  Water Science & Technology | 65.6 | 2012

Model-based knowledge acquisition in environmental decision support system for wastewater integrated management

Pau Prat, Lorenzo Benedetti, Lluís Corominas, Joaquim Comas and Manel Poch

ABSTRACT

The main goal of the Water Framework Directive is to achieve good chemical and ecological status of water bodies by 2015. The implementation of integrated river basin management, including sewer systems, wastewater treatment plants and receiving water bodies, is essential to accomplishing this objective. Integrated management is complex and therefore the implementation of control systems and the development of decision support systems are needed to facilitate the work of urban wastewater system (UWS) managers. Within this context, the objective of this paper is to apply integrated modelling of an UWS to simulate and analyse the behaviour of the 'Congost' UWS in Spain, and to optimize its performance against different types of perturbations. This analysis results in optimal operating set-points for each perturbation, improves river water quality, minimizes combined sewer overflows and optimizes flow lamination from storm water tanks. This is achieved by running Monte Carlo simulations and applying global sensitivity analysis. The set-points will become part of the knowledge base composed of a set of IF-THEN rules of the environmental decision support system being developed for this case study.

Key words | EDSS, global sensitivity analysis, integrated modelling, knowledge acquisition, Monte Carlo

Pau Prat (corresponding author)
Joaquim Comas
Manel Poch
LEQUIA, University of Girona,
Campus Montilivi, Girona, 17071,
Spain
E-mail: *paut@lequia.udg.cat*

Pau Prat
Lluís Corominas
Manel Poch
ICRA, Catalan Institute for Water Research,
Carrer Emili Grahit, 101, Girona, 17003,
Spain

Lorenzo Benedetti
BIOMATH, Department of Applied Mathematics,
Biometrics and Process Control,
Ghent University,
Coupure links 653, Ghent, 9000,
Belgium
and
Waterways srl, Via del Ferrone 88,
50023 Impruneta FI,
Italy

INTRODUCTION

The management of wastewater infrastructures in Spain has shifted due to policies promoted by the European Water Framework Directive (WFD) (2000/60/EEC) and the Spanish *Plan Nacional de Calidad de las Aguas* (PNCA) 2007–2015, which call for the integrated management and operation of wastewater infrastructures, in order to achieve good quality status of water bodies. New strategies and tools have to be developed as traditional engineering approaches focusing on the optimal management of individual components of the Urban Wastewater System (UWS) do not necessarily yield the optimum performance of the entire system (Rauch *et al.* 2002; Butler & Schütze 2005). The integrated management and operation of wastewater infrastructures (Sewer Systems (SS), Wastewater Treatment Plants (WWTP) and Receiving Water Bodies (RWB)) will improve the quality of water bodies and reduce costs. However, this is a difficult task due to the system complexity and the roles played by various stakeholders (with different expertise). Given this context, it is necessary to develop water management tools to support decision making (Poch *et al.* 2004).

Environmental Decision Support Systems (EDSSs) have been presented as interactive, flexible and adaptable computer-based systems able to tackle these complex and ill-structured domains (Poch *et al.* 2004). An EDSS can link numerical models/algorithms with knowledge-based techniques, geographical information systems and on-line data, among other technologies. They have been developed to help environmental decision makers choose between alternatives. EDSS incorporates explicit decision-making procedures based on a set of theoretical principles that justify the rationales of these procedures (Poch *et al.* 2004). Mathematical models are commonly used as part of

doi: 10.2166/wst.2012.759

EDSSs and help to better understand the interrelations within the system. Models can be used to test scenarios and evaluate failures (e.g. SS collapse), or to assess certain measures intended to improve the performance of the system against perturbations (e.g. increased hydraulic load). These models can also be used to evaluate real-time control (Erbe *et al.* 2002; Butler & Schütze 2005; Vanrolleghem *et al.* 2005; Muschalla 2008). The results of the simulated scenarios provide the EDSS with relevant and useful knowledge about the management of the wastewater infrastructures.

