000) and Ekman *et al.* (2001))

$$Q_a(t) = \frac{Q_{in}(t)S_{NH,in}(t)}{S_{NO,ref}} - \left(Q_{in}(t) + Q_r(t)\right)$$

In order to compensate for model simplifications and non-measurable disturbances an integrating feedback controller is also used. The controller showed good set point tracking and disturbance rejection when used on non-constraining conditions. However, when using the benchmark weather files the performance deteriorates to some degree. In this case, the upper limit of the recirculation rate was chosen as $5Q_{in,stab} = 92{,}230$ [m^3/d], as in the benchmark specification, and the set point for the nitrate concentration in zone five was 6 [g/m^3]. A typical example is shown in Figure 3. The nitrate concentration in zone five centres quite well around the set point, but the peaks, due to the influent ammonia, cannot be fully suppressed. During these peaks both the carbon controller and the internal recycling controller saturated.

DO set-point controller

In the aerobic parts in a nitrifying ASP, it is feasible to select the DO set points for the DO controllers using the ammonium level in the last aerobic compartment. Such a cascade strategy was, for example, used in Lindberg and Carlsson (1996). However, since the dynamics is nonlinear a gain scheduling strategy may be feasible. We have tried an approach where a first order difference equation model (ARX model) is estimated in a number of working points. Then the parameters in the following discrete time, incremental PI controller were calculated using pole placement design

$$\Delta S_{O,ref}(k) = K_p\left(e_{S_{NH,5}}(k) - e_{S_{NH,5}}(k-1) + \frac{1}{T_I} e_{S_{NH,5}}(k)\right)$$

where $\Delta S_{O,ref}$ is the incremental change of the DO set point, $e_{S_{NH,5}} = S_{NH,5} - S_{NH,5,ref}$ is the control error. The PI parameters for the DO set point controller is presented in Table 2. As

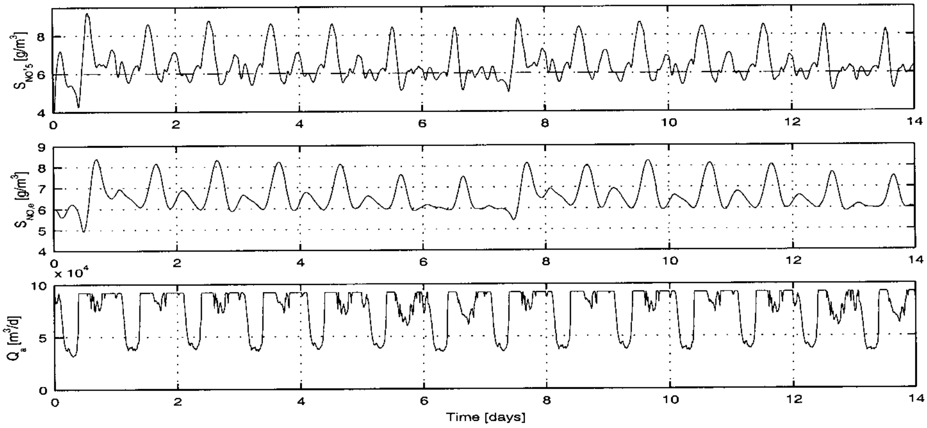

Figure 3 Nitrate concentration in zone five (upper plot), effluent nitrate concentration (middle plot) and internal recirculation flow rate (lower plot). The file dry weather influent is used. The sensors are simulated with noise and delays

seen from Table 2, the parameters in the PI controller are changed significantly in order to compensate for the nonlinear dynamics. In Figure 4 the control performance for a constant PI controller is compared with the results of using a gain scheduling controller with parameters according to Table 2. The gain scheduling controller gives a much more uniform step response.

The performance of the DO set-point controller in the benchmark was, however, not satisfactory. The problem is that the specified aeration capacity (or aeration volume) in the benchmark specification is too small. Even when the air flow rate was kept at its maximum value during the whole simulation, the ammonia peaks were only lowered marginally compared to when the DO set-point controller was used. A slight improvement was obtained by also controlling the excess sludge flow rate, see the next section.