The work presented here is part of a joint project with the *Consorci per a la Defensa de la Conca del riu Besòs* to develop an EDSS able to solve operational problems of the UWS. As part of this project, Devesa *et al.* (2009) presented the first model-based approach to evaluate different strategies for integrated management. However, no detailed scenario analysis was applied in that study. The main purpose of this paper is to apply the methodology developed in Benedetti *et al.* (2009) to find better combinations of operating parameters to handle a full set of perturbations, thereby improving the quality of the river and minimizing costs. This is part of the knowledge acquisition phase to develop the EDSS.

METHODS

Case-study

The 'Congost' UWS is part of the Besòs River Basin in northeast Catalonia (Spain) and consists of two communities, Garriga and Granollers, and several industrial parks in both communities for a total population of about 100,000 inhabitants, their corresponding drainage catchments and combined SS. Two biological WWTPs are present (the Garriga WWTP and the Granollers WWTP) with a modified Ludzack-Ettinger configuration for nitrogen removal. Both plants discharge treated water at different locations on the Congost River (a tributary of the Besòs River).

The Congost River has an average flow rate (at the starting point of the studied area) of 0.5 $m^3 s^{-1}$, with a very irregular pattern (typical of Mediterranean basins) during the year. Other infrastructures that support integrated management have been also considered: wastewater tanks before the WWTP (Garriga and Granollers) and a connection channel that allows wastewater to bypass from Garriga to Granollers WWTPs.

Model

The integrated model was implemented on a single modelling and simulation platform, WEST (mikebydhi.com) (Vanhooren *et al.* 2003), which allowed an integrated system as a single executable model with fast simulation speed.

The sub-model used for the catchment and the SS is a modified version of the KOSIM model implemented in the WEST model library (Solvi *et al.* 2005). This includes the following units (see Figure 1): (1) urban catchment, which generates domestic or industrial wastewater patterns; (2) rain, linked to a simple rain time-series vector with a uniform distribution all over the catchment; (3) pipes; and (4) storm water tanks and Combined Sewer Overflows (CSO). The models included in the KOSIM model are surface runoff calculated with the area of the catchment and the proportion of impervious and pervious area and evaporation. Pipe flow is modelled as a series of tanks where each tank is supposed to be under steady flow (it is not possible to represent backwater effects inside the SS). Storm water tanks are supposed to be ideally mixed. They are located off line of the sewer network, and once they are full they provoke CSO. A pump fixes the flow that goes back to the WWTP. Water quality components included in the model are COD (soluble and particulate), total nitrogen (TN), ammonia (NH_4^+), total phosphorus (TP) and orthophosphates (PO_4).

WWTPs were modelled using ASM2d (Henze *et al.* 2000). Both WWTPs include NH_4^+ and NO_3^- controllers (manipulating DO set-point and internal recirculation) and Garriga WWTP includes a flow-ratio controller for external recirculation. The river stretch was modelled with the RWQMn°1 (Reichert *et al.* 2001). The integrated model was constructed taking into account the information coming from Devesa *et al.* (2009).

Scenarios

Five scenarios have been defined to study the best operational strategies against different types of perturbations:

- *Reference:* This scenario assumes dry-weather flow conditions and no perturbations are generated in the system.
- *Storm:* This scenario includes typical Mediterranean rain with significant rainfall variability, up to 72 mm in less than 5 min for intense rain events, and rains with an average of 12 mm per hour. The objective of this scenario is to optimize the bypass between the WWTP and the flow going to the storm water tanks.

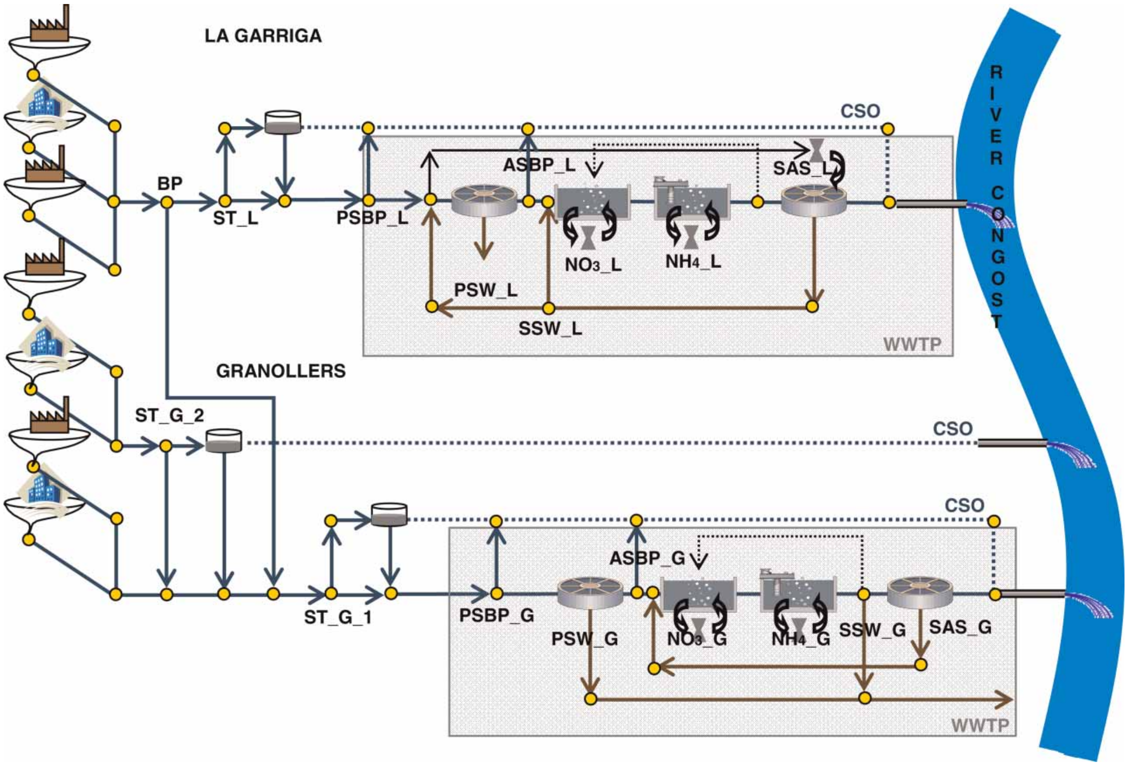

Figure 1 | Sketch of the Besòs urban wastewater system. Short names described in Table 1. Controllers are in grey.

- *Increase of population:* This scenario increases the quantity of domestic water that is generated in the catchment. Its purpose is to push the UWS to the limits and to analyse how the system minimizes the impact on the river. The population increased from 11,993 to 14,215 PE in Garriga, and from 83,113 to 98,508 PE in Granollers according to scenario 2021.
- *Organic shock Garriga:* The Besòs River Basin is characterized by a strong industrial presence; hence, uncontrolled discharges of industrial wastewater are common. The objective of this scenario is to simulate these discharges, which can overload the system. A total overload of twice the original was considered in Garriga for two consecutive days.
- *Organic shock Granollers:* The same as the organic shock in Garriga but in the Granollers wastewater system. A total overload of twice the original was considered in Granollers for two consecutive days.

Simulation methodology

There are several important operational parameters in the integrated model, which are studied by simulation to minimize the impact on the river and reduce costs against several perturbations. The parameters used in this study are summarized in Table 1.

The methods applied to find the best combinations of parameters for each scenario can be summarized as follows:

1. *Monte Carlo simulation:* 1000 Monte Carlo simulations were launched using WEST® software for the operational parameters with a triangular distribution and Latin Hypercube Sampling (LHS) solver. Each MC simulation is run at steady state for 50 days, followed by one week of dynamic conditions and then another week of dynamic conditions used for the evaluation. The output sampling frequency was set to 5 min. In this case, the outputs are evaluated against the criteria of system performance, which include the economical criteria (Operational Cost Index, Vrecko *et al.* 2007) and environmental criteria (average and minimum DO concentration, average and maximum NH_4^+ concentration downstream from the Garriga and the Granollers WWTPs) (Benedetti *et al.* 2009).
2. *Global sensitivity analysis (GSA):* MC simulation was followed by GSA with linear regression. GSA allows the