An excess sludge flow rate controller

A main problem in the current benchmark is that the high effluent ammonia concentration could not be significantly reduced with a supervision DO controller. One remedy would be to increase the sludge age in the system. But if the sludge age is increased (by decreasing the excess sludge rate Q_w) sludge escape may occur. In fact, a fixed lower value on Q_w than the original value of 385 [m^3/day] will lead to high sludge concentrations in the effluent when the weather file storm weather influent is simulated. This problem may be solved by making Q_w time varying. We will here control the sludge blanket height in the settler with Q_w as control variable. A simple discrete-time PI controller on incremental form is chosen:

$$\Delta Q_w(k) = K_P\big(e_L(k) - e_L(k-1)\big) + K_I e_L(k)$$
$$e_L(k) = L_{nb}(k) - L_{ref}$$

Table 2 Values of controller parameters K_P and T_I for different working points. A real double pole placed in $\alpha = 0.74$ for the closed loop system has been used in the pole placement

DO$_{ref}$ [g m^{-3}]	0.5	1.0	1.5	2.0	3.0	4.0
K_P	4.5	17.8	54.8	137.5	307.8	704.5
T_I	6.64	6.50	6.47	6.48	6.45	6.49

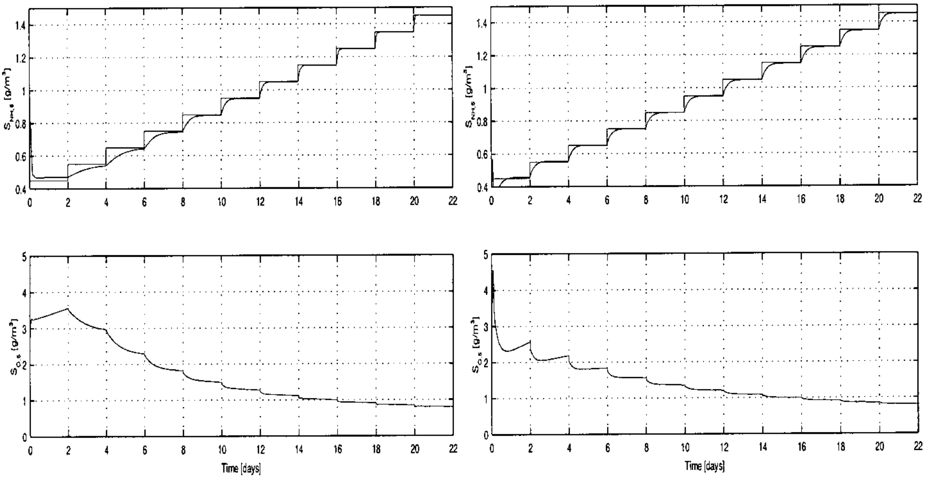

Figure 4 Comparison between a fixed PI controller (left) and a gain scheduling PI controller (right). Ammonia concentration in zone five and the set point (upper plot) and DO in zone five (lower plot)

where L_{nb} denotes the present sludge blanket height, or layer, in the settler. The settler is modelled with ten layers numbered one to ten from bottom to top. Layers two and three were found to be the only interesting layers to be used as a set point. The controller parameters K_P and K_I were tuned by trial and error and were chosen to 20 and 5, respectively. It is important to limit the maximum and minimum excess flow rate. The upper bound of Q_w was chosen to be 500 [m^3/day] and the lower bound to be 100 [m^3/day]. A typical simulation result when both the supervision DO controller and the excess sludge flow rate controller are used is presented in Figure 5. The ammonia peaks were lowered with about 1 mg/l compared to when Q_w was 385 [m^3/day].

In summary it can be concluded that the strategy presented here improves the ammonia reduction to some degree. It would, however, be desirable to have more than ten layers in the model of the settler, since the sludge blanket height could be measured more exactly then and the controller could operate more smoothly. With the rough ten-layer-dividing of the settler a relatively big range of Q_w values can give the same sludge blanket height, which makes the control strategy less exact. Another potential problem that must be considered is that an increase in the hydraulic load may occur without an increase in TSS. The increased hydraulic load will raise the sludge blanket height without an actual increase in TSS. The result is an increased excess sludge flow rate and less sludge in the system.