Table 1 | Operational parameters and ranges for the triangular distributions

Short name	Description	Unit	Min	Max	Default
BP	Flow going to Garriga, overflow is bypassed to Granollers	m^3/d	10,000	100,000	27,648
ST_L	Flow going to Garriga WWTP, overflow is bypassed to tank	m^3/d	10,000	100,000	27,648
ST_G_1	Flow going to Granollers WWTP, overflow is bypassed to tank	m^3/d	50,000	150,000	76,800
ST_G_2	Flow going to Granollers WWTP, overflow is bypassed to tank	m^3/d	15,000	60,000	30,000
PSBP_L	Flow going to primary settling Garriga, overflow goes to river	m^3/d	10,000	100,000	27,648
PSBP_G	Flow going to primary settling Granollers, overflow goes to river	m^3/d	38,400	153,600	76,800
ASBP_L	Flow going to activated sludge Garriga, overflow goes to river	m^3/d	10,000	100,000	13,994
ASBP_G	Flow going to activated sludge Granollers, overflow goes to river	m^3/d	25,000	75,000	34,440
SAS_L	Ratio between settled activated sludge and recycle flow Garriga		0.2	3	1.5
SAS_G	Recycle flow rate of settled activated sludge Granollers	m^3/d	10,000	57,760	28,800
PSW_L	Wastage flow rate of primary sludge Garriga	m^3/d	20	150	50
PSW_G	Wastage flow rate of primary sludge Granollers	m^3/d	250	1,800	600
SSW_L	Wastage flow rate of secondary sludge Garriga	m^3/d	100	400	200
SSW_G	Wastage flow rate of secondary sludge Granollers	m^3/d	250	1,500	500
NH4_L	NH_4^+ set-point of the DO cascade controller Garriga	g/m^3	0.2	3	1
NH4_G	NH_4^+ set-point of the DO cascade controller Granollers	g/m^3	0.2	3	1
NO3_L	NO_3^- set-point of the internal recirculation controller Garriga	g/m^3	0.2	3	1
NO3_G	NO_3^- set-point of the internal recirculation controller Granollers	g/m^3	0.2	3	1

sensitivity of model outputs to changes in model inputs to be quantified. The parameters were judged as sensitive or not on the basis of the calculation of the *t*-statistics on the Partial Correlation Coefficients (PCCs), which allows the parameters to be classified as significant at the 5% level with a *t*-statistic larger than 1.96 (Benedetti *et al.* 2008).

3. *Pareto front:* For each scenario, the operational parameters are selected using the Pareto method (Benedetti *et al.* 2009). To reduce the extension of the Pareto front, a screening was performed by leaving out all parameter sets that were worse than 50% of all sets for at least one criterion, thus focusing on the 'compromise' area in the trade-off between performance criteria.

For each scenario, a parameter set was found according to the given criteria and for the operational parameters selected from the GSA. Each parameter set helps to build the knowledge base composed of a set of IF-THEN rules that will be implemented as part of the core knowledge base of the EDSS. Everything is integrated in the same modelling and simulation software (WEST) used for the simulations and for the GSA. Further explanations of the method can be found in Benedetti *et al.* (2009).

RESULTS AND DISCUSSION

The best parameter sets found for each scenario are summarized in Table 2, with the most sensitive parameters in grey.

Overall, set-point values for NH_4^+, NO_3^- and sludge controllers are always sensitive. These parameters refer to aeration and internal and external recycle flows of the two WWTPs. The best configuration of these parameters will lead to better effluent characteristics and reduced costs. ST_G_2, PSBP_L and ASBP_L are not sensitive in any of the studied cases. ST_G_2 is a storm water tank with low wastewater input located at the beginning of the Granollers SS. PSBP_L and ASBP_L refer to flow going to primary settling and activated sludge, respectively, whose capacities are never overcome because BP limits wastewater flow going to the treatment plant.

- *Reference:* The system works under normal conditions, which means that the bypass between WWTPs is not used and there is no wastewater sent to the storm water tanks. All wastewater reaches the WWTPs (see that BP and ST_L, ST_G_1 and ST_G_2 are very high) without overloading them. This scenario has been mainly studied to reduce costs.

Table 2 | Parameter set found for each scenario. Most sensitive parameters are in grey

Name	Unit	Reference	Reference improved	Storm	Hydraulic shock	Organic Garriga	Organic Granollers
BP	m^3/d	27,648	43,162.7	16,769.3	24,911.5	33,092.8	55,114.3
ST_L	m^3/d	27,648	38,949.5	28,644.8	54,178.8	76,362.2	86,759.5
ST_G_1	m^3/d	76,800	103,271	11,7382	76,974.1	67,267.4	76,244.9
ST_G_2	m^3/d	30,000	40,488.8	23,371.3	35,943.1	41,735.5	40,117.5
PSBP_L	m^3/d	27,648	60,899.8	25,079.8	45,637.9	36,928.1	55,839.9
PSBP_G	m^3/d	76,800	80,984.1	77,793.9	53,114.7	79,616	79,226.9
ASBP_L	m^3/d	13,994	38,970.6	24,523.6	45,492.3	43,921.4	43,596.7
ASBP_G	m^3/d	34,440	62,566	51,538.4	68,618.6	61,059.4	53,059.4
SAS_L		1.5	0.8	0.98	0.48	0.51	0.99
SAS_G	m^3/d	28,800	23,424.8	37,898	51,076.2	27,656.6	34,991.4
PSW_L	m^3/d	50	100.23	43.19	95.63	107.26	50.86
PSW_G	m^3/d	600	598.44	659.55	377.69	942.49	1064.09
SSW_L	m^3/d	200	325.1	174.47	220.98	320.04	219.196
SSW_G	m^3/d	500	459.73	591.34	771.227	352.71	656.45
NH4_L	g/m^3	1	0.88	0.26	0.48	1.57	1.13
NH4_G	g/m^3	1	1.14	0.81	0.86	0.36	1.15
NO3_L	g/m^3	1	0.87	0.87	1.28	1.5	0.75
NO3_G	g/m^3	1	0.3	2.13	1.31	2.08	1.47

- *Storm:* The hydraulic parameters BP and ST_L become sensitive and are reduced compared with the reference improved situation. This means that more wastewater is sent to the storm water tanks (ST_G1 increases) and the flow that goes to the Granollers WWTP also increases, to maximize the total volume of treated wastewater. The storm water tanks in Granollers are not sensitive as the simulated storm does not cause any CSOs in the Granollers SS. Under wet weather conditions it is important to keep the sludge in the system and adjust recirculations to the new hydraulic conditions. In this case, external recirculation increases to move sludge from the settlers to the reactors (values of SAS_L and G). Moreover internal recirculation in Granollers increases significantly (NO3_G from 0.3 to 2.13 g m^{-3}), which is associated with an increase in the internal recirculation).
- *Hydraulic shock:* This perturbation does not cause significant troubles to the system. In the default case, the two WWTPs are underloaded and the imposed increase of population in this scenario does not completely overload the two WWTPs. In this case, the ASBP_G increases compared with reference improved, meaning the Granollers WWTP has the capacity to treat more wastewater and less wastewater is by-passed to the river after primary treatment.
- *Organic shock Garriga:* The organic load entering the Garriga system is increased and the Garriga WWTP is overloaded. Therefore, the flow of wastewater sent to the Granollers WWTP increases (BP decreases compared to the reference improved situation) and the parameters affecting the performance of the Granollers WWTP (grey parameters in Table 2) become sensitive. For both WWTPs the Mixed Liquor Suspended Solids (MLSS) increase and in order to avoid problems in the settler it is necessary to increase the wastage. This is achieved by decreasing the SAS_L and SAS_G parameters.
- *Organic shock Granollers:* The organic spill overloads the Granollers WWTP. The strategy selected indicates that