A comparison with the default benchmark set up

In Figure 6, the control performance for the original benchmark set up (the reference case) is compared with the new controllers. The total nitrogen decreases significantly whereas for the ammonia level only a marginal improvement is obtained.

Conclusions

A number of control strategies have been evaluated on a benchmark. The controllers all worked well during non-constraining conditions. It was, however, not possible to keep the effluent ammonia level low when the weather files were used. The main reason is most likely that the defined maximum aeration capacity was too low. Even when the air flow rate was kept at its maximum value, the ammonia level did not decrease significantly. Some improvement was obtained by controlling the excess sludge flow rate. A topic for further research is how to select feasible set points for the controllers and to make a global optimisation.

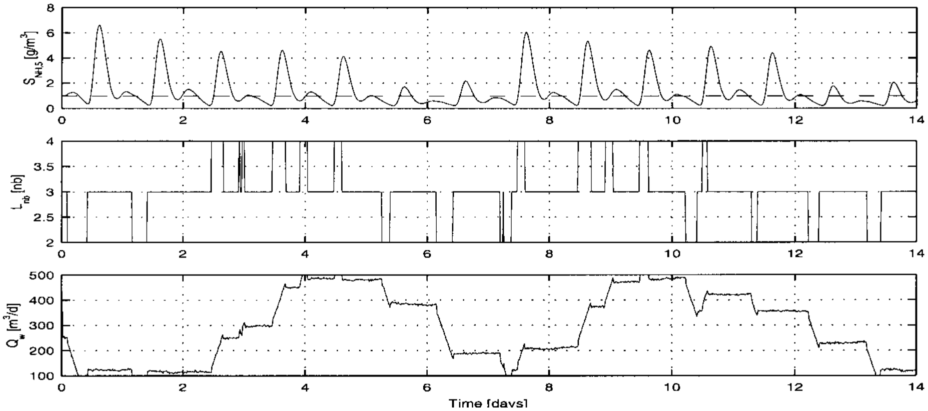

Figure 5 Ammonia concentration in zone 5 (upper plot), sludge blanket height in the settler (middle plot) and excess sludge flow rate (lower plot). The file dry weather influent is used. The sensors are simulated with noise and delays

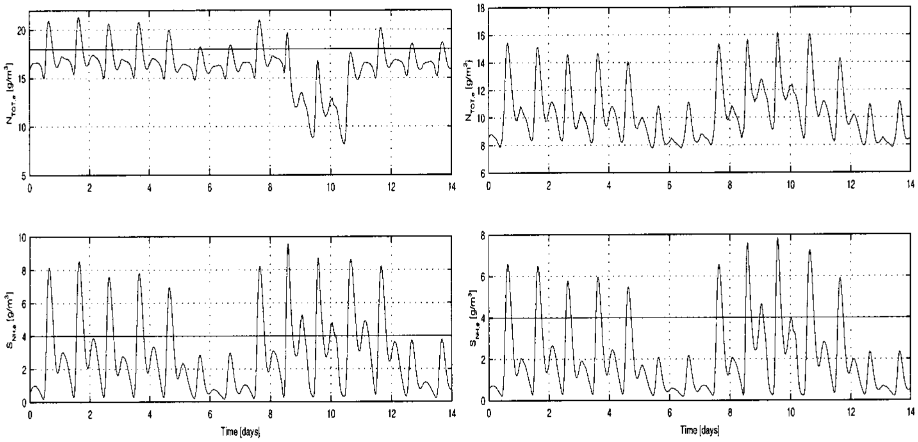

Figure 6 Results using the original plant set up (left) and using the new control strategies (right). Note the different scales in the plots. Effluent total nitrogen concentration (upper plot) and effluent ammonia concentration (lower plot). The effluent threshold values are marked with solid lines. The file rain weather influent is used and sensors are simulated with noise and delays

Acknowledgements

Thanks to Dr Ulf Jeppsson, IEA, Lund Institute of Technology, Sweden for letting us use his Matlab/Simulink implementation of the benchmark. The financial support by the MISTRA program Sustainable Urban Water Management is gratefully acknowledged.

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