Table 3 | Effluent criteria comparison between reference and best set-points for the two sampling points in the river

	DO av	DO min	NH av	NH max
Downstream from Garriga				
Reference	6.81	3.43	1.05	5.95
Best set-points	7.08	5.24	0.72	2.10
Downstream from Granollers				
Reference	6.03	2.29	2.42	15.12
Best set-points	6.53	3.06	1.56	13.34

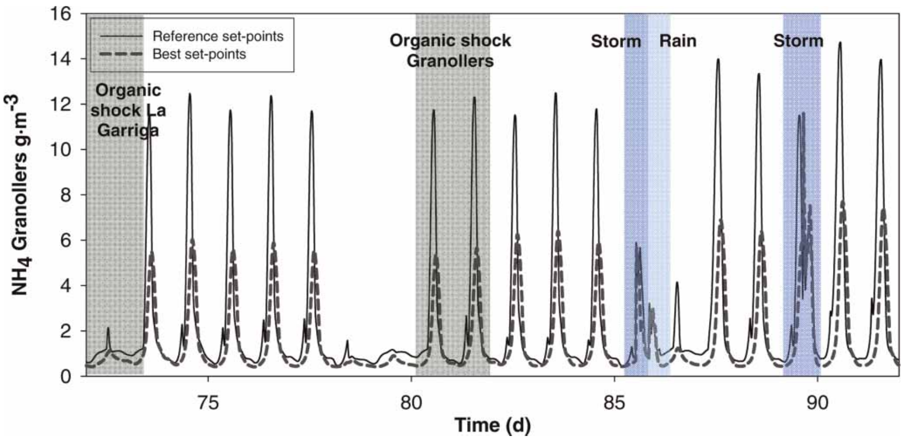

Figure 2 | NH_4^+ concentration downstream from the Granollers WWTP.

ST_G_1 becomes important, which means that more wastewater is sent to the storage tanks located just before the Granollers WWTP (ST_G_1 is much lower compared to the reference improved situation). Once the maximum capacity of the activated sludge system is exceeded the by-pass located after the primary treatment is activated (ASBP_G decreases compared to the reference improved scenario). The impact on the river is minimal as the wastewater receives primary treatment.

A controller was implemented in WEST to identify the status of the system (dry weather, storm, organic shock), and apply the best set-points found for that situation. For instance, by receiving information from the rainfall measurements, when a storm starts, the controller applies the storm set-points. In order to validate the controller efficiency a long-term simulation was run. In that case, a steady-state simulation of 50 days was conducted followed by six weeks of dynamic conditions and using the last three weeks for the evaluation. Between days 72 and 74 there was an organic shock at Garriga, between days 80 and 82 there was an organic shock at Granollers, and between days 85 and 90 there were two storms (up to 72 mm in 5 min) and one rainfall of 12 mm in 1 h. The experiment was run twice, one with the reference set-points (constant operational parameter set for the full period of simulation), and the other with the best applied to each perturbation. An improvement of the water quality and a reduction of costs are achieved for the total period of the simulation (Table 3).

Table 3 shows the effluent criteria for the simulation using reference values, and the simulation using best set-points. From that table it can be concluded that the simulations with best set-points give better results for all criteria at both sampling points. Besides, total cost is reduced by 46.5% (from 31,409.19 € to 16,601.4 € for the total simulation period). Figure 2 presents the NH_4^+ concentration downstream from the Granollers WWTP. Using best set-points, a reduction of 35.54% is achieved (Table 3) and most important is that the peaks are smoothed.

CONCLUSIONS

A model-based approach has been used to find better combinations of operating parameters to improve the performance of the Congost UWS against different types of perturbations. The sensitivity analysis indicates which parameters become important when a perturbation appears. The new set-points of the operating parameters were implemented as a knowledge base in the modelling and simulation platform. The results of the study show that the modelling approach presented here leads to better effluent characteristics and reduced costs, hence, river water quality is improved. This study stresses the importance of managing UWS from an integrated perspective, with a view to maximizing overall benefits.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support from the project CONSOLIDER-NOVEDAR-CSD2007-00055. The authors also wish to thank the *Consorci per a la Defensa de la Conca del riu Besòs*. Pau Prat received the PhD fellowship FI from the Catalan government. Lluís Corominas received the postdoctoral fellowship Juan de la Cierva from the Spanish Ministry of Science and Innovation.

REFERENCES

Benedetti, L., Batstone, D. J., De Baets, B., Nopens, I. & Vanrolleghem, P. A. 2008 Global sensitivity analysis of biochemical, design and operational parameters of the Benchmark Simulation Model no. 2. In: *Proceedings of iEMSs 2008: International Congress on Environmental Modelling and Software*, 7–10 July 2008, Barcelona, Spain.

Benedetti, L., Prat, P., Nopens, I., Poch, M., Turon, C., De Baets, B. & Comas, J. 2009 A new rule generation method to develop a decision support system for integrated management at river basin scale. *Water Science and Technology* **60** (8), 2035–2040.

Butler, D. & Schütze, M. 2005 Integrating simulation models with a view to optimal control of urban wastewater systems. *Environmental Modelling and Software* **20** (4 SPEC. ISS.), 415–426.

Devesa, F., Comas, J., Turon, C., Freixó, A., Carrasco, F. & Poch, M. 2009 Scenario analysis for the role of sanitation infrastructures in integrated urban wastewater management. *Environmental Modelling and Software* **24** (3), 371–380.

Erbe, V., Risholt, L. P., Schilling, W. & Londong, J. 2002 Integrated modelling for analysis and optimisation of wastewater systems – the Odenthal case. *Urban Water* **4** (1), 63–71.

Henze, M., Gujer, W., Mino, T. & van Loosdrecht, M. C. M. 2000 *Activated Sludge Models ASM1, ASM2, ASM2d and ASM3*. IWA, London.

Muschalla, D. 2008 Optimization of integrated urban wastewater systems using multi-objective evolution strategies. *Urban Water Journal* **5** (1), 59–67.

Poch, M., Comas, J., Rodríguez-Roda, I., Sànchez-Marrè, M. & Cortès, U. 2004 Designing and building real environmental decision support systems. *Environmental Modelling and Software* **19** (9), 857–873.

Rauch, W., Bertrand-Krajewski, J. L., Krebs, P., Mark, O., Schilling, W., Schütze, M. & Vanrolleghem, P. A. 2002. Deterministic modelling of integrated urban drainage systems. *Water Science and Technology* **45** (3), 81–94.

Reichert, P., Borchardt, D., Henze, M., Rauch, W., Shanahan, P., Somlyody, L. & Vanrolleghem, P. A. 2001 *River Water Quality Model No. 1 (RWQM1)*. IWA Publishing, London, UK.

Solvi, A.-M., Benedetti, L., Gillé, S., Schlosseler, P., Weidenhaupt, A. & Vanrolleghem, P. A. 2005 Integrated urban catchment modelling for a sewer-treatment-river system in Luxembourg. In: *Proceedings of 10th ICUD*, 21–26 August 2005, Copenhagen, Denmark.

Vanhooren, H., Meirlaen, J., Amerlinck, Y., Claeys, F., Vangheluwe, H. & Vanrolleghem, P. A. 2003 WEST: Modelling biological wastewater treatment. *Journal of Hydroinformatics* **5** (1), 27–50.

Vanrolleghem, P. A., Benedetti, L. & Meirlaen, J. 2005 Modelling and real-time control of the integrated urban wastewater system. *Environmental Modelling and Software* **20** (4), 427–442.

Vrecko, D., Volcke, E. I. P., Jeppsson, U. & Gernaey, K. V. 2007 Evaluation criteria description and example for BSM2. IWA BSM TG Technical Report.

First received 24 February 2011; accepted in revised form 30 June 2011